UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

MARKFORGED INC.,
Petitioner

v.

CONTINUOUS COMPOSITES, INC.,
Patent Owner.

Patent No. 9,987,798

IPR Case Nos.: IPR2022-01218
IPR2022-01220

DECLARATION OF SYLVIA D. HALL-ELLIS, PH.D.

I. INTRODUCTION

1. My name is Sylvia D. Hall-Ellis. I have been retained as an expert by Markforged, Inc. (collectively, "Petitioner").

2. I submit this Declaration to provide my expert opinions regarding the date of public availability or accessibility of three publications attached hereto as Exhibit 1007: *Solid Freedom Fabrication of Continuous Fiber Reinforced Composite Materials*, a Ph.D. dissertation written by Erjian Ma, which was published in the summer of 2001 by Auburn University; Exhibit 1009: *New Metal/Polymer Composites for Fused Deposition Modelling Applications*, a Ph.D. dissertation written by Moustafa Nikzad, which was published in the spring of 2011 by Swinburne University of Technology; and Exhibit 1010: UK Patent Application GB 2213793A, dated August 23, 1989. My Declaration sets forth my opinions in detail and provides the bases for my opinions.

3. I reserve the right to supplement or amend my opinions, and bases for them, in response to any additional evidence, testimony, discovery, argument, and/or other additional information that may be provided to me after the date of this Declaration.

4. I am being compensated for my time spent working on this matter at my normal consulting rate of $325 per hour, plus reimbursement for any additional reasonable expenses. My compensation does not in any way depend on the content

of this Declaration, the substance of my opinions, or the outcome of this litigation. I have no interest in this proceeding or in any of the parties.

5. All of the materials that I considered are discussed explicitly in this Declaration.

II. QUALIFICATIONS & BACKGROUND

6. I am currently an Adjunct Professor in the School of Information at San José State University. I obtained a Master of Library Science from the University of North Texas in 1972, a Master of Professional Studies from the University of Denver in 2014, and a Ph.D. in Library Science and Information Science from the University of Pittsburgh in 1985. Over the last fifty years, I have held various positions in the field of library and information resources. I was first employed as a librarian in 1966 and have been involved in the field of library sciences since, holding numerous positions.

7. I am a member of the American Library Association (ALA) and its Association for Library Collections & Technical Services (ALCTS) Division, and I served on the Committee on Cataloging: Resource and Description (which wrote the new cataloging rules) and as the chair of the Committee for Education and Training of Catalogers and the Competencies and Education for a Career in Cataloging Interest Group. I also served as the founding Chair of the ALCTS Division's Task Force on Competencies and Education for a Career in Cataloging. Additionally, I

have served as the Chair for the ALA Office of Diversity's Committee on Diversity, as a member of the REFORMA National Board of Directors, and as a member of the Editorial Board for the ALCTS premier cataloging journal, *Library Resources and Technical Services*. Currently I serve as a Co-Chair for the Library Research Round Table of the ALA.

8. I have also given over one hundred presentations in the field, including several on library cataloging systems and Machine-Readable Cataloging (MARC) standards. My current research interests include library cataloging systems, metadata, and organization of electronic resources.

9. I have previously served as an expert witness in approximately 600 cases over the course of the last decade. I have extensive experience opining on the publication status of printed references in patent litigations in federal district courts and in proceedings before the Patent Trial and Appeal Board. I have been deposed twenty-one times. I have not testified at trial.

10. During my career I have served as a Dissertation Committee Chair ten times, as a Dissertation Committee member three times, and as a Thesis (Capstone) Chair fourteen times. My personal experiences writing a master's thesis and Ph.D. dissertation and those working with students as a tenured faculty member have provided me with in-depth experience and detailed knowledge of the standardized processes that students follow as part of the culminating process to earn a graduate

degree.

11. The steps that a student takes in pursuit of a graduate degree are predictable and include a predefined number.[1] The Dissertation Chair is responsible for guiding the student and overseeing formal coursework; reviewing research activities; the preparation and defense of the proposal; the selection of committee members; drafting the dissertation document; ensuring the completion of requirements for binding; filing in the institutional digital repository and library; and submitting paperwork with the Graduate Office before specified deadlines in anticipation of conferring the degree. While there are materials that one can read about the process, there is no substitute for going through the process personally, serving as a committee member, and chairing the committee for a student. Understanding the intricacies of the process is essential to determine institutional documents, deadlines, and requirements required at institutions other than the one at which someone works.

12. My full curriculum vitae is attached hereto as Exhibit 1.

III. SCOPE OF OPINIONS

13. I am not an attorney and will not offer opinions on the law. I am, however, rendering my expert opinion on the dates of public accessibility of the references discussed herein, including when and how each reference was

[1] https://study.com/how_to_get_your_phd.html

disseminated or otherwise made available to persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence. In particular, I am rendering opinions on how such persons could have located, before August 29, 2012, the references discussed below.

IV. LEGAL STANDARDS

14. I am informed by counsel and understand that a printed publication is deemed publicly accessible as of the date it was disseminated or otherwise made available such that a person interested in and ordinarily skilled in the relevant subject matter could locate it through the exercise of ordinary diligence.

15. I also understand that public accessibility is a case-by-case determination based on circumstances particular to an individual publication. I further understand, however, that a printed publication is rendered "publicly accessible" if a person of ordinary skill in the art, exercising reasonable diligence, would have located the publication, or would have known to look for it. I further understand that a printed publication is thus rendered "publicly accessible" if it is filed in an online database, like ProQuest's Dissertations and Theses, that is cataloged and indexed such that a person interested in the relevant subject matter could locate it (*i.e.*, I understand that cataloging and indexing by an online database is sufficient, though there are other ways that a printed publication may qualify as publicly accessible). One manner of sufficient indexing is indexing according to

subject matter category. I understand that the cataloging and indexing by a database of a single instance of a particular printed publication is sufficient, even if that database is hosted by a foreign country. I understand that, even if access to a database is restricted, a printed publication that has been cataloged and indexed therein is deemed publicly accessible if the public concerned with the relevant subject matter would know of the printed publication. I also understand that the cataloging and indexing of information that would guide a person interested in the relevant subject matter to the printed publication, such as the cataloging and indexing of an abstract for the printed publication, is sufficient to render the printed publication publicly accessible.

16. I understand that routine business practices, such as general database and library cataloging and indexing practices, can be used to establish an approximate date on which a printed publication became publicly accessible.

V. PERSONS OF ORDINARY SKILL IN THE ART

17. I am informed by counsel that the subject matter of this proceeding relates to additive manufacturing of three-dimensional objects.

18. I am informed by counsel that a "person of ordinary skill in the art at the time of the inventions" is a hypothetical person who is presumed to be familiar with the relevant field and its literature at the time of the inventions. This hypothetical person is also a person of ordinary creativity, capable of understanding

the scientific principles applicable to the pertinent field.

19. I am informed by counsel that Petitioners' expert has opined that persons of ordinary skill in this subject matter or art would have had at least (1) a master's degree in mechanical engineering, materials science, or a related degree, and at least 3-5 years of experience in composite materials or additive manufacturing; or (2) a bachelor's degree in mechanical engineering, materials science, or a related degree, and at least 5-6 years of experience in composite materials or additive manufacturing. I understand that a person with less education, but more relevant practical experience may also meet this standard.

20. It is my opinion that such a person would have been engaged in research, learning, study, and practice in the field, and possibly formal instruction so that bibliographic resources relevant to his or her research would be familiar. Before August 29, 2012, such a person would have had access to an array of long-established print resources in mechanical and electrical engineering as well as online resources providing indexing information, abstracts, and full text services for computer science.

VI. LIBRARY PROFESSIONAL PRACTICES

21. In preparing this Declaration, I used authoritative databases, including the OCLC bibliographic database, the Library of Congress Online Catalog, the Library of Congress Subject Authorities, and ProQuest's *Dissertations and Theses*,

and the UK's *Online Patent Information and Document Inspection Service* database, to confirm citation details of the various publications discussed.

22. ***Indexing***. A researcher may discover material relevant to his or her topic in a variety of ways. One common means of discovery is to search for relevant information in an index of periodical and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from the publisher, a bookstore, a document delivery service, or other provider. Sometimes, the date of a document's public accessibility will involve both indexing and library date information. However, date information for indexing entries is often unavailable. This is especially true for online indices.

23. Indexing services use a wide variety of controlled vocabularies to provide subject access and other means of discovering the content of documents. The Library of Congress Subject Authorities includes standard forms of terms and cross references that are included in bibliographic records. Subject headings are terms that an individual seeking a document regardless of format can enter in the search bar of the online catalog. Subjects also connect an authenticated term (one included in the Library of Congress subject headings list) with related, broader, and narrower terms.

24. Online indexing services commonly provide bibliographic information, abstracts, and full-text copies of the indexed publications, along with a list of the

documents cited in the indexed publication. These services also often provide lists of publications that cite a given document. A citation of a document is evidence that the document was publicly available and in use by researchers no later than the publication date of the citing document. Prominent indexing services include *Scopus,* the *IEEE Xplore* database, the *ACM Digital Library, Google Scholar,* the *Internet Archive,* and ProQuest databases for dissertations, theses, journals, and digital reference materials.

25. Databases and digital repositories like those mentioned in paragraph 25 provide search capabilities through title, author, subject, keyword, and standard numbers (ISBN and ISSN) that enable information professionals and individuals to locate books, articles, conference papers, and other publications. The databases and digital repositories include retrospective collections of scanned or digitized materials and are updated regularly. Collegiate and university studies at the undergraduate and graduate level require that students develop familiarity and proficiency using indexing services, databases, and digital repositories.

VII. PUBLICATION

A. Publication 1, Exhibit 1007, *Solid Freedom Fabrication of Continuous Fiber Reinforced Composite Materials* by Erjian Ma ("Ma")

26. Attached hereto as Exhibit 1007 is a dissertation, *Solid Freedom Fabrication of Continuous Fiber Reinforced Composite Materials* by Erjian Ma

(hereafter "Ma"). Exhibit 1007 includes a true and correct copy of the title page, table of contents, and text from the ProQuest[2] database *Dissertations and Theses*.[3] The dissertation title page shows a date of August 6, 2001. I obtained this dissertation from UMI's database *Dissertations and Theses* and made the copies which comprise Exhibit 1007. Specifically, the text is complete; no pages are missing, and the text on each page flows seamlessly from one page to the next; further, there are no visible alterations to the document. Exhibit 1007 was found within the custody of the custodian to whom the author granted permission to make copies and reproductions. Exhibit 1007 is a true and correct copy in a condition that creates no suspicion about its authenticity.

27. A dissertation exhibits the following characteristics: the dissertation is attributed to a single creator or author (in this case Erjian Ma) who affixes a date of creation (in this case August 6, 2001), recognizes a committee of three or more faculty members with their affiliations (in this case Professors Bor. Z. Jang, Dan B. Marghitu and Sabit Adanur), a list of scholarly references (in this case 76 references

[2] ProQuest is the corporate global information-content and technology company founded as University Microfilms (UMI) in 1939. Over the last 80 years, the firm has grown through corporate acquisitions and product development to be a major supplier globally of databases and digital products (https://www.proquest.com/).

[3] https://about.proquest.com/en/products-services/pqdtglobal

in "References" on pages 221-227), and publishes the document through the higher education institute conferring the doctoral degree (in this case the Department of Mechanical Engineering at the Auburn University).

28. Attached hereto as Attachment 1a is a true and correct copy of the online catalog record for this dissertation from the Auburn University Library. The catalog record indicates that copies of the dissertation are located in the Main Library and off-site in the Thesis Special Collection. I personally identified and retrieved the library catalog record which is Attachment 1a.

29. Attached hereto as Attachment 1b is a true and correct copy of the MARC record for the dissertation, *Solid Freedom Fabrication of Continuous Fiber Reinforced Composite Materials* by Ma obtained from the OCLC bibliographic database. I personally identified and retrieved the MARC record that is Attachment 1b. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For Attachment 1b, that library code is "AAA," which means that the MARC record for this dissertation was created at the Auburn University Library. As can be seen in the "Entered" field in the MARC record for this exhibit, a cataloger at the Auburn University Library created OCLC record number 48433505 on November 15, 2001.

30. Attachment 1b further includes an entry in field 050 ("TA418.9.C6 $b M2 2001")—as described above, this includes a subject matter classification number

consistent with the Library of Congress classification system (analogous to the Dewey Decimal classification system). Attachment 1b includes three descriptor terms reading "Fibrous composites" (see Attachment 1c, Library of Congress subject heading sh85048037), "Composite materials" (see Attachment 1d, Library of Congress subject heading sh85029397), and "Solid freeform fabrication" (see Attachment 1e, Library of Congress subject heading sh93004626) in the 650 fields. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 1b was indexed by indexed according to its subject matter by virtue of at least two independently sufficient classifications: the field 050 entry and the field 650 entries. Further, as of November 15, 2001, the MARC record attached hereto as Attachment 1b was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that added this book to its collection, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

31. Attachment 1b indicates that the Ma dissertation as cataloged at the Auburn University is currently available from that institution. In view of above, this dissertation was publicly available no later than November 15, 2001, because by that date it had been received, cataloged, and indexed at the Auburn University Library, placed in the custody of UMI, and made part of the OCLC bibliographic database.

For these reasons, it is my opinion that Exhibit 1007 was published and accessible to the public no later than November 15, 2001.

B. Publication 2, Exhibit 1009, *New Metal/Polymer Composites for Fused Deposition Modelling Applications* by Mostafa Nikzad ("Nikzad")

32. Attached hereto as Exhibit 1009 is a dissertation, *New Metal/Polymer Composites for Fused Deposition Modelling Applications* by Mostafa Nikzad (hereafter "Nikzad"). Exhibit 1009 includes a true and correct copy of the title page, table of contents, and text from the Swinburne Research Bank[4] at the Swinburne University of Technology (Hawthorn, Melbourne, Australia). The dissertation title page shows a date of May 2011. I obtained this dissertation from the Swinburne Research Bank and made the copies which comprise Exhibit 1009. Specifically, the text is complete; no pages are missing, and the text on each page flows seamlessly from one page to the next; further, there are no visible alterations to the document. Exhibit 1009 was found within the custody of the custodian to whom the author granted permission to make copies and reproductions. Exhibit 1009 is a true and correct copy in a condition that creates no suspicion about its authenticity.

33. A dissertation exhibits the following characteristics: the dissertation is attributed to a single creator or author (in this case Mostafa Nikzad) who affixes a

[4] https://researchbank.swinburne.edu.au/items/ffe96def-3bef-4387-9666-153a64e7d6d6/1/

date of creation (in this case May 2011), recognizes a committee of three or more faculty members with their affiliations (in this case Professors S. H. Masood, Igor Sbarski, and Andrew Groth), a list of scholarly references (in this case 324 references in "References" on pages 214-236), and publishes the document through the higher education institute conferring the doctoral degree (in this case the Department of Engineering & Industrial Sciences at the Swinburne University of Technology).

34. Attached hereto as Attachment 2a is a true and correct copy of the online catalog record for this dissertation from the Swinburne University of Technology Library. The catalog record indicates that the dissertation is available as an open access document from the Swinburne research Bank. I personally identified and retrieved the library catalog record which is Attachment 2a.

35. Attached hereto as Attachment 2b is a true and correct copy of the MARC record for the dissertation, *New Metal/Polymer Composites for Fused Deposition Modelling Applications* by Nikzad obtained from the OCLC bibliographic database. I personally identified and retrieved the MARC record that is Attachment 2b. As previously noted, the library that created the record is recorded in field 040 with a unique library code. For Attachment 2b, that library code is "LE0," which means that the MARC record for this dissertation was created at the Swinburne University of Technology Library. As can be seen in the "Entered" field in the MARC record for this exhibit, a cataloger at the Swinburne University of

Technology Library created OCLC record number 742215971 on September 28, 2011.

36. Attachment 2b includes five descriptor terms reading "Fused deposition," "Manufacturing," Metal/polymer composites," "rapid prototyping," and "Rapid tooling" in the 653 fields. Thus, as of its cataloging, the publication corresponding to the MARC record attached hereto as Attachment 2b was indexed by indexed according to its subject matter by virtue of the field 653 entries. Further, as of September 28, 2011, the MARC record attached hereto as Attachment 2b was accessible through any library with access to the OCLC bibliographic database or the online catalog at a library that added this book to its collection, which means that the corresponding publication was publicly available on or before that same date through any library with access to the OCLC bibliographic database or through an individual library.

37. Attachment 2b indicates that the Nikzad dissertation as cataloged at the Swinburne University of Technology Library is currently available from that institution. In view of above, this dissertation was publicly available no later than September 28, 2011, because by that date it had been received, cataloged, and indexed at the Swinburne University of Technology Library, placed in the custody of the Swinburne Research Bank, and made part of the OCLC bibliographic database. For these reasons, it is my opinion that Exhibit 1009 was published and

accessible to the public no later than September 28, 2011.

C. Publication 3, Exhibit 1010, Method for Manufacturing a Three-Dimensionally Twisted Rotor Blade Airfoil, GB 2213793 ("Wöhrl")

38. Attached hereto as Exhibit 1010 is a UK patent application, *Method for Manufacturing a Three-Dimensionally Twisted Rotor Blade Airfoil* invented by Dr. Berhard Wöhrl and filed by MTU Motoren-und Turbinen-Union Müchen GmbH (hereafter "Wöhrl"). Exhibit 1010 includes a true and correct copy of the patent application from the UK *Online Patent Information and Document Inspection Service* database.[5] The first page shows a filing date of November 10, 1988, and a publication date of August 23, 1989. I obtained this patent from the Espacenet Patent Search website[6] and made the copies which comprise Exhibit 1010.[7] Specifically, the text is complete; no pages are missing, and the text on each page flows seamlessly from one page to the next; further, there are no visible alterations to the document. Exhibit 1010 was found within the custody of the custodian to whom the author granted permission to make copies and reproductions. Exhibit 1010 is a true and correct copy in a condition that creates no suspicion about its authenticity.

[5] https://www.ipo.gov.uk/p-ipsum/Case/ApplicationNumber/GB8826325.6

[6] https://worldwide.espacenet.com/searchResults?DB=EPODOC&PN=GB2213793&ST=advanced&compact=false

[7] https://worldwide.espacenet.com/publicationDetails/originalDocument?FT=D&date=19890823&DB=EPODOC&locale=&CC=GB&NR=2213793A&KC=A&ND=6

39. Attachment 3a indicates that the Wöhrl patent application is available from the Intellectual Property Office in the Patents, Trade Marks, Copyright and Designs of the United Kingdom government. In view of above, this patent application was publicly available no later than August 23, 1989, because by that date it had been received, cataloged, and indexed in the UK *Online Patent Information and Document Inspection Service* and placed in the custody of the Crown. For these reasons, it is my opinion that Exhibit 1010 was published and accessible to the public no later than August 23, 1989.

VIII. SUMMARY OF OPINIONS

40. In view of the foregoing, it is my opinion that the publication described above was publicly available no later than the corresponding date listed in the table below:

Exhibit	Publication	Publicly Available No Later Than
1007	Ma, Erjian. *Solid Freedom Fabrication of Continuous Fiber Reinforced Composite Materials*. Dissertation. Auburn, AL: Auburn University, c2001.	November 15, 2001
1009	Nikzad, Mostafa. *New Metal/Polymer Composites for Fused Deposition Modelling Applications*. Dissertation. Hawthorn, Melbourne, Australia: Swinburne University of Technology, 2011.	September 28, 2011
1010	GB2213793 - *Method for manufacturing a three-dimensionally twisted rotor blade airfoil*. Filed November 10, 1988; publication date August 23, 1989.	August 23, 1989

41. In signing this Declaration, I recognize that the Declaration will be filed as evidence in a case before the Patent Trial and Appeal Board of the United States Patent and Trademark Office. I also recognize that I may be subject to cross-examination in the case and that cross-examination will take place within the United States. If cross-examination is required of me, I will appear for cross-examination within the United States during the time allotted for cross-examination.

42. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

May 24, 2022

Sylvia D. Hall-Ellis, Ph.D.

Attachment 1a

Markforged Ex. 1013
Markforged v. Continuous Composites, IPR2022-01218

Solid freedom fabrication of continuous fiber reinforced composite materials / Erjian Ma.

Main Author:	Ma, Erjian, 1960-
Corporate Author:	Auburn University. Dissertations. Mechanical Engineering
Format:	Thesis, Book
Language:	English
Published:	2001.
Subjects:	Composite materials. Fibrous composites. Solid freeform fabrication.

Holdings Description Staff View

LEADER	01171ctm a2200361Ia 4500		
001	1963989		
005	20200308142810.0		
008	011115s2001 xx a b 000 0 eng d		
035			**|a** (OCoLC)ocm48433505
040			**|a** AAA **|c** AAA
049			**|a** AAAA
090			**|a** TA418.9.C6 **|b** M2 2001
100	1		**|a** Ma, Erjian, **|d** 1960-
245	1	0	**|a** Solid freedom fabrication of continuous fiber reinforced composite materials / Erjian Ma.
260			**|c** 2001.
300			**|a** xiii, 232 leaves : **|b** ill. (some col.); **|c** 29 cm.
336			**|a** text **|2** rdacontent

337			**|a** unmediated **|2** rdamedia
338			**|a** volume **|2** rdacarrier
500			**|a** Abstract.
500			**|a** Vita.
502			**|a** Thesis (Ph. D.)--Auburn University, 2001.
504			**|a** Includes bibliographical references (221-227).
591			**|a** qthes
650		0	**|a** Composite materials.
650		0	**|a** Fibrous composites.
650		0	**|a** Solid freeform fabrication.
710	2		**|a** Auburn University. **|b** Dissertations. **|b** Mechanical Engineering
948			**|a** wf:ff 11/15/01, ff (xpo, 11/15/01,)ff
994			**|a** E0 **|b** AAA
999			**|a** 1963989
852	0	0	**|b** olaf **|h** TA 418.9 .C6 M2 2001 **|z** Non-Circulating.
852	0	0	**|b** 8main,4th **|h** TA 418.9 .C6 M2 2001

Attachment 1b

Markforged Ex. 1013
Markforged v. Continuous Composites, IPR2022-01218

OCLC 48433505 **No holdings in XXX - 1 other holding**

Books

						Rec Stat		**Entered**	200111 15	**Replaced**	20190914215608.1
Type	t	**ELvl**	l	**Srce**	d	**Audn**		**Ctrl**		**Lang**	eng
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		Cont	bm	**GPub**		**LitF**	0	**Indx**	0		
Desc	a	**Ills**	a	**Fest**	0	**DtSt**	s	**Dates**	2001 ,		

040 AAA $b eng $c AAA $d OCLCQ $d OCLCF $d OCLCO $d OCLCQ $d OCLCO $d OCL
050 4 TA418.9.C6 $b M2 2001
090 $b
100 1 Ma, Erjian, $d 1960-
245 10 Solid freedom fabrication of continuous fiber reinforced composite materials / $c Erjian Ma.
264 0 $c 2001.
300 xiii, 232 leaves : $b illustrations (some color) ; $c 29 cm
336 text $b txt $2 rdacontent
337 unmediated $b n $2 rdamedia
338 volume $b nc $2 rdacarrier
502 $b Ph. D. $c Auburn University $d 2001
500 Abstract.
500 Vita.
504 Includes bibliographical references (221-227).
650 0 Fibrous composites.
650 0 Composite materials.
650 0 Solid freeform fabrication.
650 7 Composite materials. $2 fast $0 (OCoLC)fst00871682
650 7 Fibrous composites. $2 fast $0 (OCoLC)fst00923679
650 7 Solid freeform fabrication. $2 fast $0 (OCoLC)fst01125413
655 7 Academic theses. $2 fast $0 (OCoLC)fst01726453
655 7 Academic theses. $2 lcgft

Attachment 1c

Markforged Ex. 1013
Markforged v. Continuous Composites, IPR2022-01218

The Library of Congress

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LIBRARY OF CONGRESS AUTHORITIES

The Library has opened access to the reading rooms by appointment only. More. The Jefferson Building has reopened to visitors via timed, ticketed entry. More.

Help | New Search | Search History | Headings List | Start Over

◀ Previous Next ▶

MARC Display | Labelled Display

LC control no.: sh 85048037
LCCN Permalink: https://lccn.loc.gov/sh85048037
HEADING: Fibrous composites

000 00739cz a2200265n 450
001 4699749
005 20120323073657.0
008 860211i| anannbabn |b ana
010 __ |**a** sh 85048037
035 __ |**a** (DLC)sh 85048037
035 __ |**a** (DLC)7132193
035 __ |**a** (DLC)sp 85048037
035 __ |**a** (DLC)356616
040 __ |**a** DLC |**c** DLC |**d** DLC
053 _0 |**a** TA418.9.C6 |**c** General
053 _0 |**a** TA481.5 |**c** Metallic composites
150 __ |**a** Fibrous composites
450 __ |**a** Fiber composites
450 __ |**a** Fiber-reinforced composites
450 __ |**a** Filament reinforced composites
450 __ |**a** Reinforced fibrous composites
550 __ |**w** g |**a** Composite materials
670 __ |**a** NASA Thes. |**b** (Fiber composites)
906 __ |**t** 0715 |**u** te04 |**v** 0
953 __ |**a** xx00 |**b** ta21

◀ Previous Next ▶

Save, Print or Email Records (View Help)

Select Download Format: Text (Labelled Display) | Press to SAVE or PRINT

Markforged Ex. 1013
Markforged v. Continuous Composites, IPR2022-01218

Email Text (Labelled Display) to:
Press to SEND EMAIL

Help - Search - Search History - Headings List - Start Over

Library of Congress
URL: https://www.loc.gov/

Mailing Address:
101 Independence Ave, S.E.
Washington, DC 20540

Library of Congress Authorities
URL: http://authorities.loc.gov/
Library of Congress Online Catalog
URL: https://catalog.loc.gov/

Questions, comments, error reports: Contact Us

Markforged Ex. 1013
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Attachment 1d

Markforged Ex. 1013
Markforged v. Continuous Composites, IPR2022-01218

The Library of Congress

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LIBRARY OF CONGRESS AUTHORITIES

The Library has opened access to the reading rooms by appointment only. More. The Jefferson Building has reopened to visitors via timed, ticketed entry. More.

Help | New Search | Search History | Headings List | Start Over

◀ Previous Next ▶

MARC Display | Labelled Display

LC control no.: sh 85029397
LCCN Permalink: https://lccn.loc.gov/sh85029397
HEADING: Composite materials

000 00635cz a2200241n 450
001 4681673
005 20120323071033.0
008 860211i| anannbabn |a ana
010 __ |**a** sh 85029397
035 __ |**a** (DLC)sh 85029397
035 __ |**a** (DLC)28358
040 __ |**a** DLC |**c** DLC |**d** DLC
053 _0 |**a** TA418.9.C6
150 __ |**a** Composite materials
450 __ |**a** Composites (Materials)
450 __ |**a** Multiphase materials
450 __ |**a** Reinforced solids
450 __ |**a** Solids, Reinforced
450 __ |**a** Two phase materials
550 __ |**w** g |**a** Materials
670 __ |**a** TEST |**b** (Composite materials UF Composites)
906 __ |**t** 9525 |**u** te05 |**v** 0
953 __ |**a** xx00 |**b** td14

◀ Previous Next ▶

Save, Print or Email Records (View Help)

Select Download Format: Text (Labelled Display) Press to SAVE or PRINT

Email Text (Labelled Display) to:
Press to SEND EMAIL

Markforged Ex. 1013
Markforged v. Continuous Composites, IPR2022-01218

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Attachment 1e

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LC control no.: sh 93004626

LCCN Permalink: https://lccn.loc.gov/sh93004626

HEADING: Solid freeform fabrication

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010 __ |**a** sh 93004626

035 __ |**a** (DLC)sh 93004626

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040 __ |**a** DLC |**c** DLC |**d** DLC

150 __ |**a** Solid freeform fabrication

450 __ |**a** Fabrication, Solid freeform

450 __ |**a** Freeform fabrication, Solid

450 __ |**a** Layered manufacturing (Materials processing)

450 __ |**a** Manufacturing, Solid freeform

550 __ |**w** g |**a** Computer integrated manufacturing systems

550 __ |**w** g |**a** Three-dimensional printing

670 __ |**a** Work cat.: 93-642852: Solid freeform fabrication symposium proceedings (a fully integrated approach to design, materials processing, and manufacturing)

670 __ |**a** Engr. index: |**b** v. 89, Pt. IX, p. 8784, under Solid freeform fabrication (several articles)

670 __ |**a** Engineering Village, viewed February 12, 2016 |**b** (Solid freeform fabrication redirects to: Layered manufacturing)

670 __ |**a** Wkipedia, viewed February 12, 2016 |**b** (Solid freeform fabrication redirects to 3D printing; electron beam freeform fabrication and laser freeform fabrication are listed as subtypes)

670 __ |**a** Inspec, viewed Feb. 12, 2016 |**b** (uncontrolled term: Laser solid freeform fabrication)

670 __ |**a** Applied science and technology abstracts, viewed February 12, 2016 |**b** (both headings are controlled: Three-dimensional printing; Solid freeform fabrication

675 __ |**a** ASTI; |**a** NASA; |**a** Web. 3

906 __ |**t** 9328 |**u** te07 |**v** 0
910 __ |**a** Proposal saved by tc03 on 03/09/2016 at 09:09:06
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Attachment 2a

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DISSERTATION

New metal/polymer composites for fused deposition modelling applications

Nikzad, Mostafa

Swinburne University of Technology; 2011

View Online

Full text availability

Link to Resource

Details

Title

New metal/polymer composites for fused deposition modelling applications

Author/Creator

Nikzad, Mostafa

Creation Date

2011

Publisher

Swinburne University of Technology

Description

Fused Deposition Modelling (FDM) has been a leading rapid prototyping process but it has been mostly limited to use in making prototypes for design verification and functional testing applications. The commercial process can currently fabricate parts only in limited types of thermoplastics such as ABS and Polycarbonate. Very little efforts have been made to increase the range of FDM materials to include metals or metal based composites for wider application domain beyond just design and verification. This thesis presents new research in this direction by developing novel metal based composites for use in FDM technology. The principal objective of this research is to develop new metal/polymer composite materials for direct use in the current Fused Deposition Modelling rapid prototyping platform with long term aim of developing direct rapid tooling on the FDM system. Using such composites, the direct rapid tooling will allow fabrication of injection moulding dies and inserts with desired thermal and mechanical properties suitable for using directly in injection moulding machines for short term or long term production runs. The new metal/polymer composite material developed in this research work involves use of iron particles and copper particles in a polymer matrix of ABS material, which offers much improved thermal, electrical and mechanical properties enabling current Fused Deposition Modelling technique to produce rapid functional parts and tooling. Higher thermal conductivity of the new metal/polymer composite material coupled with implementation of conformal cooling channels enabled by layer-by layer fabrication technology of the Fused Deposition Modelling will result in tremendously improved injection cycles times, and thereby reducing the cost and lead time of injection moulding tooling. Due to highly metal-particulate filled matrix of the new composite material, injection tools and inserts made using this material

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on Fused Deposition Modelling, demonstrate a higher stiffness comparing to those made out of pure polymeric material resulting in withstanding higher injection moulding pressures. Moreover, metallic filler content of the new composite allows processing of functional parts with electrical conductivity and in case of using ferromagnetic fillers, namely as fine iron powders, it introduces magnetic properties, which will make FDM-built components suitable for electronic applications specifically whereby electro-magnetic shielding is of high interest. In this research project, a full characterization of the newly developed metal/polymer composites including rheological, thermal, mechanical and electrical properties has been investigated. Mathematical models have been employed in order to predict and optimize the viscous behaviour of metal/polymer composite during the course of deposition through the FDM nozzle. In order to predict the main flow parameters of the metal/polymer composites including pressure, temperature, and velocity fields through the FDM liquefier head, 2-D and 3-D numerical analysis of melt flow behaviour of acrylonitrile- butadiene-styrene (ABS) and Iron composite as a representative metal/polymer material has been carried out using ANSYS FLOTRAN and ANSYS CFX commercial codes. Results of numerical analysis have been verified by the developed empirical mathematical models. A variety of advanced techniques have been employed to fully characterize the newly developed metal/polymer composites in order to successfully process filaments for fabrication of injection mould tooling inserts. Morphological effects of metallic fillers and surfactants as well as variation of volume fractions of constituents on the viscoelastic properties of the new composite material have also been investigated. Filaments of the filled ABS has been fabricated and characterized to verify the possibility of prototyping and direct tooling using the new material on the current FDM machine. Major contributions of the thesis include: • Development of a new metal/polymer composite material for functional parts and rapid tooling solutions on Fused Deposition Modeling platform. • Development of mathematical models for predicting viscous behavior of three-component composite flow through capillary extrusion process. • Full rheological, thermal, mechanical and electrical characterization of the new metal/polymer composites. • Combining experimental and numerical methodology (tools) to predict melt flow behavior of metal/polymer composite through Fused Deposition Modeling. • Fabrication of stiff and flexible filaments of the metal-polymer composites as feedstock material for direct rapid tooling via Fused Deposition Modeling. • Fabrication of functional parts and inserts of new metal/polymer composites successfully and directly on the FDM3000 system. • Production of plastic parts using injection moulding tools made by Direct FDM-based Rapid Tooling Process.

Identifier
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653 Fused deposition
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653 Rapid prototyping
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655 4 Thesis (PhD)
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Attachment 3a

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Intellectual Property Office

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GB2213793 - Method for manufacturing a three-dimensionally twisted rotor blade airfoil

Case Details

Application Number	GB8826325.6
Application Source	Form 1
Publication Number	GB2213793
Status	Terminated before grant
Filing Date	10 November 1988
Publication Date	23 August 1989
Not In Force Date	15 May 1990
Priority Claimed	22 December 1987 in Germany - Document: 3743485
Application Title	Method for manufacturing a three-dimensionally twisted rotor blade airfoil
Address for Service	WITHERS & ROGERS Goldings House 2 Hays Lane LONDON SE1 2HW United Kingdom [ADP Number 00001776001]
Applicant / Proprietor	MTU MOTOREN-UND TURBINEN-UNION MÜNCHEN GMBH Incorporated in the Federal Republic of Germany Postfach 50 06 40 Dachauer Strasse 665 8000 München 50 Germany [ADP Number 00615849001]
Inventor	BERNHARD WÖHRL Planegger Strasse 21 8035 Gauting Germany [ADP Number 04229027001]

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Exhibit 1

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CURRICULUM VITAE SYLVIA D. HALL-ELLIS

EDUCATION

Ph.D., University of Pittsburgh, Pittsburgh, Pennsylvania, 1985
M.P.S., University of Denver, Denver, Colorado, 2014
Post Graduate Studies, University of Texas – San Antonio, Texas, 1975-1976
M.L.S., University of North Texas, Denton, Texas, 1972 B.A.,
Rockford University, Rockford, Illinois, 1971

PROFESSIONAL EXPERIENCE

1981- **Consultant for higher education, non-profit organizations, and corporations.**

2002- **Adjunct Professor, School of Information, San José State University, San José, California.** Serve as part-time faculty member teaching graduate students in technical services (cataloging, bibliographic control, classification), "core courses," and special topics.

2014-2016 **Director, Grants and Resource Development, Colorado Community College System.** Provided leadership and vision to foster the continued growth of rigorous scholarship, innovative projects, and creative work for statewide system, 13 campuses, and 50 teaching sites serving 155,000 students. Responsible for leadership and ensured efficient functioning of contract and grants in compliance with state & federal requirements and successful implementation and management. Served as a subject matter expert and liaison for college Grant Directors for all issues relating to grants and subcontracts.

2010-2014 **Senior Grant Administrator, Morgridge College of Education, University of Denver (Colorado).** Provided leadership and vision to foster continued growth of rigorous scholarship, innovative research, and creative work in the Morgridge College of Education. Ensure that contract and grants processes function effectively and efficiently for 60 faculty and researchers with a focus on the successful progression and efficient management of grants totaling $13M. Worked effectively and collegially with Department Chairs and Program Coordinators on operational grant-related management activities and with a broad range of internal and external constituencies. Supported the dissemination and promotion of faculty research and scholarship to outside constituents at conferences and through publications. Assisted Principal Investigators and grant project teams by coaching, mentoring, and financial management.

2011-2013 **Interim Director & Assistant Dean, Westminster Law Library, Sturm College of Law, University of Denver.** Planned, organized, and directed all administrative activities for the library serving students, faculty, and alumni; oversaw the employment, retention, promotion, transfer and termination of library personnel; represented the library at professional conferences and public meetings; created and promoted a climate and culture of acceptance for new programs and services, a positive high-quality image of the law library, and that reflect the organization's values, encourage excellent performance, and reward high productivity and innovation; provided leadership and set strategic direction of the organization; ensured that the library provided excellent customer service through solution-oriented staff response to patron needs and by responsiveness and continuous improvement of the organization; promoted, developed, and maintained positive working relationships with colleagues and customers including key stakeholders and groups, higher education institutions, the legal community, other regional libraries and districts statewide, and national library organizations.

2007-2014 **Associate Professor, Library & Information Science, Morgridge College of Education, University of Denver (Colorado).** Served in leadership role and worked collaboratively in program, college, campus and community environments. Advised and supervised students, taught core and specialized courses at the graduate level in an integrative, student-centered learning environment. Served on LIS, College, and University committees, and maintained working relationships with colleagues in other academic units and information professionals in the Rocky Mountain region and beyond. Served on and chair doctoral student dissertation committees. Oversaw and facilitated the College and LIS graduate student association.

2002-2007 **Assistant Professor, Library & Information Science, College of Education, University of Denver (Colorado).** Served as tenure-track faculty member teaching graduate students in "core courses," resource description and access, service learning, and independent studies. Advised graduate students, participate on LIS and College committees, and serve on doctoral student dissertation committees. Oversaw and facilitated the LIS graduate student association and alumni association.

2000-2002 **Affiliate Faculty, Library & Information Science, College of Education, University of Denver (Colorado).** Served as part-time faculty member teaching graduate students in technical services (cataloging, bibliographic control, classification), "core courses," and special topics. Oversaw and facilitated the LIS graduate student association and alumni association.

2000-2001 **Special Assistant to the Secretary's Regional Representative, U.S. Department of Education, Region VIII, Denver, Colorado.** Served as the principal advisor and representative of the U. S. Secretary of Education's Regional Representative (SRR). Ensured the implementation of major goals of the SRR and the Secretary. Provided leadership on behalf of the SRR in contacts with high-level officials in Region VIII requiring sensitive policy interpretation in communication with senior Department officials to solve problems and resolve issues raised by State and local education officials. Served as the primary contact for School-to-Work/Career, Children's Health Insurance Program, and Safe and Drug-Free Schools. Delivered technical assistance to local education agencies and institutions of higher education in technology, professional development, and school construction.

1999-2000 **Catalog Librarian, Jefferson County Public Library, Lakewood, Colorado.** Performed original, copy cataloging and classification of library materials (English and Spanish) using standard library protocols; completed original descriptive cataloging and subject analysis; enhanced brief catalog and authority records in III.

1997-1999 **Development Officer, McREL International, Aurora, Colorado.** Served as senior member of corporate management team in strategic planning, development of proposals and contracts, implementation, and evaluation of new services, products, and programs for educational agencies. Provided creative leadership to corporate committees to solicit ideas, identify goals and objectives, plan, develop, present, and evaluate professional development opportunities.

1995-1997 **Education Specialist, Education Service Center, Region One, Edinburg, Texas.** Served as member of Administrative Cabinet team in strategic planning, development of proposals and contracts, implementation, and evaluation of telecommunications capabilities, services, products, and programs for 40 school districts serving 283,000 students in 7 counties. Provided creative leadership to regional and state committees to solicit ideas, identify strategic goals and objectives, plan, develop, present, and evaluate funding opportunities and professional development for 400 librarians.

1993-1996 **Assistant Professor of Library Science, Sam Houston State University, Huntsville, Texas.** Served a faculty member teaching 400 graduate students in technical services (cataloging, bibliographic control, classification), automation, and networking. Participated in distance education program and coordinated annual conference. Conducted university and Texas Library Association-funded field research focused on library collection development and academic achievement.

1992-1993 **Head Librarian, Rocky Mountain College of Art & Design, Denver, Colorado.** Responsible for the daily operation, selection and acquisition of materials, formulation of policies for library operations, media center, and photography/slides archives. Designed and implemented library automation and delivery of electronic resources to college community.

1981-1985 **Development Officer, PRLC, Inc., Pittsburgh, Pennsylvania.** Served as senior member of corporate management team in strategic planning, development of proposals and contracts, implementation, and evaluation of new services, products, and programs for 100 institutional member organizations. Coordinated the development of proposals and contracts totaling $4,000,000 annually. Provided creative leadership to corporate committees to solicit ideas, identify goals and objectives, plan, develop, present, and evaluate professional development opportunities.

1981 **Director of Library Development, Pennsylvania Department of Education, Harrisburg, Pennsylvania.** Responsible for statewide development, technical assistance, professional development, resource sharing, children's services, institutional library services, networking, and state aid program for all libraries throughout the Commonwealth. Functioned as liaison to Governor's Advisory Council, LSCA Advisory Council, District Administrators, private colleges, universities, consortia managers, and network directors. Supervised $14,000,000 formula-based state aid program and $3,000,000 grant awards to individual libraries, consortia, and networks.

1978-1981 **Assistant Director, Southern Tier Library System, Corning, New York.** Coordinated operation of system-wide programs (technical assistance, professional development, resource sharing, technical services, outreach) to 40 public libraries in 5 counties serving 500,000 residents. Solicited ideas, identified goals, sponsored, and evaluated professional development opportunities and technical assistance sessions.

1976-1978 **Division Librarian for Technical Services, Corpus Christi Public Libraries, Corpus Christi, Texas.** Provided leadership in acquisitions, cataloging, serials control, and processing for main library and 4 branches serving 250,000 residents. Participated as senior member of library management team. Compiled and prepared technical evaluations, reports, and statistical analyses of Division operations to measure the achievement and cost of annual goals, objectives, and staff performance.

1975-1976 **System Coordinator, San Antonio Major Resource Center, San Antonio, Texas.** Served as senior member of the management team for District X Office, charged to provide technical assistance, resource sharing, media services, and professional development to librarians and staff representing 30 public library jurisdictions in 21 counties serving 1,500,000 residents. Functioned as liaison to System Director, staff, and members of governing bodies with the System Board of Directors and the Texas State Library and Historical Commission. Prepared LSCA grant applications and monitored awards totaling $1,100,000 annually.

1973-1975 **Bilingual Branch Librarian, San Antonio Public Library, San Antonio, Texas.** Worked as librarian providing reference, information, and readers' advisory services in branch serving 50,000 Spanish-speaking residents in southwest San Antonio. Participated in collection development and resource acquisition activities, specializing in children's work, Spanish language resources, and multicultural studies.

1972-1973 **Librarian, Holding Institute, Laredo, Texas.** Worked as high school librarian serving 500 boarding students in Spanish-speaking environment of private school. Provided reference, research assistance, and library instruction to students and 35 faculty members.

1966-1971 **Rockford Public Library, Rockford, Illinois.** Worked in branches as part-time as a Library Assistant, Clerk, and Page in city library serving 150,000 residents.

PUBLICATIONS

Editor-reviewed Monographs (Completed and in Progress)

Hall-Ellis, Sylvia D., and Mary Beth Weber. *Contemporary Cataloging in an RDA Environment: A Handbook for Students and Practitioners.* Chicago, IL: American Library Association. Under contract & In development.

RDA Testing: Lessons Learned and Challenges Revealed. Sylvia D. Hall-Ellis and Robert O. Ellett, Jr., eds. Binghamton, N.Y.: Haworth, 2012. 128 p.

Hall-Ellis, Sylvia D., Stacey L. Bowers, Christopher D. Hudson, and M. Claire Williamson. *Librarian's Handbook for Seeking, Writing, and Managing Grants.* Santa Barbara, Calif.: Libraries Unlimited, 2011. 315 p.

Hall-Ellis, Sylvia D., with Ann Jerabek, and Merrie W. Valliant. *Contemporary Cataloging: A Handbook for Practitioners and Students.* Open access text. Athens, GA: University of Georgia System Regents, 2011. 767 p.

Grealy, Deborah S. and Sylvia D. Hall-Ellis. *From Research to Practice: The Scholarship of Teaching and Learning in LIS Education.* Westport, Conn.: Libraries Unlimited, 2009. 175 p.

Hall-Ellis, Sylvia D. with J. Ann Jerabek. *Grants for School Libraries.* Westport, Conn.: Libraries Unlimited, 2003. 197 p.

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Hall-Ellis, Sylvia D. "Prepared to Lead: Talent, Skills, and Competencies." In *Telling the Technical Services Story*. Chicago, IL: American Library Association, 2020. In development and review.

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Hall-Ellis, Sylvia D. "Applying for Grants from Foundations, Corporations, or Government." In *The Volunteers' Guide to Fundraising: Raise Money for Your School Team, Library or Community Group.* 1st ed. Ilona M. Bray, ed. Berkeley, Calif.: Nolo, 2011. (pp. 1-38 on accompanying disc)

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Bruntjen, Scott and Sylvia D. Hall. "Attempting to Automate: Lessons Learned Over Five Years." In *Advances in Library Administration*. Volume 4. Weston, Conn.: JAI Press, 1985. (pp. 177-192)

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Hall-Ellis-Sylvia D. "Job Design for Cataloging and Metadata Librarians." Submitted to *Journal of Library Administration.* In progress.

Hall-Ellis, Sylvia D. "The Relationship of Situational Leadership and the Dreyfus Model of Skill Acquisition for Supervisors in Cataloging and Metadata Services." To be submitted to *Library Resources and Technical Services.* In progress.

Hall-Ellis, Sylvia D. *The Relationship of Core Competencies on Learning Outcomes and Employers' Expectations for Catalog Librarians and Metadata Specialists.* To be submitted to the *Journal of Education for Library and Information Science.* In progress.

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Hall-Ellis, Sylvia D. *Grant Writing Tips and Resources.* Denver, Colo.: University of Denver, 2008-2014. http://portfolio.du.edu/grants

Hall-Ellis, Sylvia D. and Duan Zhang. *Project Homeless Connect 6 Event Evaluation.* Denver, Colo.: Center for Community Engagement and Service Learning, 2008.

Hall-Ellis, Sylvia D. *Strategic Plan for Denver Medical Library System: Final Report.* Denver, Colo.: HealthONE and Denver Medical Library, 2008.

Hall-Ellis, Sylvia D. and Duan Zhang. *Project Homeless Connect 5 Event Evaluation.* Denver, Colo.: Center for Community Engagement and Service Learning, 2008.

Hall-Ellis, Sylvia D. *Strategic Plan for Denver Medical Library System: Phase Two Report.* Denver, Colo.: HealthONE and Denver Medical Library, 2007.

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Hall-Ellis, Sylvia D. *Strategic Plan for Denver Medical Library System: Phase One Report.* Denver, Colo.: HealthONE and Denver Medical Library, 2007.

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Hall-Ellis, Sylvia D. *Resources in Grant Writing for Colorado Schools and Libraries.* Sponsored by the Colorado Department of Education, Educational Telecommunications Unit, 1999. Revised September 2000.

Hall-Ellis, Sylvia D. *Lewis & Clark Fellows Concept Paper for the Bicentennial Commemoration.* Vancouver, Wash.: Lewis and Clark Bicentennial Council, 1998.

Hall-Ellis, Sylvia D. and Mary Ann Berry. *The Impact of Library Resource Centers on Academic Achievement in Public Schools in Texas: The Final Report.* Prepared under the sponsorship of the Research Enhancement Fund award from Sam Houston State University, the Texas Association of School Librarians, the Children's Services Round Table, and the Young Adults' Services Round Table. Huntsville, Tex.: Sam Houston State University, College of Education and Applied Science, 1997.

Hall-Ellis, Sylvia D. *The Impact of Library Resource Centers on Academic Achievement in Selected Public Schools in Texas.* Huntsville, Tex.: Sam Houston State University, College of Education and Applied Science, 1997.

Hall-Ellis, Sylvia D. *Planning for Educational Technology: the Distance Education Implementation Phase: An Investigation of Technology and Telecommunication Needs for Region One Education Service Center, South Texas Community College, TCI Cablevision of South Texas, Inc., Tech Prep of the Rio Grande Valley, Inc., Texas State Technical College, Centro Cultural en el Valle de Texas, McAllen Independent School District, Harlingen Consolidated Independent School District, Donna Independent School District, Edinburg Consolidated Independent School District, La Joya Independent School District, Mercedes Independent School District, Pharr-San Juan-Alamo Independent School District, Sharyland Independent School District, Easter Seal Society of the Rio Grande Valley, Inc., and McAllen Memorial Library.* Harlingen, Tex.: Tech Prep of the Rio Grande Valley, 1996.

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Hall-Ellis, Sylvia D. and Clarence L. Coffindaffer. *Montana Federation Study Identification Paper*. Denver, Colo.: The Blue Bear Group, Inc., 1992.

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Hall, Sylvia D. *The Iowa Union List of Serials as A Part of The Iowa Locator: Planning Document*. Des Moines, Ia.: State Library of Iowa, 1988.

Hall, Sylvia D. *Iowa Computer-Assisted Network (ICAN Users' Manual. IBM Compatible Edition: Version 7.0.* Des Moines, Ia.: State Library of Iowa, 1988.

Hall, Sylvia D. *Iowa Computer-Assisted Network (ICAN Users' Manual. IBM Compatible Edition: Version 5.0.* Des Moines, Ia.: State Library of Iowa, 1986.

Hall, Sylvia D. *Iowa Computer-Assisted Network (ICAN Users' Manual. Apple MacIntosh Edition: Version 5.0.* Des Moines, Ia.: State Library of Iowa, 1986.

Bruntjen, Scott and Sylvia D. Hall. *The District of Columbia Public Library Planning for Retrospective Conversion of Bibliographic Records and Automation Issues for the 1990's: Final Report*. Central City, Colo.: The Blue Bear Group, Inc., 1986.

Bruntjen, Scott and Sylvia D. Hall. *The Iowa Locator: Final Report.* Central City, Colo.: The Blue Bear Group, Inc., 1986.

Bruntjen, Scott and Sylvia D. Hall. *Discovering Resource Sharing Treasures: Accessing Pennsylvania's High School Library Collections*. Harrisburg, Pa.: State Library of Pennsylvania, Bureau of School Library Media Resources, 1985.

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Bruntjen, Scott and Sylvia D. Hall. *Altoona Automation Plan: Final Report prepared for the Altoona Area Public Library and the Altoona District Library Center*. Pittsburgh, Pa.: PRLC, 1983.

Bruntjen, Scott, Sylvia D. Hall and Paul J. Pugliese. *College Space Utilization Study*. Pittsburgh, Pa.: PRLC, Inc., 1983.

Hall, Sylvia D. *Pennsylvania Public Library Film Center Union Catalog Cataloging and Technical Services Procedures Manual*. Pittsburgh, Pa.: PRLC, Inc., 1982.

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Other Publications

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Book Reviews

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Developing a Compensation Plan for Your Library. Paula M. Singer and Laura L. Francisco, comps. 2_{nd} ed. Chicago, IL: American Library Association, 2009. 978-0-8389-0985-0, $57.00 [*Colorado Libraries,* March 2012]

Frugal Librarian. Carol Smallwood, ed. Chicago, IL: American Library Association, 2011. 978-0-83891-075-7, $42.00 [*Colorado Libraries,* February 2012]

Dowlin, Ken. *Getting the Money: How to Succeed in Fundraising for Public and Nonprofit Libraries.* Westport, Conn.: Libraries Unlimited, 2008. 978-1-59158-597-X, $50.00 [*Colorado Libraries,* February 2009]

Lundahl, Mats. *Bebo de Cuba; Bebo Valdés y Su Mundo*, by Mats Lundahl. Traducción de Linda Oakeshott Dragó. Barcelona: RBA Libros, 2008. 978-849-86-7259-6, $33.99 [*Críticas*, November 2008]

Bonelli, Florencia. *Marlene*, by Florencia Bonelli. Buenos Aires: Aguilar, Altea, Taurus, Alfaguara, 2008. 978-987-04-0995-3, $24.95 [*Críticas*, October 2008]

Keret, Etgar. Traducción de Ana María Bejarano. *Pizzería Kamikaze y Otras Relatos.* México, D.F.: Editorial Sexto Piso, 2008. 968-5679-29-0, no price given [*Críticas*, September 2008]

Littauer, Marita, and Florence Littauer. *Enriquece tu Comunicación. Miami, Fla.: Editorial Unilit, 2008.* 978-0-7899-1521-4, $11.99 [*Críticas,* August 2008]

Martínez, Guillermo. *La Muerte Lenta de Luciana B.* New York: Rayo Planeta, 2008. 978-0-06-156551-9, $14.95 [*Críticas*, May 2008]

Matthews, Joseph R. *The Evaluation and Measurement of Library Services.* Westport, Conn.: Libraries Unlimited, 2007. 978-1-59158-532-9, $50.00 [*Colorado Libraries,* April 2008]

Gómez-Jurado, Juan. *A Masacre de Virginia Tech: Anatomía de una Mente Torturada.* Barcelona: Ediciones El Andén, 2007. 978-84-935789-4-7, €16.50 [*Críticas,* February, 2008]

Matthews, Joseph R. *Library Assessment in Higher Education.* Westport, Conn.: Libraries Unlimited, 2007. 978-1-59158-531-2, $45.00 [*Colorado Libraries,* February 2008]

Chacón, Inma. *La Princesa India: Cuando el Viento Azul.* México: Alfaguara, 2006. 970-770398-9, $19.95 [*Críticas*, June 2006]

Vargas Llosa, Mario. *Israel/Palestina: Paz o Guerra Santa.* fotogs. by Morgana Vargas Llosa. Spain/U.S.: Aguilar: Santillana, 2006. 84-03-09691-7, paper, $19.95 [*Críticas*, May 2006]

Findlay, Diane. *Digging into Dewey.* Fort Atkinson, Wisc.: Upstart Books, 2005. 978-1-932146-18-9, $16.95 [*Colorado Libraries,* May 2006]

Pequeñas Resistencias 4: Antología del Nuevo Cuento Norteamericano y Caribeño. Menéndez, Ronaldo, Ignacio Padilla & Enrique del Risco, eds. Madrid**:** Páginas de Espuma, 2005. 84-95642-59-X, paper, $36.95 [*Críticas*, April 2006]

Rueda, André. *Vengo a Salvar a España: Biografía de Un Franco Desconocido.* Madrid**:** Nowtilus (Investigación Abierta), 2005. photogs., bibliog. 84-9763-202-8, paper, $23.95 [*Críticas*, March 2006]

Becerra, Ángela. *El Penúltimo Sueño.* 1st ed. Barcelona: Planeta, 2005. 84-08-05795-2, $25.95. [*Críticas*, January 2006]

Aguilar Camín, Héctor. *La Conspiración de la Fortuna.* 1st ed. México: Planeta, 2005. 970-37-0368-2, $19.95 [*Críticas*, October 2005]

México en Sus Libros. Enrique Florescano with Pablo Mijangos, editors & compilers. 1st ed. México, D.F.: Taurus Aguilar, 2004. 968-19-0783-3, $16.95 [*Críticas*, September 2005]

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Czarnowsky, Christyne A. and Michael H. Williams. *Managing Your Wired Workforce: A Practical Guide.* Denver, Colo.: Bradford Pub., 2003. 1-883726-79-4, $24.95 [*Colorado Libraries,* 2004]

Abraham Lincoln. Colección Grandes Biografías. Madrid: Edimat Libros, 2003. 84-8403-858-0, €4.95 [*Críticas*, 2004]

Alponte, Juan María. *Colón: el Hombre, el Navegante, la Leyenda.* México, D.F.: Aguilar, 2003. 968-19-1260-8, $16.95 [*Críticas*, 2004]

Olcese Salvatecci, Alfieri. *Cómo Estudiar con Èxito: Téchnicas yHhábitos Para Aprender Major.* México, D.F.: Alfaomega Grupo Editor, 2002. 970-15-0764-9 [*Críticas*, 2003]

Mujeres Como Islas: Antología de Narradoras Cubanas, Dominicanas, Puertoriqueñas. Edición: Olga Marta Pérez, Thelma Jiménez, Andrés Blanco D., eds. Santo Domingo, República Dominicana: Ediciones Ferilibro, 2002. 959-209-419-5 [*Críticas*, 2003]

Tibol, Raquel. *Los Murales de Diego Rivera: Universidad Autónoma Chapingo.* México, D.F.: Editorial RM, Universidad Autónoma Chapingo, 2002. 968-5208-08-5 [*Críticas*, 2003]

Lindsay-Poland, John. *Emperors in the Jungle: the Hidden History of the U.S. in Panama.* Durham, N.C.: Duke University Press, 2003. 0-8223-3098-9, $18.95 [*Críticas*, 2003]

Kaplan, Allison G. and Ann Marlowe Riedling. *Catalog It! A Guide to Cataloging School Library Materials.* Worthington, Ohio: Linworth Pub., 2002. 1-58683-014-7, $44.95 [*Colorado Libraries,* 2002]

Bardach, Ann Louise. *Cuba Confidential: Love and Vengeance in Miami and Havana.* New York: Random, 2002. 0-375-50489-3, $25.95 [*Library Journal*, 2002]

Swan, James. *Fundraising for Libraries: 25 Proven Ways to Get More Money for Your Library.* New York: Neal Schuman, 2002. 1-55570-433-6, $69.95 [*Colorado Libraries*, 2002]

Puíg de Lange, Victoria. *Sol Con Agua.* Nashville, Tenn.: Editorial Vistazo/Ediciones Reio Negro, 2002. 0-9724506-0-2, $17.75 [*Críticas*, 2002]

The Encyclopedia of Latin American Politics. Edited by Diana Kapiszewski; assistant editor, Alexander Kazan. Westport, Conn.: Oryx Press, 2002. 1-57356-306-4, $74.95 [*Library Journal*, 2002]

Vargas Lizano, Isabel. *Y Si Quieres Saber de Mi Pasado.* Con la colaboración de J.C. Vales. Madrid: Santillana Ediciones Generales, S.L., 2002. 84-03-09278-4, $18.95 [*Críticas*, 2002]

Ruy Sánchez, Alberto. *Los Jardines Secretos de Mogador: Voces de Tierra.* México, D.F.: Alfaguara, S.A., 2001. 968-19-0879-1, $16.95 [*Críticas*, 2002]

Chávez, Ricardo and Celso Santajuliana. *El Final de las Nubes.* Barcelona: RBA Libros, S.A., 2001. 84-7901-760-0, $11.95 [*Críticas*, 2002]

The Power of Language / El Poder de la Palabra: Selected Papers from the Second REFORMA National Conference. Edited by Lillian Castillo-Speed and the REFORMA National Conference Publications Committee. Englewood, Colo.: Libraries Unlimited, 2001. 1-563089459, $35.00 [*Colorado Libraries*, 2001]

Martínez, Rubén. *Crossing Over: A Mexican Family on the Migrant Trail.* Metropolitan: Holt, 2001. 0-8050-4908- 8, $26.00 [*Library Journal*, 2001]

Guevara, Ernesto "Che." *The African Dream: the Diaries of the Revolutionary War in the Congo.* Translated from the Spanish by Patrick Camiller. With an introduction by Richard Gott and a foreword by Aleida Guevara March. New York: Grove Press, 2001. 0-8021-3834-9, $13.00 [*Library Journal*, 2001]

Cooper, Gail and Garry Cooper. *New Virtual Field Trips.* Englewood, Colo.: Libraries Unlimited, 2001. 1-56308-887-8, $27.50 [*Colorado Libraries*, 2001]

NATIONAL SERVICE & PROFESSIONAL AFFILIATIONS

American Library Association, Life Member
Association for Library Collections & Technical Services (now CORE)
Cataloging, Classification, and Metadata Section
ALCTS Editorial Board, Member, 2015-2019
Committee on Cataloging: Description and Access, Member, 2008-2012
Test Site for RDA, Manager, 2009-2011
Nominating Committee, Member, 2007-2008
Committee for Education and Training of Catalogers, Chair, 2006-2007, Member, 2003-2007
Competencies & Education for a Career in Cataloging Interest Group, Chair, 2010-2012; Member, 2010-
President's Program Committee, 2015-2016
Education Committee, Member, 2005-2007
Task Force on Competencies and Education for a Career in Cataloging, Chair, 2007-2009
2007 Annual Meeting Pre-conference, "What They Don't Teach in Library School: Competencies, Education and Employer Expectations for a Career in Cataloging," Steering Committee Chair
Fundraising Committee, Member, 2004-2006
Office of Diversity
Committee on Diversity, Chair, 2010-2011
Diversity Research Advisory Committee, Member, 2009-2010
Spectrum Scholar Mentor, 2009
Diversity Grants Review Committee, Member, 2007, 2010, 2012
Office of Statistics and Research
Research and Statistics Committee, Member, 2005-2007; Intern, 2003-2005
Library Research Round Table
Membership Committee, 2019-2021
Board of Directors, Member At-Large, 2009-2012
Member, 2003-
Office of Accreditation
Accreditation Panel Member (training completed 2004)
Accreditation Review Panel Member (training completed 2004)

REFORMA, Life Member
National Board of Directors, 2005-2013
National Fundraising Chair, 2005-2013
National Recruiting and Mentoring Committee, 2008-2010
Colorado Chapter, Secretary, 2004-2005
Colorado Chapter Liaison to National Board of Directors, 2004-2013

American Association of Law Libraries (AALL), Life Member
Online Audiovisual Catalogers Association (OLAC)

American Association of University Women Association for Library and Information Science Education (ALISE)
University of Denver ALISE Representative, 2003-2008; 2010-2011
Membership Advisory Committee, 2007-2010
Technical Services Education Special Interest Group, 2003-
Garfield Doctoral Dissertation Award Reviewer, 2012
Garfield Doctoral Dissertation Scholarship Reviewer, 2014

American Association of University Professors (AAUP), 2006-

American Grant Writers Association, 2014-
Grant Professionals Institute, 2016-
National Grants Management Association, 2014-
Grant Reviewer (National and Regional Team Leader), U.S. Department of Education, 1998-
Grant Reviewer, Broadband Technologies Opportunity Program, U.S. Department of Commerce, 2009
Grant Reviewer, Institute of Museum and Library Services, 1998-2000
Grant Reviewer, Colorado Department of Education, 2014-
Grant Reviewer, Colorado State Library, 1998-
Grant Reviewer, American Association of Community Colleges *Working Connections* program, 1999
Peer Reviewer, *Journal for Library and Information Science Education,* 2005-
Peer Reviewer, *Journal of Library Metadata,* 2009
Peer Reviewer, *International Journal of Library and Information Science,* 2011
Regular Columnist, *The Bottom Line*, 2013-2016
Reviewer, *The Bottom Line,* 2022-
Book Reviewer, *Library Journal*, 2001
Book Reviewer, *Críticas,* 2002-2009
Book Reviewer, *Colorado Libraries,* 2000-2012

REGIONAL SERVICE & PROFESSIONAL AFFILIATIONS

Mountain Plains Library Association

Professional Development Grants Committee, Member, 2005-2006
Professional Development Policy and Guidelines Sub-committee Chair, 2006

Colorado Association of Libraries

"Student Voices" Column Editor, *Colorado Libraries,* 2005-2006
Conference Planning Committee, Member, 2002
Technical Services and Automation Division, Chair, 2002-2003; Member, 2000-
Academic Libraries Division, Peer Review Conference Papers Committee, Member, 2007-2009
Education Committee, Member, 1988-1993
Diverse Populations Committee, Member, 2009-2013

SERVICE TO THE UNIVERSITY OF DENVER

Center for Teaching and Learning Faculty Advisory Board, 2007-2008; 2010-2012
Center for Community Engagement and Service Learning Advisory Board, 2007-2012
Faculty Senate
Executive Committee, 2008-2013
Nominations, Rules & Credentials Committee, Chair, 2008-2013; Member 2007-2013
Appointment, Promotion, and Tenure Revision Committee, 2010-2012
Grievance Policy Committee Member, 2007-2010
Law Library Director Search Committee Chair, 2012-2013
PROF Grant Review, College Representative to the University Review Team, 2006, 2008
Project Homeless Connect Evaluations, Principal Investigator, 2006-2009
University Technology Council, 2007-2009
University of Denver Hyde Interviews for Incoming Freshmen, 2003-2012

SERVICE TO THE MORGRIDGE COLLEGE OF EDUCATION

Appointment, Tenure & Review Committee
Member, voting, 2003-2005; 2007- 2009
Chair, Clinical Faculty Promotion & Tenure Policy Subcommittee, 2008-2009
Member, Community Engagement Subcommittee, 2007-2009
Member, Tenure Review Panel, 2003
Advancement and Alumni Relations Committee, Chair, 2003-2007; Member, 2002-2007
College Building Committee Member, 2004-2010
College of Education Student Association, Faculty Advisor, 2004-2007; 2009-2010
Faculty Senator, 2007-2013
Research and Scholarship Committee, Chair, 2008-2009; Member, 2002-2003, 2008-2009
Research and Grant Mentoring Committee, Chair, 2009-2010
Research Task Force Member, 2010-2012
Search Committee Member, Assistant Professor for Curriculum & Instruction, 2010-2011
Workload Task Force Member, 2010-2011

SERVICE TO THE LIBRARY & INFORMATION SCIENCE PROGRAM

Library and Information Science Student and Alumni Association, Faculty Advisor, 2002-2008
ALA Student Chapter, Faculty Advisor, 2005-2008
Beta Phi Mu Phi Chapter, Faculty Advisor, 2004-2014
Steering Committee Member, Accreditation by the American Library Association, 2001-2004
Search Committee Member, Associate Professor for LIS, 2006
Search Committee Chair, Assistant Professors for LIS, 2003, 2005, 2006, 2007
Search Committee Ex-Officio Member, Director for LIS, 2004

SERVICE TO SAM HOUSTON STATE UNIVERSITY

Rio Roundup: South Texas Literature Conference, Conference Coordinator, 1993
External Relations, Fund Raising, Grants Committee, Chair, 1993-1995
Advisory Council Committee, Chair, 1993-1995
Students, Admissions, and Advisement Committee, Chair, 1994
Institutional Effectiveness Committee, Member, 1993-1995

SERVICE TO THE COLLEGE OF EDUCATION AND APPLIED SCIENCE

Faculty Affairs Committee, Member, 1993-1995
Curriculum Committee, Member, 1993-1995
Continuing Education Committee, Member, 1993-1995

SERVICE TO THE COMMUNITY

French Teacher & Student Exchange with Laon, France, Monarch High School, Boulder Valley School District (Boulder, Colorado), 2017-
Denver/Boulder Games 2022, Board of Directors, Secretary-Treasurer, 2015-2018
United Way Campaign Committee, College of Education, 2006
Arapahoe County, Election Judge for the County Clerk and Recorder, 2000-2005
Arthritis Foundation, Rocky Mountain Chapter, Certified Educator & Trainer, 1999-2008
Bonfils Blood Center, Silver Level Donor, 2000-2016
Denver Museum of Natural History, Docent, 1992
Tech Prep of the Lower Rio Grande Valley, Inc. (Harlingen, Texas) Board of Directors, 1995-1997
Executive Committee, 1996-1997; Chair, Development Committee, 1995-1997; Chair, Fiscal Agency Committee, 1995-1996; Chair, Colleges and Universities Committee, 1996-1997
Gilpin County (Colorado) Public Library Board of Trustees, 1986-1989; Vice President, 1987-1989
City of Central (Colorado) Economic Development Committee, 1987-1989
Columbine Family Health Centers, Inc. (Nederland and Black Hawk, Colorado) Board of Directors, 1988-1989

CERTIFICATION

Permanent Public Librarian Certificate - Pennsylvania, New York, Texas
Westlaw Expert Witness, 2008-
Certified Grant Writer®, 2016-

AWARDS AND HONORS

Advanced Practitioner for Service Learning and Community Engagement, University of Denver, 2011
Platinum Star Alumnae, College of Information, Library Science & Technologies, University of North Texas, 2009
Commendation for Integration of Technologies in Teaching & Learning Environment, University of Denver, 2006
Outstanding Adjunct Faculty Member Award, College of Education, University of Denver, 2002
Beta Phi Mu, Pi, University of Pittsburgh, 1985
Alpha Lambda Sigma, University of North Texas, 1972
Albert Nelson Marquis Lifetime Achievement Award, Who's Who in America
Who's Who in American Women
Who's Who of Women Executives
Dictionary of International Biography
Who's Who in the East
Who's Who in the South and Southwest
Who's Who in the World
Who's Who of Online Professionals
Who's Who in Library and Information Science
2,000 Notable Women
Who's Who of Emerging Leaders
Who's Who in Professional and Executive Women
Who's Who in American Education
International Who's Who of Professional and Business Women
International Leaders in Achievement
International Educator of the Year
Who's Who in Finance and Industry
Who's Who in Finance and Business

Invited International and National Conference Presentations

Hall-Ellis, Sylvia D., Virginia Tucker, and Lei Zheng. *Information Organization MLIS Career Pathway.* Presentation delivered at the School of Information, San José State University Student Lunch & Learn Session, San José, California, February 24, 2022.

Driscoll, Margaret, Christy Confetti Higgins, Scott Brown, and Sylvia D. Hall-Ellis. *A View from Within: Open House Tour of Three Canvas Core Courses*. Presentation delivered at the School of Information, San José State University Professional Development Seminar, San José, California, October 17, 2019.

Hall-Ellis, Sylvia D. *Invest in Me -- I'm Your Future: Succession Planning for Libraries.* Keynote presentation delivered at the ALCTS President's Symposium, Boston, Mass., January 8, 2016.

Seidel, Kent E. and Sylvia D. Hall-Ellis. *Making Grants Work for You: Strategies for Doctoral Students and Early Career Scholars.* Presentation delivered at the University Council for Educational Administration, Early Career Scholars Session, Indianapolis, Ind., November 9, 2013.

Hall-Ellis, Sylvia D. *So You Want to be a Manager; Leadership Skills and Competencies for Technical Services Managers and Administrators.* Presentation delivered at the 138th Annual Conference, American Library Association, Chicago, Ill., June 29, 2013.

Seidel, Kent E., Karen S. Riley, Lyndsay Agans, Susan Korach, and Sylvia D. Hall-Ellis. *Making Grants Work for You (Instead of Just Working for Grants).* A panel discussion delivered at the University Council for Educational Administration, Early Career Scholars Session, Denver, Colo., November 17, 2012.

Hall-Ellis, Sylvia D. *After the Great TS Reorganization: The Westminster Law Library.* Presentation delivered at the 137th Annual Conference, American Library Association, Anaheim, Calif., June 23, 2012.

Hall-Ellis, Sylvia D. *Conversations with Catalogers in the 21st Century.* A panel discussion sponsored by the ALCTS Competencies for a Career in Cataloging Interest Group, delivered at the 137th Annual Conference, American Library Association, Anaheim, Calif., June 22, 2012.

Hall-Ellis, Sylvia D., moderator. *Mid-Career Leaders Program.* A panel discussion sponsored by the ALA Committee on Diversity delivered at the 136th Annual Conference, American Library Association, New Orleans, La., June 26, 2011.

Hall-Ellis, Sylvia D., moderator. *Diversity Town Hall.* A community conversation sponsored by the ALA Committee on Diversity delivered at the 136th Annual Conference, American Library Association, New Orleans, La., June 24, 2011.

LaBarre, Kathryn, Sylvia D. Hall-Ellis, Karen Anderson, Rick Hasenyager, Christopher Cronin, and Penny Baker. *Briefings from RDA Test Participants.* A panel discussion delivered at the Midwinter Conference, American Library Association, San Diego, Calif., January 7, 2011.

Miksa, Shawne, Marjorie Bloss, and Sylvia D. Hall-Ellis. *Educating the Next Generation of Catalogers: Teaching RDA.* A panel discussion delivered at the 97th Annual Conference, Association for Library and Information Science Education, San Diego, Calif., January 7, 2011.

Hall-Ellis, Sylvia D., Robert Maxwell, John Hostage, and George Prager. *RDA Panel: What Cataloging Managers Need to Know.* Presentation delivered at the 103rd Annual Conference, American Association of Law Librarians, Denver, Colo., July 12, 2010.

Hall-Ellis, Sylvia D. and Stacey L. Bowers. *Catalogers in the RDA Environment: Skill Sets, Expectations and Challenges.* Presentation delivered at the 103rd Annual Conference, American Association of Law Librarians, Denver, Colo., July 11, 2010.

Hall-Ellis, Sylvia D. *Comfortable in Your Cataloging and Metadata Specialist Skin? Or, So You Want to Hire a Cataloger.* Presentation delivered to the ALCTS Research Group at the 134th Annual Conference, American Library Association, Chicago, Ill., July 11, 2009.

Perez, Megan, Sylvia D. Hall-Ellis, and Denise Anthony. *From Novice to Expert: Collaboration for Succession Planning.* A "hot topic" presentation delivered at the 14th ACRL Conference, Seattle, Wash., March 13, 2009.

Hall-Ellis, Sylvia D. *Cataloging in the RDA Environment: Skill Sets, Expectations and Challenges.* Presentation delivered to the ALCTS Research and Publications Committee at the Midwinter Conference, American Library Association, Denver, Colo., January 24, 2009.

Hall-Ellis, Sylvia D. *LIS Cataloging Education for the 21st Century: Expectations and Challenges.* A panel discussion held at the 95th Annual Conference, Association for Library and Information Science Education, Denver, Colo., January 23, 2009.

Chu, Clara, Sylvia D. Hall-Ellis, and Mark Winston. *The Doctoral Degree & Building a Career.* A panel discussion delivered at the ALA Office of Diversity Spectrum Doctoral Fellows E.J. Josey Leadership Institute, Midwinter Conference, American Library Association, Denver, Colo., January 20, 2009.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Fundamentals of Cataloging Course: An Overview of the ALCTS Online Course.* Presentation delivered to the ALCTS Big Heads Group, 133rd Annual Conference, American Library Association, Anaheim, Calif., June 30, 2008.

Hall-Ellis, Sylvia D. *Employers' Expectations for Technical Services Librarians: What We Don't Know.* Presentation delivered to the ALCTS Research and Publications Committee Program, 133rd Annual Conference, American Library Association, Anaheim, Calif., June 28, 2008.

Hall-Ellis, Sylvia D., Virginia R. Maloney, and Mary Stansbury. *Institutional Responses to Engaged Scholarship: The Carnegie Foundation Engaged University Classification at Two Universities.* Presentation delivered to the 94th Annual Conference, Association for Library and Information Science Education, Philadelphia, Pa., January 11, 2008.

Hall-Ellis, Sylvia D. *Puzzles, Problems, and Predicaments.* Presentation delivered to the ALCTS Research Discussion Group, 132nd Annual Conference, American Library Association, Washington, D.C., June 23, 2007.

Hall-Ellis, Sylvia D. *Cataloging Education: A New Emphasis for the Library and Information Science Curriculum.* Presentation delivered to the ALCTS Pre-conference, 132nd Annual Conference, American Library Association, Washington, D.C., June 22, 2007. http://www.loc.gov/catdir/cpso/careercat.html

Ellett, Jr., Robert O. and Sylvia D. Hall-Ellis. *Copy Cataloging Done Smarter.* Presentation delivered to the International Conference on Interdisciplinary Information Sciences and Technologies (InSciT2006), October 25-28, 2006.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Cooperative Cataloging: Challenges and Opportunities for Defense Libraries.* Presentation delivered to the 1st Annual Conference of Defense Libraries, Spanish Ministry of Defense, Madrid, Spain, July 7, 2006.

Hall-Ellis, Sylvia D. *Cataloger Competencies: Do the Employers Require What the Professors Teach?* Presentation delivered to the ALCTS CCS Heads of Cataloging Discussion Group, 131st Annual Conference, American Library Association, New Orleans, La., June 26, 2006.

Grealy, Deborah S. and Sylvia D. Hall-Ellis. *From Research to Practice: The Scholarship of Teaching and Learning in LIS Education.* Presentation delivered to the at the 92nd Annual Conference, Association for Library and Information Science Education, San Antonio, Tex., January 18, 2006.

Hall-Ellis, Sylvia D. *Employers' Expectations for Entry-Level Catalogers: What Position Announcement Data Indicate.* Research paper delivered to the Technical Services Special Interests Group, 91st Annual Conference, Association for Library and Information Science Education, Boston, Mass., January 12, 2005. http://dlist.sir.arizona.edu/

Common Errors in MARC Records Prepared by LIS Students: What Does It Mean? Research paper delivered to the ALCTS CCS Cataloging Norms Discussion Group, Mid-Winter Conference, 90th American Library Association, San Diego, Calif., January 10, 2004.

Hall-Ellis, Sylvia D. *Visual Arts as Foundation for Successful Library Automation: The Rocky Mountain College of Art & Design Experience.* Paper delivered at the 6th Annual Conference of Higher Education, Charleston, S. C., 1993.

Hall, Sylvia D. *Design Elements for Bibliographic Databases: An Overview.* Paper delivered at the 14th Online National Conference, New York, 1983.

Invited Regional Conference Presentations

Hall-Ellis, Sylvia D., Hudson, Christopher D., Brittany Cronin, and Kathryn Michaels. "The Colorado Law Project: Meeting the Public's Need for Legal Information." Panel discussion delivered at the Mountain Plains Library Association Conference, Billings, Mont., April 9, 2011.

Grealy, Deborah S. and Sylvia D. Hall-Ellis. *Education for Information Professionals in New Mexico: Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the New Mexico Library Education Summit, Las Vegas, N.M., September 26, 2005.

Hall-Ellis, Sylvia D. *Public Library-School Library Partnerships.* Presentation delivered at the 3rd Annual Colorado Association of Libraries Conference with the Mountain Plains Library Association, Denver, Colo., October 22, 2004.

Hall-Ellis, Sylvia D. *Learn All You Can – Educational Partnership Opportunities for the Lewis and Clark Bicentennial Commemoration.* Paper delivered at the 3rd Annual Lewis and Clark Bicentennial Council National Planning Conference, Bismarck, N.D., April 26, 1998.

Invited State Conference Presentations

Grealy, Deborah S. and Sylvia D. Hall-Ellis. *Academic Library Leadership Changes: Using Succession Planning and Mentoring*. Presentation delivered at the Minnesota Library Education Conference, St. Cloud, Minn., October 10, 2013.

Hall-Ellis, Sylvia D., Merrie Valliant, and Melissa Powell. *RDA: What Is It and What Do You Need To Do With It At Your Library?* Presentation delivered at the Colorado Library Consortium Spring Conference, Ft. Morgan, Colo., April 26, 2013.

Hall-Ellis, Sylvia D. *Service Learning and the Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 4th LEADS Scholars Orientation, Denver, Colo., August 5, 2009.

Hall-Ellis, Sylvia D. *Service Learning: Enhancement to Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 3rd LEADS Scholars Orientation, Denver, Colo., June 2008.

Hall-Ellis, Sylvia D. *Law Librarianship: A Community Conversation.* Sponsored by the Colorado Association of Law Libraries. Paper delivered at the Colorado Supreme Court Library, Denver, Colo., May 14, 2008.

Hall-Ellis, Sylvia D. *Opportunities and Challenges in Law Librarianship: A Community Conversation.* Presentation delivered at the Sturm College of Law, Denver, Colo., November 7, 2007.

Hall-Ellis, Sylvia D. *Grant Writing Resources for Nursing Professionals.* Presentation delivered at the Presbyterian / St. Luke's Health One Medical Center 1st Annual Research Symposium, Denver, Colo., October 17, 2007.

Project Homeless Connect 4 Event Evaluation – Insights and Lessons Learned. Presentation delivered at the Homelessness Research Symposium: What is DU Doing about Homelessness in Denver, Denver, Colo., September 14, 2007.

Hall-Ellis, Sylvia D. *Service Learning and the Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 2nd LEADS Scholars Orientation, Denver, Colo., August 10, 2007.

Hall-Ellis, Sylvia D. *Education for Information Professionals in a Digital Environment: Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 15th Spring Mountains and Plains Parapros Conference, Denver, Colo., February 24, 2007.

Hall-Ellis, Sylvia D. *Public Library Service to Spanish-Speaking and Latino Residents in Denver: A Case Study.* Presentation delivered at the 4th Annual Colorado Association of Libraries Conference, Denver, Colo., November 10, 2005.

Hall-Ellis, Sylvia D. *Education for Information Professionals in a Digital Environment: Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 14th Annual Mountains and Plains Parapros Conference, Aurora, Colo., July 29, 2005.

Hall-Ellis, Sylvia D. *Educational Opportunities: Library & Information Science Graduate Education at the University of Denver.* Presentation delivered at the 13th Annual Mountains and Plains Parapros Conference, Centennial, Colo., August 6, 2004.

Hall-Ellis, Sylvia D. *Library Education & Training: Focus on the West: An LIS Faculty Member's Personal Response*. Presentation delivered at the 1st Annual Colorado Association of Libraries Conference, Keystone, Colo., October 18, 2002.

Hall-Ellis, Sylvia D. *Grant Writing for School Librarians.* Presentation delivered at the 2002 Annual Colorado Education Media Association Conference, Colorado Springs, Colo., February 15, 2002.

Hall-Ellis, Sylvia D. *Grants – Opportunities for the Future.* Paper delivered at the Southeast Regional Accountability Annual Conference, Lamar, Colo., November 12, 1998.

Hall-Ellis, Sylvia D. *The Texas Library Connection and Interlibrary Loan: An Experiment in Resource Sharing.* Paper delivered at the Texas Computer Educators' Association Annual Conference, Austin, Tex., February 6, 1997.

Hall-Ellis, Sylvia D. *Finding Grant Sources on the Internet: A Guide for Librarians.* Paper delivered at the 2nd Annual Institute for School Library Personnel, Pharr-San Juan-Alamo North High School, Pharr, Tex., July 29, 1996**.**

Hall-Ellis, Sylvia D. *Mathematical and Logical Thinking: A Critical Intelligence.* Paper delivered at the 3rd Annual Paraprofessional Conference at the University of Texas - Pan American, Edinburg, Tex., March 8, 1996.

Hall-Ellis, Sylvia D. *Cataloging Trends and Issues: Update Session.* Paper delivered at the 1st Annual Institute for School Library Personnel, South Texas Community College, McAllen, Tex., July 19, 1995.

Hall-Ellis, Sylvia D. *Grant Writing: Tips and Encouragement for School Librarians.* Paper delivered at the 1st Annual Institute for School Library Personnel, South Texas Community College, McAllen, Tex., July 18 and 19, 1995.

Hall-Ellis, Sylvia D. *How to Become an Expert Grant Writer.* Paper delivered at the 3rd Annual High School Principals' Academy, South Padre Island, Port Isabel, Tex., June 19, 1995.

Hall-Ellis, Sylvia D. *Texas Library Study: Results from Regions I and II.* Paper delivered at the 3rd Annual Technology Conference, Texas A&M University, College Station, Tex., November 18, 1994.

Hall-Ellis, Sylvia D. *Academic Achievement and Middle School Students.* Paper delivered at the 8th Annual Young Adult Conference, Sam Houston State University, Huntsville, Tex., November 5, 1994.

Hall-Ellis, Sylvia D. *Multimedia Resources for Library Leaders.* Paper delivered at the Institute for Librarians in A Multicultural Environment, Sam Houston State University, Huntsville, Tex., June 10, 1994.

Hall-Ellis, Sylvia D. *Finding the Resource: Empowering the User, or, the Case for Curriculum Based Subject Access to Learning Resource Center Collections.* Paper delivered at the 81st Annual Texas Library Association Conference, Corpus Christi, Tex., April 12-16, 1994.

Hall-Ellis, Sylvia D. and William H. Pichette. *Sam Houston State University Makes Use of OCLC/AMIGOS Collection Analysis CD.* Paper delivered at the 81st Annual Texas Library Association Conference, Corpus Christi, Tex., April 12-16, 1994.

Hall, Sylvia D. *Funding and Library Development in Pennsylvania: A Symbiotic Relationship.* Paper delivered at the Annual Graduate Student Colloquia, University of Pittsburgh, School of Library and Information Science, 1982.

Hall, Sylvia D. *Leadership for Public Library Trustees.* Paper delivered for the Trustees Division, Pennsylvania Library Association Annual Conference, Lancaster, Penn., 1981.

Seminar and Professional Development Presentations

Taylor, Meredith, and Sylvia D. Hall-Ellis. *Talent Management and Succession Planning.* ALCTS eForum, held March 22, 2017.

Hirsh, Sandra, Heather O'Brien, Michelle Holschuh Simmons, Michael Krasulski, and Sylvia D. Hall-Ellis. *Information Services Today: An Introduction. Part 3: Information Services: Roles in the Digital Age*. Rowan and Littlefield in partnership with Library Journal webinar, recorded February 5, 2015.

Hall-Ellis, Sylvia D. and Jennifer Sweda. *Copy Cataloging in an RDA Environment.* ALCTS eForum, held May 14 and 15, 2013.

Hall-Ellis, Sylvia D. *Law Librarianship: A Community Conversation.* Sponsored by the Colorado Association of Law Libraries, presented at the Colorado Supreme Court Library, Denver, Colo., May 14, 2008.

Hall-Ellis, Sylvia D. and Beatrice Z. Gerrish. *Reading and Libraries: Recent Research in Reading.* Presentation at the Ricks Center for Gifted Education, Denver, Colo., March 4, 2008.

Hall-Ellis, Sylvia D. *Cataloger Competencies: Do the Employers Require What the Professors Teach?* Presentation for the School of Library and Information Science, San José State University, February 12, 2008.

Hall-Ellis, Sylvia D. and Robert O. Ellett, Jr. *Cooperative Cataloging: Rules, Tools, and Conventions for Building a Multi-institutional Catalog.* Sponsored for the Spanish Ministry of Defense, Madrid, Spain, July 10, 2006.

Hall-Ellis, Sylvia D. *Cash for Kids: Grant Writing Opportunities for Youth Services Librarians.* Sponsored by the Colorado Young Adult Librarians; presented at Bemis Memorial Library, Littleton, Colo., November 13, 2002.

Hall-Ellis, Sylvia D. *MARC Records and Authority Control: Planning for Bibliographic Database Migration.* Sponsored and held at the Douglas County Public Library, Castle Rock, Colo., May 28, 2002.

Hall-Ellis, Sylvia D. *Grant Writing: A Refresher for Librarians.* Sponsored by Library and Information Science Program, College of Education, University of Denver; presented at University Center at Chaparral, August 12, 2000.

Hall-Ellis, Sylvia D. *Shaking the Money Tree – Basic Grant Writing for Colorado Educators.* Sponsored by the Office of Educational Telecommunications of the Colorado Department of Education.
Pikes Peak Community College, Colorado Springs, Colo., November 16, 1998.
Pueblo School District 60, Pueblo, Colo., November 12, 1998.
University of Northern Colorado, Greeley, Colo., November 10, 1998.
United Technology Educational Partnership, Grand Junction, Colo., November 9, 1998.

Hall-Ellis, Sylvia D. *Cataloging Multimedia, Kits, Globes and Map Materials in USMARC.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 24, 1997 and December 12, 1996.

Hall-Ellis, Sylvia D. *New Standards for School Library Media Centers.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 15, 1997.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future.* Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., April 4, 1997.

Hall-Ellis, Sylvia D. *Cataloging Sound Recordings and Audio Materials in USMARC.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., March 20, 1997 and November 21, 1996.

Hall-Ellis, Sylvia D. *Evaluating and Selecting CD-ROMS for School Library Media Collections.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., March 18, 1997.

Hall-Ellis, Sylvia D. *Cataloging Audiovisual Materials in USMARC.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., February 27, 1997, November 7, 1996 and October 24, 1996.

Hall-Ellis, Sylvia D. *Introduction to Dialog: Basic Searching Strategies.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., February 14, 1997.

Hall-Ellis, Sylvia D. *Cataloging Books in USMARC.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., January 30, 1997, October 10, 1996, September 26, 1996 and August 8, 1996.

Hall-Ellis, Sylvia D. *Advanced Internet Searching Techniques for Librarians.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., January 21, 1997.

Hall-Ellis, Sylvia D. *Texas Library Connection Full-Text Searching.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., December 13, 1996 and October 25, 1996.

Hall-Ellis, Sylvia D. *Developing Evaluation Strategies for Grants and Proposals.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., December 10, 1996.

Hall-Ellis, Sylvia D. *Developing Needs Assessment for Grants and Proposals.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., November 12, 1996.

Hall-Ellis, Sylvia D. *Texas Library Connection Union Catalog Searching.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., November 8, 1996 and September 6, 1996.

Hall-Ellis, Sylvia D. *Grant Resources on the Internet.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., October 23, 1996.

Hall-Ellis, Sylvia D. *Preparing a Response to the Telecommunications Infrastructure Fund Board: Needs Assessment, Professional Development Framework, and Evaluation Strategies.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., October 16, 1996.

Hall-Ellis, Sylvia D. *Texas Library Connection: Building the Districtwide Bibliographic Database.* Sponsored and hosted by Mercedes Independent School District, Mercedes, Tex., September 13, 1996 and August 8, 1996.

Hall-Ellis, Sylvia D. *Texas Library Connection: Building the Districtwide Bibliographic Database.* Sponsored and hosted by Los Fresnos Consolidated Independent School District, Los Fresnos, Tex., August 12, 1996.

Hall-Ellis, Sylvia D. *School-to-Work and Special Education: An Inclusive Partnership for Success.* Sponsored and hosted by the Office of Special Education, Region One Education Service Center, Edinburg, Tex., September 11, 1996.

Hall-Ellis, Sylvia D. *Telecommunications Infrastructure Fund Board: An Overview of Funding for Secondary Schools.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., August 31, 1996.

Hall-Ellis, Sylvia D. *Cataloging Books, Multimedia, and Realia in USMARC.* Sponsored and hosted by Edinburg Consolidated Independent School District, Edinburg, Tex., August 6, 1996.

Hall-Ellis, Sylvia D. *Internet Resources for Grant Writers.* Sponsored and hosted by Region One Education Service Center, Edinburg, Tex., April 20, 1996.

Hall-Ellis, Sylvia D. *Enhanced Grant Writing Skills for Mathematics Educators: Writing Skills for Campus Teams.* Sponsored and hosted by the Office of General Education, Region One Education Service Center, Edinburg, Tex., March 22, 1996.

Hall-Ellis, Sylvia D. *Internet Resources for Grant Writers.* Sponsored and hosted by the College of Education and Applied Science, Sam Houston State University, Huntsville, Tex., March 9, 1996.

Hall-Ellis, Sylvia D. *Grant Writing for Mathematics Educators: A Development Process for Campus Teams.* Sponsored and hosted by the Office of General Education, Region One Education Service Center, Edinburg, Tex., March 4, 1996.

Hall-Ellis, Sylvia D. *Shaking the Money Tree: Preparing Successful Technology Grant Applications.* Sponsored and hosted by the Office of Technology and Media Services, Region One Education Service Center, Edinburg, Tex., February 29, 1996 and April 29, 1996.

Hall-Ellis, Sylvia D. *District-wide Technology Planning: Technical Assistance for the Texas Education Agency Initiative.* Sponsored and hosted by the Office of Technology and Media, Region One Education Service Center, Edinburg, Tex., February 2, 1996.

Hall-Ellis, Sylvia D. *Enhanced Grant Writing Skills.* Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., January 27, 1996.

Hall-Ellis, Sylvia D. *United States Copyright Act of 1976, Video Transmissions, Computer Software and the Internet.* Sponsored and hosted by the Office of Technology and Media, Region One Education Service Center, Edinburg, Tex., January 24, 1996.

Hall-Ellis, Sylvia D. *The Grant Writing Development Process.* Sponsored and hosted by Pharr-San Juan-Alamo Independent School District, Pharr, Tex., January 20, 1996.

Hall-Ellis, Sylvia D. *MARC Cataloging of Materials for Library Media Centers.* Sponsored and hosted by the Office of Media Services, Region One Education Service Center for the Donna Independent School District, Donna, Tex., August 17, 1995.

Hall-Ellis, Sylvia D. *Classification.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., May 10, 1995.

Library Technical Services. Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., April 26, 1995.

Hall-Ellis, Sylvia D. *Grant Writing: An Introduction for Public School Administrators.* Sponsored and hosted by the Office of Administrative Services, Region One Education Service Center, Edinburg, Tex., April 19, 1995.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future.* Sponsored and hosted by the United Independent School District, Laredo, Tex., March 31, 1995.

Hall-Ellis, Sylvia D. *Using USMARC.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., March 29, 1995.

Hall-Ellis, Sylvia D. *Library Media Center Policies and Guidelines: How to Prepare for School Board Adoption.* Sponsored and hosted by the Office of Technology and Media Services, La Joya Independent School District, La Joya, Tex., March 10, 1995.

Hall-Ellis, Sylvia D. *Developing District-wide Policies and Guidelines for Library Media Centers.* Sponsored and hosted by the Office of Technology and Media Services, La Joya Independent School District, La Joya, Tex., January 10, 1995.

Hall-Ellis, Sylvia D. *MARC Cataloging of Audiovisual Materials for Library Media Centers.* Sponsored and hosted by the Office of Library Media and Technology Services, Cypress-Fairbanks Independent School District, Houston, Tex., December 1, 1994.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future.* Sponsored and hosted by United Independent School District, Laredo, Tex., October 14, 1994.

Hall-Ellis, Sylvia D. *The School Library Media Specialist in the 21st Century: Visions for the Future.* Sponsored and hosted by the Laredo Independent School District, Laredo, Tex., October 7, 1994.

Hall-Ellis, Sylvia D. *MARC Cataloging for Library Media Centers.* Sponsored by the Office of Library Media and Technology Services, Cypress-Fairbanks Independent School District, Houston, Tex., October 5, 1994.

Hall-Ellis, Sylvia D. *Jump to the Head of the Class: Undergraduate Library Resources Available at Sam Houston State University.* Sponsored by the Office of the Associate Vice President for Student Services, Sam Houston State University, Huntsville, Tex., October 4, 1994.

Hall-Ellis, Sylvia D. *CD-ROMs - 1994's Newest and the Best for Secondary Level Media Centers.* Sponsored and hosted by Clear Lake Independent School District, Houston, Tex., June 3, 1994.

Hall-Ellis, Sylvia D. *Introduction to Classification.* Sponsored by AJ Seminars, Rockville, Maryland; presented at Holiday Inn, Market Center, Dallas, Tex., May 18, 1994.

Hall-Ellis, Sylvia D. *Basic Descriptive Cataloging.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., May 4, 1994.

Hall-Ellis, Sylvia D. *Shaking the Money Tree - Part II: Writing Successful Grant Applications.* Sponsored by Donna Independent School District, Donna, Texas, and Region One Education Service Center Edinburg, Texas; presented at South Texas Community College Library, McAllen, Tex., April 29, 1994.

Hall-Ellis, Sylvia D. *Using MARC.* Sponsored by AJ Seminars, Rockville, Maryland; presented at Holiday Inn, Market Center, Dallas, Tex., April 6, 1994.

Hall-Ellis, Sylvia D. *Automated Authority Control.* Sponsored by AJ Seminars, Rockville, Maryland; presented at University Hilton Hotel, Houston, Tex., March 23, 1994.

Hall-Ellis, Sylvia D. *Automating the District School Library Media Centers: Choices and Opportunities.* Sponsored and hosted by the Office of Technology and Library Media Services, Fort Bend Independent School District, Sugar Land, Tex., March 4, 1994.

Hall-Ellis, Sylvia D. *Shaking the Money Tree - Part I: Preparing Successful Grant Applications.* Sponsored and hosted by the Office of Library Media Services, Donna Independent School District, Donna, Tex., February 4, 1994.

GRADUATE COURSES TAUGHT

San José State University, School of Library and Information Science

INFO 249 – Advanced Cataloging and Classification (Fall 2015, 2016; Summer 2016)
INFO 287 – Special Topics in Cataloging and Classification (Spring 2017, 2018, 2019, 2020, 2021, 2022; Fall 2020, 2021, 2022)
LIBR 248 – Beginning Cataloging and Classification (Summer 2002, 2003, 2004, 2005, 2006)
LIBR 249 – Advanced Cataloging and Classification (Summer 2003; Fall 2014; Summer 2015)

University of Denver, Morgridge College of Education

HED 5991 – Grant Writing in Higher Education (Spring 011)
LIS 4010 – Organization of Information (Fall 2002, 2003, 2004, 2005, 2006, 2009; Winter 2005; Spring 2004, 2005, 2006)
LIS 4020 – Professional Principles and Ethics (Summer 2000)
LIS 4040 – Management of Libraries and Information Centers (Fall 2010; Spring 2003, 2009 (DS); Winter 2005)
LIS 4070 – Cataloging and Classification (Winter 2008, 2009, 2010, 2011, 2012; Fall 2009 (DS))
LIS 4321 – Collection Management (Spring 2005)
LIS 4326 – LIS Research (Winter 2009 (DS); Spring 2009 (DS))
LIS 4350 – Adult Materials and Services (Summer 2006, 2009)
LIS 4379 – Social Sciences Resources (Spring 2009)
LIS 4400 – Cataloging and Classification (Spring 2000, 2001; Winter 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009; Summer 2005, 2006 – course renumbered LIS 4070, September 2007)
LIS 4401 – Descriptive Cataloging (Winter 2001; Spring 2002, 2003, 2006, 2007, 2008, 2009; Summer 2005)
LIS 4402 – Subject Cataloging (Spring 2001, 2009; Summer 2005, 2006, 2007, 2008)
LIS 4403 – Classification Schemes (Fall 2007, 2008, 2009 (DS)
LIS 4405 – Authority Control (Winter 2009)
LIS 4510 – Materials and Services for Children (Winter 2004; Summer 2005)
LIS 4620 – Grant Writing and Fundraising (Summer 2000, 2002, 2004, 2010; Winter 2006; Fall 2006, 2007, 2008, 2009)
LIS 4700 – Seminar in Technical Services (Fall 2001)
LIS 4700 – Seminar in Public Libraries (Summer 2002)
LIS 4804 – Management of Electronic Records (Spring 2004; Fall 2005)
LIS 4902 – Capstone Projects (Winter 2003, Spring 2008, 2009, 2011)
LIS 4910 – Independent Study (every quarter Winter 2000 through Spring 2011)
LIS 4920 – Service Learning (every quarter Summer 2004 through Spring 2011)
Grant Writing Certificate Seminar for Non-Profit Organizations (Fall 2020, 2021; Spring 2021)
RMS 4954 – Grant Writing (Summer 2013, 2014)
RMS 4959 – Content Analysis Methodology (Spring 2015)
QRM 4978 – Grant Writing (Summer 2011, 2012)

Rutgers University, School of Communication and Information

SC&I 522 – Cataloging and Classification (Summer 2013)

University of Arizona, College of Behavioral and Social Sciences

LIS 602 – Cataloging and Classification (Summer 1995)
LIS 612 – Advanced Online Search and Retrieval (Summer 1995)

Sam Houston State University, College of Education & Applied Science

LIS 532 - Cataloging and Classification (Fall 1993, 1994, 1995)
LIS 563 - Advanced Cataloging and Classification (Summer 1994)
LIS 567 - Research Methods (Spring 1994, Spring 1995)
LIS 591 - Educational Technology (Spring 1994, 1995)
LIS 596 - Networking and Computer Technologies in Education (Fall 1993, Summer 1994, Fall 1995)

Dissertations at the University of Denver

Bowers, Stacey L. *Library Anxiety of Law School Students: A Study Utilizing the Multidimensional Library Anxiety Scale.* Chair, May 5, 2010.

Fattor, Melissa M. *Student Engagement Differences by Ethnicity and Scale for Ninth Grade Students.* Chair, November 1, 2010.

Fulton, Roseanne. *A Case Study of Culturally Responsive Teaching in Middle School Mathematics.* Kent Seidel, Chair, June 18, 2009, Outside Chair.

Grealy, Deborah S. *Tribes and Territories in Library and Information Studies Education.* Bruce Uhrmacher, Chair, June 10, 2008, Committee Member.

McCord, J. Michael. *Developing a Standard of Care for Educational Malpractice.* Chair, April 15, 2011.

Priebe, Sarah J. *Distinguishing Effects of Domain and General Knowledge on Passage Fluency and Comprehension.* Jan Keenan, Chair. July 21, 2011, Outside Chair.

Snyder-Mondragon, Sandra M. *Institutional Factors that Impact the Retention of Graduate Students of Color in Schools of Library and Information Science: A Metaregression of Accredited Library School Statistics on Student Retention and Graduation Rates.* Kathy Green, Chair, July 24, 2009, Committee Member.

Taylor, Karen Pickles. *Effective Teaching.* Elinor Katz, Chair, July 15, 2009, Outside Chair.

Thompson, Jennifer. *Distinguishing a Western Women's College: A History of the Curriculum and Student Experience at Colorado Women's College.* Edith W. King, Chair, July 16, 2010, Committee Member.

Walker, Emelda. *Influence of Organizational Factors on Job Satisfaction of Disability Service Providers at Postsecondary Institutions.* Chair, April 29, 2010.

Dissertation Proposals at the University of Denver

Bowers, Stacey L. *Library Anxiety of Law School Students: A Study Utilizing the Multidimensional Library Anxiety Scale.* Chair, November 5, 2009.

McCord, J. Michael. *Developing a Standard of Care for Educational Malpractice.* Edith W. King, Chair. April 23, 2010.

Thompson, Jennifer. *History of Colorado Women's College.* Edith W. King, Chair, October 30, 2008. Committee Member.

Walker, Emelda. *Influence of Organizational Factors on Job Satisfaction of Disability Service Providers at Postsecondary Institutions.* Chair, July 21, 2009.

Dissertations at Other Institutions

Rodríguez-Mori, Howard. *The Information Behavior of Puerto Rican Immigrants to Central Florida, 2003-2009: Grounded Analysis of Six Case Studies Use of Social Networks during the Migration Process.* Kathleen Burnett, Chair, April 10, 2009, Florida State University, Committee Member.

Schwartz, Brian *More than a Look-up Skill: Medical Information Literacy Education in Osteopathic Medical Schools.* D. Mirah Dow, Chair, July 18, 2017. Emporia State University, Committee Member.

Snow, Karen. *A Study of the Perception of Cataloging Quality among Catalogers.* Shawne D. Miksa, Chair, August 1, 2011. University of North Texas, Committee Member.

Dissertation Proposals at Other Institutions

Schwartz, Brian *More than a Look-up Skill: Medical Information Literacy Education in Osteopathic Medical Schools.* D. Mirah Dow, Chair, December 4, 2015. Emporia State University, Committee Member.

Snow, Karen. *A Study of the Perception of Cataloging Quality among Catalogers.* Shawne D. Miksa, Chair, May 11, 2010. University of North Texas, Committee Member.

Master's Thesis at the University of Denver

Hemingson, Jeff. *Recital Paper.* Lamont School of Music, February 2010, Outside Chair.

Capstones at the University of Denver

Anthony, Alisa. *Correlation of Library and Information Science Program outcomes and Vacant Position Qualifications Listed on the Colorado State Library Jobline by Employers During the Period September 1, 2000 through August 31, 2002.* Chair, Winter Quarter, 2003.

Borden, Donna M. *Improving Emergency Communications Systems: Is a Radio Communications Network the Answer?* Fall Quarter, 2014.

Bowden, Heather L.M. *Exploring Biological Models for Long-term Data Preservation.* Chair, Spring Quarter, 2008.

Casenada, Cassandra Y. *Challenges to the Recruitment, Education, and Retention of Librarians of Color*. Chair, Spring Quarter, 2008.

Chang, Jennifer C. *Legal Research Practice and Preference: A Law Firm Perspective.* Chair, Spring Quarter 2011.

Ellis, Megan S. Fitzgerald. *Design of a Public Library Adult Volunteer Recruitment Program and Training Curriculum.* Chair, Winter Quarter, 2003.

Kircher, Kathy. *Development of a Library Pathfinder for Exobiology and Posting it on the Internet.* Chair, Winter Quarter, 2003.

Melhado, Loretta. *Design of St. John's Episcopal Church Library.* Chair, Spring Quarter, 2008.

Radcliff, Kathy. *Original Cataloging of Archival materials in the HERS Collection in Penrose Library.* Chair, Winter Quarter, 2003.

Sass, Carol Ann. *ACT Periodical Index: Access to Catholic Thinking Periodical Index: Web Index to Select Catholic Periodicals.* Spring Quarter 2000.

Stone, Sergio D. *Conducting Community Analysis for the Bemis Public Library (Littleton, Colorado) Using 2002 U.S. Census Data and the Online Outcome-Based Evaluation Toolkit.* Chair, Winter Quarter, 2003.

Tureson, Tamara. *Design and Use of an Information Audit Tool for Use in a Law Library.* Chair, Winter Quarter, 2003.

Tweed, Beth. *Evaluation of Email Reference Service in a Consumer Health Library Environment.* Chair, Winter Quarter, 2003.

GRANTS AND CONTRACTS

Student Learning in Agriculture STEM through Teacher Professional Development. Research team: Stanton Gartin (PI) and Cyndi Hofmeister, Northeast Junior College; Jeff Cash, Cheryl Sánchez, Anne-Marie Crampton, Lamar Community College; Suzanna Spears, Morgan Community College; Jack Wiley, Kerry Gabrielson, Trinidad State Junior College; Michael J. Miller, Colorado State University; Michael Womochil (Co-PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Agriculture, Agriculture and Food Research Initiative, Food, Agriculture, Natural Resources and Human Sciences Education and Literacy Initiative, $404,460 (2017-2020)

Leading and Achieving: the Colorado Agriculture Regional Consortium. Research team: Jack Wiley (PI), Kerry Gabrielson, Trinidad State Junior College; Jeff Cash (PI), Cheryl Sánchez, Anne-Marie Crampton, Lamar Community College; Suzanna Spears, Morgan Community College; Cyndi Hofmeister, Northeast Junior College; Michael Womochil (Co-PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Agriculture, Hispanic Serving Institutions Education Grants Program, $504,414 (2017-2020)

Cyber Prep Program Planning Grant. Research team: Debbie Sagen (PI), Brenda Lauer, Pikes Peak Community College; Gretchen Martin, Koiosa Insights; and, Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Commerce, Regional Alliances and Multi-stakeholder Partnerships to Stimulate (RAMPS) Cybersecurity Education and Workforce Development, $199,681 (2016-2018)

Career and Technical Education in Colorado: Pathways to Education and Employment. Research team: Heather McKay (PI), Rutgers University; Sarah Heath, Casey Sacks, Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Education, Institute of Education Sciences, $1,400,000 (2017-2021)

Pre-Alliance Planning Grant Colorado Community College Alliance. Research team: Victor Vialpondo (PI) and Janel Highfill, Community College of Aurora; Heidi Loshbaugh (Co-PI), Community College of Denver; Rick Reeves, Bill McGreevy, Liz Cox, and Kristin Aslin, Red Rocks Community College; Cathy Pellish, Front Range Community College; Samuel DeVries, Arapahoe Community College; Sylvia D. Hall-Ellis, Colorado Community College System. National Science Foundation, Louis Stokes Alliance for Minority Participation (LSAMP), $86,817 (2016-2017)

Towards Scalable Differentiated Instruction Using Technology-enabled, Competency-based, Dynamic Scaffolding. Research team: Karen Wilcox (PI) and Vijay Kumar, Center for Computational Engineering, Massachusetts Institute of Technology; Flora McMartin, Broad-based Knowledge; Quinsigamond Community College; and, Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Education, First in the World Developmental Grant, $2,891,882 (2015-2019)

Colorado Strategic Partnerships Emergency Grant. Research team: Elise Lowe-Vaughn (PI), Amy Hodson, Celia Hardin, Barbara McBride, James Newby, Christopher Dewhurst, Nina Holland, Kate Anderson, MaryAnn Roe, Chrystalynn Chrystalynn, Elaine Edon, Mona Barnes, Tom Morgan, Rob Hanni, and Marie Valenzuela, Colorado Department of Labor and Employment; Steve Anton, Joelle Brouner, and, Katie Griego, Colorado Department of Human Services; Rebecca Holmes, Judith Martinez, and Jennifer Jirous, Colorado Department of Education; Emily Templin Lesh, Colorado Workforce Development Council; Cory Everett, Colorado Department of Regulatory Agencies; and, Casey Sacks and Sylvia D. Hall-Ellis, Colorado Community College System. U.S. Department of Labor, Strategic Partnerships Emergency Grant, $5,000,000 (2015-2017)

CAEL Jump Start Program: Competency-Based Education. Research team: Jerry Migler (PI), Casey Sacks, Debra Cohn, Thomas Hartman, and Sylvia D. Hall-Ellis, Colorado Community College System; Matt Jamison, Front Range Community College; Mike Coste, Red Rocks Community College; Amanda Corum, Pueblo Community College; Janet Colvin, Pikes Peak Community College; and, MaryAnn Matheny, Community College of Denver. Council for Adult and Experiential Learning, $15,000 (2015)

Summit on the Redesign of Developmental Education. Research team: Jerry Migler (PI), Casey Sacks, and Sylvia D. Hall-Ellis, Colorado Community College System; Chip Nava, Pueblo Community College; Kim Moultney, Arapahoe Community College; Debbie Ulibarri, Trinidad State Junior College; and, Kris Bernard, Front Range Community College. American Association of Community Colleges, $15,000 (2015-2016)

Equity in Excellence at Colorado Community Colleges. Research team: Keith Howard (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Estela Mata Bensimon, Center for Urban Education, University of Southern California; and Kerry Gabrielson, Trinidad State Junior College. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, $150,000 (2015-2016)

MBA High School of Business in Colorado. Research team: Laurie Urich (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Rudolph Sumpter and Beatrice Gerrish, Boulder Valley Schools; Keith Curry Lance, RSL Research Group. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, $501,295 (2015-2016)

Fullbridge Program in Colorado. Research team: Keith Howard (PI) and Sylvia D. Hall-Ellis, Colorado Community College System; Suzanna Spears, Fort Morgan Community College; and, Cheryl Sánchez and Anne-Marie Compton, Lamar Community College. Colorado Department of Higher Education, Colorado Opportunity Scholarship Program, $300,000 (2015-2017)

Colorado Community College System Alternative Credit Program. Research team: Jerry Migler (PI), Keith Howard, and Sylvia D. Hall-Ellis, Colorado Community College System. American Council on Education, $13,000 (2015)

Internationalization in Higher Education. Researcher: Samuel D. Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $8,000 (2014-2015)

International Perspectives on Bilingual Education. Researcher: Sharolyn Pollard-Durodola. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $3,700 (2014-2015)

Cultivating Culturally Relevant and Responsive Curriculum and Pedagogy in College. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, iRise Grant, $5,000 (2014-2015)

Project EMERGE (Educational Model for Evaluation and Replicability in Gifted Environments). Research team: Norma Hafenstein (PI) and Bruce Uhrmacher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Lynde and Harry Bradley Foundation, $235,000 (2014-2015)

Collecting Asian American Refugee Stories. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. American Educational Research Association, Research Grant, $5,000 (2014-2015)

Developing Expertise in Teaching K-5 Mathematics. Research team: Julie Sarama (PI) and Douglas H. Clements (Co-PI), in partnership with the School of Education at the University of Michigan. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, $130,344 (2013-2015)

Investigation of the Long-Term Outcomes for Special Education Students. Researcher: Antonio Olmos-Gallos. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Jefferson County School District, Office of Assessment, $40,000 (2014)

Refugee Community Collaboration. Researcher: Vicki Tomlin (PI) in partnership with the African Community Center and Jewish Family Service. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, $14,854 (2014-2015)

Access to Mathematics for All. Research team: Richard S. Kitchen (PI), Nicole M. Russell (Co-PI), and Terrence Blackman (Co-PI), Curriculum Studies and Teaching Program, Morgridge College of Education; Álvaro Árias (Co-PI, Department of Mathematics); and, James Gray (Co-PI), Department of Mathematics, Community College of Aurora. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, The Robert Noyce Scholarship Program, Capacity Building Project, $349,926 (2014-2016)

Cognitive Test Battery for Intellectual Disabilities. Research team: Karen Riley (PI), Lyndsay Agans, Jessica Lerner, and Karin Dittrick-Nathan in partnership with David Hessl (PI), The MIND Institute at the University of California – Davis, and Elizabeth Berry-Kravis, Rush University Medical Center. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Institutes of Health, Outcome Measures for Use in Treatment Trials for Individuals with Intellectual and Developmental Disabilities (R01), $2,499,996 ($588,672 at DU) (2014- 2019)

Broadening Participation in Engineering among Women and Latino/as: A Longitudinal, Multi-Site Study. Researcher: Patton Garriott (PI) in partnership with the University of North Dakota and the University of Missouri. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, HER Core Research, $677,390 ($69,992 at DU) (2014-2019)

Designing a Teacher Evaluation System to Improve Teacher Effectiveness for Culturally and Linguistically Diverse Learners. Research team: María del Carmen Sálazar (PI), Jessica Lerner, and Kathy Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, $29,988 (2014-2016)

Developing a College-Going Culture in Latina/O Families: Exploring the Influence of Funds of Knowledge on Family Outreach Programs. Researcher: Judy Marquez Kiyama. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, $18,720 (2014-2016)

Assessment of Quality of Life in Neutral Implantation Surgery for the Treatment of Parkinson's Disease. Researcher: Cynthia McRae. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $3,967 (2014-2015)

Pura Vida: Cloud Forest, Curriculum and Cross-Cultural Study. Research team: Norma Hafenstein (PI) and Bruce Uhrmacher (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $8,000 (2014-2015)

Online Course Development for Curriculum and Instruction. Researcher: Ruth Chao. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: María del Carmen Sálazar. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: Jessica Lerner. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2014)

Online Course Development for Curriculum and Instruction. Researcher: Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2014)

The Mathematics Education of African Americans, 1866 – 1954. Researcher: Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Academy of Education, Spencer Foundation Postdoctoral Fellowship, $55,000 (2014-2016)

Early Childhood Care and Education Study. Research team: Carrie Germeroth (PI), Melissa Mincic, and Douglas H. Clements. Technical reviewer for MCE: Sylvia D. Hall-Ellis. State of North Dakota, Department of Public Instruction, $73,500 (2013-2014)

Graduate Level Specialty in Addiction Counselor Training with Emphasis on Integration of Native American Specific Content. Research team: Ruth Chao (PI) and Michael J. Faragher (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. The Galena Foundation, $289,732 (2013-2016)

The Collecting Asian American and Pacific Islander Refugee Stories (CARS) Project. Researcher: Samuel Museus. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, $15,000 (2014)

Parents in Transition: A Multiple Case Study of Parent and Family Orientation Programs. Researcher: Judy Marquéz Kiyama. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $1,500 (2014-2015)

The Sistah Network: Black Women Graduate Students Supporting and Retaining Each Other. Researcher; Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $2,708 (2014-2015)

Evaluation of the Northeast Denver Babies Ready for College Program. Research team: Carrie Germeroth (PI), Melissa Mincic, and Douglas H. Clements. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High Montessori, $9,922 (2013-2014)

Developing Teaching Expertise in K-5 Mathematics. Research team: Julie Sarama (PI) and Douglas Clements (University of Denver), in partnership with Timothy Boerst (PI), Meghan Shaughnessy, Deborah Ball, Hyman Bass (School of Education at the University of Michigan). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, $449,827 ($130,344 at the University of Denver (2013-2015)

Early Learning Care and Education Study Program Grant for the State of North Dakota. Research team: Carrie Germeroth (PI), Melissa Mincic, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. State of North Dakota Department of Public Instruction, $73,500 (2013-2014)

Local Professional Learning Community for School Leaders. Research team: Susan Korach (PI), Kristina Hesbol, and Rebecca McClure. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Education Development Center, $10,950 (2013)

Healthy Eaters, Lifelong Movers 2: Implementing Evidence-Based School Environment, Policy, and Curricular Changes to Increase Opportunities for Healthy Eating and Physical Activity in Low Income, Rural Colorado. Research team: Elaine Berlansky, University of Colorado at Denver (PI), Nicholas Cutforth, University of Denver (Co-PI), and Allison Reeds. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, $3,103,108 (2013-2017)

Hughes Rare Books Library Room Renovation in the Sturm College of Law. Project team: Patti H. Marks, Sylvia D. Hall-Ellis, and Leigh Elliott. Mabel T. Hughes Charitable Trust, $34,000 (2013-2014)

The Promise Center Partnership with the Marsico Institute for Early Learning and Literacy and the City and County of Denver. Research team: Karen Riley (PI), Douglas H. Clements (Co-PI), and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. The Piton Foundation, $223,468 (2013-2014)

Center of Excellence for Problem Gambling. Research team: Ruth Chao (PI) and J. Mike Faragher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, $68,021 (2012-2013)

United Way Implementation and Validation Review. Research team: Douglas H. Clements (PI), Amanda Moreno, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High United Way, $19,737 (2013)

Math/Science Partnership in Rural Districts. Research team: Kristen Bunn (PI, Eagle County Schools), Paul Michalec (Co-PI), and Alegra Reiber. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Education, Colorado's Mathematics and Science Partnership Program, $750,000 (2013-2014)

Mathematics and Science Education of African Americans. Research team: Nicole Russell (PI), Sylvia D. Hall-Ellis, Steve Fisher (Penrose Library). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, $29,994 (2013-2015)

Online Course Development for Curriculum and Instruction. Researcher: Nicole Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $3,000 (2013)

Discourse and Opportunity: Undocumented Students and Higher Education Policy. Researcher: Ryan Gildersleeve. Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Academy of Education, Spencer Foundation Postdoctoral Fellowship, $55,000 (2012-2014)

An Anthropological Study of the Latino Graduation Ceremony. Researcher: Ryan Gildersleeve. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Spencer Foundation, $39,900 (2012-2013)

Fragile-X and Pharmaceutical Company: Clinical Trial of AFQ056. University of California – Davis Children's Hospital MIND Institute (Sacramento), Children's Hospital Denver, and Rush Children's Hospital at Rush University Medical Center (Chicago). Karen Riley, PI. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Novartis Pharmaceuticals Corporation, $394,206 (2012-2014)

Project Engage, Phase 2, a DAPRA Grant in partnership with Total Immersion Systems, Inc., and Texas A&M University. Research team: Karen Riley (PI) and Lyndsay Agans (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Defense, $60,000 (2011-2013)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, $14,951 (2012-2013)

Online Course Development for Curriculum and Instruction. Research team: Bruce Uhrmacher (PI) and Norma Hafenstein (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Teaching and Learning, $18,193 (2012-2014)

Writers in the Schools. Research team: Karen Riley (PI) and Amanda Moreno (Co-PI).Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Humanities, $4,965 (2012-2013)

Learning Ecosystem Validation Grant. Research team: Karen Riley (PI), Lyndsay Agans, Kent Seidel, and Shimelis Assefa. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Bill & Melinda Gates Foundation, $315,000 (2012-2013)

Project Words of Oral Reading and Language Development (WORLD). Research team: Jorge E. Gonzalez (PI), Texas A&M University; Laura Saenz (Co-PI), University of Texas – Pan American; and, Sharolyn Pollard-Durodola (Co-PI), University of Denver. Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, $53,354 (2012-2015); award $640,718, transfer from Texas A&M University

Increasing the Efficacy of an Early Mathematics Curriculum with Scaffolding Designed to Promote Self-Regulation. Research team: Douglas H. Clements (PI) and Julie Sarama (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, $1,445,315 (2008-2014); award $4,541,975, transfer from University at Buffalo, The State University of New York

Using Rule Space and Poset-based Adaptive Testing Methodologies to Identify Ability Patterns in Early Mathematics and Create a Comprehensive Mathematics Ability Test. Research team: Douglas H. Clements (PI) and Julie Sarama (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, $323,791 (2010-2014); award $1,194,944, transfer from University at Buffalo, The State University of New York

Comprehensive Postdoctoral Training in Scientific Education Research. Researcher: Julie Sarama (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Education, Institute of Education Sciences, $133,458 (2010-2014); award $613,353, transfer from University at Buffalo, The State University of New York

Longitudinal Study of a Successful Scaling Up Project: Extending TRIAD. Research team: Douglas H. Clements (PI), Julie Sarama (Co-PI), and Abt Associates (Carolyn Layzer, Fatih Unlu, Laurie Bozzi, Lily Fesler, Alina Martinez, Cristofer Price, James van Orden). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Institute of Education Sciences, $384,940 (2011-2015; award $1,250,286, transfer from University at Buffalo, The State University of New York

Early Childhood Education in the Context of Mathematics, Science, and Literacy. Research team: Julie Sarama (PI), Douglas H. Clements (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. National Science Foundation, $990,020 (2010-2014; award $2,285,228, transfer from University at Buffalo, The State University of New York

Early Childhood Clearinghouse Information Center Redesign. Research team: Karen Riley (PI) and Amanda Moreno (Co-PI).Technical reviewer for MCE: Sylvia D. Hall-Ellis. Office of the Lt. Governor of Colorado, $12,000 (2012-2013)

Morgridge Rural Educational Leadership Initiative. Research team: Lyndsay Agans (PI), Linda Brookhart (Co-PI), Susan Korach, and Rebecca McClure. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Morgridge Family Foundation, $100,000 (2012-2014)

Center of Excellence for Problem Gambling. Research team: Patrick Sherry (PI) and J. Mike Faragher. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, $55,000 (2012-2013)

Intermodal Transportation Institute Research Initiatives. Researcher: Patrick Sherry. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University Transportation Centers Program, Research and Innovative Technology Administration, U.S. Department of Transportation. $600,000 (2012-2014)

Mile High United Way Social Innovation Fund Early Literacy Initiative. Gloria L. Miller, PI, Amanda Moreano, Kim Hartnett-Edwards, and Sheridan Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Mile High United Way, $89,992 (2012-2013)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, $1,000 (2012-2013)

Refugee Student Art Outreach. Researcher: Karin Dittrick-Nathan. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $3,000 (2012-2013)

Resistance, Resilience, and Reciprocity: Centering the Voices of Black Doctoral Women with Faculty Aspirations. Researcher: Nicole M. Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $2,965 (2012-2013)

Assessing Learning through Student Notebooks. Research team: Keith Miller, Nancy Sasaki, and Kathy Green. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Professional Research Opportunities for Faculty, $30,000 (2012-2014)

International School Psychology Practicum Exchange. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $2,000 (2012-2013)

ELO in Colorado. Research team: Cynthia Hazel and Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Legacy Foundation, $150,000 (2012-2013)

Creating Online LIS Courses. Research team: Mary C. Stansbury (PI), Shimelis Assefa, Denise Anthony, Xiao Hu, and Krystyna Matusiak. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, $15,000 (2011-2013)

Maritime Piracy Seminar. Researcher: Ved Nanda, The Nanda Center, Sturm College of Law. Technical reviewer for Sturm College of Law: Sylvia D. Hall-Ellis. Arsenault Family Foundation, $15,000 (2012-2013).

Early Childhood Librarianship: An Interdisciplinary, Experiential Learning MLIS. Researcher: Mary C. Stansbury (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Laura Bush's 21st Century Librarians Program, Institute for Museums and Library Services, $249,066 (2012-2014)

Learning Ecosystem Planning Grant. Research team: Karen Riley (PI), Lyndsay Agans, Kent Seidel, and Shimelis Assefa. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Bill & Melinda Gates Foundation, $281,217 (2011-2012)

Advanced Service Learning Practitioner Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Community Engagement and Service Learning, $400 (2011)

Evaluating and Enhancing the EspeciallyMe Program. Research team: Lori D. Patton and Nicole Russell. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, Public Good Fellowship Grant, $24,780 (2012)

Choosing Excellence: Let Every Child Bloom. Research team: Shimelis Assefa (PI) and Mary C. Stansbury (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Community Engagement and Service Learning, Public Good Grant, $7,657 (2012)

K-8 STEM Content Specific Professional Development to Improve Elementary Student Achievement. Research team: Kent Seidel (PI), Nicole Russell (Co-PI), Kimberly Hartnett-Edwards, Paul Michalec, Jeff Farmer, Keith Miller, Alegra Reiber, and Nancy Sasaki. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Education, Improving Teacher Quality Grant, (Title II ESEA), $307,299 (2011-2012)

Building a Better Principal Pipeline to Boost Student Achievement. Researcher: Susan Korach. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Denver Public Schools; a subcontract from the Wallace Foundation Grant, $170,000 (2011-2017)

Center of Excellence for Problem Gambling. Research team: J. Mike Faragher (Co-PI) and Bobbie Vollmer (PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Department of Behavioral Health, $79,999 (2011-2012)

An Exploration of Novice Teachers' Core Competencies: Impacts on Student Achievement, and Effectiveness of Preparation. Research team: Kent Seidel (PI), Kathy Green (Co-PI), Kimberly Hartnett-Edwards, and Duan Zhang. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Institute of Education Sciences, Effective Teachers and Effective Teaching, $990,987 (2012-2015)

Project Engage, a DAPRA Grant in partnership with Total Immersion Systems, Inc., and Texas A&M University. Research team: Karen Riley (PI) and Lyndsay Agans (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. U.S. Department of Defense, $49,964 (2011-2014)

User-centered Evaluation of Music Search Engines. Researcher: Xiao Hu. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Faculty Research Fund, $2,931 (2011-2012)

Educational Practicum in Vietnam and China to Promote the Inclusion of Young Children with Disabilities. Researcher: Gloria L. Miller. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Office of Internationalization, $5,000 (2011-2012)

Evaluation of Colorado's Enhancing Quality in Infant-Toddler (EQIT) Initiative. Research team: Virginia R. Maloney and Amanda Moreno. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Buell Foundation, $395,884 (2011-2013)

Creating Engaging Environments to Teach Pre-Algebra Mathematics to Elementary Students. Research team: Álvaro Arias, Mario López, María del Carmen Salazar, and Lyndsay Agans. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver Interdisciplinary Grant, $60,000 (2011-2012)

Morgridge Education Technology Accessible (META) Resource Project. Research team: Lyndsay Agans (PI) and Shimelis Assefa (Co-PI). Technical reviewer for MCE: Sylvia D. Hall-Ellis. Morgridge Family Foundation, $36,000 (2011)

MCE Connect: A 21st Century Framework for Faculty Development. Research team: Bruce Uhrmacher (PI), Shimelis Assefa (Co-PI), Lyndsay Agans (Co-PI), Kimberly Hartnett-Edwards, Norma Hafenstein, Xiao Hu, Paul Michalec (Co-PI), María del Carmen Salazar (Co-PI), and Sandra Snyder-Mondragon. Technical reviewer for MCE: Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, $22,355 (2011-2012)

Parent Education and Parent Leadership and Advocacy. Research team: Virginia Maloney (PI) and Amanda Moreno, Marsico Institute for Early Learning and Literacy. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, $27,358 (2010-2011)

Intentional School Culture. Researcher: Cynthia Hazel. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Denver Public Schools, $38,040 (2010-2011)

Healthy Eaters, Lifelong Movers: Implementing Evidence-Based School Environment, Policy, and Curricular Changes to Increase Opportunities for Healthy Eating and Physical Activity in Low Income, Rural Colorado. Research team: Elaine Berlansky, University of Colorado at Denver (PI), Nicholas Cutforth, University of Denver (Co-PI), and Allison Reeds. Technical reviewer for MCE: Sylvia D. Hall-Ellis. Colorado Health Foundation, $1,683,277 (2011-2014)

Second Life Learning Community. Research team: Don McCubbrey (PI), Sylvia D. Hall-Ellis (Co-PI), Walter LaMendola, and Paul Novak. University of Denver, Center for Teaching and Learning, $13,000 (2010-2011)

Reintroducing the Value of Law Librarians to Academic and Public Librarians in Colorado through the Identification and Use of Emerging Technologies. Research team: Sylvia D. Hall-Ellis (Co-PI), Stacey L. Bowers (PI), and Christopher Hudson, in partnership with Denver Public Library, Arapahoe Library District, and the Colorado State Supreme Court Library. University of Denver, Center for Community Engagement and Service Learning, $5,773 (2010-11)

Reintroducing the Value of Law Librarians to Public Librarians through the Identification and Use of Emerging Technologies and Resources. Research team: Stacey Bowers (PI) and Sylvia D. Hall-Ellis (Co-PI). American Association of Libraries, Wolters Kluwer Law & Business Grant Program, $2,725 (2010-2011)

Faculty Service Learning Pod. Research team: María del Carmen Salazar and Nicholas Cutforth (Curriculum and Instruction Program), Frank Tuitt (Higher Education Program), Cynthia Hazel and Gloria Miller (Child, Family, and School Psychology Program), and Sylvia D. Hall-Ellis (Library and Information Science Program). University of Denver, Center for Community Engagement and Service Learning, $8,000 (2010-2011)

Lincoln Collaborative. Research team: Antonio Esquibel (Principal, Lincoln High School), María del Carmen Salazar (Curriculum and Instruction Program), and. Sylvia D. Hall-Ellis. School Improvement Grant, Denver Public Schools, $375,000 (2010-2012)

Future LEADers of America: Leaders III. Research team: Denver Public Library (Kristen Svendson, PI), the University of Denver (Sylvia D. Hall-Ellis), the Colorado Chapter of REFORMA (Orlando Archibeque), and the Colorado Association of Libraries (Martin Garnar). Laura Bush's Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, $988,366 (2009-2012)

Teaching for Success in the Library Environment: LIS 4030 in Library 2.0. Research team: Deborah S. Grealy (PI) and Sylvia D. Hall-Ellis (Co-PI). University of Denver, Center for Teaching and Learning, $ 9,350 (2009-10)

Writing Group Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Community Engagement and Service Learning, $750 (2008-2009)

Collaborative Learning Faculty Grant, Sylvia D. Hall-Ellis, University of Denver, Center for Teaching and Learning, $1,500 (2008)

Connecting Information Literacy to Learning. Research team: Lori Micho, Merrie Valliant, Amanda Samland, and Sylvia D. Hall-Ellis. Colorado State Library, LSTA Discretionary Grant Program, $19,548 (2008-2009)

Law Librarianship Fellows Program. Research team: Sylvia D. Hall-Ellis (PI), Stacey Bowers (Co-PI), and Christopher Hudson, Westminster Law Library. Laura Bush's 21st Century Librarians Program, Institute for Museums and Library Services, $999,370 (2008-2012)

Grant Writing in a Cooperative Learning Environment. Sylvia D. Hall-Ellis. University of Denver, Center for Teaching and Learning, $2,000 (2008-2009)

Project Homeless Connect 6 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, $9,785 (2008)

Project Ecuador: International Learning Service Libraries – A Faculty Development Experience in Ecuador. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, $600 (2007)

Project Ecuador: International Learning Service Libraries – A Faculty Development Experience in Ecuador. Sylvia D. Hall-Ellis, International Service Learning Office, University of Denver, $400 (2007)

Project Homeless Connect 5 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, $1,000 (2007)

Project Homeless Connect 4 Event Evaluation. Research team: Sylvia D. Hall-Ellis and Duan Zhang. University of Denver Center for Community Engagement and Service Learning, $4,595 (2007)

Future LEADers of America: Leaders II. Research team: Denver Public Library (Kristen Svendson, PI), the University of Denver (Sylvia D. Hall-Ellis), and the Colorado Chapter of REFORMA (Orlando Archibeque). Laura Bush's Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, $988,518 (2007-2010)

Strategic Planning Assistance for the Denver Medical Library. Sylvia D. Hall-Ellis. Denver Medical Library, Inc., $30,000 (2006-2007)

Destiny Software for JMAC Student Lab. Sylvia D. Hall-Ellis, gift from the Sagebrush Corporation, Minneapolis, Minnesota, $10,000 (2006)

Libraries: Tools for Education and Development Worldwide: A Faculty Development Experience in France. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, $800 (2005)

Denver Public Library: Opportunities for Change. Sylvia D. Hall-Ellis, Colorado Community Based Research Network, $2,000 (2005)

Future LEADers of America. Research team: Denver Public Library (Letty Icolari and Steve Taylor, PIs), Emporia State University (Jim Agee), and the University of Denver (Sylvia D. Hall-Ellis). Recruiting Librarians for the 21st Century Program, Institute for Museums and Library Services, $670,315 (2005-2008)

American Association of University Professors Summer Institute Professional Development Grant. Sylvia D. Hall-Ellis, American Association of University Professors, $300 (2005)

Beta Phi Mu Alumni Tea. Sylvia D. Hall-Ellis, gift from the Office of Alumni and Parent and Relations, University of Denver, $2,000 (2005)

Spectrum Software for LIS Student Lab. Sylvia D. Hall-Ellis, gift from the Sagebrush Corporation, Minneapolis, Minnesota, $5,000 (2005)

Developing Research Capacity in Community Organizations and Residents through Training and Technical Assistance. Nicholas J. Cutforth (PI) and Sylvia D. Hall-Ellis. Piton Foundation, $25,000 (2005-2006)

Libraries: Tools for Education and Development Worldwide: A Faculty Development Experience in Argentina. Sylvia D. Hall-Ellis, Office of Internationalization, University of Denver, $500 (2004)

Developing Research Capacity in Community Organizations and Residents through Training and Technical Assistance. Research team: Nicholas J. Cutforth (PI), Gary Lichtenstein and Sylvia D. Hall-Ellis, Piton Foundation, $25,000 (2003-2004)

Increasing Spanish-Speaking and Hispanic Diversity among Library and Information Science Students at the University of Denver: Development of a Student Recruitment Model. Researcher: Sylvia D. Hall-Ellis (PI), Office of Multicultural Excellence, University of Denver, $2,750 (2003-2004)

Collection Development Enrichment to Support the Cataloging & Classification Specialization and School Librarianship within the Library & Information Science Program at the University of Denver. Research team: Sylvia D. Hall-Ellis (PI) and Deborah S. Grealy. Women's Library Association, University of Denver, $4,000 (2003)

Collection Development Enrichment to Support the Library & Information Science Program at the University of Denver. Research team: Deborah S. Grealy (PI) and Sylvia D. Hall-Ellis. Women's Library Association, University of Denver, $4,000 (2001)

Wireless LAN for Library Education. Research team: Deborah S. Grealy (PI) and Sylvia Hall-Ellis. University of Denver, Center for Teaching and Learning, $24,000 (2001-2002)

Upward Bound – A Program for South Texas Youth. Research team: Monte Churchill, Executive Director of Community Relations; Gary R. Sauceda, Outreach Coordinator; Raymond Hernandez, (PI) Associate Dean for Student Success; and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). U.S. Department of Education, Office of Postsecondary Education, $2,672,003 (1999-2003)

Write Now! Improving Elementary Students' Writing Skills. Research team: Caryl G. Thomason, Assistant Superintendent (PI); Karen Tankersley, Principal; and, Hal Anderson, Director of Technology, Cheyenne Mountain School District 12 (Colorado Springs, Colorado); and Sylvia D. Hall-Ellis. Colorado Department of Education, Educational Telecommunications Unit, $189,453 (1999-2001)

Operation Quick Start -- Distance Learning in Rural Colorado. Research team: Randal Weigum, Technology Coordinator (PI); Bonnie Barns, Director of Federal Programs and Staff Development; and, Adam "Joe" Raskop, Executive Director, Southeastern Board of Cooperative Educational Services (Lamar, Colorado); and Sylvia D. Hall-Ellis. Colorado Department of Education, Educational Telecommunications Unit, $400,000 (1999-2001)

Advanced Technological Training for Information Professionals for the 21st Century. Research team: Mario Reyna, Division of Business Director (PI) and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). Phi Delta Kappa and the National Science Foundation, $250,000 (1999-2001)

Working Connections – Training Information Technologies Professionals for the 21st Century. Research team: Mario Reyna, Division of Business Director (PI) and Sylvia D. Hall-Ellis, South Texas Community College (McAllen, Texas). Microsoft Corporation and the American Association of Community Colleges, $1,147,775 (1999-2001)

The ROAD (Research Oriented Amplification of Development to Literacy) Program. Research team: Deborah J. Leong (PI), Metropolitan State University; Elena Bodrova, Metropolitan State University; Dmitri Semenov, Robert J. Marzano, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Foundation, $25,000 (1998-1999)

Press to Literacy. Research team: Deborah J. Leong (PI), Metropolitan State University; Elena Bodrova, Metropolitan State University; Dmitri Semenov, Robert J. Marzano, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). The Denver Post and the Robert S. McCormick Foundation, $49,818 (1998-1999)

International Telementor Center. Research team: David Neils, David B. Frost (PI), and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Philanthropy, $100,000 (1998-1999)

America Reads: Providing Tutor Training for the America Reads Challenge. Research team: Louis F. Cicchinelli (PI) and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Department of Education, Office of Educational Research and Improvement, $306,000 (1998-1999)

Comprehensive School Reform. Research team: Louis F. Cicchinelli (PI), J. Timothy Waters, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Department of Education, Office of Educational Research and Improvement, $285,000 (1998-1999)

Sustainable Energy Education (SEE) Program for Grades 4-8: Preparing Today's Youth for Lifelong Learning and Responsible Actions in Energy Conservation. Research team: Mary Gromko, Colorado Department of Education; Gene McCarthy, Rocky Flats Field Office, U.S. Department of Energy; Gina Kissell, National Renewable Energy Laboratory; and Barbara L. McCombs (PI), Janet L. Bishop, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). State of Colorado Governor's Office for Energy Conservation, $499,936 (1997-1999)

Review of Kansas Curriculum Standards in Mathematics and Language Arts. Research team: Robert J. Marzano (PI), John S. Kendall, David B. Frost, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Submitted to the Kansas State Department of Education, $25,903 (1998)

International Telementor Center. Research team: David Neils, John Kuglin, Chris Rapp, David B. Frost (PI), and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). Hewlett-Packard Company, $54,752 (1998)

Genesis Mission: Education Public Outreach. Developed in partnership by the Jet Propulsion Laboratory, California Institute of Technology, Los Alamos National Laboratory, Lockheed Martin Astronautics, and the Mid-continent Regional Educational Laboratory (Aurora, Colorado). Research team: John T. Sutton (PI), Alice Krueger, Martha Henry, Greg Rawls, Shae Isaacs, Jeff Johnson, Deb Jordan, Arlene Mitchell, David B. Frost, Jana Caldwell, J. Timothy Waters, and Sylvia D. Hall-Ellis. National Aeronautics and Space Administration, $139,700,000; subcontract award, $4,750,000 (1997-2007)

North Dakota Mathematics Assessment Project. Developed in partnership by the North Dakota Department of Education and Mid-continent Regional Educational Laboratory (Mid-continent Regional Educational Laboratory). Research team: Ann Clapper, Clarence Bina, Greg Gallagher, North Dakota Department of Education; Don Burger (PI), Hillary Michaels, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Office of Education, $1,618,214; subcontract award, $389,076 (1997-2001)

Pacific Resources for Education and Learning Distance Education: Project Evaluation. Developed in partnership by the Pacific Educational Community, the Pacific Resources for Education and Learning (PREL), and Mid-continent Regional Educational Laboratory (McREL). Research team: John W. Kofel (PI), Executive Director, PREL; J. Timothy Waters, Executive Director; Joan Buttram, Robert Keller, and Sylvia D. Hall-Ellis, Mid-continent Regional Educational Laboratory (Aurora, Colorado). U.S. Office of Education, Star Schools Program, $10,000,000; subcontract award, $500,000 (1997-2002)

Identification of Bilingual Gifted and Talented Children: A Comprehensive School Grants for Bilingual Education. Developed in partnership by Hidalgo (Texas) ISD, Los Fresnos (Texas) CISD, Progreso (Texas) ISD, University of Texas – Pan American (Edinburg, Texas), and Education Service Center, Region One (Edinburg, Texas). Research team: Hilda Medrano, Dean, College of Education, University of Texas – Pan American; Linda Phemister (PI), Janie Navarro, and Sylvia D. Hall-Ellis, Education Service Center, Region One. U.S. Department of Education, Office of Bilingual Education and Minority Languages Affairs, $1,670,633 (1997-2002)

Academics 2000: First Things First -- The Texas Goals 2000. Developed for Jim Hogg (Hebbronville, Texas) County ISD, Mirando City (Texas) ISD, and San Isidro (Texas) ISD. Research team: Hilda Medrano, Dean, College of Education, University of Texas - Pan American (Edinburg, Texas); Angie Lehmann, Amy Mares, Ellen Gonzalez (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg, Texas). Texas Education Agency, $339,987 (1997-2000)

Southwestern Bell's Learning Communities Initiative. Developed for Tech Prep of the Rio Grande Valley, Inc. (Harlingen, Texas); the Center for Professional Teacher Development, University of Texas – Brownsville; Teach for America – Rio Grande Valley (McAllen, Texas); and Education Service Center, Region One (Edinburg, Texas). Research team: Patricia G. Bubb, Executive Director (PI), Tech Prep of the Rio Grande Valley; Martin Winchester, Executive Director, Teach for America – Rio Grande Valley; Aileen Johnson, Director, School of Education, University of Texas – Brownsville; and Sylvia D. Hall-Ellis. Southwestern Bell Foundation, $100,000 (1997-1998)

Texas School to Work: Regional Implementation. Developed for Tech Prep of the Rio Grande Valley, Inc. (Harlingen), South Texas Community College (McAllen), Texas State Technical College (Harlingen), Texas Southmost College (Brownsville), Empowerment Zone of the Rio Grande Valley (Mercedes), Project VIDA (Weslaco), Youth Fair Chance (McAllen), and Education Service Center, Region One (Edinburg). Research team: Patricia G. Bubb (PI), Tech Prep of the Rio Grande Valley; Stephen Vassberg, Texas State Technical College; Ellen Trevino, Youth Fair Chance; Wanda Garza, Project VIDA; Leonardo Olivares, University of Texas – Pan American; Michael Bell, South Texas Community College; and Sylvia D. Hall-Ellis. Texas Workforce Commission, $4,250,000 (1997-2002).

Comprehensive Bilingual Education Grant for Hidalgo ISD and Roma ISD. Developed for Hidalgo (Texas) ISD, Roma (Texas) ISD, College of Education, University of Texas – Pan American (Edinburg, Texas), and Education Service Center, Region One (Edinburg, Texas). Research team: Tomas Thomas (PI), Director, Office of Bilingual Education and Sylvia D. Hall-Ellis. U.S. Department of Education, Office of Bilingual Education and Minority Languages Affairs, $1,531,361 (1997-2002)

Lopez High School, Porter High School, Rivera High School, Central Middle School, and Perkins Middle School, Brownsville (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $1,473,611 (1997-1998)

Donna High School, Todd Middle School, and Solis Middle School, Donna (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $704,052 (1997-1998)

Memorial Middle School and Nellie Schunior Middle School, La Joya Independent School District (Texas). Telecommunications Infrastructure Fund Board, $293,641 (1997-1998)

Martin High School, Christen Middle School, Cigarroa Middle School, Lamar Middle School, Laredo (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $1,200,000 (1997-1998).

Lasara Middle School, Lasara (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $246,210 (1997-1998)

Los Fresnos High School and Resaca Middle School, Los Fresnos (Texas) Consolidated Independent School District. Telecommunications Infrastructure Fund Board, $500,000 (1997-1998)

Lyford Junior High School, Lyford (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $354,997 (1997-1998)

Travis Middle School, McAllen (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $269,139 (1997-1998)

Mission High School, Mission (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $297,010 (1997-1998)

Progreso High School, Progreso (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $300,000 (1997-1998)

San Perlita High School, San Perlita (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $293,490 (1997-1998)

Myra Green Junior High School, Raymondville (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $225,000 (1997-1998)

Rio Grande City High School, Ringgold Middle School, Gruella Middle School, Rio Grande City (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $809,934 (1997-1998)

Rio Hondo Junior High School, Rio Hondo (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $297,024 (1997-1998)

Roma High School, Roma (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $333,178 (1997-1998)

San Benito High School, Miller Jordan Junior High School, San Benito (Texas) Consolidated Independent School District. Telecommunications Infrastructure Fund Board, $547,000 (1997-1998)

Santa Maria High School and Santa Maria Middle School, Santa Maria (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $400,000 (1997-1998)

Salvador High School, United Independent School District (Laredo, Texas). Telecommunications Infrastructure Fund Board, $250,879 (1997-1998)

Weslaco High School, Cabaza Middle School, Cuellar Middle School, Weslaco (Texas) Independent School District. Telecommunications Infrastructure Fund Board, $874,242 (1997-1998)

Principals' Assessment and Training Center. Developed for Education Service Center, Region One (Edinburg, Texas). Research team: Roberto Zamora, Leonel Barrera, William H. Parry, and Sylvia D. Hall-Ellis. Texas Principals' Leadership Initiative, Texas Association of Secondary School Principals, Texas Association of Elementary School Principals, and the Sid Richardson Foundation. $461,439 (1996-1998)

The Texas Library Connection -- Integrating and Sharing Resources. Developed for Hidalgo County Library System (McAllen), Cameron County Library System (Brownsville), South Texas Community College (McAllen), the University of Texas - Pan American (Edinburg), University of Texas – Brownsville, and Education Service Center, Region One (Edinburg). Research team: William R. McGee, Coordinator, Hidalgo County Library System; Joe Garcia, Director, Cameron County Library System; Michael D. Bell, Library Director, South Texas Community College; Eleanor Folger Foster, University Library, University of Texas - Pan American; Jaime Vela (PI), Director of Instructional Technology and Media Services, Ron Pontius, Instructional Technology, and Fabiola Fuentes, Media Services, Education Service Center, Region One; and Sylvia D. Hall-Ellis. Office of Library Media Services, Technology Services, Texas Education Agency. $8,000 (1996-1997)

Developing Leadership Communities for Improving Algebra I for All Students. Developed for a partnership of the Region One Statewide Systemic Initiative Team. Research team: Noel Villarreal (PI), Eduardo Cancino, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Statewide Systemic Initiative for Reform in Mathematics, Science and Technology Education to The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin. $25,000 (1996-1997)

Academics 2000: First Things First -- The Texas Goals 2000. Developed for Edinburg (Texas) CISD. Research team: Hilda Medrano, Dean, College of Education, University of Texas - Pan American (Edinburg); Helen Jones, Director (PI), Gifted and Talented Education, Edinburg CISD; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, $750,000 (1996-2001)

Texas Teachers Empowered for Achievement in Mathematics (TEXTEAM) Institute for Algebra I. Developed for Hidalgo ISD, Jim Hogg (Hebbronville) County ISD, La Joya ISD, La Villa ISD, Lyford ISD, Mission CISD, Pharr-San Juan-Alamo ISD, Rio Hondo ISD, San Isidro ISD, San Perlita ISD, Santa Maria ISD, Santa Rosa, Sharyland ISD, Valley View ISD, Webb (Laredo) CISD, Weslaco ISD, and Zapata County (Zapata) ISD. Research team: Noel Villarreal (PI), Chuck McInteer, Ellen M. Gonzalez, Education Service Center, Region One (Edinburg); and Sylvia D. Hall-Ellis. Charles A. Dana Center for Mathematics and Science Education, University of Texas - Austin, $15,975 (1996)

Community Learning Center for La Villa, Texas. Developed for Edcouch-Elsa Independent School District. Research team: Noe Gonzalez (PI), Assistant Superintendent, Edcouch-Elsa Independent School District, and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, $325,000 (1996-1997)

Monte Alto (Texas) Community Learning Center. Developed for Monte Alto Independent School District. Research team: Homero A. Diaz (PI), Superintendent, Monte Alto Independent School District, and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, $300,000 (1996-1997)

Community Learning Center for La Villa, Texas. Developed for La Villa Independent School District. Research team: Sam Gonzalez (PI), Assistant Superintendent, La Villa Independent School District; and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, $325,000 (1996-1997)

Building Project for Taylor Elementary. Developed for Mercedes (Texas) Independent School District. Research team: Mrs. Denise Rivera, Librarian, and Eduardo Infante, Principal, Taylor Elementary School; Ismael S. Cantu (PI), Federal Programs Director, Mercedes Independent School District; and Sylvia D. Hall-Ellis. Delta Region Subzone, Rio Grande Valley (Texas) Rural Empowerment Zone, $375,000 (1996-1997)

Border Education Network (BEN) - Distance Education through Cable Television. Developed for Edinburg (Texas) Consolidated Independent School District. Research team: Noe Torres (PI), Library Media Specialist, Magdalena
Rosas, Library Media and Technology Coordinator, Edinburg Consolidated Independent School District; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Edinburg (Texas) Consolidated School District, $250,000 (1996-1997)

Multiservice One-Stop Open Enrollment Charter School. Developed for the Information Referral Resource Assistance, Inc. (McAllen, Texas). Research team: Pablo Perez and Aguie Pena (PI), Executive Director, Information Referral Resource Assistance, Inc.; Roberto Zamora and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, $3,066,000 (1996-2001)

Project OK: A Community Youth Opportunities Grant for Summer, 1996. Developed for McAllen (Texas) Independent School District, St. Joseph the Worker Catholic Church, and the Office of Adult Education, Education Service Center, Region One. Research team: Father Bart Flatt, St. Joseph the Worker Catholic Church; Noe Calvillo (PI), Office of Adult Education; Maria Louisa Garcia, McAllen Independent School District; and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Protective and Regulatory Agency through the Office of the Mayor, City of McAllen, $350,000 (1996-2001).

Early Childhood: a Time of Discovery. Developed for a partnership of Lasara ISD, Rio Hondo ISD, San Perlita ISD, the School of Education, University of Texas - Brownsville, and Education Service Center, Region One (Edinburg). Research team: Hugo Rodriguez, Dean, School of Education, University of Texas - Pan American; Leonel Barrera and Jack Damron, Field Service Agents, Ellen M. Gonzalez (PI), Administrator for Student Instructional Services, Ruth Solis, Education Specialist in Special Education, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, $722,090 (1996-2001)

Innovative Gifted and Talented Programs for Early Childhood and Elementary Education Students. Developed for a partnership of Edinburg (Texas) CISD, the School of Education, University of Texas - Pan American (Edinburg), and Education Service Center, Region One (Edinburg). Research team: Hilda Medrano, Dean, School of Education, University of Texas - Pan American; Helen de la Garza (PI), Director of Elementary Curriculum and Instruction, Edinburg CISD; and Sylvia D. Hall-Ellis. Texas Education Agency, $750,000 (1996-2001)

Reading Recovery in Early Elementary Grades. Developed for a partnership of La Villa (Texas) ISD the School of Education, University of Texas - Pan American (Edinburg), and Education Service Center, Region One (Edinburg). Research team: Hilda Medrano, Dean, School of Education, University of Texas - Pan American; Marcario Salinas (PI), Supervisor of Elementary Curriculum and Instruction, La Villa ISD; and Sylvia D. Hall-Ellis, Education Service Center, Region One. Texas Education Agency, $750,000 (1996-2001)

Connected Mathematics Project for Middle and Junior High Students. Developed for a partnership of Michigan State University, The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin and Region One Statewide Systemic Initiative Team. Research team: Jack Damron, Chuck McInteer, Noel Villarreal (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). National Science Foundation through Michigan State University to the Charles A. Dana Center at the University of Texas - Austin, $539,610 (1996-1999)

Sharing Resources: Testing the Interlibrary Loan Potential of the Texas Library Connection -- Integrating Media Resources. Developed under the sponsorship of the Hidalgo County Library System (McAllen) and Education Service Center, Region One (Edinburg). Research team: William H. McGee, Hidalgo County System Coordinator; Fabiola Fuentes, Library Media; Ronald Pontius (PI), Instructional Technology, Education Service Center, Region One; and Sylvia D. Hall-Ellis. Library Media Services Program, Office of Technology Services, Texas Education Agency, $25,000 (1996-1997)

State and Federal Adult Education JOBS Program. Developed for Education Service Center, Region One (Edinburg). Research team: Noe Calvillo (PI), Director, Adult Education Program, and Sylvia D. Hall-Ellis. Adult Education Program, Texas Education Agency, $532,846 (1995-1996)

Creating Safe and Drug-Free Schools and Communities. Developed for a partnership of the Region One Consortium for Safe and Drug-Free Education Environments. Research team: Clara Contreras (PI), Health Specialist, and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Education Agency, $150,000 (1995-1996)

Developing Leadership Communities for Improving Mathematics Performance for All Students on Title I Campuses. Developed for a partnership of the Region One Statewide Systemic Initiative Team. Research team: Jack Damron, Chuck McInteer, Noel Villarreal (PI), and Sylvia D. Hall-Ellis, Education Service Center, Region One (Edinburg). Texas Statewide Systemic Initiative for Reform in Mathematics, Science and Technology Education to The Charles A. Dana Center for Mathematics and Science Education, The University of Texas at Austin, $50,669 (1995-1996)

The Impact of Library Resource Centers on Academic Achievement in Selected Public Schools in South Texas. Sylvia D. Hall-Ellis (PI). Developed under the sponsorship of the Department of Library Science, College of Education and Applied Science, Sam Houston State University (Huntsville). Texas Association of School Librarians, Children's Services Round Table, and Young Adults Round Table (Austin, Texas), $2,500 (1995)

School Library Media Specialists Fellowship Program. Sylvia D. Hall-Ellis (PI). Developed under the sponsorship of the Department of Library Science, College of Education and Applied Science, Sam Houston State University (Huntsville, Texas). U.S. Department of Education, HEA Title II-B, Library Education and Human Resource Development Program, $44,000 (1995-1996)

Planning for Educational Technology. Research team: Ruth Ann Riggins (PI), Director of Library Media and Technology Services, Donna (Texas) Independent School District; Noe Torres, Education Service Center, Region One; Patricia G. Bubb, Tech Prep of the Rio Grande Calley, Inc; Michael D. Bell, South Texas Community College; and Sylvia D. Hall-Ellis, Sam Houston State University. Developed under the sponsorship of Donna (Texas) Independent School District, Education Service Center, Region One (Edinburg), Tech Prep of the Rio Grande Valley, Inc. (Harlingen), South Texas Community College (McAllen), and the Department of Library Science, Sam Houston State University (Huntsville). Funded through Infusion of Educational Technology Planning Grant Program (H.B. 18: Models). Texas Education Agency, $18,000 (1993-1994)

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Retrospective Conversion Projects: North Central Regional Library Service (Mason City, IA), 1987-1988; Southeastern Library Services (Davenport, IA), 1986-1987; Virginia Theological Seminary (Alexandria), 1984-1985; California University of Pennsylvania (California, PA), 1984-1985; Kennametal Corporation (Latrobe, PA), 1984-1985; West Virginia University (Morgantown), 1983-1985; Altoona Area Public Library (Altoona, PA), 1983-1984; George Washington University (Washington, DC), 1983-1984; Indiana University of Pennsylvania (Indiana, PA), 1983-1985; Health Education Center (Pittsburgh), 1983-1984; Central Pennsylvania District Library Center (Bellefonte, PA), 1982-1985; Duquesne University Law School Library (Pittsburgh), 1982-1983; Allegheny County Law Library (Pittsburgh), 1982-1984; Calgon Technical Information Center (Pittsburgh), 1982; Dow Corning Corporation, Technical Information Center (Midland, MI), 1982-1983; Tri-System Public Library Retrospective Conversion Project (Binghamton, Corning, and Ithaca, NY), 1978-1981, Technical Project Director.

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SOLID FREEFORM FABRICATION OF CONTINUOUS FIBER REINFORCED COMPOSITE MATERIALS

ERJIAN MA

A Dissertation

Submitted to

the Graduate Faculty

of Auburn University

in Partial Fulfillment of

the Requirements for

the Degree of

Doctor of Philosophy

Auburn Alabama

August 6, 2001

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COMPOSITE MATERIALS

Except where reference is made to the work of others, the work described in this dissertation is my own or was done in collaboration with my advisory committee

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DISSERTATION ABSTRACT
SOLID FREEFORM FABRICATION OF CONTINUOUS FIBER REINFORCED COMPOSITE MATERIALS

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Doctor of philosophy, August 6, 2001
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240 Typed pages

Directed by Bor. Z. Jang

A novel computer-controlled composite layer manufacturing (CLM) process has been proposed and investigated. The CLM process may be considered to be a new development direction in the field of rapid prototyping and manufacturing (RP&M) technology. A traditional RP&M process is capable of producing a concept model or investment-casting pattern point by point and layer by layer by using monolithic materials such as an un-reinforced resin or metal. In contrast, the presently developed CLM process is capable of building a three-dimensional object of a complex shape from a high-strength fiber reinforced composite material.

In the present dissertation study, the technical feasibility of the CLM process has been demonstrated with a CLM machine constructed that is capable of fabricating both thermoplastic and thermosetting resin matrix composites. This automated manufacturing technology could potentially provide (1) a reduction in time from composite part design to production, (2) a cost-effective method of fabricating complex-

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shaped composite components, (3) an approach to the fabrication of integrated structures for a reduced number of parts in a system and minimized need for part-to-part joining or welding, and (4) added capabilities for filament-winding.

The dissertation research began with the formulation of new process concepts, continuing with the analysis of part forming strategies, material selection, concept designs for the system, feasibility experiments, detail designs, software and hardware integration, to a final construction of a prototype machine.

Over ten part-forming methods were studied. Several feasibility experiments have been carried out to prove these forming strategies and two main fabrication processes have been selected. They are named Self-Anchoring process and Automatic Extrusion process, respectively. The error sources for the Self-Anchoring Forming Process were analyzed. Based on these results, the requirements of the software development have been established. To find the best parameters for both Self-anchoring and Automatic extrusion Forming Processes, related simulation models have been proposed and evaluated. According to the result of this modeling study, new design plans were conceived and proposed.

Both of the two CLM fabrication methods have been studied experimentally and a system for self-anchoring forming process has been designed and installed. The towpreg, a semi finished material used for the Self-Anchoring process was successfully formed.

To compare the mechanical properties of the parts prepared by the new CLM method and by the conventional composite fabrication methods, three point bending tests were carried. The results indicate that the parts fabricated by CLM have acceptable mechanical properties.

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ACKNOWLEDGMENT

I would like to thank my advisor and committee chairman Dr. Bor. Z. Jang for providing knowledge, leadership, advice, and the opportunity to work on this project.

I would like to offer my appreciation to Dr. Dan B. Marghitu and Dr. Sabit Adanur for serving on the advisory committee, support, encouragement and advice for my dissertation and to Dr. G. Mills for reading and correcting my dissertation.

I would like to thank the members of our team, Dr. Leon W. Wu, Professor Jun H. Liu and Jessica Li, for their friendship, encouragements and help.

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CHAPTER 1 INTRODUCTION

§1-1 FOREWORD

1-1-1 Background

In industry, three basic factors should be considered in developing a new part or structure: cost, quality and time. The quality includes geometry and precision, mechanical properties, convenience for using, safety, durability etc. To obtain a desired geometry, various conventional methods can be employed and they can be classified into several different categories (See Table 1-1).

In response to the different requirements of a part, new fabrication methods are emerging. During the last decade, a new technology has appeared, which is called solid freeform fabrication (SFF), layer manufacturing (LM), or rapid prototyping and manufacturing technology (RP&M or, simply, RP). What is RP? What are the special features of RP? What are their advantages and shortcomings as compared with traditional fabrication technologies? And how does their future hold? All these issues will be briefly introduced in the following.

What is RP? So far, there has been no generally accepted definition of RP. The concept of RP may be considered as a process in which a computer-aided design model of a part can be converted into a physical object through some special materials additive means. A significant difference between the new RP and traditional fabrication

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	Typical Method	Features	Application Field
Subtractive Material	Lathe, turning, Planing, Boring,	General Precision	Common Metal Removing
	Electric Spark Machining, Etching Machine,	High Precision, Forming Speed are Low	Mold Manufacture, Special Forming
Additive Material	Welding, Casting	Precision is lower, Mass product	Semi finished Product
	Filament Winding, Injection Molding,	Mass Product	Plastic manufacture
	CVD and PVD,	High Precision and small product	Electric Manufacture
	RPT	Few product	Model Forming, Medical purpose
Deform Material	Forging, Blanking, Stamping	Mass Product	Auto Manufacture
	Plastic Blow	Mass Product	Plastic Manufacture

Table 1-1 Classification of fabrication methods.

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techniques are the fact that most of these new techniques build objects by adding material (e.g. layer by layer) instead of removing materials (such as in CNC milling).

What are the features of RP? The new RP methods can be used to build parts or structures with an arbitrarily complex 3D geometry. Some structure simply could not be formed by any other technique except RP (e.g., see Figure 1-1). In a typical rapid prototyping process, a 3-D object is first designed by using a computer-aided design (CAD) approach with a 3-D solid model being created based on the computer data.

Based on a computer-controlled system, the RP process planning begins with transforming a CAD data file into a special interface such as Stereolithography file (STL) to represent the geometry of the object. The STL file is then sliced into layer-wise data to define the outlines or contours of individual cross-sections (A combination of these constituent cross-sections reconstructs a geometric representation of the object). Then, depending upon the specific RP apparatus, this layer file is converted to generate a tool path file, which can be used to control the operations of a forming apparatus to form the desired object layer by layer. Since any complex shape can be sliced into constituent layers or cross-sections, theoretically any object can be made layer by layer. This is why SFF is also commonly referred to as layer manufacturing.

As another feature, a SFF process normally makes use of a generic fabrication machine and does not require the utilization of a part-specific tooling (no mold, die or other shape-forming tool is required). A SFF or RP apparatus requires minimal or no human intervention to operate. The RP technology requires integration of computer software, control, and materials and, in some cases, lasers technologies. The advances in

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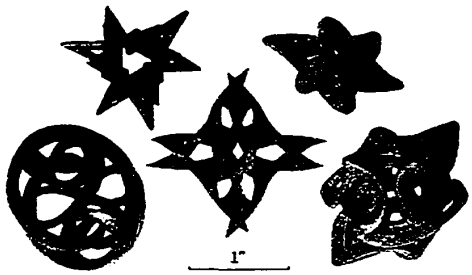
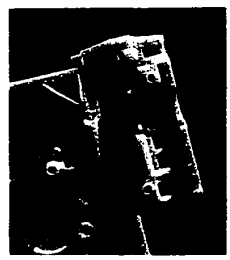
(a) Snake
Made by Z™ 402
3D Color Printing of Z Corp.



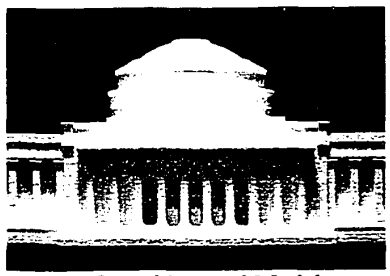
(b) Sculpture Models
Made by Solidscape Modelmaker 2.

(c) Complex aircraft System
Produced by SLS Process DTM Corp.



(d) Complex Wax Model
Made by Multi Jet Modeling Process
TNO Industrial Technology.

(e) Sensaos,
An Egyptian Mummy
Made by MJM process
TNO Industrial Technology.



(f) Architectural Model
MIT Three Dimensional
Printing Laboratory

(g) Gearing Assembly
Made by Stratasys
FDM Process
TNO Industrial Technology.

Source: (a) download from http://www.zcorp.com/
(b) Download from http://www.protoshape.com/
(c) Download from http://www.dtm-corp.com/
(d), (e), (g) download from http://www.ind.tno.nl/en/productiondevelopment/

Figure 1-1 The Typical Models And Parts Formed By RPT.

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computer science in the last decade have made it possible to develop various RP technologies and have given RP various applications. The following subsections describe these new applications [1].

Advantages and limitations Although RP techniques have only been developed in recent years, the advantages that offer have quickly become obvious. Prototyping is a process of building pre-production models of a product to test various aspects of its design. Usually this process is slow and expensive. The RP technology offers methods that allow a user to quickly produce physical prototypes with the important benefit of reducing the time to market. By use of these methods, prototypes can be built in an automated fashion; the skill of individual craftsmen is needed only at the completion. The resulting design cost will be decreased considerably. Another advantage of the RP technology is the capability of producing complex-shaped objects, especially for cases in which only a small number of parts or structures are needed at a given time, such as for aerospace and medical purposes. Objects can be formed with a comparable precision in a one-step process.

Like any other technology, the RP method has its own limitations. Most RP technologies require the use of specific materials such as photo-curable epoxy, fine powders, thin wire or laminates as well as the need for sophisticated equipment employing different physical principles such as lasing, sintering, etc. These materials could shrink during the curing process, possibly resulting in part distortion. In the meantime, since most of RP processes involve adding materials to form an object with an

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overhang or other unsupported feature, a support structure is required. This requires a large amount of additional time and skill to clean up the prototypes and waste materials.

1-1-2 Frequently Used SFF Processes

SFF building strategies include photolithography, laser fusion, lamination, extrusion, and ink-jet printing. Listed in the following are most commonly used SFF systems, along with the schematic description of their corresponding operating principles and the range of application.

Stereolithography (SL) One of the earliest developed and most widely used rapid prototyping system [2, 3].

Applications:

1. To fabricate parts used for concept evaluation and for form-fit testing.
2. To fabricate master patterns for processing tools (e.g., in investment casting).
3. To prepare medical models.
4. To prepare electro-forms for Electro Discharge Machining.

Advantages and Disadvantages:

1. Possibility of manufacturing parts, which are impossible to produce conventionally in a single process.

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2. Continuous unattended operation, high part resolution and capability of making any geometrical shape with virtually no limitation.

3. Necessity to have support structures.

4. Accuracy is not in the range of mechanical part manufacturing due to materials shrinkage.

5. Application is restricted due to given material properties and the size of model being limited by the chamber dimensions.

6. Labor requirements for post processing, especially cleaning.

Fused Deposition Modeling (FDM) FDM is considered as one of the most promising SFF methods that have great commercial potential [4, 5].

Range of Applications The object formed by FDM is not only used as a model but also used as tooling, such as tooling for investment casting and injection molding. If the object is built from a metal or a thermoplastic material, it can be used as a real part, tooling or for mold repair. Thus far, however, the commercial FDM machines have been limited to the fabrication of models from low melting point polymers.

Laminated Object Manufacturing (LOM)

Range of Applications Considering the specifications of the procedure, the main application of LOM is for conceptual design. LOM can be used for preparation of large bulky models such as sand casting patterns [6-8].

Selective Laser Sintering (SLS)

Range of Applications This method is used for making visual presentation models, functional, tough prototypes and cast metal parts (by use of wax) [9-12].

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According to the above analyses, the salient features of SFF may be summarized as follows:

1. Range of applications: the physical prototypes can be rapidly and efficiently produced.

   a. For concept design.

   b. To find design errors.

   c. To check assembly process.

   d. For Metal casting.

   e. For medical purposes.

   f. To produce complex objects, especially for small quantity production at a given time such as aerospace, medical, and die forming.

2. Limitations

   a. Special materials are required for most RP technologies, such as photo-curable epoxy, fine powders, thin wire or laminates.

   b. Most of those materials have some shortcomings: brittleness, low strength, low stiffness, high shrinkage and/or high cost.

   c. Sophisticated equipment is required, such as a laser system.

   d. Support structure is required for some RP processes.

   e. The process speed is lower than that of conventional mass production methods.

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1-1-3 Conventional Composite Fabrication Processes

The fabrication technologies for polymer matrix composites are briefly reviewed.

First reviewed are selected processing techniques for thermosetting polymer composites, which have dominated the composite material market in the last three decades and this dominating status will continue for at least another decade [13-15].

Thermosetting Resin Matrix Composite:

A. Wet lay-up Method and Prepreg lay-up Method:

In wet lay-up, a fabric or mat is laid into or onto a mold and then catalyzed resin is poured, brushed, or sprayed over the reinforcement. The wet composite layer is rolled by hand or with a proper tool to evenly distribute the resin and to remove air pockets. Another layer of reinforcement is placed on top of this first layer and impregnated with the resin. This procedure is repeated until a desired thickness is reached. The whole part is then cured by temperature and pressure schedule.

In the prepreg lay-up method, a prepreg material is first prepared by impregnating a unidirectional tape or woven fabric with a resin. Layers of prepreg are then cut to desired phases, laid up together, and cured in a mold. This method permits a better control of the resin/fiber ratio, this is simple and can be used to form a structure in which accuracy is not a requirement [16].

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B. Vacuum Bagging and Autoclave Curing:

The vacuum bagging process is used predominantly in the aerospace industry where composite part properties rather than high production rate is a priority consideration. The autoclave provides pressure beyond what can be achieved with a vacuum only and therefore imparts greater compression, resulting in reduction of void content. Curing in the autoclave produces a part that is superior to that produced through non-pressure curing in terms of mechanical properties. Autoclave curing requires a heavy capital investment on equipment and the process is slow and tedious [17, 18].

C. Filament winding:

A continuous band or tape of resin-impregnated fibers is wrapped over a mandrel to produce a hollow part. One of the advantages of filament winding is that parts of widely varying size may be produced. Also, non-cylindrical shapes can be made. Panels and fittings for reinforcement can be easily included in the winding process. Low void content and good fiber/resin ratio can be achieved. Parts with high-pressure ratings can be fabricated. But resin viscosity and pot life must be carefully chosen and monitored. Control of key parameters such as fiber tension, fiber wet-out, and resin content is important. Filament winding is not capable of readily making parts with a concave surface or any complex shape [19, 20].

D. Pultrusion:

Pultrusion is a continuous process used to produce fiber-reinforced plastic structures of a constant cross-sectional shape. The process involves feeding collimated bundles of reinforcement fibers through a resin bath, allowing the fiber tows to be

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impregnated with the matrix resin. The impregnated tows are then driven to go through a preforming die and a final shaping/curing die. The hardened/cured composite is pulled to a cutting device or a winding drum. Pultrusion differs from filament winding in that filament winding places the primary reinforcement in the hoop direction, while Pultrusion has the primary reinforcement in the longitudinal direction [21, 22].

E. Liquid Composite molding (LCM)

LCM includes the resin transfer molding (RTM) and structural reaction injection molding (SRIM).In the RTM process, reinforcement preforms are placed inside a closed and sealed mold and then the resin is injected into the cavity of the mold. SRIM is a very similar process, but usually faster than RTM. In SRIM, mold release and reinforcement sizing are varied to optimize their chemical characteristics for the SRIM chemistry. Once the mold has been closed; the resin is rapidly injected into the mold and reacts quickly to cure fully within a few seconds or minutes. These methods require building a specific mold for each part shape [23-25].

Thermoplastic Matrix Composites:

F. Manufacture of Thermoplastic Prepreg

Mixing a high-performance thermoplastic with continuous fiber tows is a difficult task, mainly because of the high viscosity of a polymer melt, requiring a high shear stress and long residence time to permeate and wet out a fiber bundle. Greatly increasing the melt temperature to lower the resin viscosity is not always possible because decomposition can begin to occur before viscosity reaches a reasonable value. These

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considerations have made it difficult to fabricate thermoplastic prepreg materials using a conventional hot-melt process.

G. The "FIT" Process.

In this process, fiber tow is spread, passes through a fluidized bed of powder less than *10* microns in size and then is extrusion coated to encapsulate the powder and the tow in a film sheath, forming a "towpreg". The towpreg can later be woven, braided, stitched into a textile structural shape, which is then pressed after powder fusion and allowed to solidify under a desired pressure [26].

H. The Wet Powder Technology.

This process involves dispersing the thermoplastic matrix powders in an aqueous suspension to form slurry, which is used to impregnate the fiber tows. The impregnated tows, again called "towpregs", are dried and wound around a drum. The towpreg can later be woven or braided into a composite shape, which is then pressed after powder fusion and allowed to solidify under a desired pressure [27].

I. The Dry Powder Technology.

The process entails feeding and spreading a fiber tow into a fluidized bed containing moving thermoplastic powder particles. The powder particles are electrostatically charged and the tow is electrically grounded to promote powder pickup. The powders are then partially melted to allow the polymer to glue to the fiber, yet maintaining isolated particles. This process appears to be capable of producing a towpreg rapidly without imposing severe stresses on the fibers or requiring excessively long high-temperature residence times for the polymer [28, 29].

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J. Commingled Yarn Technology. The "hybrid yarn" concept represents a major step forward in the developments of thermoplastics composite processing technology. The commingling process requires a texturing procedure to open the reinforcement yarn bundle (for accommodating thermoplastic filaments) without damaging the brittle fibers. This may be difficult to accomplish for a high filament count carbon tow. There is certainly an added cost to produce filaments form matrix polymers. The commingled fibers can later be woven or braided into a composite shape. The thermoplastic filaments are then melted with the whole composite shape being pressed and allowed to solidify under a desired pressure [30, 31].

The shortcomings of the conventional composite fabrication processes are:

1. Part specific tooling is required for most processes.
2. Some processes can only produce semi-finished products, axially symmetric shapes, or structures of a constant cross-section shape.
3. Cannot be used for net-shape fabrication of complex 3D objects.

§1-2 MOTIVATION BEHIND THE DISSERTATION RESEARCH

A 3-D model formed by a RP technology presents a better communication tool than 2-D pictures or a simulated 3-D model on a monitor. The 3-D physical model can be seen and can be touched by the designer for a detailed inspection. With a 3-D physical model at hand, the designer can easily find design errors and eliminate the errors before the part is put on the production line.

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The part can be readily re-designed to reach the desired shape. However, a model is an object used for the evaluation of its "form" only (but not "fit" and "function"). The shape cannot be used as a real part or structure. Most materials used in a RP process have the following shortcomings: brittleness, low strength, low stiffness, high shrinkage and/or high cost. In many cases, good strength is needed for a desired object. For example, a human artificial limb should be made with proper mechanical properties and an individual shape. Some parts or structure for aerospace applications need a high strength-to-weight ratio. In some cases, the number of identical parts needed at a time is small. These requirements can be met provided the RP technology is extended for the fabrication of advanced fiber composites.

1-2-1 LM Technology for the Fabrication of Continuous Fiber Composite

The Composite Layer Manufacturing (CLM) takes advantages of the SFF technology (its flexibility in 3D forming) and the superior mechanical properties of composite materials. The primary advantages of CLM are given as follows:

1. As a rapid method of making models of high mechanical integrity:

Advanced fiber reinforced polymer and metal matrix composites normally have great specific stiffness (modulus-to-density ratio), specific strength (strength-to-density ratio), creep and fatigue resistance, and fracture toughness. A prototype or real part made with an advanced composite will be of superior structural integrity and durability.

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2. As a cost-effective way of producing tools:

Composite design approaches have advanced to the status that, by judiciously selecting fibers and their orientations, one can readily produce a composite with a desired Coefficient of Thermal Extension (CTE) e.g. zero CTE. Zero-CTE materials such as INVAR have been shown to meet thermal and durability requirements and are used in current aircraft production programs. INVAR tooling, however, is very expensive and requires a long fabrication lead-time. The presently proposed technology will permit cost-effective, rapid fabrication of durable tools, which themselves are made from continuous fiber composites with thermal characteristics that are compatible with those of the intended composite parts.

3. Potentially a cost-effective composite fabrication method:

Most of the current composites processing techniques are not capable of manufacturing structural parts of a complex geometry. SFF concepts provide effective approaches to the production of complex composite structures without incurring operator interventions or utilizing part-specific tooling (mold or die). Cost-effective processing techniques will significantly broaden the scope of application for composites.

§1-3 LITERATURE SURVEY

1-3-1 History of Commercial RP Systems

1. In 1987, the first commercially available RP system in the world was introduced, which was the precursor to today's popular SLA-250 machine. The SLA-

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250 of 3D systems is used for mechanical part design based on the Stereolithography (SL). After that, NTT Data/CMET and Sony/D-MEC SL systems were commercialized in Japan in 1988 and 1989, respectively [32]. Then, Electro Optical Systems (EOS) of Germany sold its first Stereos Stereolithography system in 1990. Cubital introduced Solid Ground Curing (SGC) in 1991, which also works with UV-sensitive liquid polymer. The SGC involves solidifying whole layers at once by flooding UV light through masks created with electrostatic toner on a glass plate. In 1994, Fockele & Schwarze of Germany introduced a stereolithography machine, but on a limited basis.

In 1991, Stratasys invented the Fused Deposition Modeling (FDM) system. In 1994, Model Maker that deposits wax materials with an inkjet print head became available by Sander Prototype. In 1996, Ballistic Particle Manufacturing (BPM) Technology sold its first commercialized Personal Modeler 2100, which deposits high impact polystyrene materials using an inkjet print head [33].

2. In 1991, Helisys introduced Laminated Object Manufacturing (LOM), and in 1994, Kira Corp. of Japan commercialized the first non-stereolithography system called Solid Center that is using paper lamination [34].

3. DTM introduced the Selective Laser Sintering (SLS) system and Teijin Seiki commercialized the technology and named it Soliform Stereolithography System in 1992.

4. In 1993, Massachusetts Institute of Technology (MIT) invented and patented a process, which is named Direct Shell Production Casting (DSPC) for use

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in investment casting process though depositing liquid binder onto ceramic powder to form a shell [35, 36]. The same 3-D powder printing technique is now commercialized by Z-Corp. for producing concept models.

1-3-2 Present Profile of RP

1. **Patents:** By the end of October 2000, the US Patent and Trademark Office (USPTO) has proved and issued 666 patents related to RP. Most of the patents (531 items) appeared during 1996 to 2000. After browsing most of the patens, several salient features of these of patents can be found: new processes and material are still the focused points, and most organizations are considering system details to improve existing RP machines.

2. **Open Literature Including Conference and Periodical Paper**: Many home pages, which are related RP can be found through Internet searching using the key words "Rapid Prototyping". A profile of RP developing can be found directly.

a. Over 2500 Journal articles and conference papers related to RP have been published worldwide.

b. *Rapid Prototyping Journal* "Keeps you fully informed of the latest developments in rapid prototyping." The journal focuses primarily on rapid product development in a manufacturing environment, but also cover applications within other areas such as medicine and construction. This

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internationally acclaimed information resource provides truly global perspectives on this dynamic and exciting area.

c. *CAD/CAM Publishing publishes The Rapid Prototyping Report.* The monthly Rapid Prototyping Report is the only independent periodical devoted to rapid prototyping and helps a technology development engineer or manager avoid mistakes by publishing in-depth, objective appraisals of the strengths and weaknesses of each technology.

d. *Rapid News* - time-compression technologies magazine. The magazine discusses the use of time-compression technologies to speed new products to market, with applications-oriented feature articles, news, reviews published by Communications Technologies, Inc.

e. These are many specialized publications.

The status of RP industry has been well summarized by Wohler and associates [37]. The following are the key findings of this report.

3. **RP units sold by US manufacturers**: The Charts 1-1(a) shows the RP system units sold by US manufactures in 1997. Out of 1057 units nearly one-third came from 3D Systems. In 1996, Stratasys units accounted for nearly 41% of the systems sold by US manufactures. 3D System and Stratasys have dominated the market for several years.

4. Industries Being Served In the early days of RP, the automotive and aerospace industries dominated the RP market, accounting for about half of the total

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market. This is no longer the case as RP has spread into other industries. Charts 1-1 (b) show the industry sectors that are now using RP technology.

5. **How RP Models are Being Used** About 28% of all RP models are being used for fit and function applications, while nearly 36% serve as visual aids for engineering, tooling, requesting quotes, and presenting proposals. Meanwhile, about 25% are being used as patterns for prototype tooling and metal casting. Charts1-1 (c) shows how customers are using RP models.

6. **RP Education**The use of RP at educational institutions started in the late 1980's with a core of about 10 universities worldwide. The number of schools has grown steadily during the 1990s. From 1994 through 1996, the number of universities involved in RP worldwide soared. In 1996, an estimated 225 research institutions, technical colleges, and even a few high schools used RP in some way.

1-3-3 New Developments in RP Technologies

1. **New System** Scientists are always interested in new technology. That is one reason why new technology is appearing one after another. Now several new RP and RT processes are being developed in laboratories around the world. But the challenge still is how to package these technologies into commercially viable products.

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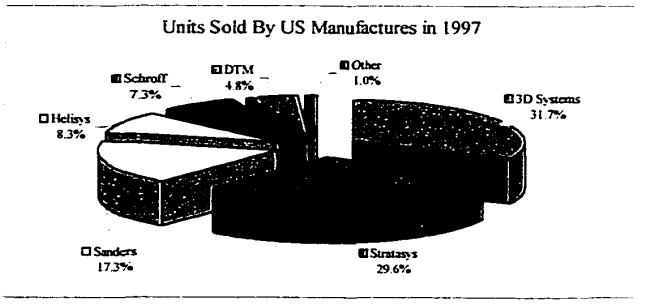
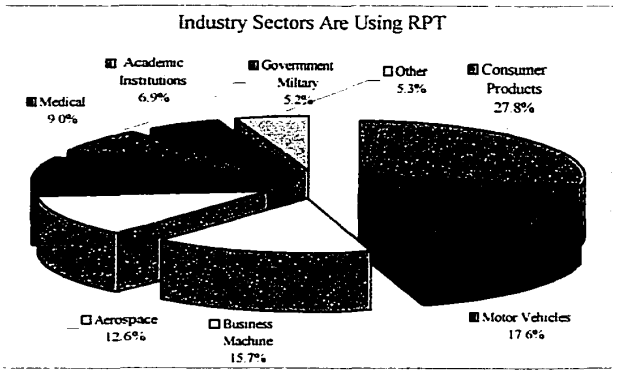
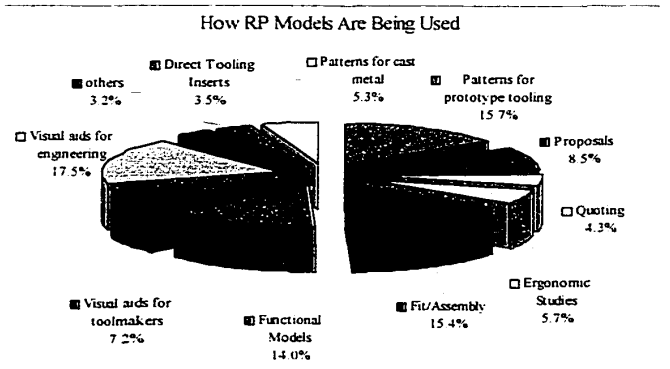


Charts 1-1 (a)



Charts 1-1 (b)



Charts 1-1 (c)

Charts 1-1 Present Profile of RPT (Source: Wohlers Associates, Inc).

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a. **LENS at SNL** A new technology named Laser Engineered Net Shaping (LENS) that can make 3D metallic parts or structures directly from CAD solid models has been developed at SNL (Sandia National Laboratories Albuquerque, NM). Metal materials as applied in RPT are a very important research direction and have been achieved by different research organizations [38, 39].

b. Directed Light Fabrication at LANL Directed Light Fabrication (DLF) used to form metal components also is being developed at Los Alamos National Laboratory (LANL). The process uses a computer-controlled nozzle system to deposit metal powder into a pool of melted metal created by a focused laser beam. Layer thickness is typically *0.075* to *0.125* mm, which can be built into fully dense, near-net-shape metal components. Similar to LENS and DLF, a system called Laser Generating has been developed by the Fraunhofer Institute for Production Technology (IPT) and the Fraunhofer Institute for Laser Technology (ILT), both are located Aachen, Germany.

c. **Topographic Shell Fabrication (TSF)** The process is developed by Formus (San Jose, CA). The TSF prints shells as large as 3.4×1.8×1.2 meters with silica sand and paraffin wax, and then the shell severs as a temporary form for molding shapes in fiberglass, resin or other materials.

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d. **Larger and Faster** LASTFORM (Large Scale Tooling for Rapid Manufacture) has focused on the manufacture of large laminate dies for the aerospace industry. Large RP equipment can form large concept molds; e.g., the car contour. With a large instrument, it is possible to form several molds in one forming operation. Now, some high-speed RP processes can form a part within hours or days instead of days or weeks. Actually, the required mold accuracy requires slicing more logic layers and build more physical layers, thereby extending the forming time. Speed and accuracy still appear to be mutually exclusive for most RP processes [40-44].

2. **New materials** paper is employed in the LOM system and epoxy is employed in the Stereo-lithography system as visual aids only. The parts produced are good enough for prototyping and testing applications. The new materials for RP being developed have the following features:

   a. **Modifying the existing RP material** Filler components are added into epoxy to decrease the laser scan time, reduce the shrinkage, and improve mechanical properties.

   b. **Function material** Thermoplastic, such as ABS and nylon materials that exhibit good mechanical properties were studied by FDM system users.

   c. **Metal** Especially high melting temperature alloys, stainless steel, nickel-based super-alloys such as Incone l625, 690, and 718, H13 tool steel,

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tungsten, Ti-6Al-4V, Nickel Aluminates, and others have been fabricated with certain systems such as LENS.

d. **Composite material** is another focused material for RP and will be discussed in the next section

e. **Other materials** Scientists at Tsing Hua University (Beijing, China) are investigating the creation of ice models using inkjet printing of water [45].

3. **Software Development** a RP process could not be invented without computer software development. The software, which is used in RP, could be used to convert CAD models into a format that is suitable for controlling the operation of a RP system. The most popular format, used by all commercial RP machines, is the STL (STereoLithography) file developed by 3D Systems. And most CAD software packages can output STL format file now. But the STL files contain flaws and require modifications. New software products and utilities such as Magics can be used to view, measure, slice, and repair STL files.

1-3-4 RP Technology with Composite Materials:

The SFF techniques that potentially can be used to fabricate short fiber- or particulate-reinforced composite parts or their precursor performs include fused deposition modeling (FDM), laminated object manufacturing (LOM) or related lamination-based process, and powder-dispensing techniques. The FDM process operates

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by employing a heated nozzle to melt and extrude out a material such as nylon, ABS plastic (acrylonitrile-butadiene-styrene) and wax in the form of a rod or filament [46]. The filament or rod is introduced into a channel of a nozzle inside which the rod/filament is driven by a motor and associated rollers to move like a piston. The front end, near a nozzle tip, of this piston is heated to and melted; the rear end or solid portion of this piston pushes the melted portion forward to exit through the nozzle tip. The nozzle is translated under the control of a computer system in accordance with previously sliced CAD data to trace out a 3-D object point by point and layer by layer. In principle, the filament may be composed of a fiber or particulate reinforcement dispersed in a matrix (e.g., a thermoplastic such as nylon). In this case, the resulting object would be a short fiber composite or particulate composite. The FDM method has been hitherto limited to low melting materials such as thermoplastics and wax and has not been practiced for preparation of metallic parts, possibly due to the difficulty in incorporating a high temperature nozzle in the FDM system.

A more recent patent reveals a FDM process for forming 3-D solid objects from a mixture of a particulate composition dispersed in a binder [47]. The method involves additional operations of preparing a mixture of particles and binder and forming the mixture into a filament or rod form. The mixture in this filament or rod form is then introduced into a nozzle with the leading portion of the filament/rod melted and extruded to deposit onto a work surface point by point and layer by layer to form a 3-D shape. The binder in this 3-D shape is later burned off with the remaining particulate composition identified by re-impregnation or high-temperature sintering. A large amount of binder, up

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to *60-80%* by volume, must be burned off and this represents a significant waste of material and requires a long duration of time to accomplish.

Other melt extrusion-type processes include those disclosed in Valavaara [48-49]. These melt extrusion based deposition systems, if adapted for forming short fiber or particulate composite object, would suffer from the same shortcomings as in FDM. Furthermore, the incorporation of *20 - 40%* short fibers or particulate in a matrix melt would further increase the viscosity of the material in a flow channel, making it more difficult to operate the FDM or related extrusion-based process.

In a series of U.S. patents [e.g., 50], Sachs, et al. disclosed a 3-D powder printing technique that involves using an ink jet to spray a computer-defined pattern of liquid binder onto a layer of uniform-composition powder. The binder serves to bond together those powder particles on those areas defined by this pattern. Those powder particles in the unwanted regions remain loose or separated from one another and are removed at the end of the build process. Another layer of powder is spread over the preceding one, and the process is repeated. The "green" part made-up of those bonded powder particles is separated from the loose powder when the process is completed. This procedure is followed by binder removal and metal melt impregnation or sintering. This technique is limited to one type of powder particles in one layer and is useful for fabricating uniform-composition materials only. The technique does not lend itself for varying the powder composition from point to point for the preparation of heterogeneous materials.

This same drawback is true of the selected laser sintering or SLS technique [51] that involves spreading a full-layer of powder particles and uses a computer-controlled,

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high-power laser to partially melt these particles at desired spots. Commonly used powders include thermoplastic particles or thermoplastic-coated metal and ceramic particles. The procedures are repeated for subsequent layers, one layer at a time, according to the CAD data of the sliced-part geometry. The loose powder particles in each layer are allowed to stay as part of a support structure. The sintering process does not always fully melt the powder, but allows molten material to bridge between particles. Commercially available systems based on SLS are known to have several drawbacks. One problem is the long time required to heat up and cool down the material chamber after building. In addition, the process has not been successfully applied to fabrication of fiber composite parts.

Most of other prior-art layer manufacturing techniques also have been largely limited to producing parts with homogeneous material compositions. Furthermore, due to the specific solidification mechanisms employed, many other LM techniques are limited to producing parts from specific polymers. For instance, Stereo Lithography and Solid Ground Curing (SGC) rely on ultraviolet (UV) light induced curing of photo-curable polymers such as acrylate and epoxy resins. Additionally, most of the current RP systems are not effective in adding fibers into a RP material or varying the fiber type of a composite object from layer to layer and from spot to spot.

Modified laminated object manufacturing (LOM) has been used to prepare polymer matrix and ceramic matrix composites [52]. The process involves, for instance, feeding, laminating and cutting thin sheets of prepregs (pre-impregnated fiber perform) in a layer-by-layer fashion according to computer-sliced layer data representing cross

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sectional layers of a 3-D object. The process cycle typically consists of laminating a single sheet of prepreg to an existing stack, laser cutting the perimeter of the part cross section, and laser-dicing or "cubing" the waste material. After all layers have been completed, the part block is removed from the platform, and the excess material is removed to reveal the 3-D object. This process results in large quantities of expensive prepreg materials being wasted.

§1-4 CHALLENGES FOR THE FUTURE

1. Cost Saving Current RP system price is very high, from *$50,000* to *200,000* per unit. Many agree that RP must cost less before it will penetrate manufacturing companies worldwide.

2. **Faster, Larger, and Stronger for industries**

a. Some RP processes are extremely slow to build a component. Days even weeks may be needed. To reduce the forming cycle time is a challenge for each RP process. Desired forming cycle time is within one day or hours.

b. RP capability or fabrication scale is limited by the size of the forming chamber, working raged of a 3D- motion device, or dimensions of the platform. Large-Scale Model, which are used for automotive industry is another developing direction.

c. The shape stability and mechanical properties of the RP formed components should be considered in next development step.

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3. **Smaller and Cheaper for Family** Desktop RP system and price within thousands is desired for children to practice their design intelligence and everybody can create their own 3D articles at home.

4. **New Applications** Most application of RP technology is practiced on model making used for concept design, error checking, assembly testing and so on. RP technology could be expected to offer advantages in the following fields:

a. Relief Map The received data from a satellite can be converted to a format recognizable and realizable with a RP system. A 3D map could be made within hours or less. The relief map could be used for military purposes or in emergency situations.

b. **Medical.** "RP for medical applications is a sleeping giant". In fact, in medical purpose, RP can show its fabulous advantages: process object rapidly and individually.

c. **Metal Casting and Mold Repair**: RP with metallic materials is a large field for RP application. Die-casting had remained the greatest focus in the last few years and probably has the most potential.

5. **New Software Development** Most commercialized software is depending on a specific process. A new process requires new software to match it. For example, CLM requires its own software to control the towpreg deposition.

The current CAD tool can create a 3D machine or structure with different colored components, but could not create arbitrary colors within a component or a structure, nor output a file with a color symbol. Once the problem is solved, RP will

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be colorful and more useful. Initial success in this aspect has been achieved recently by Z-Corp.

§1-5 RESEARCH OBJECTIVES

The proposed process included impregnating a fiber tow with a matrix material in a liquid state (e.g., melt) and laying up the impregnated tow (towpreg) point-by-point and layer-by-layer according to a computer-aided design file. The main objectives of this dissertation research are:

1. Identification of the necessary operations of fiber tow impregnation, movement and deposition that can be integrated for manufacturing continuous fiber reinforced composite parts of high structural integrity and dimensional accuracy.
2. Development of a simple prototype apparatus to demonstrate the technical feasibility of the presently proposed approach and to evaluate its strengths and limitations.
3. Process simulation and analysis:
   (A) Simulation of the molten materials flowing inside a nozzle to develop ability for predicting the best process parameters.
   (B) Analysis of the effect of the towpreg lay-up sequence and fiber orientation on the mechanical properties of a composite.

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CHAPTER 2 CONCEPT DESIGN AND ANALYSIS FOR COMPOSITE LAYER MANUFACTURING (CLM)

§2-1 INTRODUCTION

The motivations behind the proposed research have been indicated in the previous chapter. The advantages and features of Composite Layer Manufacture (CLM) and its future development have also been briefly cited. Discussions in this chapter will be focused on how to achieve the proposed research objectives to find the best way to realize the designed plan, and to demonstrate the feasibility of all the concept designs.

To develop a new product technology or a new process, a proper procedure and scientifically sound experimental method of would greatly reduce the effort. For a specific technology, to meet the requirements of the market, more attention should be paid to three basic aspects: cost, quality and time.

The tasks of the present dissertation research project were to develop a new RPT process and a prototype machine using both layer manufacturing and composite fabrication concepts. The new technology and its relation with both RPT and composite fabrication are discussed in this chapter.

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§2-2 DEVELOPMENT METHODOLOGIES

2-2-1 Developing a New Technology

A flow chart for developing a new process is shown in Figure 2-1. RPT is an interdisciplinary subject that includes machinery, mechanics, automatic control, computer, optics, materials science, etc. It is necessary to cooperate within a development team and to divide the whole development project into several periods. Each period has its specific goals and tasks [53].

a. Information collection: The advantages and features of the current RPT and various composite fabrication technologies have been summarized in Chapter 1, which provided the foundation of concept design for the present project.

b. Concept design: All collected valuable information is taken into consideration for concept design. In §2-6, there is an introduction of several concept designs based on this principle.

c. Feasibility test: After a concept design is drafted, it is time to do the feasibility test. Several feasibility-testing experiments are necessary to evaluate all parameters possibilities.

2-2-2 Feasibility Experiment

The feasibility experiment is simple and easy to do. It needs just a short period of time and a low cost. Sometimes, an existing equipment can be used to get a judgment

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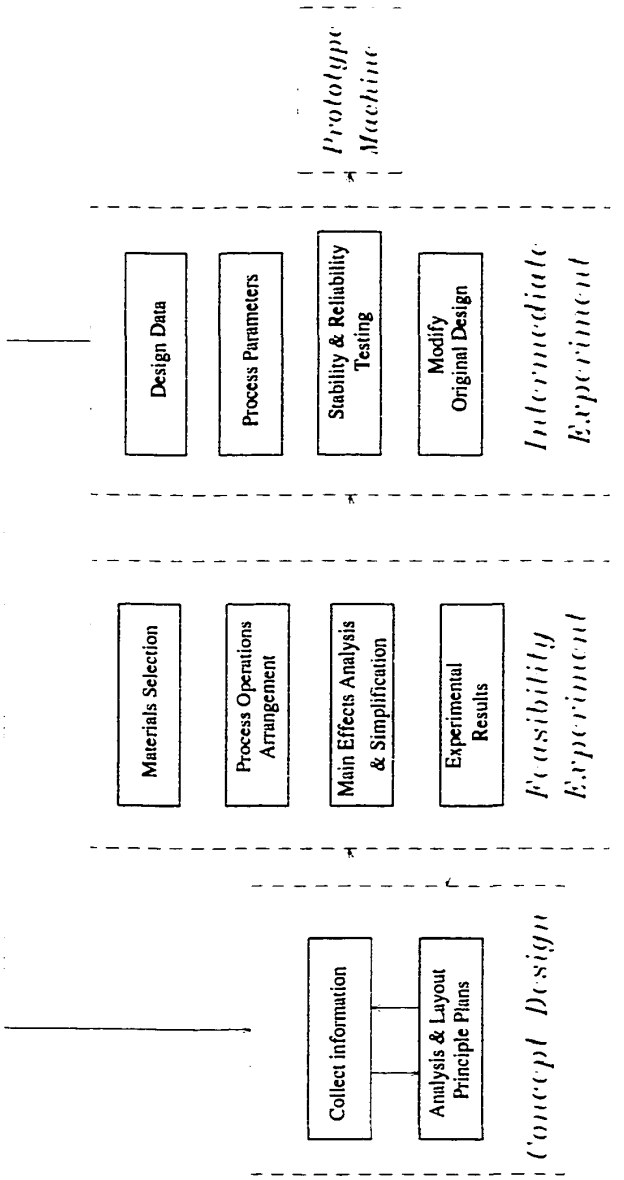

Figure 2-1 Flow chart for a new process development.

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result (YES or NO) to serve as a guide for following the experiment. A feasibility experiment can be done using the most important control parameters that simulate the key behavior in a real situation. Commonly, the positive conclusions can be published, but negative conclusions cannot be published, there are positive results if some parameters or conditions have been changed. Anyway, the feasibility experiment can be taken as a positive result at once, and then the experiment can be varied or expanded basically around this design.

The feasibility experiment is a single target experiment with less parameters. The cross-effects are neglected, and care should be taken to interpret the experiment results. Additional intermediate experiments may be needed to verify important conclusions.

To grasp the essence of an issue, the feasibility experiment should be properly done. Throughout the feasibility experiment, modification or optimization of the original plan, through the intermediate experiments, must be constantly executed.

The feasibility of a design can be double checked by means of intermediate experimental verification that is done with various overlay-effort influences. In fact, some parameters and conditions cannot be simulated, nor demonstrated during the feasibility experiment period. Therefore, the true result is confirmed by the intermediate experiment only. So, the intermediate experiments bridges the result of the feasibility experiment to the machine prototype. The optimal design parameters could be found via the intermediate experiment, which will be the foundation of subsequent designs of the prototype machine. Sometimes, when a series of intermediate experiments have been done, the new prototype of the machine will appear.

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2-2-3 Intermediate Experiment

During the intermediate experiment, the various process parameters could be determined accurately. The impossible plan could not be seen through, no matter how the experimental parameters changed. In case of the feasible plan, if the designed parameter is not in a right range, an error-judgment also could appear and result in the good technology plan could be abandoned. If the parameter could be controlled exactly, we should consider all possibility of cross-influence during the intermediate experiment. The impossible plans that were shown as "possible" in the original feasibility experiment could be found and thrown-out during this period.

Another important purpose of the intermediate experiment is to check the stability and reliability of a technology. Some parameters such as a stable extruding speed, or an equivalent temperature can only be stabilized when the system was run a period of time. Some problems could not be appeared throughout a short period of time, such as a roll up error, etc. The stability study results can be seen in two aspects: the best technology parameter and whether a plan could be done in a right principle or not. For example, if some RPT machine, such as BPM (Ballistic Particle Manufacturing) is being run for a long time, the polymer that remains inside of the nozzle or transferring hose could age and form scraps that block the hole of the nozzle or the hose. The disadvantage of the design concerning the transportation of materials would be exposed at a longer time.

All the unstable influences must be eliminated at this intermediate experiment period, and then the subsequent development work will be continued. In fact, all kinds of successful developments including both new products and new technology during the

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time of development could not be seen. But we can only see the success side and cannot see what is behind the success. Why is it successful? How could it be successful? What kind of failure occurred? Only those engineers who are following the basic rule of developmental procedure can do the development. Certainly the new technology that includes new processes and new product development is the process of creating. This kind of creation is not only shown in the result, but also in procedure. The result is to create new products or new technologies, but the market must check them. The development process creates new products and obeys all the developing rules. Only the procedure that is done step by step carefully, will avoid failure.

§2-3 OBJECT FORMING THEORY FOR CLM

For a RP Technology, the different additive methods must be employed for different forming strategies using different materials.

2-3-1 General RPT Depositing Method

Look at Stereolithography (SL): A piece of sweeper that is dipped with epoxy sweeps and coats a thin layer of epoxy upon the object to add a new layer. Another material additive method for Stereolithography is implemented by moving the object elevator downward one layer of thickness each time. Then the epoxy overflows above the top layer, which has been built to add a new raw material layer that is waiting to be scanned and solidified. To build a layer, In the LOM system, the collector roller feeds a

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sheet of paper onto a platform. Then, the laser beam cuts the corresponding cross-section contours. In the SLS technology, a layer of very fine powder particles is spread on top of the previous layer through a powder-leveling roller. Then the powders are laser-fused at selected contour locations to allow these powders to be bonded together and adhere to the previous layer contour.

FDM, BPM and 3D Print Technology are among the earliest developed and most widely used rapid prototyping system of delivering materials by similar means. This is accomplished by transferring material to the object through a depositing hand commonly called a nozzle. Inside the nozzle, the material state has been changed to a melt or plasters state, and then is squeezed out under the effect of a continuous pressure or pulse pressure.

The common characteristic of the technologies SL, LOM and SLS is that the unit adds materials layer by layer to build an object. For instance, in technologies of FDM, BPM and SLS etc, the method of adding material is particle by particle, line by line and layer by layer, respectively. Because of a laser's very high focusing ability, the heat influence area is small and the thickness of paper is very thin, so the staircase effect is small in SL, LOM, and SLS technologies, leading to a good forming precision. But in FDM, the material being added is something like grains or beads of liquid or plaster passing through the nozzle orifice for deposition. The forming precision is related to the nozzle's orifice directly and the staircase effect in FDM can be observed clearly.

2-3-2 A Concept of Active Material Supplying and Passive Material Supplying

Because CLM is similar to the process of FDM, the characteristics of the

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material-adding method for the FDM technology are analyzed and summarized in the following:

1. The material is affected by the pressure inside the nozzle that pushes the fluent material out of the orifice and propels the dispensed material toward the object with a certain speed. This way of adding materials to an object being built is called Active Material Supplying. So far, in all the RPT, the material-adding method can be generally regarded as the Active Material Supplying. In the CLM, another material-adding concept is introduced and is called Passive Material Supplying. The detail information and advantages about the Passive Material Supplying will be discussed later.

2. Due to the viscoelastic nature of a polymer melt and the fluctuation of pressure in the nozzle, especially at the time of starting and stopping, the deposition speed may vary with time and a change in the nozzle pressure may cause a delayed variation in the deposition speed.

3. The forming quality of a previous layer dose not influence the forming of the current layer, in the case of active material supplying such as in FDM. However in the case of passive material supplying, the quality of a previous layer has a profound effect on the forming quality of the current layer.

The unique characteristics of the CLM forming process are listed as follows:

1. It is difficult and also unnecessary to form any complicated-shaped parts by only one continuous line of composite material, which is called towpreg. A moving nozzle or depositing head, upon completion of an area of a layer, has to move to another area or another layer, after the nozzle is relocated to another area, the

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towpreg that still links the nozzle and the object should be cut off to free the nozzle. If a machine for CLM process is to be designed properly, the cutting function should be considered and this function need to be reliable and durable.

2. It may be necessary to build a support structure for such features as overhangs and isolated islands in a layer. Another nozzle for forming the support structure is necessary. Obviously, if the support structure is formed by the same nozzle and material, the supports structure could be hard to remove after the part was finished. CLM process has another advantage to be mentioned here. In some cases, CLM could use a simplified support structure. For example, a structure of a part is shown in Figure 2-2. When the area included BCEF is to be formed using the FDM technology, the support structure must be formed in the first layer or BC layer before a subsequent layer could be continued. But the support structure is not needed in this situation if the CLM is employed because when BC layer is being formed, each line is arranged in order A→B→C→D, the towpreg between B and C acts like the bridge that supports the subsequent layers between the BCEF.

3. Because the towpreg that links the nozzle and the object has a high tensile strength, it is possible to use Passive Material Supplying. The definition of Passive Material Supplying is that, when the object is moved relative to the nozzle during the forming process, the towpreg is pulled out by the object instead of being pushed out by nozzle pressure. In the nozzle, the forming material is passively moved out by the object's pulling force and not squeezed out actively by its pressure. In the composite forming fabrication, the Filament Winding Process could be considered as a Passive Material Supplying.

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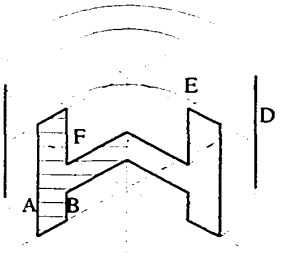

Fig. 2-2A a part is shown with 3-D Model.

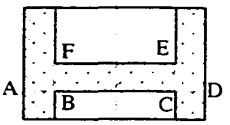

Fig. 2-2B The Cross Section of the Part.

Fig. 2-2 Support structure can be simplified.

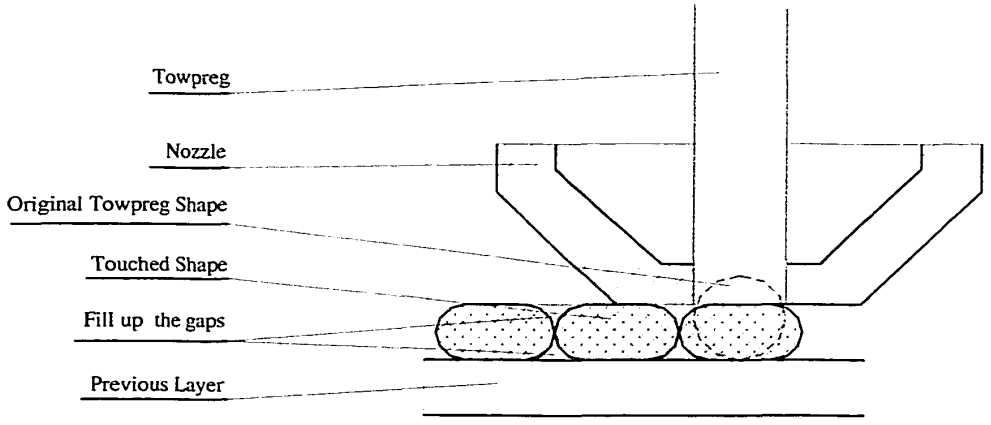

Fig 2-3 Materials distribution.
the towpreg shape has been changed during the deposition process.

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4. Because a towpreg has very a high tensile strength, at the beginning of depositing, and especially at the end of the forming process, the deposition process could be easy to control. So the part's precision should be relatively high.

5. With the increase of the fiber volume fraction in towpreg, the effect of adhesion between lines, and layers could become weak. Thus, the volume fraction of fiber is limited in the towpreg.

6. In order to increase the compactness of the composite part and to get proper mechanical properties, it is necessary to keep a proper pressure to the towpreg while being deposited. The bottom surface of the nozzle may be used to push down the deposited towpreg. The distance between the bottom of the nozzle and the surface of the previous layer may be chosen to be slightly less than the diameter of towpreg. The relative position of the nozzle and the object is shown in Figure 2-3. The cross-section shape of a towpreg and the orifice of nozzle are not the same. Because a shape of the cross-section is different in the same forming layer, the boundary condition for deposition is different. Defects could appear such as areas with excessive or deficient resin.

§2-4 EFFECTS OF MATRIX AND FIBER IN THE CLM PROCESS

The RP material used for a model could be selected from wood, wax, gypsum, glass, and even wheat powder or chocolate. But the resulting object may be relatively weak and brittle. If the CLM technology is used to form a model or a real component, the

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proper material for both matrix and reinforcement fiber should be chosen rationally. The combination of matrix and fiber is illustrated in Figure 2-4.

There are discussions about how to choose matrix and fiber for advanced composite materials in many textbooks, but the matrix and reinforcement fiber in the CLM have to meet certain requirements.

2-4-1 Selecting the Matrix Materials:

Generally if the physical plate of any material can be changed to become a liquid, this material could be applied as a matrix material for RPT. During a common composite forming process, matrix is used as the forming carrier, which solidifies to form the shape of the composite. The fiber is used to improve the mechanical properties of the whole composite. A matrix for the CLM process must meet the following requirements:

1. The phase change speed must be sufficiently high, no matter what kind of energy is applied; the matrix can receive the energy quickly and can cause it to change its physical state as soon as possible. For example, photo curable epoxy, a common RP materials, must be capable of solidifying immediately when it is exposed to a UV beam. The RP forming process is based on adding the materials line by line and layer by layer to build an object. Increasing the phase change the speed decreases the forming time for each line and layer, leading to a reduction in the total forming time.

2. The price of a matrix material should be reasonable especially in forming a large number of parts or a large size structure.

3. The matrix and reinforcing fiber should have high affinity, particularly when

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fiber impregnation and towpreg deposition are done at the same time. The matrix is required to impregnate the fiber tow immediately.

2-4-2 Accelerating the Phase Change Procedure

The phase change speed is very important for RPT processes. How to change the phase and increase the phase change speed are challenges and fundamental questions for the RPT developer. If a phase changing method is found, a new RPT is invented.

In the earliest developed SL system a laser system and photosensitive epoxy were applied. The laser beam spot can be focused to become very small, and the energy can be concentrated upon a small area to solidify the thermosetting material in a twinkling. The combination of laser beam and laser sensitive epoxy is an ideal material for RPT, but the price of UV-curable epoxy is very high. And the laser generating and control system is complicated and has a high price. Therefore, other curing mechanisms
are needed. The following methods or ideas were proposed and studied for thermosetting resin materials during the period of this dissertation:

Keep the resin in the B-Stage: fiber tow is impregnated with a thermosetting material to form the towpreg, then the towpreg is treated and kept in the B-stage. Towpreg, a Semi-finished product of composite materials in the B-stage could remain inactive for a long time at low temperatures. When needed to do a forming process, a towpreg is heated or is exposed to energy by other means during the depositing movement and is quickly solidified and allowed to adhere to the previous layer. All the deposition and adhering procedures for a towpreg segment could be finished in a short

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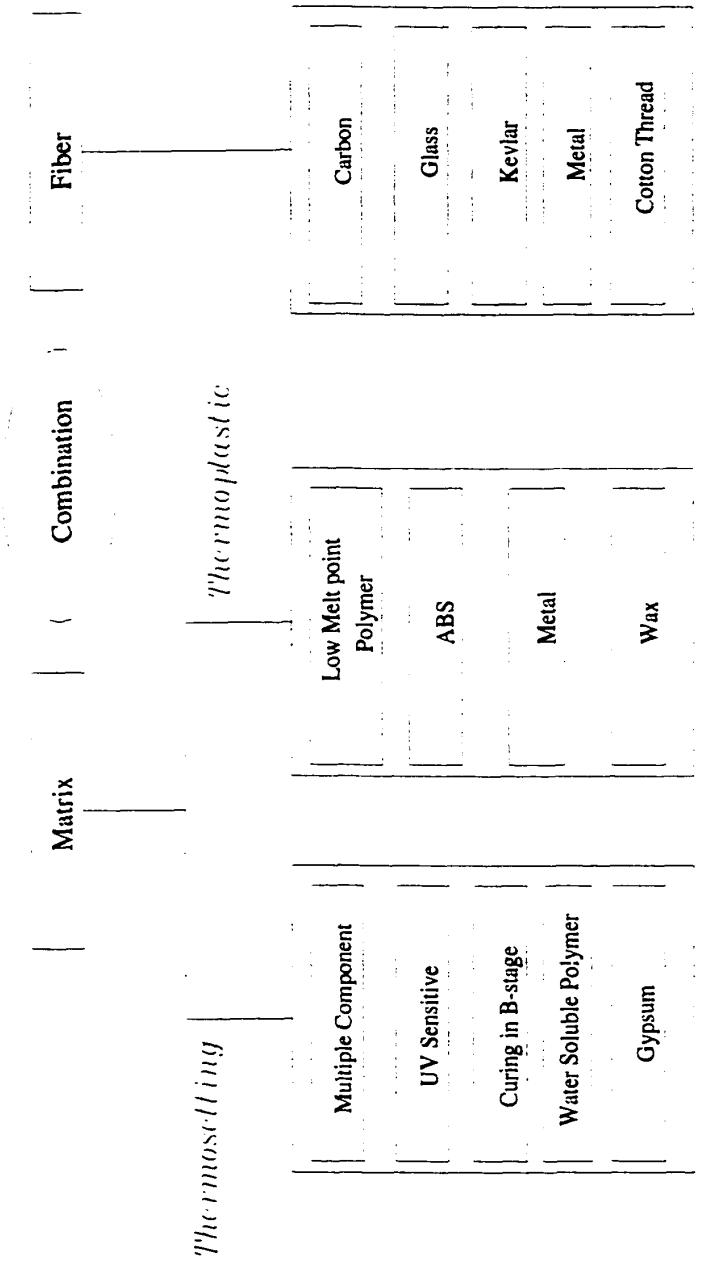

FIG. 2-4 Materials selecting for the CLM process.

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time (*0.01-0.1* Second). This method is proposed for common thermosetting materials used in the CLM process.

During the deposition procedure, a curing agent and other ingredients are added into the matrix material with a catalyst and/or photo-initiator to cure and solidify the material resin. Such a chemical method is applied to increase phase change speed as illustrated in Figure 2-5.

Electromagnetic and mechanical methods: the methods are considered to use based on some materials, which are called Electro-Rheological Fluid materials. The ER fluid can exhibit a phase change by applying or removing an electromagnetic field. When an electromagnetic field is applied to the forming platform, an electromagnetic field sensitive material can be mixed into the matrix and deposited upon the platform; the matrix could be solidified immediately. Also a common thermosetting material can be mixed into this matrix. When the whole object is completed, it can be heated in an oven to finalized the object shape with the electromagnetic field being maintained until the thermosetting material is completely cured.

Some materials called shear-thickening or dilatant fluids have been considered as the materials for RPT. The state of stress that is exerted on these materials is controlled to change their phases. This is called the Mechanical Method for RPT. If this kind of material is stirred violently inducing fast solidification, and deposited layer by layer at the nozzle orifice or at the depositing area, the materials could be applied in RPT. But to achieve the proposed mechanism is still a challenge.

All the methods mentioned above have been employed in feasibility experiments except for the electromagnetic and the Mechanical Methods.

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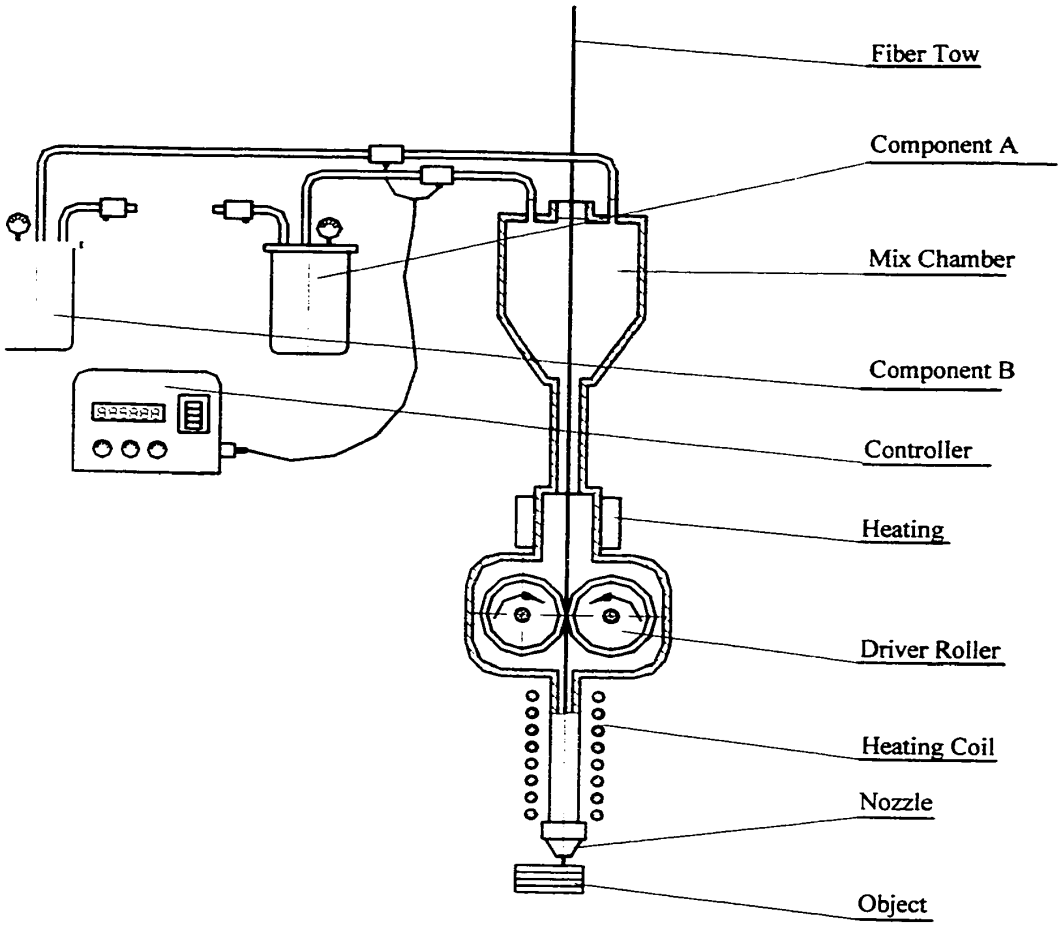

Fig. 2-5 Multi - components matrix composite.

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As for thermoplastic materials, in order to increase the phase change speed or solidification speed, the temperature of the nozzle should not be too high; but should be high enough to insure the deposited current layer adheres to a previous layer. The temperature of the nozzle orifice is only 1° C higher than the melting point of the thermoplastic material in the FDM process. The environment temperature near the forming zone could not be too high. Setting the temperature of the forming chamber is another big issue and will be discussed in later chapters.

Speeding up the phase change will reduce the total part or model building time. When a typical thermosetting epoxy material with very low viscosity μ is deposited upon an object, the thermosetting material may not be able to maintain its own shape at the moment and it may flow around arbitrarily, preventing the deposition process from being continued. Hence another basic requirement for matrix materials and deposition processes is that the material fluid should maintain a geometric shape when the matrix is carried to a forming platform.

The phase change speed is acceptable and is relatively easy to control for the thermoplastic materials. For example, they are used in FDM, 3D Print and other RPT.

2-4-3 Effects of Fibers and the Selection of Fibers for CLM

In a composite, if the fiber volume percentage is 50%, the fiber will share over 90% of the force that is loaded on the composite. The mechanical effect of the fiber can be clearly during the composite application. However during the composite forming

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period, the fiber dose not undergo a phase change. So the fiber properties may not appear to be important for composite forming except for the Filament Winding process and CLM. Effects of the fiber and how to choose the fiber are described as follows:

1. If a fiber reinforcement effect is to be expected, the high physical and mechanical properties of the fiber must be considered.

2. The fiber should have high affinity with the matrix material so that the fiber tow could be impregnated immediately and wetted completely. The fiber must be flexible and pliable so that the towpreg can be formed with small angles when the matrix is in a fluid state.

3. The towpreg must be readily cut off where necessary. This is a required function of the CLM technology.

4. In some RPT processes, which use a UV curable epoxy, some fiber like cotton thread may be pre-mixed with the epoxy during the forming process in order to save the expensive photosensitive epoxy. The fiber is not only the forming process carrier but is also the filler material that is required to be inexpensive, soft, and has good affinity with the epoxy.

§2-5 FORMING STRATEGY AND CONCEPT DESIGN FOR CLM

The strategy for selecting the matrix and fiber for CLM has been analyzed. The selection of the component materials in a composite related to the forming strategy. The concept design and feasibility experiment should be done after conducting enough literature review and analyses. During the course of the present study, these two tasks

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were done alternately. By carrying out the feasibility study, features and limitation of CLM could be identified, clearly understood and then a new concept design could be performed.

In the discussion of forming a strategy design, two widely used plastic materials have been considered as the matrix materials, which are thermosetting and thermoplastic. Different kinds of materials could have different forming strategies. Even the same kinds of matrix materials could have different forming principles. There also have been a forming design to fit for two kinds of materials.

2-5-1 Concept Design for Thermosetting Matrix Materials

A thermosetting epoxy material was used for the feasibility experiment first. This feasibility experiment is illustrated in Figure 2-6, and more details about it will be explained in the next paragraph and in Chapter 5. Generally, the epoxy curing time takes several minutes or even several hours, which is far different from the requirement of PT. In RPT, the ideal solidification time or phase change time should be within one second, or even one-tenth of a second. Therefore, there are two forming strategies to follow for CLM that involves curing of a thermosetting resin. First, the towpreg could be prepared and kept in the B-stage [54, 55] as a semi-finished product to be used in the depositing procedure. These procedures are depicted in Figure 2-7. The towpreg in the B-State retains a certain cross-section shape, and also has the necessary tackiness. The towpreg is feed into a heated nozzle in which the resin is made to become fluent and chemically re-activated. The towpreg is pulled out of the nozzle orifice for deposition

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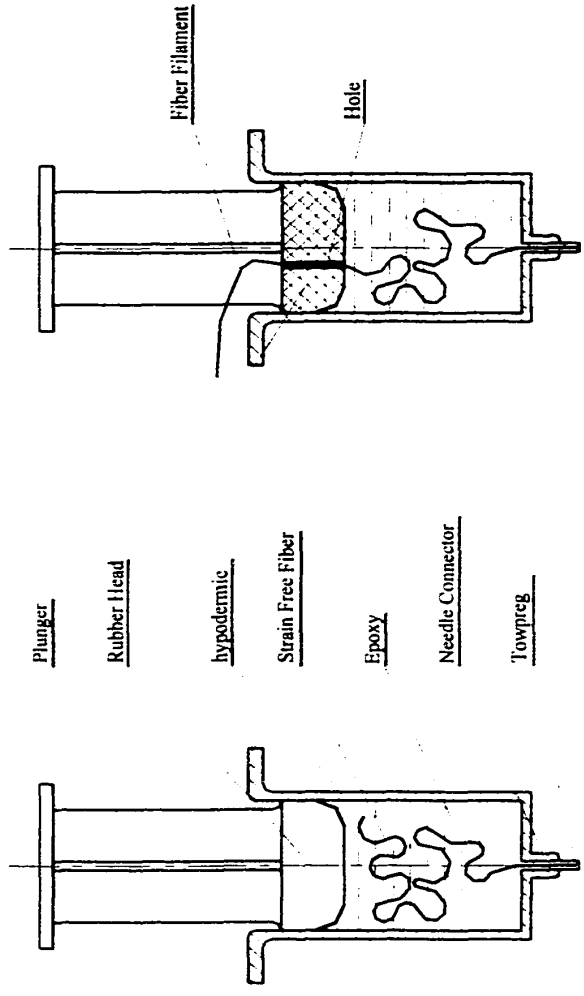

Fig. 2-6 A
A segment of fiber tow was placed inside a hypodermic in where it was pilled out along with epoxy resin.

Fig. 2-6 B
one end of a segment of fiber tow was placed outside the hypodermic, another end was positioned inside the syringe through the rubber head.

Fig. 2-6 A feasibility experiment.

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onto a platform or a previous layer. As soon as a segment of towpreg is deposited, the resin in this segment is solidified.

Another method for forming thermosetting materials, mentioned previously, is shown in Figure 2-5. This is called a one-step method because the impregnation and deposition are done at the same time. But the method shown in Figure 2-7 is called a two-step method with this definition.

As shown in the Figure 2-5, the component A is a thermosetting material, and component B is a curing agent. First component A and component B are mixed together and the mixture is used to impregnate the fiber tow to make a towpreg. Then the towpreg is pushed or pulled out of the nozzle and deposited on the top layer of an object by some means. On the current forming layer, the deposited towpreg is heated or treated in way so as to solidify and adhere it to the previous layer.

2-5-2 Concept Design for Thermoplastic Matrix Materials

Up to now, most research and development work done for CLM are based on the thermoplastic matrix. Actually, no matter what matrix material is used, a problem exists with material delivery. The concepts of Active Material Supplying and Passive Material Supplying have discussed in §2-3. The features, principle and concept design of each material supply method will be studied in more detail in this section.

The Active Material Supplying method has been applied in many RPT processes such as FDM. Before several Active Material Supplying methods are introduced, a

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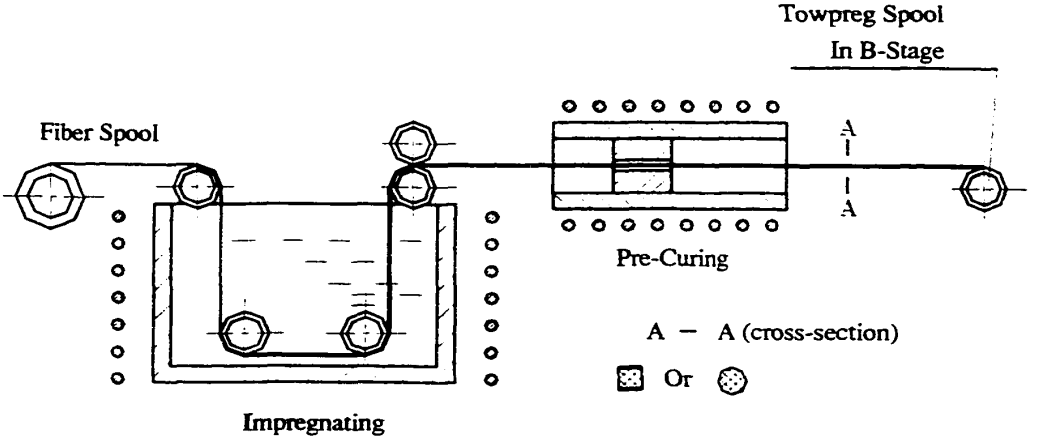

Fig. 2-7A
The step 1: The towpreg is made and kept on B-stage.

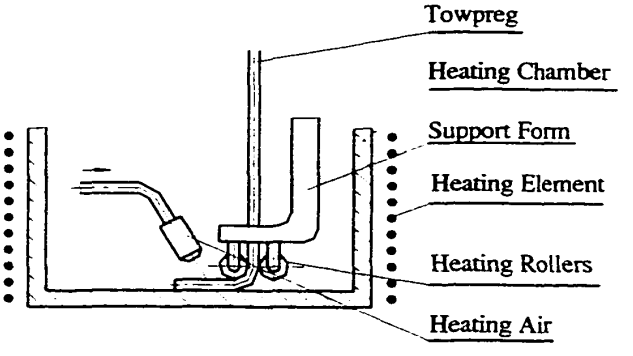

Fig. 2-7B
Step 2: the towpreg is deposited.

Fig. 2-7 CLM using thermosetting materials, a two-step forming method.

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feasibility experiment could be used to understand the requirements for the realization of these methods.

The feasibility experiment is shown in Figure 2-6. For the experiment, a piece of fiber tow is put in a hypodermic syringe and one end of the fiber tow is placed outside of the needle connector. Another end of the fiber tow is placed inside of the hypodermic syringe unrestrained. Then the epoxy fluid is filled in the syringe, allowing the thermosetting matrix resin to impregnate the fiber tow. During the experiment, a plunger is pushed forward to extrude out the epoxy. The following phenomena has been observed: with the plunger being pushed forward, the downward flow of the polymer fluid helps to drive the impregnated fiber tow out of the needle connector. From this experiment, one can conclude that:

1. The impregnation and deposition procedures could be done in one step.
2. Active Material Supplying could also be realized with composite materials.

In order to simplify this experiment, the thermosetting epoxy was used as the matrix material at room temperature. But the melted thermoplastic material is expected to work in the same fashion. From the experiment, the design requirements for the CLM process are recognized as the follows:

1. An adjustable pressure vessel is needed in this process and the pressure can be kept at a constant value. An impregnated fiber tow with a matrix, called towpreg, can be pushed out smoothly under the pressure.
2. The fiber tow can be introduced continuously to the vessel to form

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the towpreg.

3. If a fiber tow is supplied through a hole in the vessel, the hole is sealed using a one-directional seal mechanism like a check-valve. It could let the fiber tow come into the vessel but avoid the pressured resin to flow backward.

To meet the above requirements, the following designs were given for consideration and discussion in the early stage:

A design is shown in Figure 2-8. Thermosetting or melted thermoplastic matrix is poured into the vessel by a gear pump or an extruder machine to create a pressure field. Under this pressure the matrix polymer could flow out through the nozzle's orifice. The impregnated fiber tow could be brought out by the effect of a shear stress. There is a cone-shape sealing washer at the fiber tow entrance made from a rubber like material that is elastic and can withstand a temperature higher than the melting point of the thermoplastic. The fiber tow can be pulled in through the designed sealing washer only, but the matrix could go up through the washer.

Friction exists between the fiber tow and the rubber washer. The fiber tow is pulled in and pushed out through the vessel only by the shear stress that might not able to surpass the friction. To insure that the fiber tow can be pulled in the vessel smoothly, a couple of rollers are provided, which are controlled by a motor to drive the fiber tow into the vessel. Between the rollers and the nozzle, a segment of towpreg is tensile free and can be pushed out only by the vessel pressure.

This design appeared questionable after it was studied in detail. The sealing washer was not reliable in order to seal the high-pressured resin from going up, and the sealing washer might scratch the filaments of the Kevlar fiber tow. The design is perhaps

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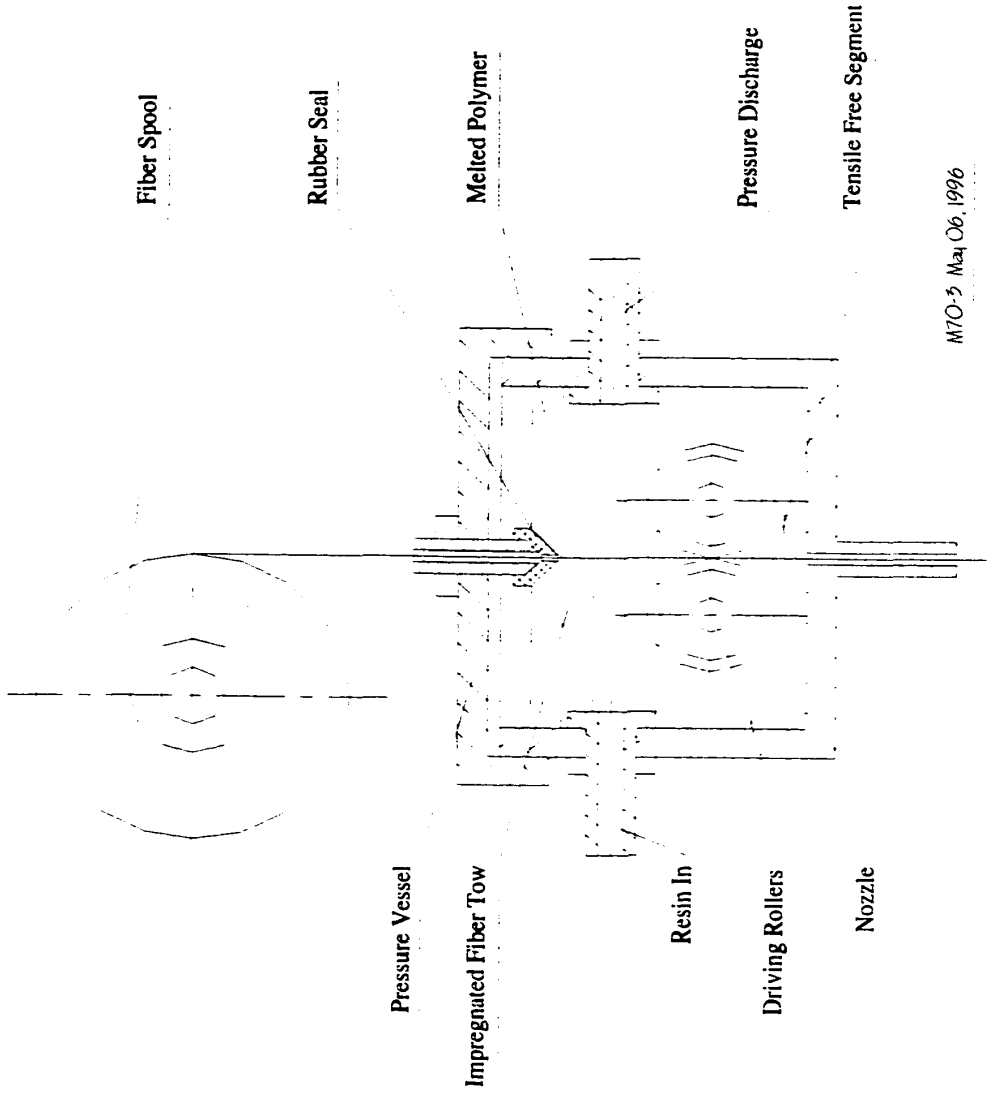

Fig. 2-8 The towpreg was pushed out by resin shear stress.

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only suitable for glass fiber or for fibers not sensitive to friction.

Improved designs based on these concepts are pictured in Figure 2-9. The fiber spool is put into the vessel directly, so the sealing washer is no longer needed. Such a design is shown in Figure 2-9A, and it looks very simple. However, the fiber spool is soaked in resin. If the materials are not exhausted in one time, perhaps it could not be reused for a next forming process. Therefore the remaining fiber would be wasted.

To solve the problem, another design is shown in Figure 2-9 B. the matrix resin is filled to half volume of the vessel only; the fiber spool is positioned in the upper part of the container. The resin fluid level is monitored and is controlled at a certain level in order not to reach the fiber spool. So, the fiber spool is kept dry. Either by pumping in resin or pumping in air, a certain pressure inside the vessel could be built.

The shortcoming of this design is that the pressure of air cannot be kept at an exact value, especially at the beginning or stopping of deposition, because the air volume can change too much under pressure. In order to solve the problem, several designs were considered at the earliest research stage.

One of the designs is schematically shown in Figure 2-10. In this principle design, there are series of clips that keep the fiber tow held steadily and these clips are adjusted on circulating conveyer belt. They are being opened when they do not touch the fiber tow; they are brought through a parallel channel that continuously carries the fiber tow downward because the channel changes from wide to narrow and then wide again. Each of the clips hold the fiber tight in the narrow segment, and the fiber tow is pulled down.

Another design idea is shown in Figure 2-11. The principle is that a motor through a connector drives the bevel gear and then an impeller is driven to turn it. One or more

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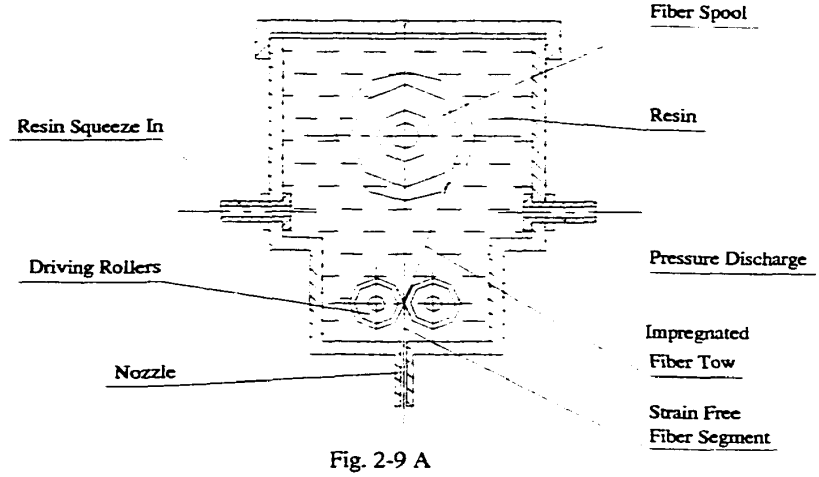

Fig. 2-9 A

Fiber spool is placed inside the vessel and soaked in resin.

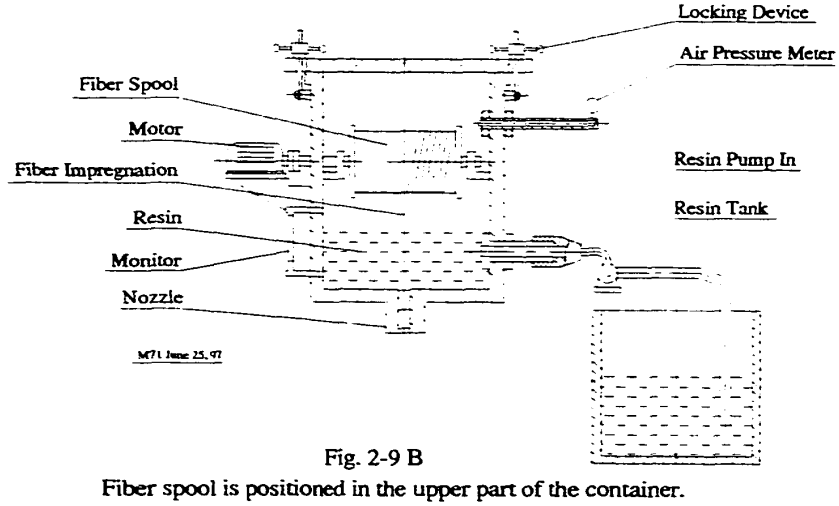

Fig. 2-9 B

Fiber spool is positioned in the upper part of the container.

Fig.2-9 Fiber spool is positioned inside the pressured vessel.

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helix blades are fitted on the impeller. When the helix blades are rotated in the vessel, a downward directional field of resin fluid flow is created. The resin fluid impregnates the fiber tow and drives it out through a nozzle. There is a hole on the center axis of the impeller. The fiber tow can be pulled through it to the vessel, but the matrix resin cannot go up through the hole because the resin flows downward. Therefore any a seal washer is not necessary. In the mechanism, the pump or extruder provide only a melted polymer and could not provide pressure to the vessel.

A different design is illustrated in Figure 2-12. The main idea is that the fiber tow is impregnated and driven down by a high-speed resin stream. In this design, an annular pipe replaces the nozzle. A ring slit is cut off from the lower side of the annular pipe. When the annular pipe is injected with matrix resin, a resin stream could be directed through the slit to the fiber tow at an angle to push down and impregnate the fiber tow. The scattered surplus matrix resin is reflected by the fiber tow and collected by a tray. If a photo curable resin is employed for this design, a laser beam should be focused on a point, this point is where the resin stream hits the fiber tow. Around the laser beam focused area, the towpreg is pre-solidified and is deposited on a desired place.

The designs introduced above are used to illustrate how to solve the problem of depositing and impregnating in one step, and how the fiber tow could be added and pushed upon at a desired point. If CLM process is separated into two steps, the design of each process step should be simple. A two-step method for the thermosetting matrix has been introduced in the previous section. In fact, the CLM with the thermoplastic matrix can be separated into two steps too. Figure 2-13 also illustrates the CLM process done in two steps. First, in the fiber tow is impregnated and becomes a towpreg. The second step

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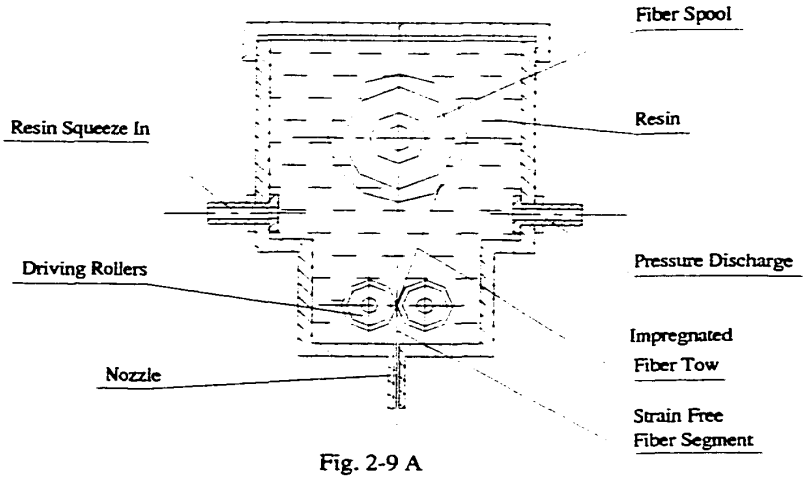

Fig. 2-9 A

Fiber spool is placed inside the vessel and soaked in resin.

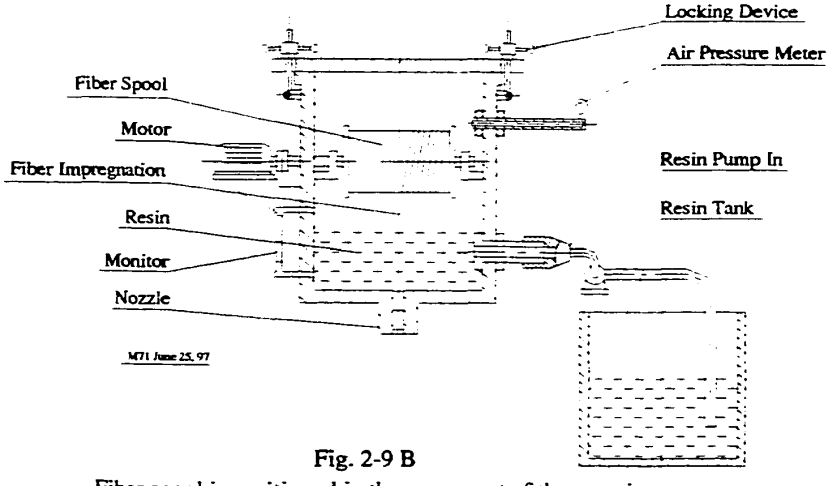

Fig. 2-9 B

Fiber spool is positioned in the upper part of the container.

Fig.2-9 Fiber spool is positioned inside the pressured vessel.

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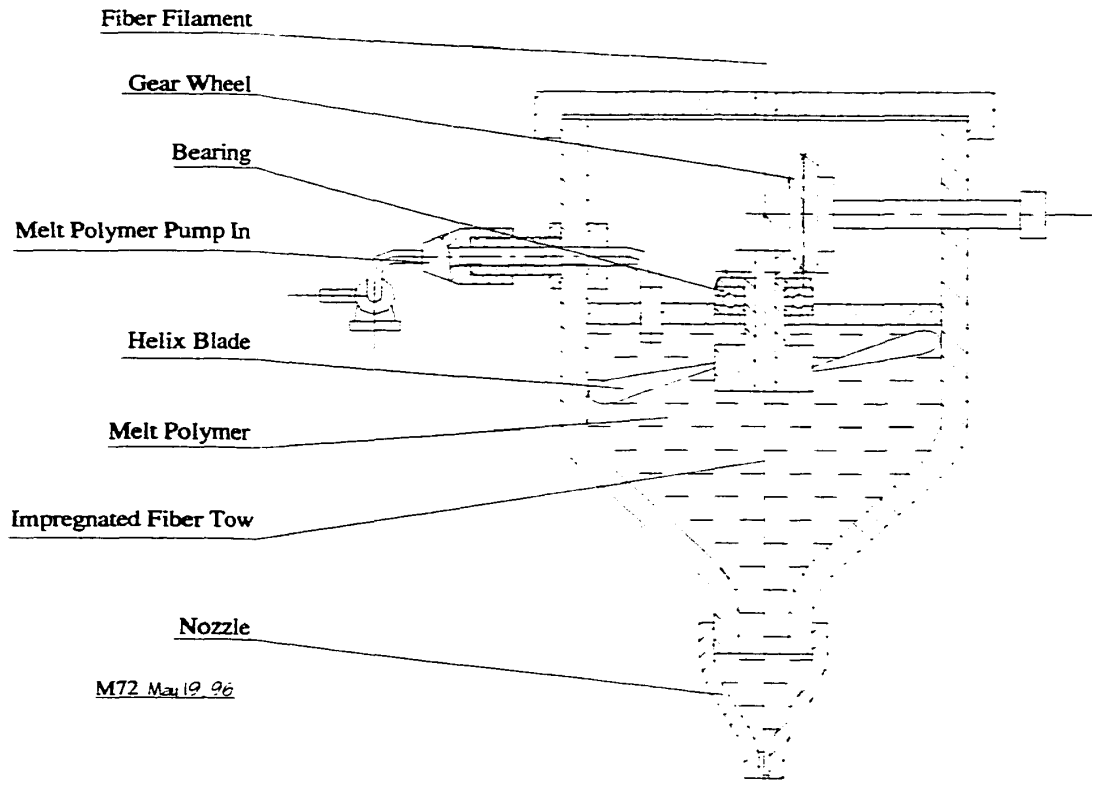

Fig 2-11 When the helix blades are rptated in the vessel, a downward directional velocity field of the resin fluid flow is created. The resin fluid impregnates the fiber tow and drives it out through a nozzle.

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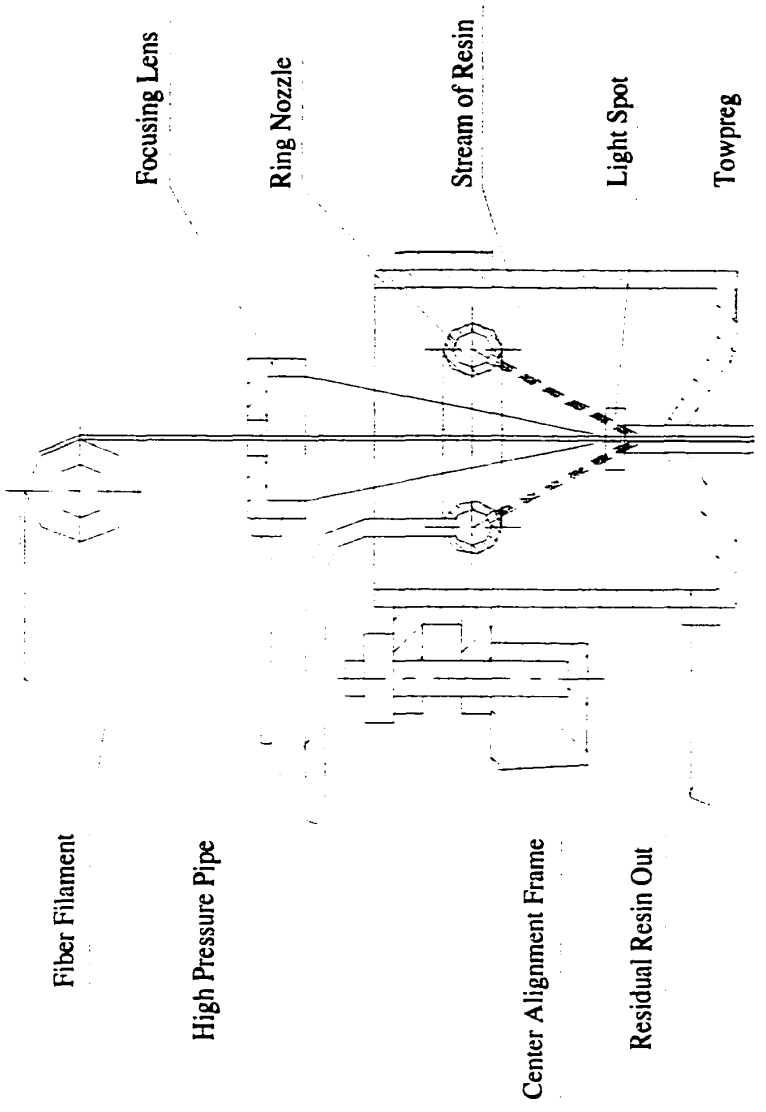

Fig. 2-12 the fiber tow is impregnated and driven down by a high-speed resin stream.

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the solidified towpreg is employed as a raw material for deposition. In the schematic design, the main process can be seen. When the fiber tow is passed through the melted thermoplastic material bath, it could be impregnated fully and becomes a towpreg. Then it is cooled to solidify. In Figure 2-13, the solidification of the thermoplastic matrix is done by cool air. But solidification should be faster if water is used as a coolant.

After solidification, a towpreg is like a wire with certain rigidity and can be controlled by a couple of rollers to drive forward and backward reliantly. The depositing process is similar to the FDM process, but the towpreg cutting off function should be considered.

Two methods similar to FDM are designed and pictured in Figure 2-14. A towpreg is delivered to the heating nozzle by a couple of driving rollers and squeezed out of the nozzle. Before the towpreg is driven into the nozzle, it has enough rigidity to perform like a piston. When the towpreg is driven into the nozzle with a temperature gradient, the resin in the towpreg is changed from a solid to a soft and melted substance. The solid towpreg, the piston, is driven by the roller downward to push the melted towpreg out of the nozzle.

An improved design is shown in Figure 2-14B. A cooling water sleeve is installed at the nozzle's entrance. The nozzle's entrance is expected to keep a certain temperature, and the towpreg is ensured to have the piston effect in this design.

The RPT with a metal matrix composite material is expected to work on a similar forming principle. A concept design for the metal matrix composite with RPT process is given in Figure 2-15. The composite contains aluminum as the matrix and continuous carbon fibers as the reinforcement material. As the picture shows, the aluminum metal

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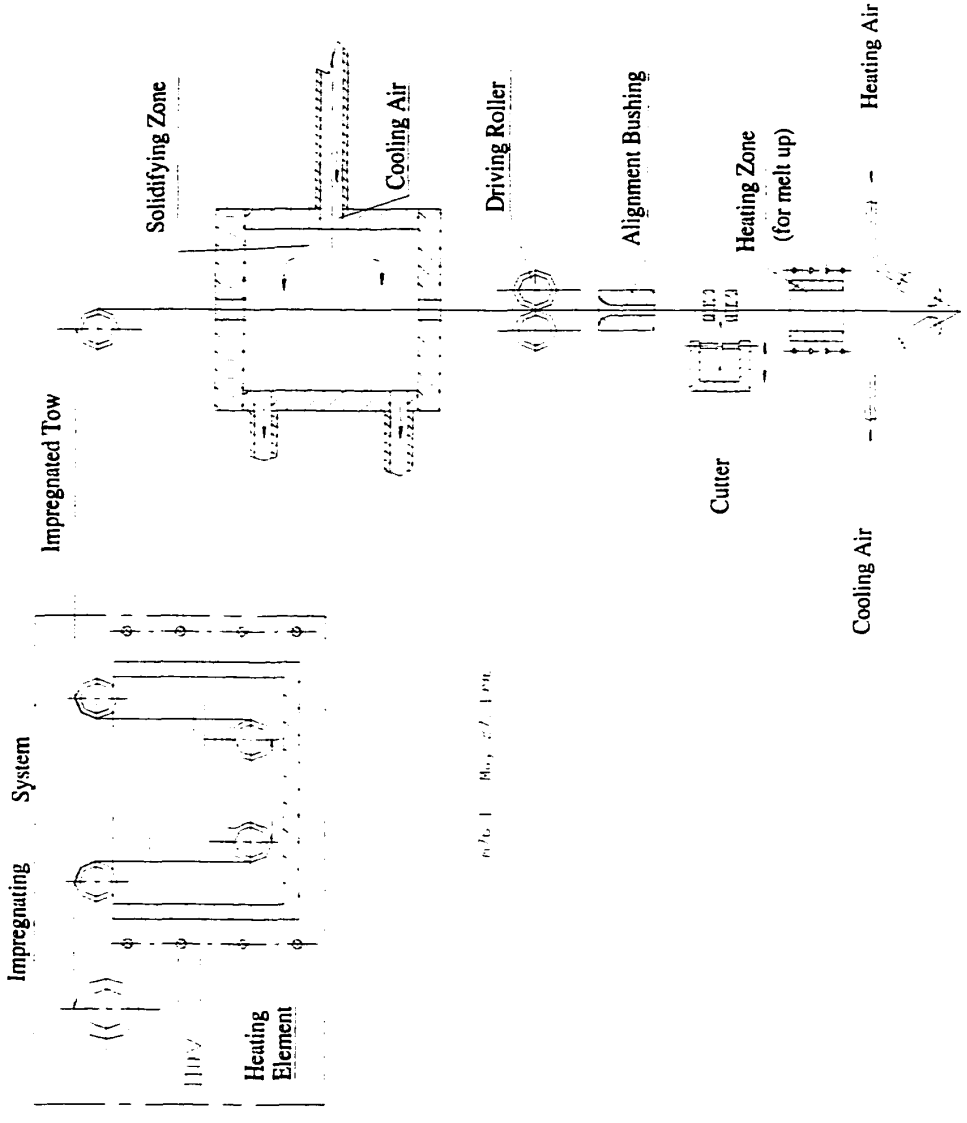

Fig. 2-13 a two-step method for thermoplastic matrix.

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stick is driven by a couple of controlling rollers, and there is a hole in the middle of the aluminum stick. Carbon fiber can leave through the hole smoothly. Before the stick is melted, it is a solid and can be used as a piston to push the front part (melted aluminum) and fiber tow together to flow out the nozzle. The entrance diameter of the nozzle is 3 or more times larger than the exit. The solid stick has an enough rigidity to push the melted aluminum. In order to ensure a proper volume fraction of fiber, when the fiber passes through the hole of metal stick center, its speed could be much higher than the stick's forward speed to add into the front melted zone, the molten bath. This is a concept design without much calculation and feasibility test. One of the questions is that the distorted metal could stick as the fiber tow passes through the hole in the soft zone. Even if the principle of the design is correct, the parameters and geometric shape of the nozzle should be studied carefully.

It may be noted that plastic welding can be seen as a RPT process. According to the concept, a deposition method like plastic welding is pictured in Figure 2-16 [56, 57]. If a towpreg made of a thermoplastic material matrix has enough rigidity and can be controlled forward or backward by a device, it can be used as a welding rod to build an object. But in general, the welding rod is thick, and the precision of the welding seam is lower than the requirement for a RPT. It is possible to use the towpreg as the welding rod to build a larger structure or component because the thick towpreg is relatively thin in the larger part. On the other hand, if the towpreg is used as the welding rod in a real plastic welding process, the mechanical properties of the welding seam should be high because the fiber can reinforce the welding seam. The concept designs are shown in from Figure 2-7 to Figure 2-16 and are briefly analyzed above, whatever the materials, all the designs

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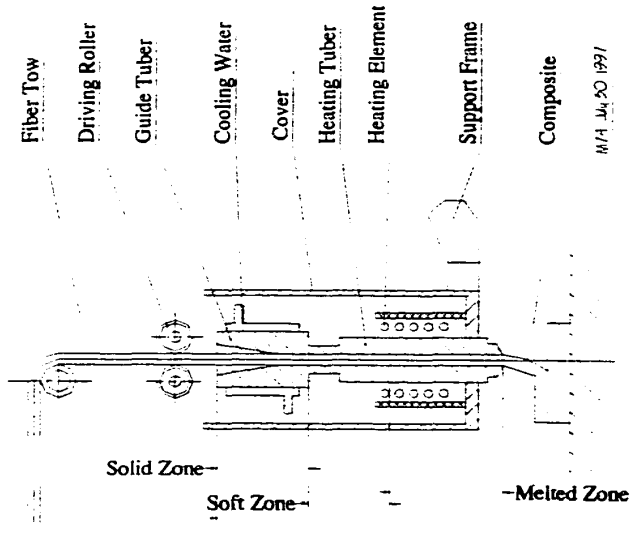

Fig. 2-14B
a cooling water sleeve is installed at the nozzle's entrance to keep a certain temperature.

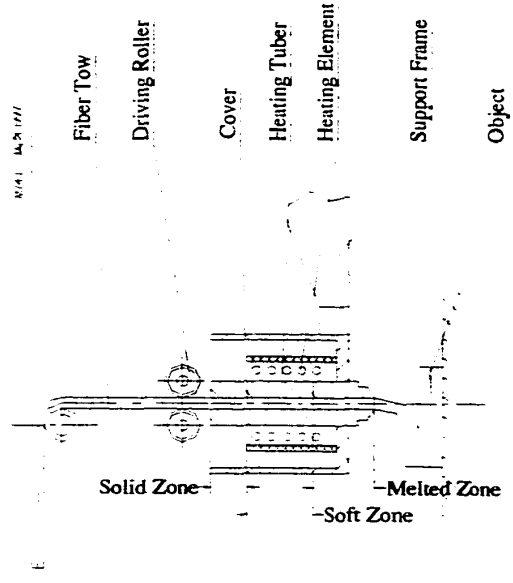

Fig. 2-14A
a towpreg is delivered to the heating nozzle by a couple of rollers and squeezed out of the nozzle by the piston effect.

Fig. 2-14 the piston effect deposition

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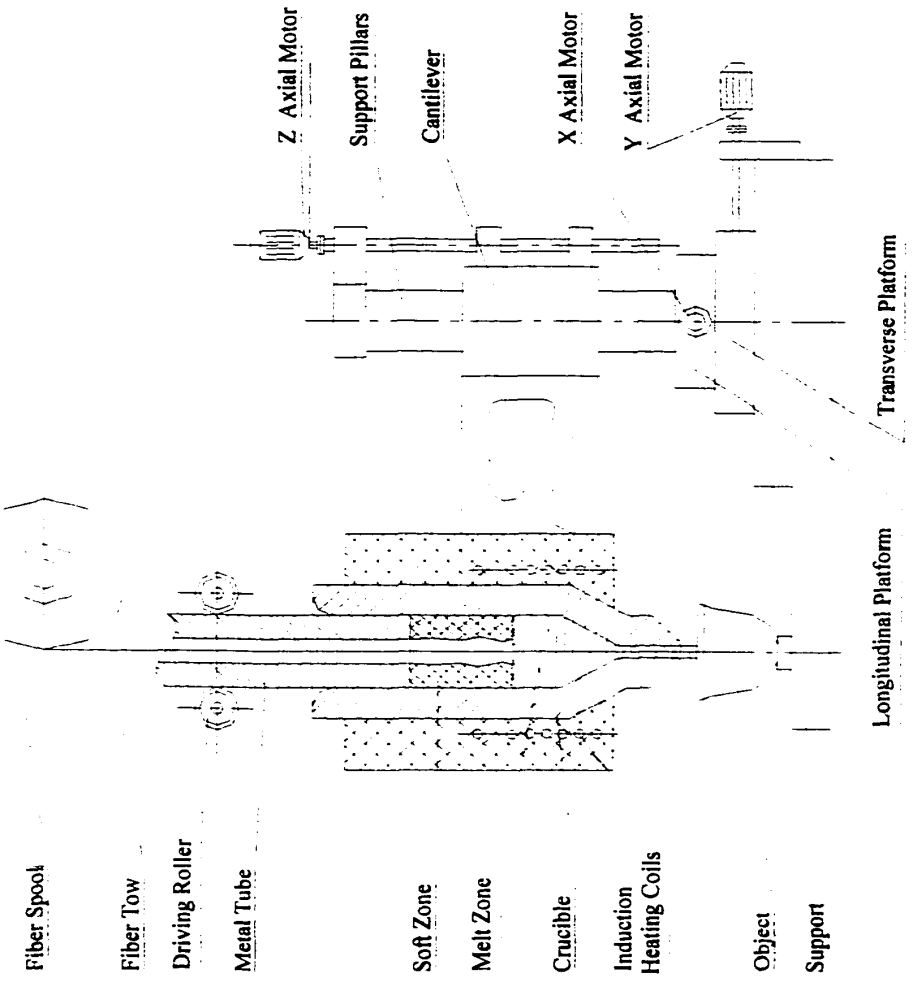

Fig. 2-15 CLM with metal matrix composite is deposited by the piston effect.

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can be classified into the Active Material Supplying method.

There is another materials delivery method, Passive Material Supplying. An example that works on this principle is the Filament Winding process. In Figure 2-17, a Filament Winding Machine is shown schematically. When the mandrel is rotated, the filament or fiber is pulled from a carriage and welded on the mandrel layer by layer. The filament path and winding style for each layer can be designed and led by the moving carriage and mandrel rotation. The process is used to form an axisymmetric part or uniform cross-section part only. But from this process, a new material-delivering concept for RPT, the Passive Material Supplying method, can be evaluated and used in the CLM process.

The advantages and shortcomings of the Active and Passive Material Supplying are compared and summarized as follows:

1. Active Material Supplying:

   a. The deposition speed would not be limited by the quality of deposition. If the deposited material can be solidified immediately, the depositing speed would only be limited by the speed of a motion device.

   b. An error or a mistake in the previous layer does not interrupt the forming process of the current layer.

   c. The support structure can be simplified in some situations, which are analyzed in §2-3.

   d. The depositing process can be resumed and restarted on demand at once.

   e. The machinery and controlling system for this method are

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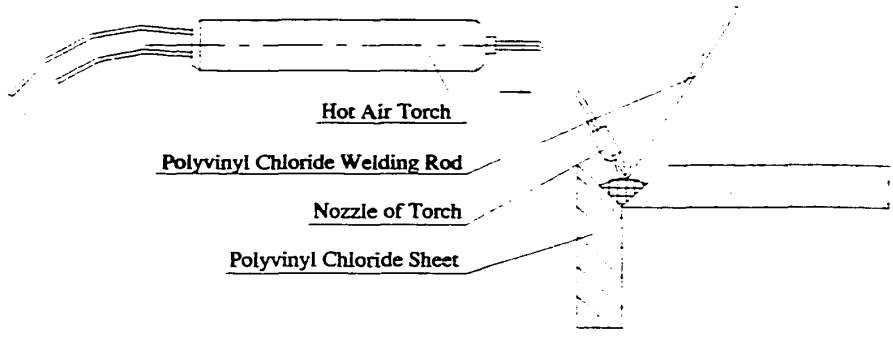

Fig. 2-16 a depositing principle like the plastic welding.

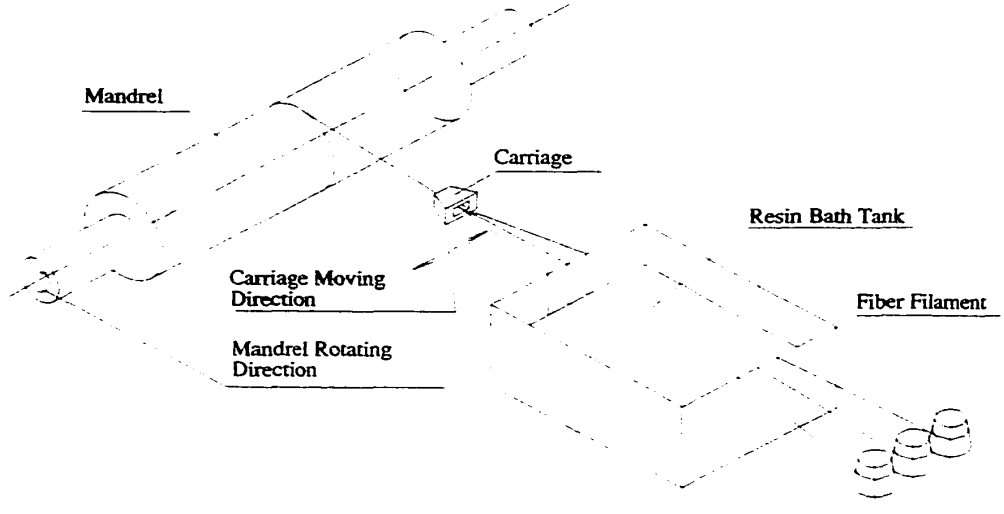

Fig. 2-17 a CLM deposition principle like the filament winding machine.

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relatively complex.

2. Passive Material Supplying:

a. The machinery and controlling system for this method are relatively simple.

b. The depositing speed depends on whether or not the towpreg is anchored to the previous layer. The deposition process could be interrupted by a mistake in the previous layer.

c. The method of restarting should be considered.

Two concept designs are described for the Active Material Supplying and Passive Material Supplying methods, respectively. The dissertation research was centered on these two methods.

A two-step, Passive Material Supplying method and for thermoplastic matrix composites is shown in Figure 2-18, but the method of making the towpreg is not shown in these pictures. The towpreg is driven to pass a heating pipe by a couple of driving rollers, and then is heated by the radiation of the heating pipe to a molten state (See Figure 2-18A). Another couple of rollers called a depositing roller is positioned near the bottom of the heating pipe to pull the molten towpreg downward and to help the towpreg roll to a desired location. Then the deposition is realized. But in the design, the axis of the depositing rollers must be perpendicular to the direction of deposition at all times. The software and machinery designs for this situation would be quite demanding.

A simplified design is shown in Figure 2-18B. The depositing roller is replaced by an alignment ring i.e. nozzle. Its diameter is larger than the diameter of the towpreg. During the deposition step, the nozzle is pressed on the molten towpreg to help it adhere

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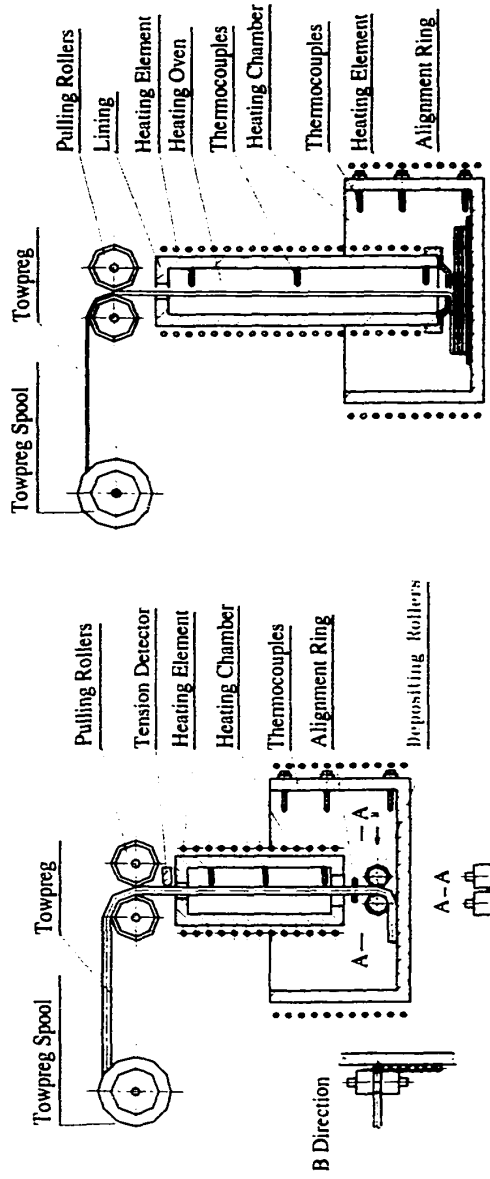

Fig 2-18A a couple of deposition roller is positioned near the bottom of the heating tube to pull the molten towpreg downward and to help the towpreg roll to a desired location.

Fig. 2-18B The deposition roller is replaced by an alignment ring.

Fig 2-18 Passive and active material supplying deposition methods.

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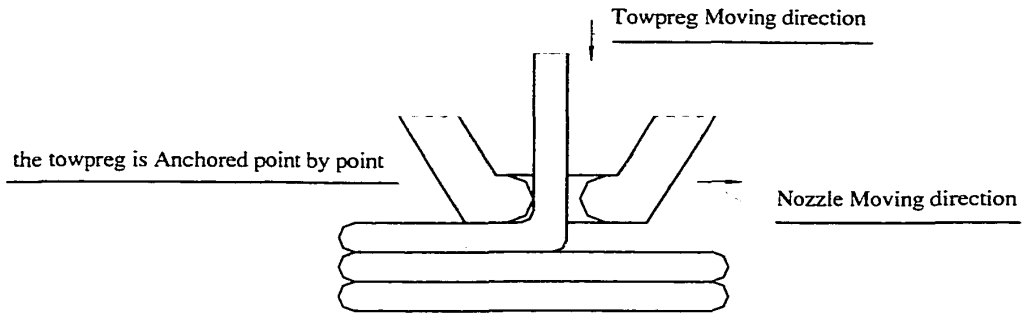

Fig. 2-19 the passive material supply mechanism.

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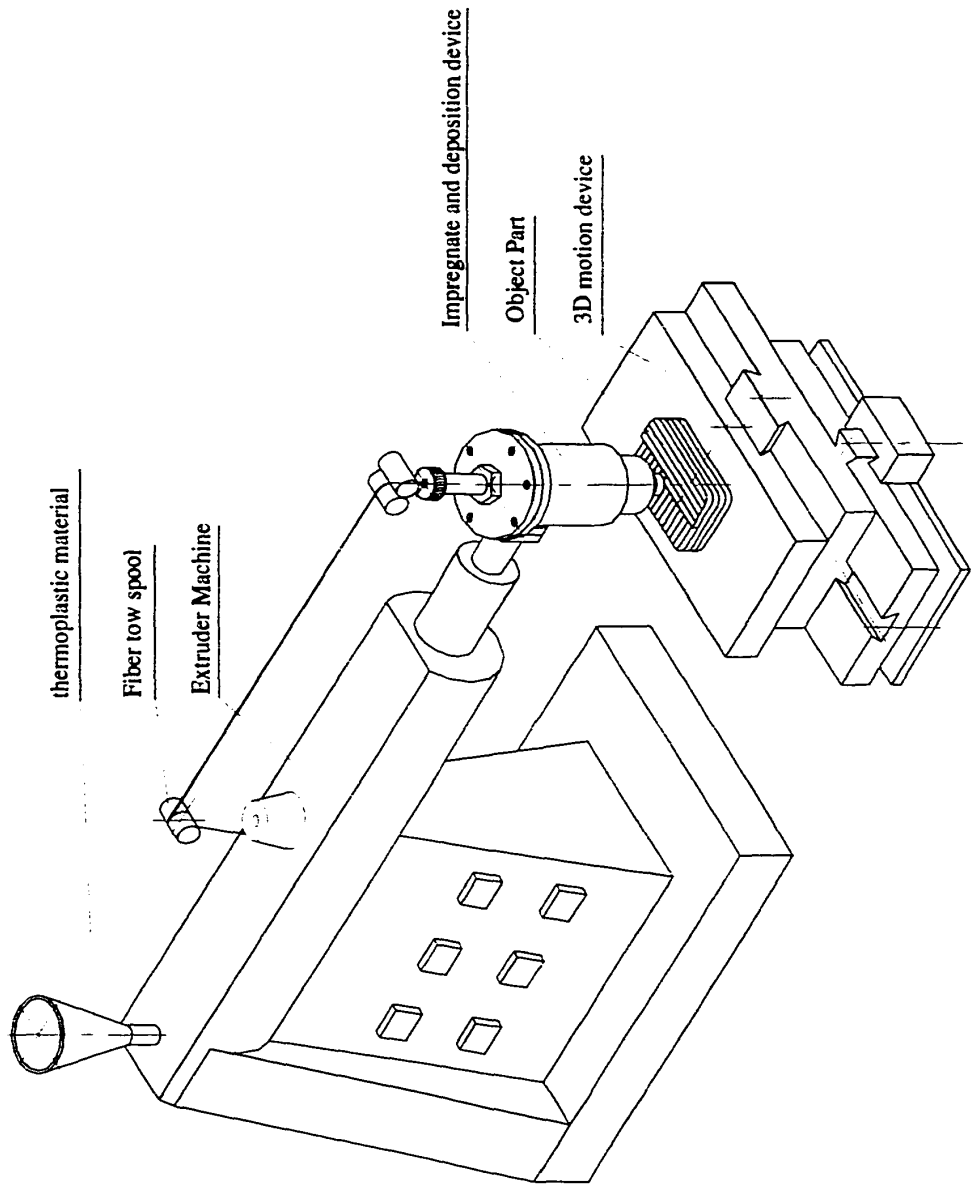

Fig. 2-20 the Active Material Supply method, a one-step forming process.

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to the previous layer. The forming mechanism is depicted in Figure 2-19. When the molten towpreg is deposited on the previous layer, under the surrounding temperature, the towpreg is solidified and glued to the previous layer immediately. The towpreg forms a series of anchor points. Because the anchor points adhered to the object, the towpreg should be pulled automatically out from the nozzle when the nozzle is continuously moved relative to the object. Then the deposition procedures are repeated to form successive layers of an object.

Throughout the above analysis and based on a feasibility testing, the design called self-anchoring method, shown in Figure 2-18B, has been selected as the primary design.

Also, an Active Material Supplying method shown in Figure 2-20 has been selected. It is designed for the thermoplastic, one-step method. In addition, a lot of research and development have been done around the designs. More detailed explanations will be given in Chapter 4 and Chapter 5.

§ 2-6 CHAPTER CONCLUSIONS

1. The development strategy of a new technology has been analyzed, and a research outline for CLM has been presented.

2. The forming theories of the CLM and the material selection issues for CLM have been studied.

3. The new concept of Active and Passive Materials Supplying has been put forward to help categorize and create a new deposition method.

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4. Several concept designs have been given and analyzed in this chapter.

5. Two designs are considered as the best plans.

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CHAPTER 3 PRINCIPLES OF TOOLPATH DESIGN

§3-1 INTRODUCTION

The principle of CLM forming, concept design and developmental procedure have been discussed before. The methods of material delivery have been analyzed and are divided into two main kinds, which are Active Materials Supplying and Passive Materials Supplying discussed in Chapter 2. In this chapter the precision of deposition and the pre-design of mechanical properties will be studied. We will also investigate the requirements of software to control the toolpath in a certain deposition procedure.

The depositing method for CLM technology is different from any other method, in terms of the sources of error and how the system error can be reduced. These are problems unique to the CLM technology. Once the CLM precision question is answered, the rules for software development and tool path generation will be obtained.

How high should the precision be for a new forming technology? What are the mechanical properties for all the formed parts? How are the mechanical properties be achieved? These are questions to be answered for all new technology development efforts. So first of all, we should research the precision in more details.

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§3-2 POTENTIAL SOURCES OF ERRORS AND CONTROL METHODS FOR CLM

3-2-1 Potential Origins of Errors

The forming process of RPT is realized by adding material layer by layer. Depending on how much material is added each time, the precision could be affected directly. The cross sections of complicated shape parts are not uniform. Because the dimensions of a cross-section can vary from layer to layer, no matter what RPT forming process is used, there will be a Staircase Effort. The Staircase Effect and its dependence on the layer thickness are illustrated in Figure 3-1.

The Staircase Effect between layers is influenced by the thickness of each layer. The thickness of layers at the left side of Figure 3-1 is two times that of the right side. Therefore, the difference between the theoretical contour and the formed part profile line at the left is larger than that of the right side. For example, in the LOM and SL technologies, each added layer is very thin. Furthermore, StereoLithography is currently approaching the point where *90%* of all the measurements on a commonly used accuracy standard test part will be within five mils (*0.005*") of their CAD value. The Staircase Effect is so small that it could not be recognized by the naked eye.

In the FDM technology the thickness of each layer is determined by the diameter of rods, which is deposited by a nozzle. If the orifice diameter of the nozzle, *Dn*, is *1mm*, the max error is ½ *Dn*, or *0.5mm* in principle. If the orifice diameter of the nozzle becomes small, the error could be reduced proportionately. But the orifice diameter of the nozzle could

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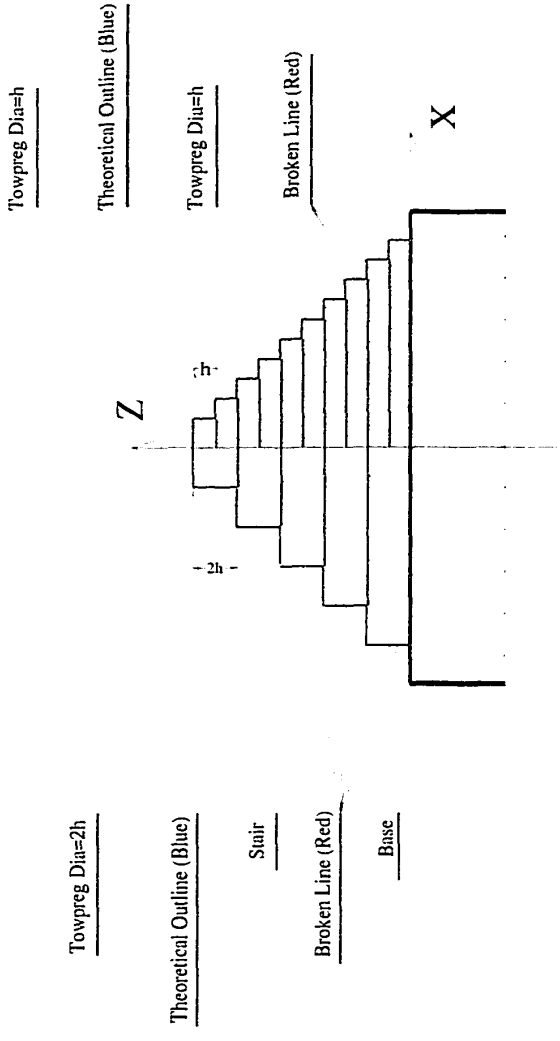

Fig. 3-1 Staircase effect and its dependence on the layer thickness.

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not be reduced without a limitation. The limiting factors of the nozzle's orifice diameter are discussed as follows:

1. If the nozzle orifice diameter becomes small, the number of layers that are needed to build the whole part would increase, resulting in an increased part-building time.

2. If a pressure is needed to extrude the material, the nozzle supplied pressure, P_n, is inversely proportional to the reciprocal of the forth power of the nozzle's orifice diameter D_n, $P_n \propto 1/(D_n)^4$. The pressure that is needed to extrude materials out of the nozzle is increased dramatically with a smaller orifice. In other words, if the orifice diameter of the nozzle becomes too small, it may be come extremely difficult, if not impossible, to extrude out the material. The extrusion process may be come unstable and difficult to control. The smallest orifice dimension will be studied in Chapter 4.

Besides the staircase effect between layers and even inside a layer, there may also be the error that is called "In Layer Error". The sources of this type error are analyzed in the following:

1. The diameter of a towpreg could be a source of error. The two common kinds of In Layer Errors are shown in Figure 3-2.

Materials are deposited line by line to cover a whole layer; the deposition direction is along the X-axis direction and the towpreg line increment direction is along the Y-axis. An error occurs where a broken line replaces the arc, which is the theoretical contour (See Figure 3-2A). The towpreg size in the upper portion is two

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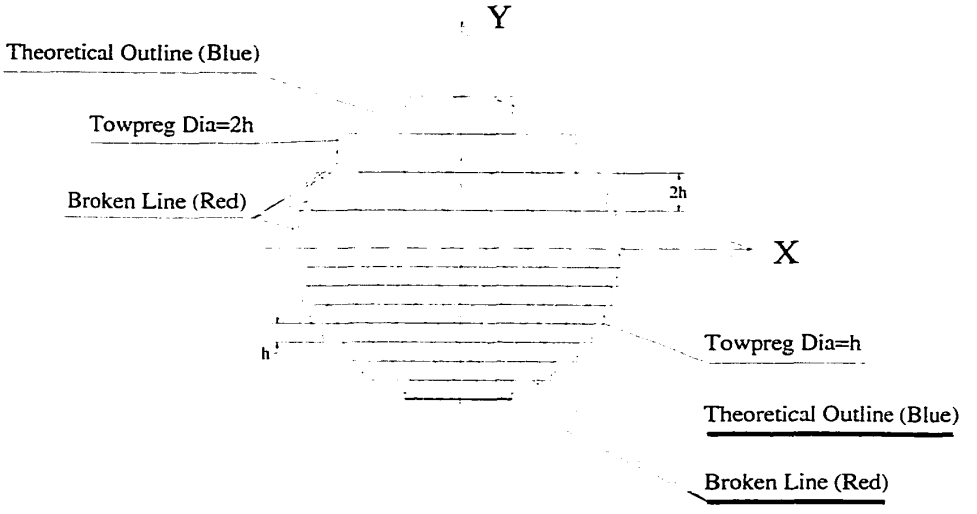

Fig. 3-2A In Layer Staircase Effect.

Fig. 3-2B Turn deposition direction induced errors.

Fig. 3-2 In layer errors.

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times of that in the lower portion of Figure 3-2A. An influencing factor in this error is obviously the towpreg diameter.

An error is introduced during the deposition process and is shown in Figure 3-2B. When the deposition direction is changed and the towpreg is bent at an angle, at depositing direction-changing points, an error occurs. The error is more pronounced when the turn angle is larger and/or the towpreg is thicker.

2. In the case of towpreg extrusion as a way of active material supplying and under the assumption that 3D motion control error is negligible, the discrepancy between the material delivery speed and the motion device speed could also become a source of error.

3. An error is induced by material shrinkage, which is the problem many RP technologies could face. On CLM, the shrinkage error should be smaller since the fibers, which occupy at least *50%* by volume of the towpreg, do not shrink much within the common working temperature range.

4. An error could occur as a result of nozzle pressure variations. If a nozzle-supplied pressure fluctuates during deposition, the supplied material could also fluctuate particularly at the beginning and end.

5. A difference between the nozzle orifice diameter and towpreg diameter could also cause an error: In the case of Active Material Supply, material is pushed out of the nozzle, and the diameter of the towpreg is equal to the diameter of the nozzle's bore. If the Extruding Die Swell Effect of a plastic material is considered, the diameter of the extruded towpreg could be larger than the bore of the nozzle. But, in the case of Passive Material Supply, the diameter of the nozzle bore should be

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larger than the diameter of towpreg. Otherwise, a frictional force between the orifice and the towpreg will be large and the force that is needed to pull the towpreg out of the nozzle will correspondingly be larger. If the friction force arrives at a certain value, the process could not be continued. The diameter difference between the nozzles bore and the towpreg is shown in Figure 3-3. These kinds of errors will be studied in the next subsections in more detail.

6. There is another error brought in during the deposition process for Passive Material Supply. When the deposited towpreg could not be immediately solidified and anchored to a previous layer, a larger error will be induced. These problems will be discussed in more depth in Chapter 4.

3-2-2 Controlling the Errors

1. In order to reduce the staircase effect, a general method may be followed which involves building a perimeter area (exterior or interior boundary) by using a smaller-bore nozzle and building the interior of a layer by using a thicker towpreg.

2. The forming precision is related to the forming speed, and one normally has to strike a balance between part accuracy and forming speed. When high accuracy is required, the deposition speed may have to be reduced.

3. The precision may change as the deposition direction is changed, so at the turning point of the of deposition direction, a reduced forming speed is necessary. When a straight line is formed, the forming speed could be increased as high as possible to reduce over-all the forming cycle time.

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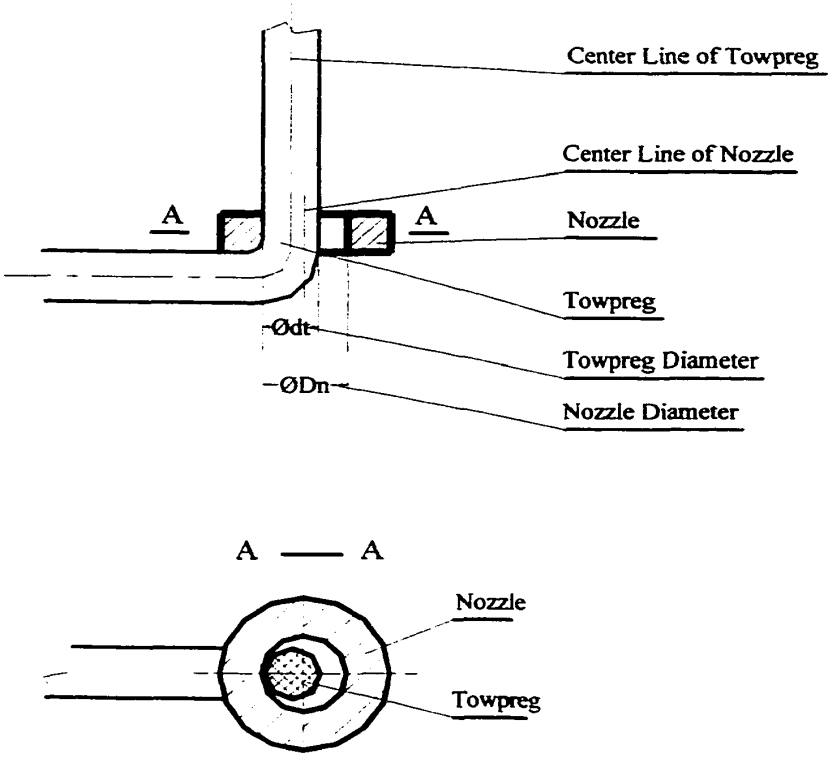

Fig. 3-3 Difference in Diameter of the nozzle bore and the towpreg.

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4. The material compositions of the towpreg may be re-formulated to reduce shrinkage.

5. At starting points or stopping points, an error sometimes occurs especially in the case of Active Material Supply. Therefore, a materials compensation method may be considered by way of software or hardware variations.

§3-3 ERRORS CAUSED BY DEPOSITION DIRECTION CHANGES

In the self-anchoring method, using a device of Passive Material Supply, the bore diameter D_n of the nozzle is larger than the outside diameter of the towpreg d_T. During deposition, it is possible to make a big error, especially when the nozzle makes a big-angle turn. Situations in which an error could be induced include:

1. When the self-anchoring method or other Passive Material Supply methods are employed to deposit the towpreg,

2. When the diameter of the towpreg is less than the diameter of the nozzle's bore, and

3. When the deposition changes direction.

Figure 3-4 illustrates the latter possibility. The difference in diameter between the nozzle bore D_n, and the outside diameter d_T of the towpreg is shown in Figure 3-4A. According to the toolpath, the center of the nozzle is moved from point A to point B_0 and then is turn a right angle to move along $B_0 C$ direction, (which is perpendicular with line AB_0) to B_1, B_2, ... to point C. What is a moving regularity of the towpreg center point (X_0, Y_0)? If the regularity is found, the error can be figured out immediately. Now, the error can be

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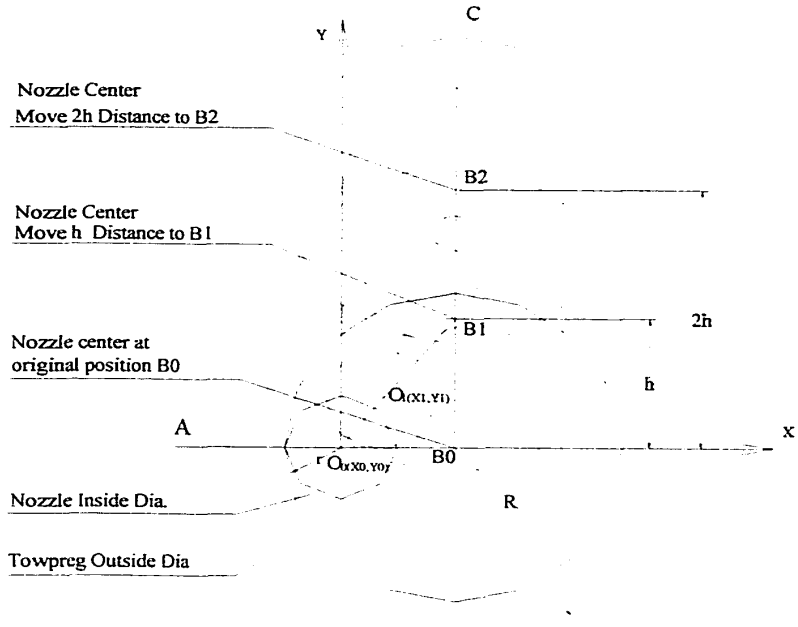

Fig. 3-4A.

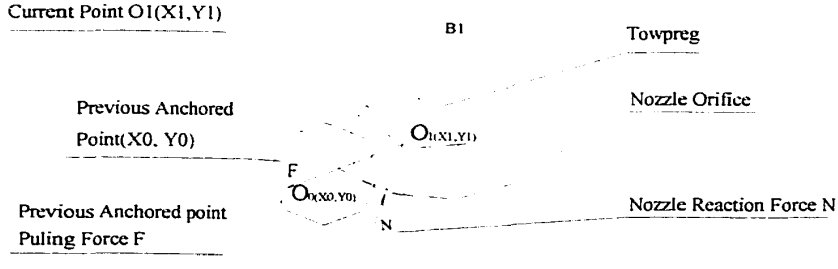

Fig. 3-4B Free Body Diagram.

Fig. 3-4 Right angle turn.

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determined by the difference between the center track of towpreg and the center track of the nozzle.

3-3-1 A Mechanics Model

To set up a mechanics model, several assumptions are made:

1. Mechanics Assumptions:

   a. All inertial forces are neglected.

   b. Gravity and friction forces are not considered.

   c. The forces imposed on the center of the towpreg are given only by the reaction force N from the nozzle and the pulling force F, which is induced by the previous anchored point. The situation of forces is shown in Figure 3-4B.

2. Physics Assumptions:

   a. The previous point is anchored completely at once, which means the solidification time should be very short.

   b. In practice, if the deposition speed is slow enough, the assumption could be justified.

3. Geometry Assumptions:

   a. It is supposed that the nozzle center point moves a distance H from B_0 to B_1.

   b. In fact the nozzle is moved continuously, and the distance H should be infinitesimal. But in practice, a small value can be used for the distance H and the nozzle is assumed to move step by step.

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3-3-2 A Derivation for the Towpreg Center Tracks

The question could be converted to determining the positions of the towpreg center with each moving step of the nozzle center. Suppose that the towpreg is at an original point (X_0, Y_0), at which the resin has been solidified completely and a reliable anchored point has been formed. According to the Force Balance Condition, a new towpreg center point should be judged to be a point of balance between the two forces, which are the nozzle reaction force N and the pulling force F at the original point O_0 (X_0, Y_0). When the nozzle center is moved from B_0 to B_1, a new towpreg center point O_1 $(X_1, Y1)$ must be on the point of intersection between the connection line O_0B_1 and the circle, whose center is set at B_1 and radius with R-r.

Based on the above assumptions and analysis, an equation can be derived to determine the towpreg center point O_1 (X_1, Y_1).

$$(h-y_1)^2+(R-r-x_1)^2=(R-r)^2$$

$$y_1=\frac{h}{R-r}X_1 \qquad (3-1)$$

where: R = bore radius of the nozzle,

r = towpreg radius,

h = the length of the nozzle moving step.

From equation (3-1), a coordinate O_1 (X_1, Y_1) of the towpreg center can be determined when the nozzle moves by one-step of length h. When the nozzle continuously moves along the toolpath B_0C to point B_2, O_1 (X_1, Y_1) is regarded as the new anchored point, and the position of O_2 (X_2, Y_2) could be found the in same way. Based on

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these rules, the track of the towpreg center point could be found. Equation (3-2) describes the track of the towpreg center point.

$$(i\times h - y_i)^2 + (R - r - x_i)^2 = (R - r)^2 \tag{3-2}$$

$$yi = \frac{ih - yi - 1}{R - r - xi - 1}(xi - x_{i-1}) + y_{i-1} \qquad i = 2,\ 3,\ 4,.....$$

where $i = i^{th}$ moving step of the nozzle.

3-3-3 Discussions of the Calculated Results

Equation (3-2) is a dispersion equation; the coordinate $O_i\ (X_i,\ Y_i)$ of the towpreg center is determined by each moving step length h of the nozzle and by how many steps have been executed. A total moved distance of the nozzle is the product i times h. Equation (3-2) is also a convergence function. When the nozzle is moved to the i times, $O_i\ (X_i,\ Y_i)$ is gradually converges to the toolpath line B_0C, and the line of B_0C is the infinite position of the track $O_i\ (X_i,\ Y_i)$. The track of $O_i\ (X_i,\ Y_i)$ could be obtained when a value for h is given. When the step length h is changed, the convergence value of each point $O_i\ (X_i,\ Y_i)$ is not the same (Figure 3-5).

According to Equation (3-2), when the length of each step h is changed, the center point of the towpreg converges to different locations. In a real deposition process, the nozzle is moved continuously, which means that the length of step $h \rightarrow 0$, only when the length of each step is small enough, Equation (3-2) could describe the actual condition.

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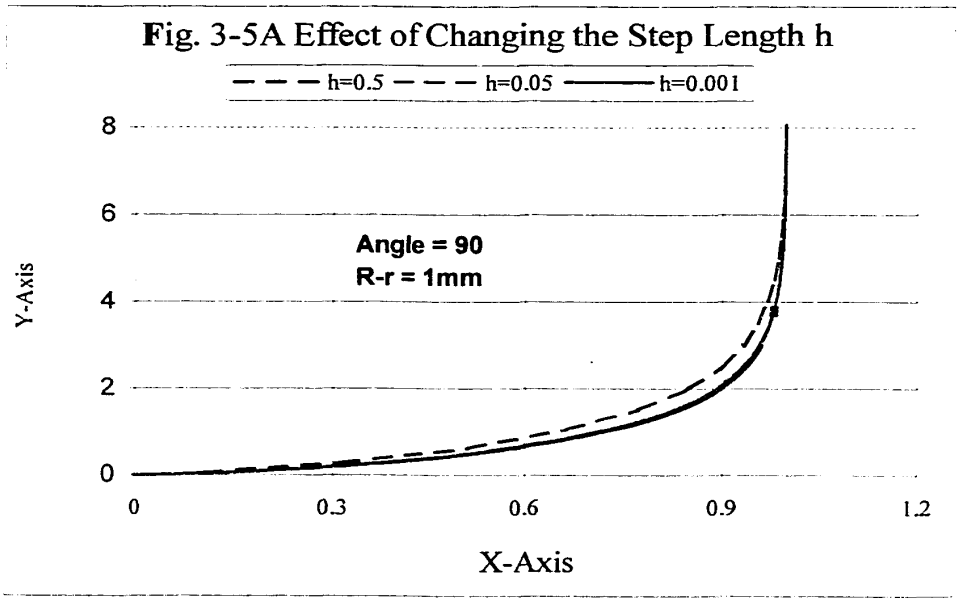

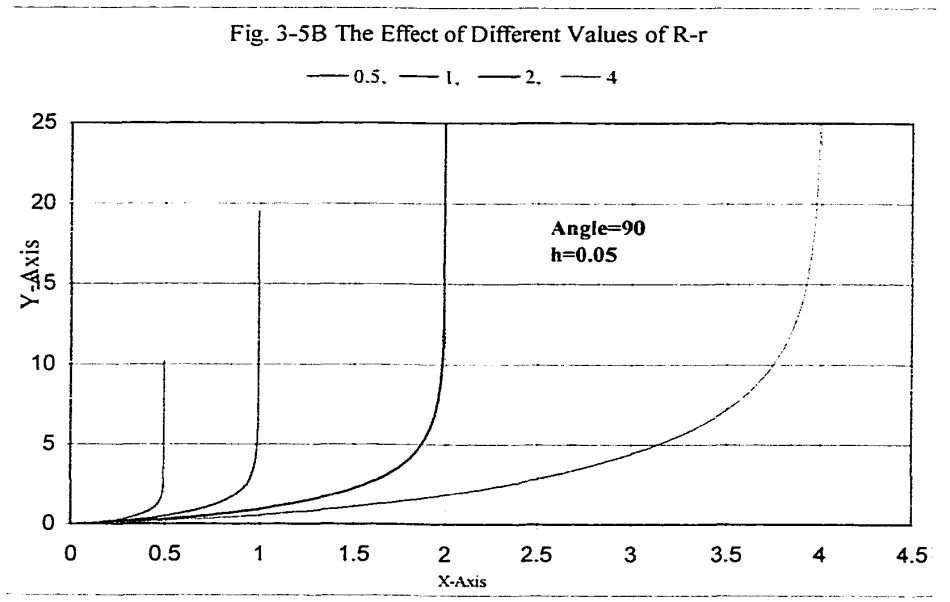

Figure 3-5.

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If a small value δ_x, a distance between the points O_i (X_i, Y_i) and the X-axis direction B_0C, is set as a controlling target, the value $\delta_x = 10^{-2}$ mm is accurate enough and could be regarded as coinciding with line B_0C. Then the step length h is set at $h_1=10^{-1}$, $h_2=10^{-2}$, $h_3=10^{-3}$ and is substituted into Equation (3-2), respectively, see Figure 3-5A. When $h<10^{-2}$ and the iterative times in Equation (3-2) are greater than the value $i \times h$, each track is always converged to a same δ_x.

The 3D motion device, which is employed for the CLM experiment, is driven by three stepper motors to move along the X, Y and Z-axes, respectively. The step length of these motors is a half-degree, *1/720*. The diameter of the driving shaft is *20 mm* and the pitch of screws is *3*mm. The moving length of each step for each of the linear motion devices is $3/720 \approx 4\times10^{-3}$ *mm*. When the simulation step length is set to 10^{-3} *mm*, the situation is more realistic. After proper values are assigned to the bore diameter of the nozzle, $D_n = 2R$, diameter of the towpreg $d_T = 2r$, the controlled value of error δ_x and the supposed length of step h, then the error of the towpreg center could be calculated by using Equations (3-1) and (3-2). An algorithm flow chart is shown in Figure 3-6A. Figure 3-5A and Figure 3-5B are then calculated results after the above parameters have been changed.

In Figure 3-5A, we could see the moving regularity of the towpreg. The moving direction of the nozzle is changed (new direction is perpendicular to the original direction) after appointing a new length value so that the nozzle can move along a new direction. The center of the towpreg converges very fast to the toolpath. Finally, only a value R-r, which is the difference between the track of the nozzle center and the track of the towpreg center, is reminded.

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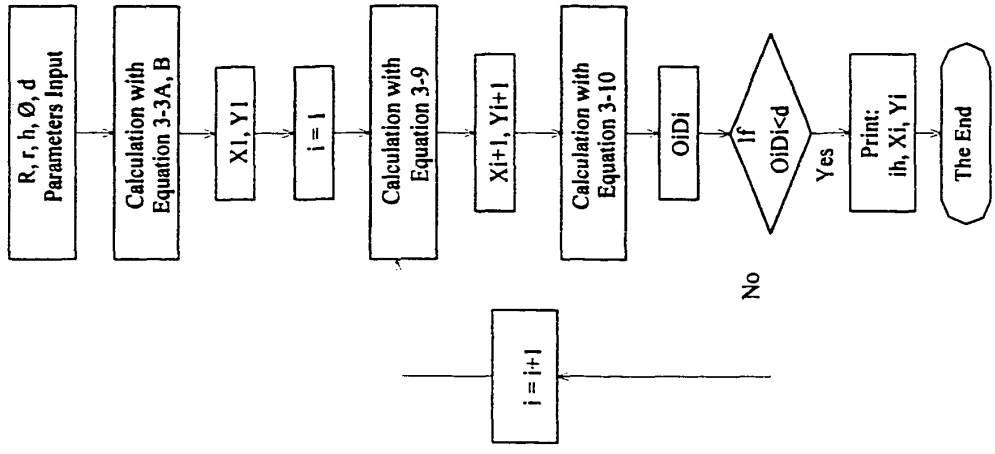

Figure3-6B Obtuse Angle Turn.

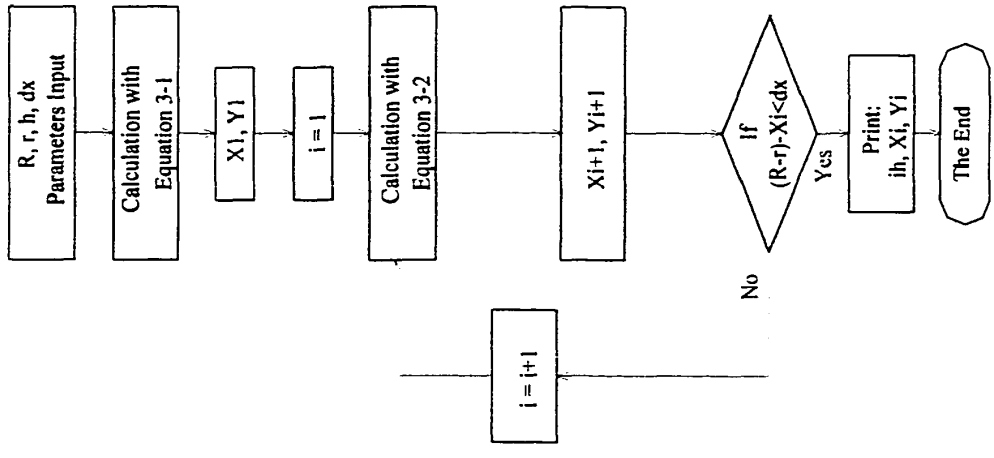

Figure3-6A Right Angle Turn.

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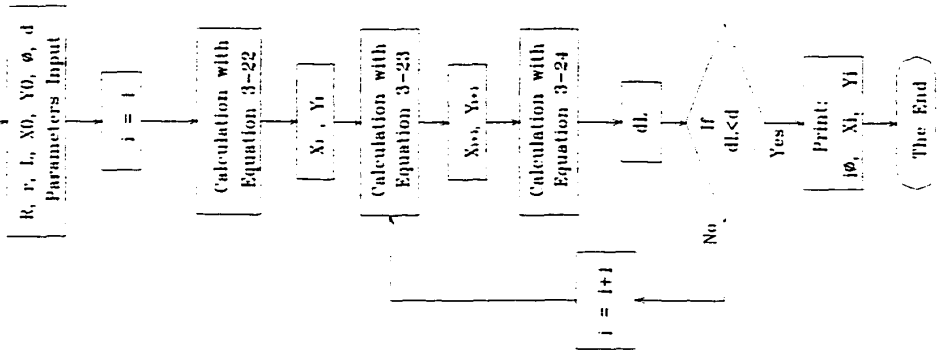

Figure 3-6D Error Evaluation for the case of depositing an arc.

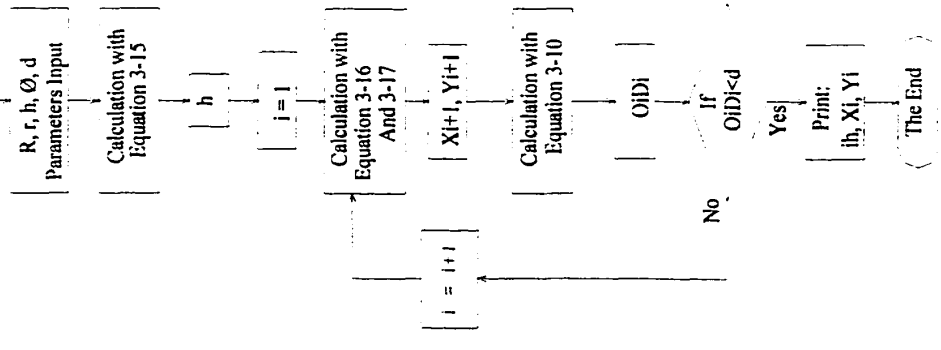

Figure 3-6C Acute angle turn flow chart.

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When $h<0.05$ mm, the difference of the each towpreg center tracks is not obvious (In Figure 3-5A). With other conditions being the same and h being set at $h=0.05$, and $h=0.001mm$, the curved lines of the two towpreg center arcs almost overlap with each other. Figure 3-5B shows the variation of the towpreg tracks with a differing R-r value. The result shows that when R-r is larger, the error is bigger. Then, the distance that is needed to converge to the toolpath is larger.

3-3-4 Analysis of Case 1: Obtuse Angle Turn

The deposition direction of the nozzle could be change by an angle between $0°$ and $180°$. The resulting error will be discussed in the following sections. First, we will examine the case of making a turn in an obtuse angle; the situation is shown schematically in Figure 3-7. A nozzle is controlled to move from left A, to right B_0, and then at B_0, the nozzle is turned at an obtuse angle θ in order to move toward C. The same assumptions used in the previous section for the case of a right angle turn arc are employed in the present case.

For convenience, the initial conditions are presumed to be: nozzle center is placed at B_0, center of the towpreg located at O_0 (X_0, Y_0), and turned angle being ϕ. When the nozzle is moved by a one-step length h, the position of the towpreg center could be at O_1 (X_1, Y_1), which could be evaluated by equations (3-3A) and (3-3B).

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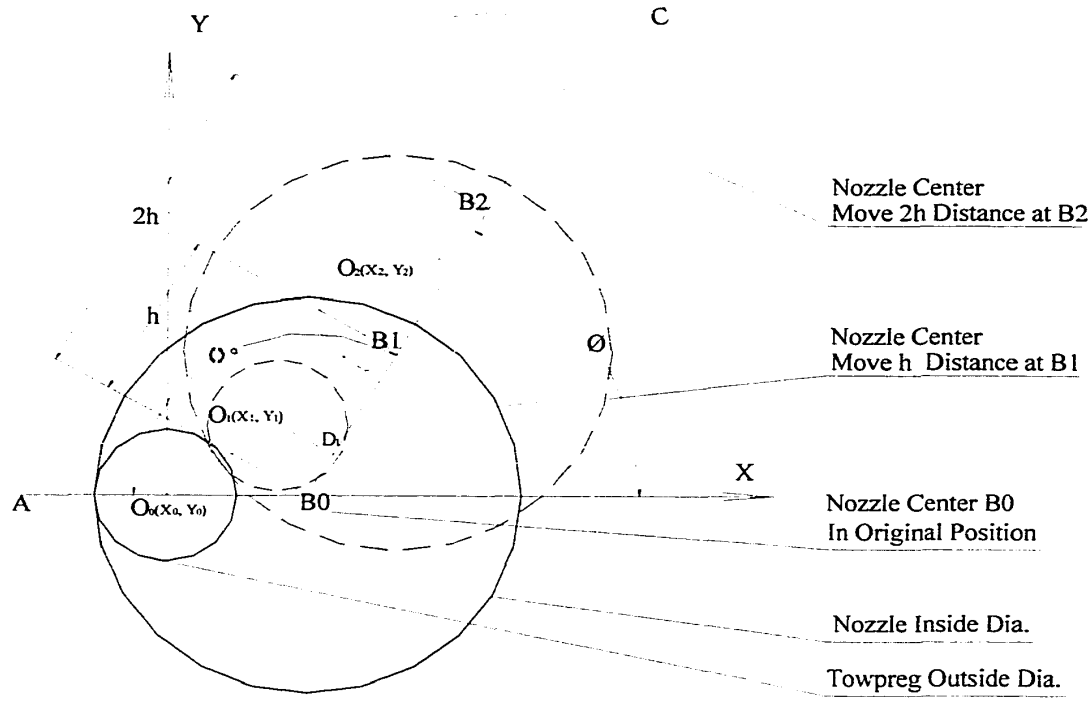

Fig. 3-7 Obtuse angle turn.

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$$(h\cdot\sin\phi - y_1)^2+(R-r + h\cdot\cos\phi-X_1)^2=(R-r)^2 \qquad (3\text{–}3A)$$

$$y_1 = \frac{h\cdot\sin\phi}{R-r+h\cdot\cos\phi} X_1 \qquad (3\text{–}3B)$$

where: h = nozzle moving length of each step,

θ = an obtuse angle,

$\phi = 180°-\theta$.

Substituting Equation (3-3B) into (3-3A), one obtains Equation (3-4):

$$(h\cdot\sin\phi-\frac{h\cdot\sin\phi}{R-r+h\cdot\cos\phi}X_1)^2+(R-r+h\cos\phi-X_1)^2=(R-r)^2 \qquad (3-4)$$

The value of X_1 can obtained from equation (3-4) and then the X_1 value can be substituted into (3-3B) to get Y_1. The point O_1 (X_1, Y_1) is a new location of the towpreg center.

To calculate the error (a distance between the point O_1 (X_1, Y_1) and line B_0C) a line O_1D_1 is drawn from point O_1 (X_1, Y_1) to be perpendicular to B_0C. See Figure 3-7. Equation (3-5) is a straight-line equation to indicate line O_1D_1.

$$Y = kX + b \qquad (3-5)$$

Because $O_1D_1 \perp B_0C$,

$$Tan\phi\cdot k = -1, \qquad and \qquad k=\frac{X_1}{Tan\phi}$$

Substituting k into equation (3-5) to get b:

$$b = Y_1 + \frac{X_1}{Tan\phi}$$

Equation (3-5) is re-written as equation (3-6):

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$$Y = \frac{1}{Tan\phi}(X - X_1) + Y_1 \qquad (3-6)$$

An equation for the straight line B_0C could be obtained at same time:

$$Y = Tan\phi[X - (R - C)] \qquad (3-7)$$

Combining Equation (3-6) and Equation (3-7) to have the intersection point D_1:

$$\overline{X}_1 = \frac{X_1 + Y_1 Tan\phi + (R-r) \times Tan^2\phi}{1 + Tan^2\phi}$$

$$\overline{Y}_1 = \left[\frac{X_1 + Y_1 Tan\phi + (R-r)Tan^2\phi}{1 + Tan^2\phi} - (R-r)\right] Tan\phi$$

The distance from point O_1 to point D_1 is given by:

$$\overline{O_1 D_1} = \sqrt{(\overline{X}_1 - X_1)^2 + (\overline{Y}_1 - Y_1)^2} \qquad (3-8)$$

So far, the first step has been finished and it is a very important step. The following track of the towpreg center points can be obtain in the same manner by using Equations (3-9):

$$(ih\sin\phi - Y_i)^2 + (R - r + h\cos\phi - X_i)^2 = (R-r)^2$$

$$\frac{Y_i - Yi - 1}{X_i - X_i - 1} = \frac{ih \cdot \sin\phi - Y_i - 1}{R - r + h\cos\phi - X_i - 1} \qquad (3-9)$$

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where: $i = 1, 2, 3, \ldots\ldots$ and when $X_0 = 0$, $Y_0 = 0$.

Using the same principle as in step one, the distance between each point of the towpreg center to the nozzle center could be obtained by equations (3-10), (3-11) and (3-12):

$$\overline{OiDi} = \sqrt{(\overline{X}_i - X_i)^2 + (\overline{Y}_i - Y_i)^2} \qquad (3-10)$$

$$\overline{Y}_i = \frac{1}{Tan\phi}(\overline{X}_i - X_i) + Y_i \qquad (3-11)$$

$$\overline{Y}_i = Tan\phi\left[\overline{X}_i - (R-r)\right] \qquad (3-12)$$

A calculation algorithm is shown in Figure 3-6B.

Figure 3-8 shows the errors vs. turned angles ϕ and different R-r with other conditions being the same as before. From the diagram, the following observations can be made:

1. No matter how big the turn angle is, when the nozzle along the new direction moves a distance, which is 5~7 times of $(R-r)$, the track of the towpreg almost always coincides with the nozzle path. The deviation is less than 10^{-4} mm.

2. When the turning angle is smaller, the error is larger and the required converging distance is longer.

When the angle $\phi = 90°$, this is described previously in the condition for the nozzle turning at a right angle. When the turn angle that the nozzle makes is less than $90°$,

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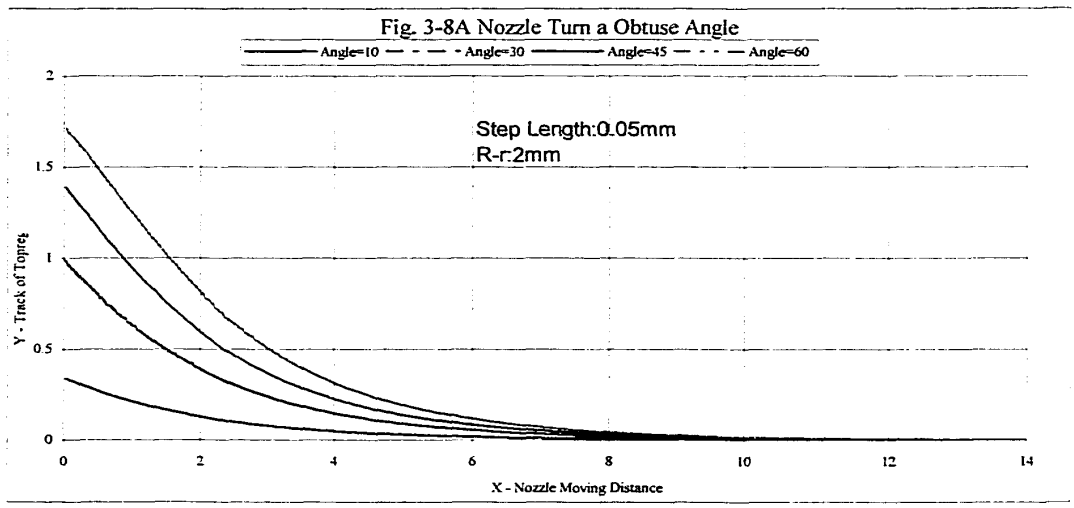

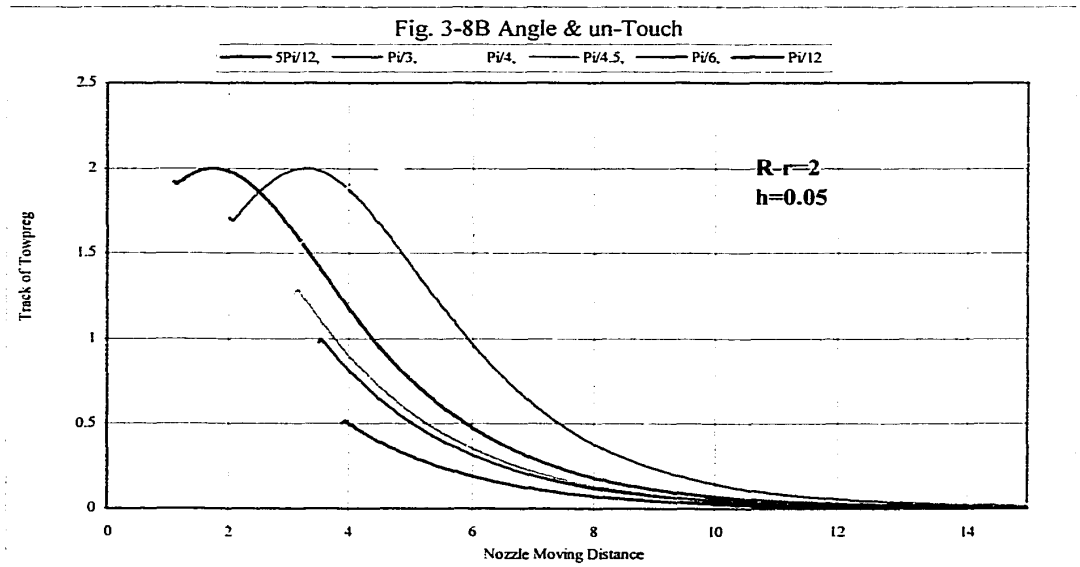

Figure 3-8. The toolpath has an obtuse angle turn.

Fig. 3-8A shows the towpreg track vs. different turned angles,
Fig. 3-8B shows the towpreg track vs. different value of *R-r*.

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such a situation is complicated and will be studied in the next section. The reason is because during a short distance, the nozzle could not touch the towpreg.

3-3-5 Analysis of Case 2: Acute Angle Turn

For convenience, suppose that the nozzle moves from right side A to the left direction B and then turns at an angle, ϕ *to* C. The angle ϕ between the toolpath AB and BC is less than 90°.

Referring to Figure 3-9A. Point B is regarded as the original position where the towpreg center is at O_0 (X_0, Y_0), and the center of the nozzle is at $B(0, 0)$. When the nozzle at point B changes direction, during a certain period of time the nozzle could neither control nor touch the towpreg again until it comes to B_1. After B_1, the effect of the nozzle on the moving behavior of the towpreg is as same as in the case of an obtuse angle that was analyzed above. Therefore B_1, the nozzle center, should be found under the condition of turning an acute angle first.

Assume that the towpreg is kept at the original position until is touched again and the distance of BB_1 is h. The original coordinate of the towpreg center is:

$$X_0 = R - r, \qquad Y_0 = 0 \qquad (3-13)$$

Inside the nozzle, an equation of a circle, which is through the center of the towpreg could be written as:

$$(H\cos\phi - x)^2 + (H\sin\phi - y)^2 = (R-r)^2 \qquad (3-14)$$

Substituting equation (3-13) into (3-14) to get equation (3-15):

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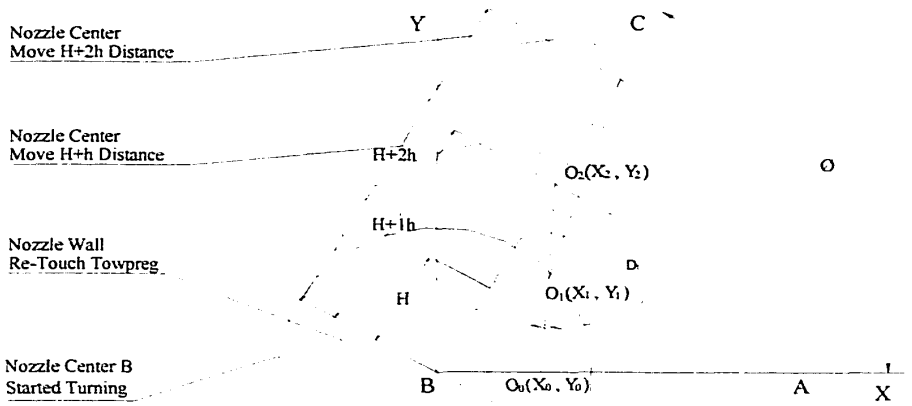

Fig. 3-9A.

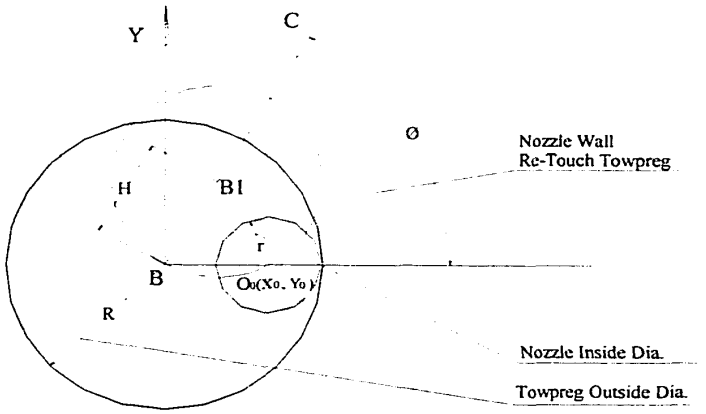

Fig. 3-9 B.

Fig. 3-9 Acute angle turn.

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$$H = 2(R-r)\cos\phi \qquad (3-15)$$

When the nozzle center exceed the point H, and moves one more step, the track of the towpreg center can be described as:

$$[(H+ih)\cdot\sin\phi - Y]^2 + [(H+ih)\cdot\cos\phi - Xi]^2 = (R-r)^2 \qquad (3-16)$$

$$\frac{Y_i - (H+ih)\sin\phi}{X_i - (H+ih)con\phi} = \frac{Y_{i-1} - (H+ih)\sin\phi}{X_{i-1} - (H+ih)con\phi} \qquad (3-17)$$

$$Ki = \frac{Y_{i-1} - (H+ih)\sin\phi}{X_{i-1} - (H+ih)\cos\phi} \qquad (3-18)$$

Where i = 1, 2 , 3.....

ϕ = turning angle,

h = one-step length of nozzle movement.

Substitution of i = 1, $X_0 = R\text{-}r$, $Y_0 = 0$, $H=2(R\text{-}r)\ Cos\phi$ into Equations (3-16), (3-17), (3-18) and simplify them to get X_1, K_1. Equation (3-19A) gives X_1:

$$K_1 = \frac{-(H+h)\sin\phi}{(R-r)-(H+h)\cos\phi} = -\frac{(R-r)\sin 2\phi + h\sin\phi}{(R-r)\cos 2\phi - h\cos\phi}$$

$$X_1 = (R-r)\cos 2\phi - h\cos\phi \pm \frac{R-r}{\sqrt{1+K_1^2}}$$

$$X_1 = (H+h)\cos\phi + \frac{R-r}{\sqrt{1+K1^2}} \qquad (3-19A)$$

Substitution of Equation (3-19A) into Equation (3-16) yields Y_1. Equation (3-19B) gives Y_1:

$$Y_1 = K_1\,[X_1 - (H+h)cos\phi] + (H+h)sin\phi \qquad (3\text{-}19B)$$

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If set $i = 2$, then substitute Equations (3-19A) and (3-19B) into Equations (3-16) and (3-17) to get X_2 and Y_2 values and the track of the towpreg could be obtained. Using the same principle with obtuse angles, Equations (3-10), (3-11) and (3-12) are employed again to yield the deviations for each point of the towpreg center. A calculation flow chart is depicted in Figure 3-6C. A toolpath for turning at an acute angle is illustrated in Figure 3-8B. These angle directions are different with the obtuse situations and need to be specified in the diagram.

When the nozzle moves along a new direction by a segment, it does not touch with the towpreg. The segment is longer with a smaller turn angle of turn. When the turn angle is zero degree, nozzle go back to the opposite direction, and the length of the segment that the towpreg could not be touched is *2(R-r)*.

§3-4 ERRORS IN DEPOSITING AN ARC-SHAPED SEGMENT

3-4-1 Evaluation of Errors in Depositing an Arc

When the nozzle moves along an arc, the route of the towpreg is different from the route analyzed in the previous section. In building a part using CLM, the arc is the most commonly deposited shape, so a study for the nozzle moves along an arc is emphasized in this section.

A deposition along an arc is schematically shown in Figure 3-10. All assumptions are same as made before.

The toolpath is an arc with radius L and center at point O with turning in the

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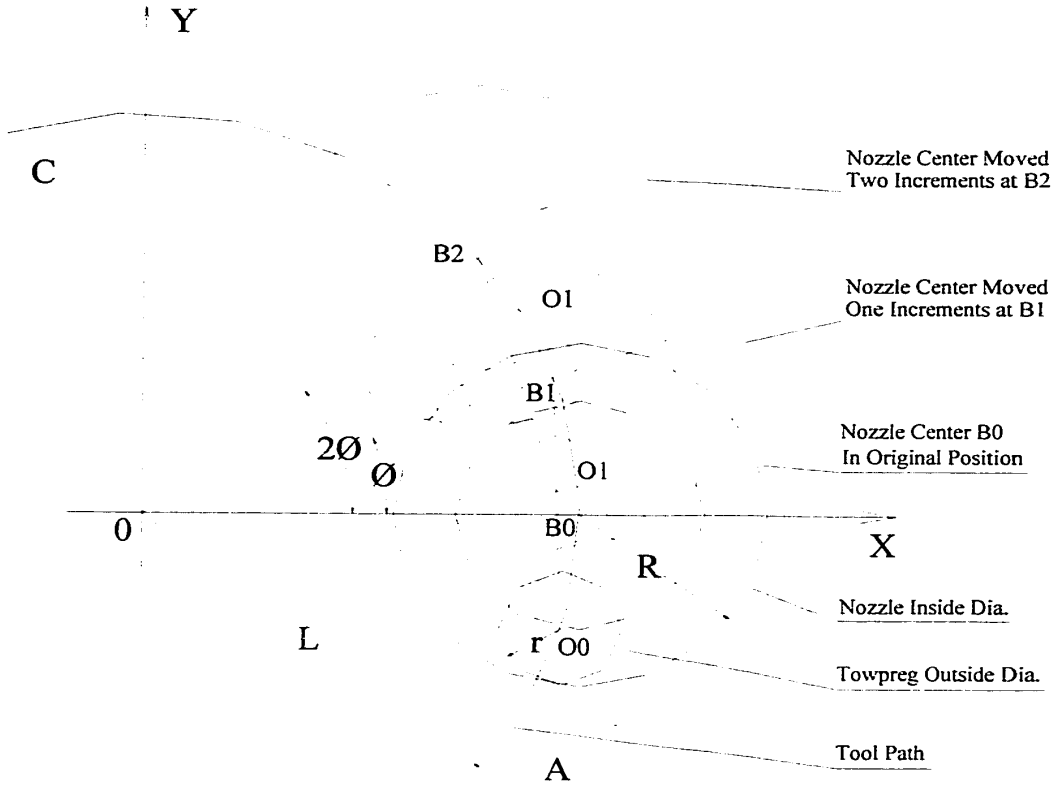

Fig. 3-10 Nozzle moving along an arc toolpath.

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anticlockwise direction. The original position of the towpreg center is on the arc toolpath and is placed at 0_0; the nozzle center is at B_0. Actually, throughout an analysis, no matter where the original position is when the towpreg moves an arc distance with the moving nozzle, the towpreg center could come to a balanced position. The balanced position is calculated in the following.

For convenience, assume that the radius L of the arc is a constant, which means that the nozzle moves along a circle. So, the coordinates of B_0 and O_0 could be written directly since for point O_0

$$X^2 + Y^2 = L^2$$

$$(X - L)^2 + Y^2 = (R - r)^2 \qquad (3-20)$$

And for point B_0: $X = L$, $Y = 0$.

where R = the bore radius of the nozzle,

r = the towpreg radius,

L = the toolpath radius.

From Equation (3-20), X_0 and Y_0 can be solved:

$$X_0 = \frac{2L^2 - (R-r)^2}{2L}$$

$$Y_0 = \frac{R-r}{2L}\sqrt{4L^2 - (R-r)^2}$$

Here, let the angle ϕ be used as an increment for the nozzle moving along the toolpath, because this angle ϕ can be conveniently observed. In the software development, a length of the arc should be used as the increment. When the nozzle is moved along the arc to point B_1, based on the original position O_0 (X_0, Y_0) and the first

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increment turning angle step ϕ, the center position of the towpreg could be point O_1.

$$(X - L\cos\phi)^2 + (Y - L\sin\phi)^2 = (R - r)^2$$

$$\frac{Y - Y_0}{X - X_0} = \frac{L\sin\phi - Y_0}{L\cos\phi - X_0} \tag{3-21}$$

where ϕ = increment angle for nozzle moving each step.

From equation (3-21) we can get the coordinates of point O_1:

$$X_1 = \frac{C_1K_1 + L\cos\phi}{1 + K_1^2} \pm \sqrt{\left(\frac{C_1K_1 + L\cos\phi}{1 + K_1^2}\right)^2 - \frac{C^2\cos^2\phi + C_1^2 - (R - r)^2}{1 + K_1^2}}$$

$$Y_1 = K_1(X_1 - X_0) + Y_0 \tag{3-22}$$

where:

$$K_1 = \frac{L\sin\phi - Y_0}{L\cos\phi - X_0}$$

$$C_1 = K_1X_0 + L\sin\phi - Y_0$$

When the nozzle is moved along the circle with any angle $i\phi$, the position of the Towpreg center is:

$$Xi = \frac{CiKi + L\cos i\phi}{1 + k^2i} \pm \sqrt{\left(\frac{CiKi + L\cos i\phi}{1 + K_i^2}\right)^2 - \frac{L^2\cos^2(i\phi) + C^2i + (R - r)^2}{1 + K_i^2}}$$

$$Yi = Ki(Xi - Xi - 1) + Yi - 1 \tag{3-23}$$

where:

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$$Ki = \frac{L\sin(i\phi) - Yi - 1}{L\cos(i\phi) - Xi - 1}$$

$$Ci = KiX_{i-1} + L\sin(i\phi) - Yi - 1$$

$i = 2, 3, 4, \ldots$

The deviation, a distance from the towpreg center point O_i (Xi, Yi) to the nozzle toolpath, is:

$$\Delta L = L - \sqrt{X_i^2 + Y_i^2} \qquad (3-24)$$

A calculation flow chart is given in Figure 3-6D and the results are charted in Figure 3-11A, B, and C. From these charts, a deposition error is obtained. When the nozzle is moved by a certain distance, the towpreg center reaches a balanced track, which is like another circle and its radius being smaller than the radius of toolpath. This is an important result, which should be considered during software development.

Figure 3-11A shows the errors vs. ϕ, the increment length.

Where: R-r = *2mm*,

L = *10mm*,

l = Arc length is conversed from ϕ with,

$$l = \frac{\phi\pi}{180}L$$

When ϕ = *1/5°, 1/10°, 1/100°* and *1/1000°*,

then l = *0.03491, 0.01745, 0.00171* and *0.00017*, respectively.

In Fig 3-11A, we could find that when step length l is smaller than *0.00171* (*1/100°*), the variation in error of the towpreg is not large, and the two curved lines of step length

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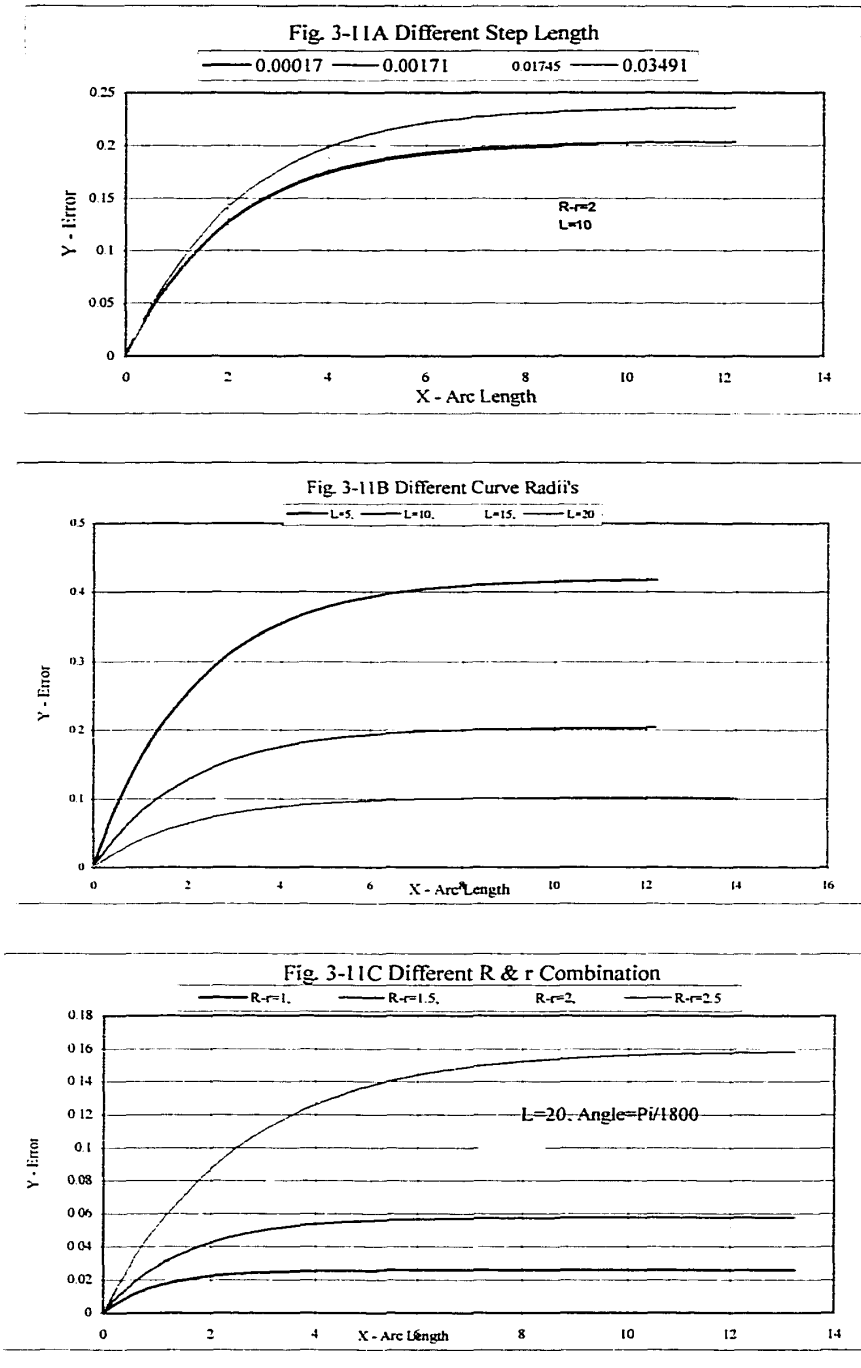

Figure 3-11. Calculation results for an arc toolpath.

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*0.01°*and *0.001°*almost coincide.

Fig 3-11B shows the regularity with which the error changes as the changing radius of the toolpath varied. When the toolpath radius is small the error is large.

Fig 3-11C shows another effect that error changes with different *R-r* value. Then the larger the difference of *R-r* value is, the larger the error is.

3-4-2 Sources and Factors that Affect the Errors

In §3-3 and §3-4, the deposition errors induced in certain situations have been discussed and calculated. The original error sources and their effects are summarized in the following:

1. A toolpath is made up of a group of straight-line segments, when the nozzle moves along one of the lines and turns to move along another line, the error could be induced due to a difference in *R-r*. No matter how many degrees the nozzle has turned, the track of the towpreg could converge quickly over to the toolpath. Finally, the deviation is given by *R-r* only.

2. From point 1 it follows that the simulation step length does not affect the convergence result but the convergence shape. When the step length is smaller than an appointed value, (i.e. < 0.05), the calculation result is not much different.

3. When a toolpath is an arc, the center of the towpreg could converge very fast on another circle at a balanced position. The radius of this circle is smaller than the radius of toolpath. The difference between the radius of

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the balanced circle and the radius of the toolpath is determined by the *R-r* value, the radius of the arc toolpath.

4. From conclusion 3 it follows that, the simulation step length affects the balanced position. But, when the arc length is less than *0.00171*, the final result is not much different.

5. These errors, cited in Conclusion one and Conclusion three are small compared with toolpath dimension and will converged to zero or to a certain value quickly.

6. Because the method of depositing is unique, the mechanics model that describes this process is also unique. It was assumed that at any deposition point, the towpreg is anchored to the previous layer immediately, and the previous point and the nozzle moving direction determine the position of the next point. Hence, the equations, which describe the process, are the dispersion equations. If the step length is longer, realistic condition could not be simulated.

§3-5 DESIGN AND PREDICTION OF COMPOSITE MECHANICAL PROPERTIES PRODUCED BY CLM

A component made from a composite material normally has excellent mechanical properties [58-60]. Many composite materials scientists have experimentally studied mechanical properties and failure mechanism of various composite structures. Other have developed micro-mechanics and macro-mechanics models that are capable of predicting

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mechanical properties of a composite based on the properties, proportions, and orientations of its constituent phases. With the great computing capability of a modern computer, many complicated composite mechanics problems can be readily solved.

The forming flexibility of RP technology gives a possible way to build a structure with desired mechanical properties. This is another advantage for CLM technology.

Fiber reinforced composite materials are a kind of orthotropic materials. For example, a fiber-reinforced composite laminate structure is shown in Figure 3-12. A symmetric structure is arranged and shown in Figure 3-12A. When the laminates are over-layered and pressed together to form a panel, the panel will be a cross plied quasi-isotropic laminate .

This kind of structure could not be used as a part directly. But a part that is shown in Figure 3-12C is cut off from the panel and is indicated by the dashed line in Figure 3-12B. The part will process a quasi-isotropic character. Several methods to make the part with desired mechanical properties will be introduced.

3-5-1 Arranging Layer Directions with LOM

A good method to finish the cross permutation between different layers is to use LOM technology for forming a 3-D composite part. RPT has another important feature, which is the ability to regulate the mechanical properties during the forming process.
An improved LOM (Laminate Object Manufacturing) technology device is illustrated in Figure 3-13. The basic forming principle and structure are similar to traditional LOM. The differences are as follows:

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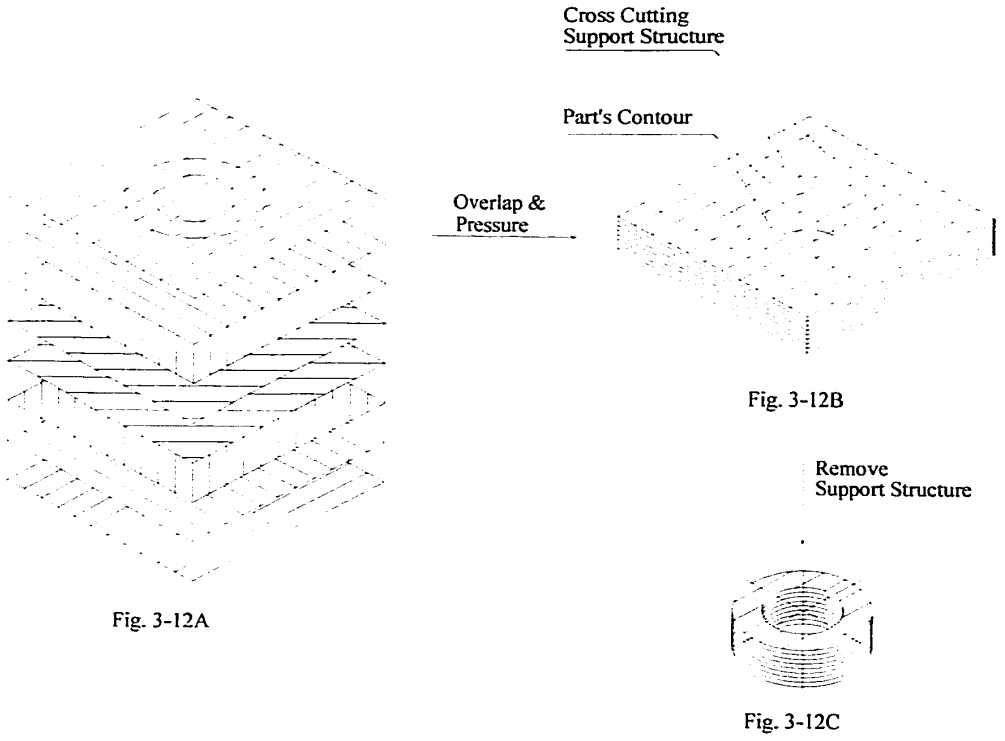

Fig. 3-12A

Fig. 3-12B

Fig. 3-12C

Fig. 3-12 Cross plied quasi-isotropic part.

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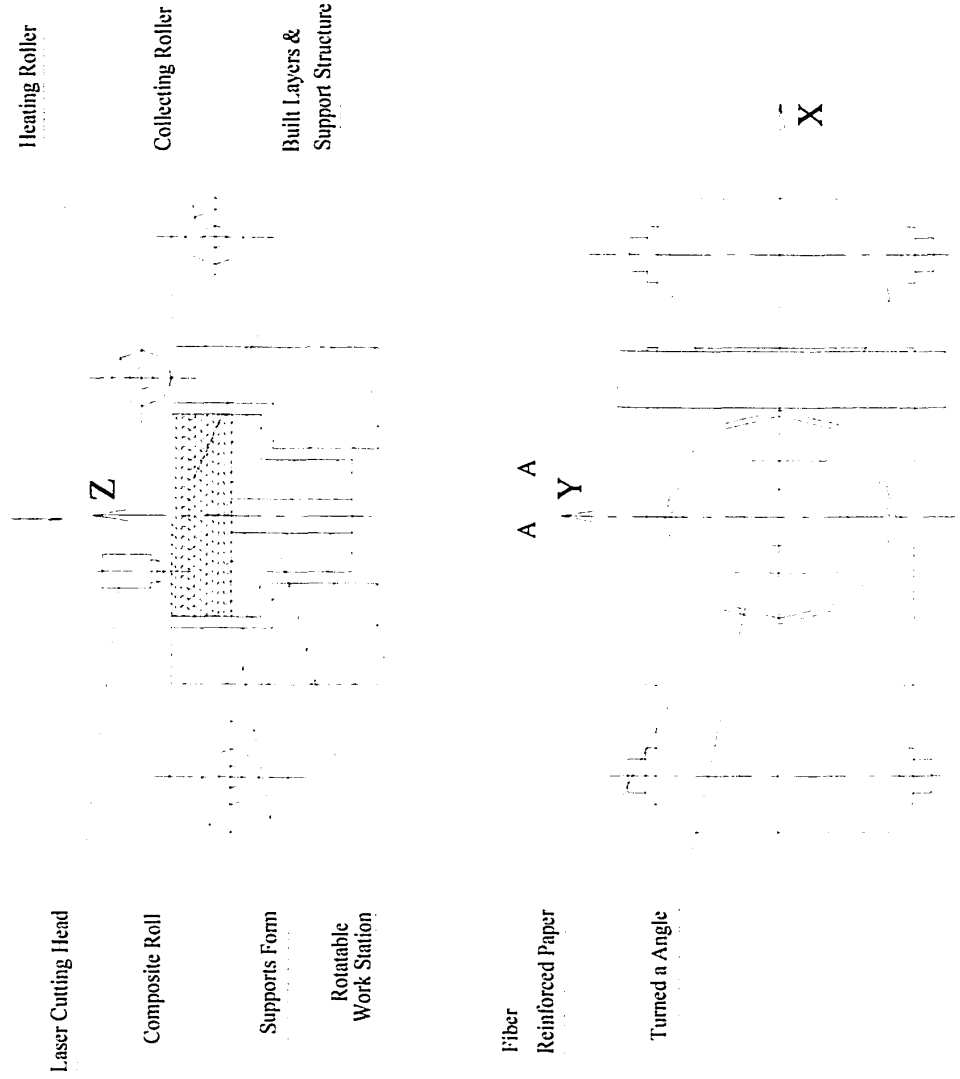

Figure 3-13 Composite forming process based on the LOM.

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1. The material that is used is not paper with glue on its back, but is a kind of material that has a thickness similar to that of paper, for instance, a continuous fiber reinforced thermoplastic matrix where fiber direction is parallel with the feeding direction. Such a material could be made easily with a low cost.

2. Another difference is the working platform. In the common LOM technology, when a layer is formed at each time, the working platform is moved down one layer thickness. Then, a new layer could be carried in. In the improved LOM system, the working platform is not only moved up and/or down, but also could be rotated around the Z-axes to arrange the composite with a cross direction. With such a method, a part as shown in Figure 3-12C could be readily formed.

3. Software has to be modified: A computer-controlled laser cutting head is employed to cut the contour of a cross section for each layer. When the working platform is rotated at an angle, a new toolpath should be rotated at the same angle to match the required contour and make the required support structure.

4. The heating device is different. A heating roller or a heating plate is used to melt the thermoplastic materials and make the current layer stick to the pervious layer.

3-5-2 In Layer Mechanical Properties

On the improved LOM technology the orientation angle of all the reinforcing fibers in a layer is uniform throughout the layer. In contrast, in the present CLM technology, the

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fiber orientation can vary from spot to spot in a layer and can vary from one layer to another. This feature makes it possible to tailor-make the mechanical properties, essentially point by point and layer by layer. For example, two laminates that are subjected to the same force condition but are arranged in different fiber orientations are shown in Figure 3-14.

A stress field distribution exerted on the laminate is shown in Figure 3-14A. A stress concentration could be induced around a small hole as indicated with the dashed line in Figure 3-14A. However, along the Y-axes direction, the load-carrying capability is limited. Another fiber orientation arrangement style is shown in Figure 3-14B. A fiber reinforced towpreg may be deposited around the hole by CLM to reinforce the strength of the laminate in the vicinity of the hole. Another example is depicted in Figure 3-15, which shows an arbitrary plane of a component, along with its shear stress condition and fiber orientations. It is obvious that the stress concentrations are present in at areas A, B, and C, and a crack could be readily initiated at these areas. In contrast, if the towpreg orientation is arranged like that shown Figure 3-15B, this plane could exhibit a much higher strength.

The above analysis is only qualitative in nature. For a complex-shaped structure, which is loaded even with a simple force (i.e. tensile or compressive force) only, the stress condition could be difficult to determine for the whole structure and for individual layers. This is a challenging research direction in the future for the CLM technology.

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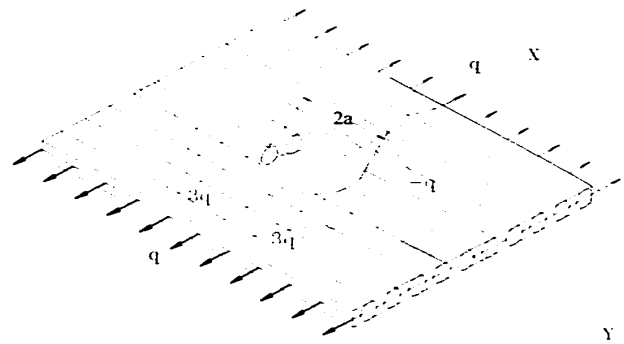

Fig. 3-14A

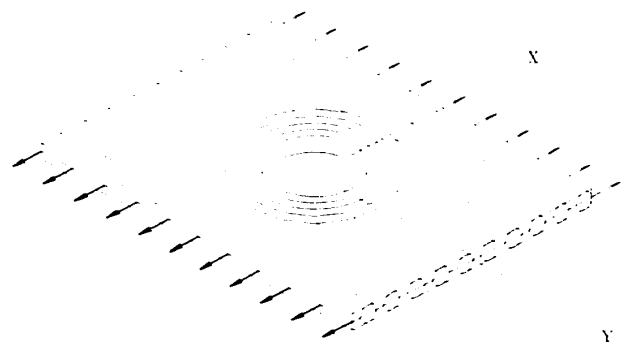

Fig. 3-14B

Fig. 3-14 In layer mechanical properties tailor.

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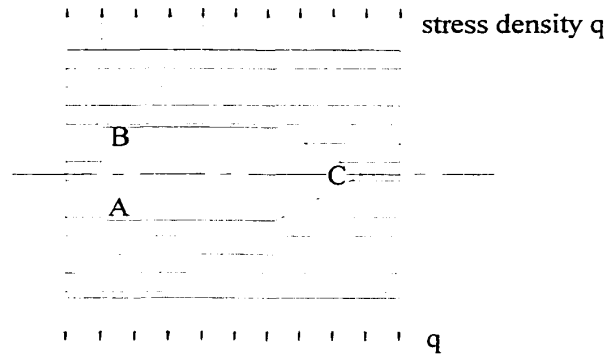

Fig. 3-15A

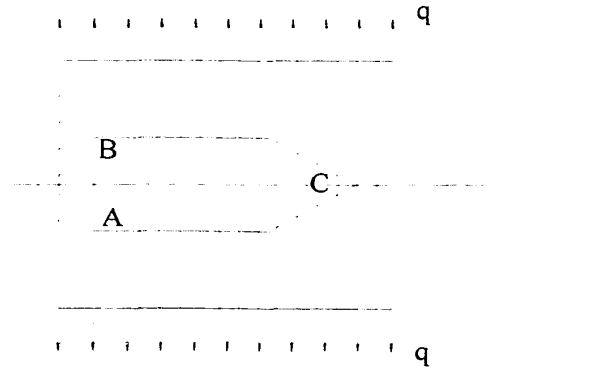

Fig. 3-15B

Figure 3-15 Toolpath orientation arrangement.

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§3-6 SOFTWARE DEVELOPMENT STRATEGY

In the current software market, many specialized software packages for RPT development are available. These software packages are capable of automatically slicing a solid model to generate contours for each layer from a 3-D CAD file such as in STL file format. Then, according to the requirement for a specific system, the contours are converted to a programmed signal to control the toolpath. The toolpath signals are used to drive the work platform to move relative to a deposition head.

This software that is developed for several current kinds of RP technologies such as SLA, FDM, LOM, etc, is not suitable for CLM. Hence, new software needs to be developed to meet the specific requirements of CLM. Only the requirements for writing the software will be discussed here. The software development details for CML are introduced in other articles.

3-6-1 Software Development Considerations

The CLM forming principle and concept design have been studied in Chapter 2. Also the errors, depositing deviation, and mechanical properties have been analyzed in the previous section of this chapter. All these could be considered as the foundation requirement for the software development. There are several unique features associated with the deposition of continuous fiber composites:

1. Cutting off the towpreg: the function of cutting is important in the CLM system, and the function of the cutting device should be a simple and reliable design.

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A monitoring sensor should be used to ensure that cutting is finished completely. The function could be written simply with the CNC G and M code to implement the cutting action.

2. After an intermittent cut-off, a towpreg must be re-attached to a spot in a different region of a layer or in a different layers, and a dwell time may be required to accomplish this function. The nozzle could stop on an initial point for 1/4-1/2 seconds. In practice the dwell time could be obtained by an experiment.

3. Optimization of cutting times: With the cutting times being reduced not only the complete forming cycle time could be reduced, but also the part forming precision could be improved. For example, three different toolpath designs for a layer of a part are shown in Figure 3-16. The toolpath direction design shown in Figure 3-16A requires the longest cutting times. A second longest cutting time is needed in Figure 3-16B, and the shortest cutting times are shown in Figure 3-16C. But the degree of difficulty in automatically generating a toolpath logic is just in the opposite order; in Figure 3-6A, the toolpath could be generated most easily.

4. Mechanics considerations: The software could be developed to generate a toolpath with desired mechanical properties, as suggested in the previous subsection.

5. To makes up the errors: The software could compensate for the errors that could occur in the process as analyzed in §3-3 and §3-4.

To generate a toolpath, a proper towpreg orientation could be used for a given layer for the purpose of optimizing the toolpath orientation and to minimize cutting times, as discussed in the following:

The required minimum cutting times for each layer and the needed fiber

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orientation with an angle for two adjoining layers could impose conflicting constraints on the toolpath design. In any structure, two adjacent layers almost have the same geometric shape. If one of the layers is optimized with a minimum cutting time but for another layer the toolpath could be turned at an angle in order to have proper mechanical properties. Under this condition, the cutting times for this second layer could not be minimized. To overcome the contradiction, the following strategy is suggested,

1. The mechanical property is the first priority consideration. Parts having excellent mechanical properties are one important reason to develop the CLM technology. The mechanical property is sensitive to the towpreg orientation. When a layer toolpath is created, the towpreg in the following layer should be first turned by an angle to rearrange the current layer direction.

2. Interlayer direction is considered first. The direction of the towpreg in a layer is considered second. When the towpreg direction is determined for a certain layer, according to the results analyzed in a previous section, a partial reinforcing orientation arrangement should be considered to protect the laminate against stress concentration.

3-6-2 A Method to Optimize the in-Layer Toolpath

Once a main orientation is determined for each layer, the partial reinforcing effect is then considered. If a structure is complicated, its cross-section should be complex also. To automatically arrange an in-plane towpreg orientation for each layer and to minimize cutting times through a general rule is still a challenge. Several methods have been studied, one of which, the region partition method, is introduced here.

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A cross-section layer of a part is shown in Figure 3-17. A rectangular hole and a groove hole do not require any deposit of materials on it. A towpreg depositing direction is arranged parallel to the X-axis (See Figure 3-17A). When deposition proceeds near the rectangular hole area, the deposition order could be from point *A* to point *B*. It could be stopped during the towpreg being cut at point *B*. After that, towpreg could be jumped to and restarted at point *C* and then continue to processed until point *D*. Such a start – stop-cutting- restart procedure could occur many times in the rectangular slide area, and the same procedure will be repeated in the groove area.

A new depositing arrangement is shown in Figure 3-17B. The layer is divided into *6* solid regions. The dashed lines are used to indicate the boundaries and *1, 2, 3, 4, 5, 6* are assigned for each region, respectively. In each region, the deposition could be finished at one time by starting and stopping with one towpreg. There are six total starting and stopping times.

A direction of deposition being parallel with the Y-axis is shown in Figure 3-18A. According to the same principle, the layer could be divided into six regions by the straight lines, which are parallel to the X-axis. If the deposition direction is needed to be turned 45° degrees relative to the X-axis, another 6 regions are divided. The case is shown in Figure 3-18B.

Figures 3-17B, 3-18A and 3-18B, serve to illustrate the region-dividing method. This method can be carried out by a computer automatically. Figure 3-18C shows an optimized region dividing method, and the layer is divided into only two regions. Therefore, a deposition process should need only two starting and stopping times. But the dividing logic is complicated.

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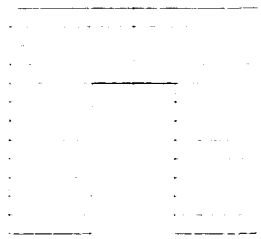

Fig. 3-16A

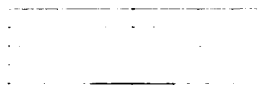

Fig. 3-16B

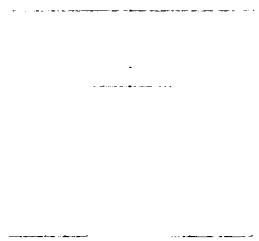

Fig. 3-16C

Figure 3-16 Different toolpath design.

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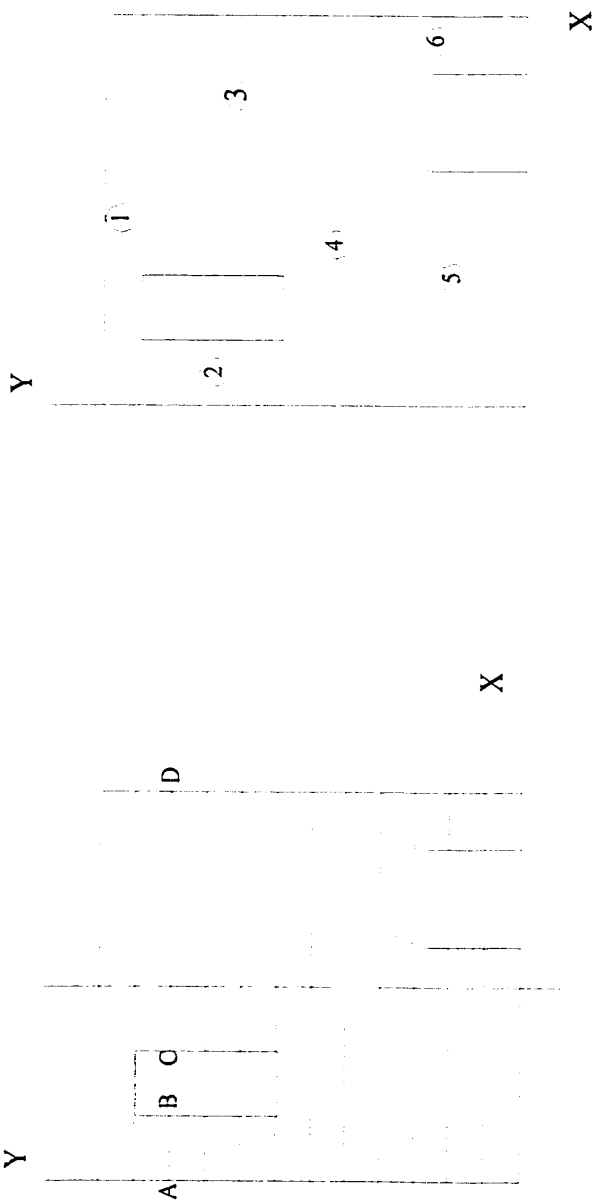

Fig. 3-17A

Fig. 3-17B

Fig. 3-17 To divide the deposition region.

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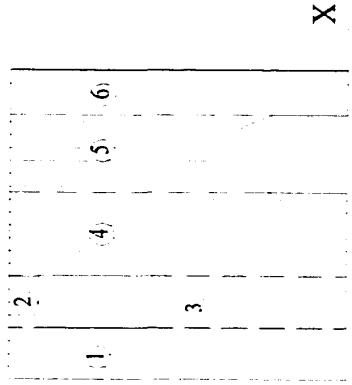

Fig. 3-18A Perpendicular to x-axis.

Fig. 3-18B An angle with respect to x-axis.

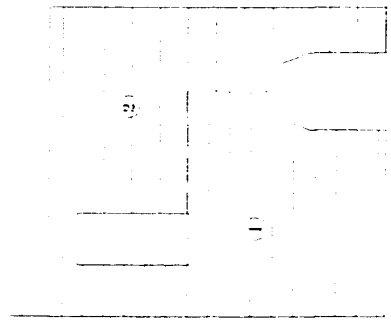

Fig. 3-18C Optimized dividing ragen.

Fig.3-18 Region dividing methods.

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§3-7 CHAPTER CONCLUSIONS

1. The error sources, values, and governing factors in the CLM Technology have been analyzed and evaluated.

2. The method for in-priori design of mechanical properties and the method for reducing cutting time are introduced.

3. These results could be used in developing the software for CLM.

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CHAPTER 4 THE SIMULATION OF THE CLM PROCESS

§4-1 INTRODUCTION

The fundamental theory for the CLM forming process has been studied in Chapter 2. The two forming strategies and related concept designs were selected because these forming methods have the greatest potential. In Chapter 3, the forming precision has been calculated to help on the design of a toolpath. In this chapter, the two forming methods will be numerically simulated and analyzed.

The reasons for simulating the CLM processes are:

1. The modeling of the process could lead to a betters understanding of the part forming theory.
2. The result of a simulation study could help confirm the feasibility of a forming method.
3. Proper process parameters could be found through a simulation study such as, the best temperature and the maximum forming speed.
4. The shape, dimension and the suitable position of a part could be optimized.

Computer simulation and optimization have been developed as essential tools in the theoretical research and for real applications. Simulation and optimization have been commercialized for the composite industry, such as for the optimization of composite

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structures, simulation of resin transfer molding, modeling of textiles, damage analysis etc. Computer software has played a key role in the development of the RP technology as a field. Specific software specifically for the CLM technology has to be developed for generating the toolpath and controlling the system. But, a process simulation by using a computer is still a challenging task. In this chapter, two models will be built and studied based on the existing CLM processes. These forming processes are complicated and are influenced by many factors. Therefore, several assumptions will be made to simplify the problem. These simulation approaches, although highly simplified, do provide deep insight into the CLM processes.

§4-2 SIMULATION OF THE SELF-ANCHORING PROCESS

4-2-1. Basic Theories

The self-anchoring method, a Passive Materials Supply Method, has been demonstrated to be an effective process for CLM. Its features and forming precision have been studied in the preceding chapters. How dose self-anchoring, basic forming mechanisms work? This will be investigated in more detail.

In the self-anchoring forming method, a towpreg made of a thermoplastic matrix is re-melted and deposited onto an object; the towpreg could be solidified to a certain degree and glued to a corresponding point of the base or the previous layer immediately to form a point of anchoring. Then, with the nozzle being moved forward, the anchored point of towpreg servers as a stationary point to pull the towpreg out of the nozzle. Thus,

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more towpreg could be deposited into the object. The sequence "towpreg deposited□ solidified □ anchored□ pulled out□ deposited again" is the basic procedural steps of the self-anchoring process, which is also called *Deposited and Anchored At Once* forming principle. The forming mechanism for self-anchoring is illustrated in Figure 4-1. Figure 4-1A shows an overall profile of the forming process; Figure 4-1B shows that the towpreg is in the deposited condition.

It is expected that these steps can occur immediately, continuously, repeatedly and simultaneously. It takes some time for any step to be accomplished. But, a time for each step should be within a reasonable range, so as a main task for simulation, the range of time would be found.

4-2-2 Some Preliminary Concepts about Thought on the CLM Process

A stepper motor drives a delivery roller to supply the towpreg, where the later stays free of tensile force and the towpreg inside the heating tube is tensile force free (see the Figure 4-1, the roller is not shown in this sketch). The friction force between the towpreg and the nozzle is neglected. The force acting on anchored points lies on the nozzle-moving plane. In order to simulate and optimize the self-anchoring process, the requirements and restrictions on this process should be considered first.

1. Part Quality Considerations:

   a. Errors induced by the different diameters between the towpreg and the bore of the nozzle have been analyzed in Chapter 3, and there errors could

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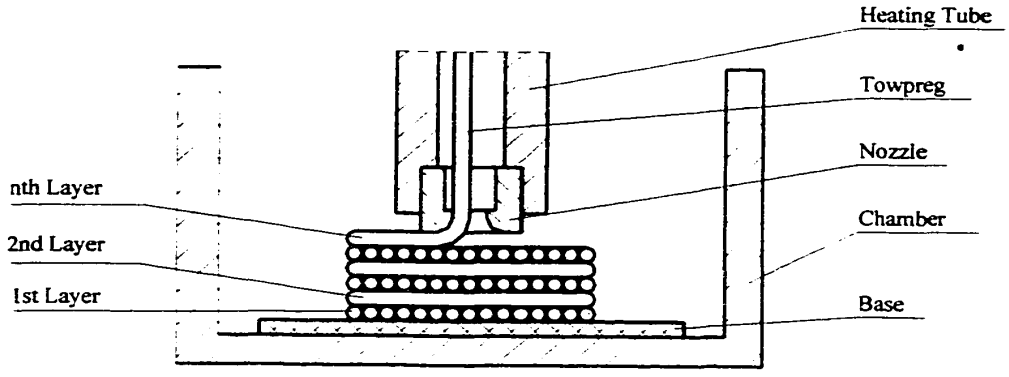

Fig. 4-1A

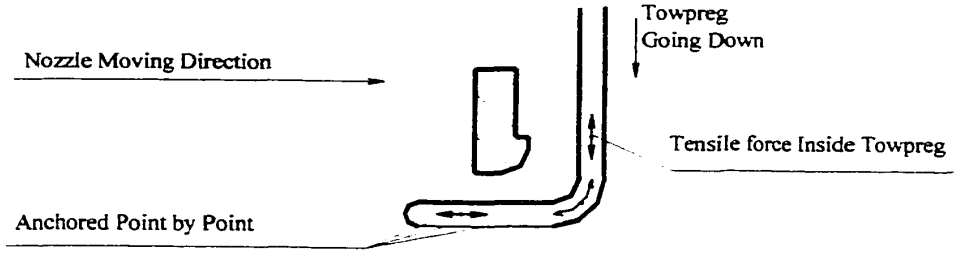

Fig. 4-1B

Fig. 4-1 Forming mechanism of the self- anchoring method.

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be eliminated or compensated for by a modification to the software.

b. A toolpath error could be generated if an anchoring point is not formed properly. An arc toolpath is shown in Figure 4-2, and the nozzle is programmed to move along the arc toolpath from point *A* to points *B*, *C*, and *D*. Ideally, the towpreg is firmly anchored at point *A*. When the nozzle arrives at point B, the towpreg is supposed to be deposited and anchored at once to form a new anchoring point at *B*. Then the nozzle is moved to point *C* and so on to deposit the towpreg be following the path indicated with the broken line $ABCDE\cdots$. However if the towpreg is not solidified to a certain degree and is not anchored completely at point *B*, the partially anchored point could not be serve as a stationary point to pull the towpreg out of the nozzle. With the nozzle being moved continuously to point *C*, a point in the towpreg that was supposed to be anchored at point *B* skids to B_1 and is anchored at *B1* instead. For the same reason, a point in the towpreg expected to be deposited at *C* is actually anchored at point C_1. Therefore, the real formed line $AB_1C_1D_1$ is deviated from the theoretical line *ABCD*.

The extent of this error depends on the forming condition, particularly the forming speed relative to the depositing speed or the nozzle moving speed. For example, in Figure 4-2, during the same period, as mentioned in the above paragraph, but with a higher nozzle moving speed, then when the nozzle arrived at point *E* instead of at point *C*, the towpreg is slid to B_2 instead of B_1. Therefore, the error is larger than the

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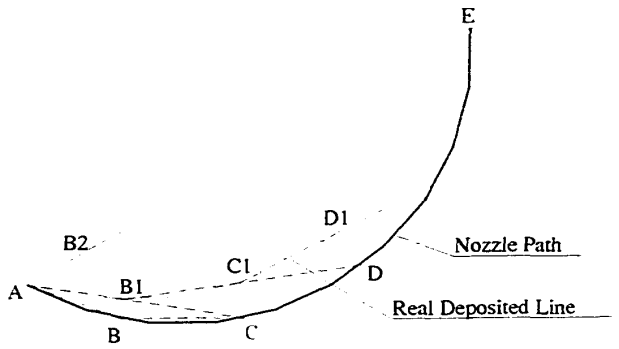

Fig. 4-2 An error is generated by the mechanism of the forming process.

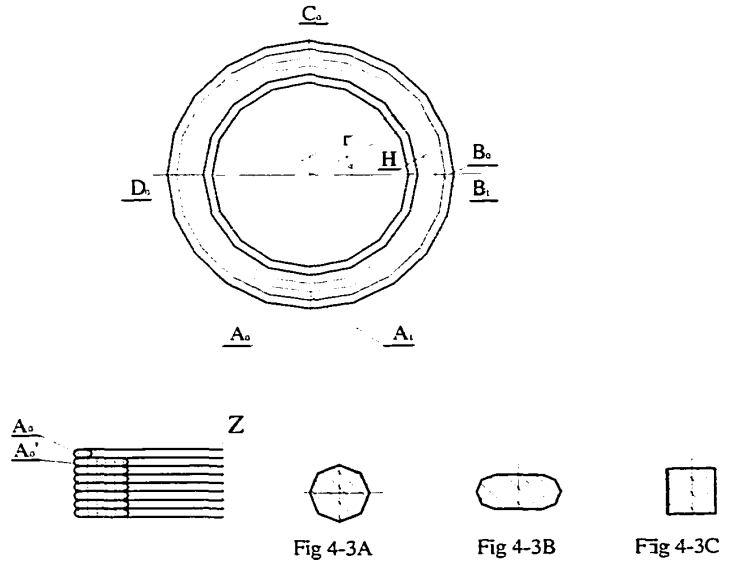

Fig. 4-3 Different boundary conditions for the thermal field.

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case of deposition at a lower speed. In fact, in this situation the deposition is regarded as failure.

2. Speed considerations: as a matter of fact, the forming speed is relatively slow for most RPT processes. In the self-anchoring process, the forming quality is directly related to the forming speed, as has been analyzed in the preceding paragraph. However, the forming speed is limited by the present forming mechanism, and other influencing factors should be considered:

   a. The machine capability: any CNC machine has the maximum X-Y and/or Z interpolation speed, which is also the maximum depositing or scanning speed. For the Mini-Mill machine that is employed for the present CLM process, the maximum X-Y interpolation speed (G01, G02, G03 etc) is *6350 mm/min.*

   b. Towpreg melting speed: the self-anchoring process is a two-step method. In the first step, the towpreg is fabricated with the continuous fiber being impregnated with a thermoplastic material. During the deposition step, the towpreg is re-melted with a heating tube. The heating tube cannot be very long. If the towpreg is heated by radiation heating, it may take sometime for the towpreg to go from room temperature T_R to the melted point T_M. Thus, the delivery speed for the melted towpreg is restricted by:

$$V_m = \frac{L_t}{t_h} \qquad (4-1)$$

where V_m = Delivery speed of the melted towpreg, mm/s

L_t = Length of the heating tube, mm,

t_h = the time needed to heat the towpreg from T_R to T_M, s.

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If $L_t = 150$ mm, $t_h = 30$ second, then $V_m = 5$ mm/s, this means that the forming speed could not exceed 5 mm per second. Optimizing the tube structure and/or raising the heating temperature of the tube could somewhat relax this restriction. In the following process simulation, the towpreg melting speed in the tube is not considered, but one must bear in mind that the melting speed could be a constraint.

According to the above analysis, the major concern is the forming speed. The simulation for the self-anchoring process is related to the forming speed.

4-2-3 Transformations and Simplification of the Problem

To investigate the *Deposited and Anchored At Once* forming principle, and optimize forming parameters, the forming speed is the priority consideration. But this problem may change into a research of a temperature field for the forming process because in the self-anchoring process, the durations of time required of solidification and anchoring are directly related to temperature changes.

As Figure 4-1 shows, the depositing process is done in a chamber that has closed surroundings and opened at the top. The interior of the chamber is at a constant temperature, which is a very important parameter. During the forming process, the molten towpreg is deposited line by line to form a layer, and layer by layer to build a whole part or structure. The temperature of the added new line or layer is higher than the temperature of the previous line or layer. The newly added line or layer is regarded as a thermal source, which can heat the previous layer. But after a short period of time, the

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chamber temperature and the surrounding temperature are in equilibrium with the temperature of the formed layers or lines.

The temperature inside a chamber could not be set too high because it is necessary to increase the solidification speed of the towpreg in order to anchor it into a previous layer as soon as possible. However, the temperature inside the chamber could not be set too low either. If the temperature is too low and the cross-section of a part is too large, then when a new segment of the towpreg is added onto the top of the object, the heat quantity of the towpreg may not be sufficient to melt the corresponding point of the previous layer, which is already in equilibrium with the low surrounding temperature. As a result, the newly added towpreg could not be glued effectively to the previous layer, and the formed part will have delamination defects.

Not only the temperature field of the chamber but also the sign and shape of the part affect the solidifying speed of the towpreg. The result is shown in Figure 4-3.

For example, in a layer, the tool path is from $A_0 \rightarrow B_0 \rightarrow C_0 \rightarrow D_0$ and then to $A_1 \rightarrow B_1 \ldots$. For the different points, their thermal boundary conditions are different, and the temperature of each point could not be the same. The results analyzed above show that the effects of different temperatures on the forming speed are much different. If a part is significantly larger and more complicated, and has a larger cross section than the others, then it should take more time to finish one layer. When a previous layer has been built and a new layer has started to form, the starting point A_0 in the new layer is supposed to be anchored to a corresponding point A_0', which is in the previous layer (Figure 4-3). Because the time is too long, the temperature of A_0' is much different from that of A_0. Perhaps the temperature of point A_0' has already reached the surrounding

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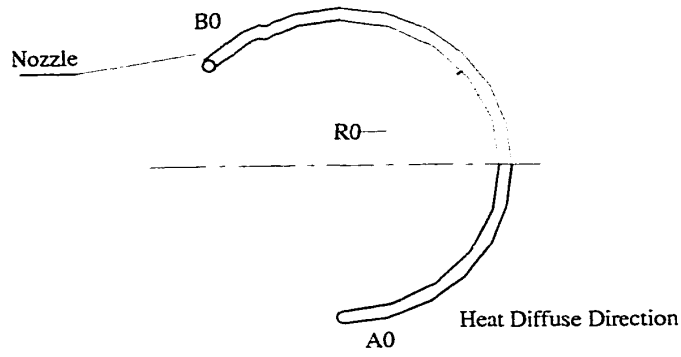

Fig. 4-4A Thermal transfer direction in a single towpreg line.

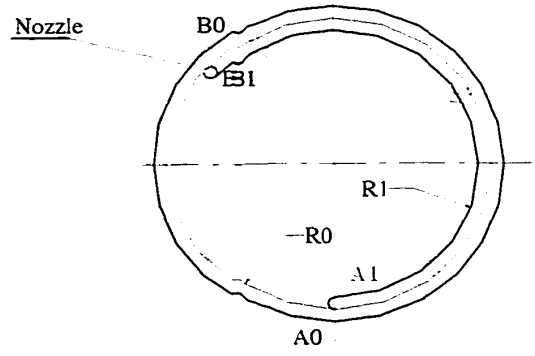

Fig. 4-4B Thermal transfer direction in the multiple line.

Fig. 4-4 Thermal transfer direction.

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temperature, and point A_0 could not re-melt point A_0'. As a result, it could not be anchored to the point A_0'.

If a layer area is significantly smaller than other layer, then it is possible that the temperature of the starting point of a layer has not reached the equilibrium point before the nozzle returns to this point for starting to build the next layer. In this case, one may have an unsuccessful anchoring.

If the cross-section of a structure is more complex, the condition for heat dissipation and/or absorption may vary from point to point, such as point B_0 and point H in Figure 4-3. The cross-sectional shape of a part or structure varies from part to part; even in a particular structure, all cross-sections are not the same. But, it is practically impossible to adjust the chamber temperature and nozzle moving speed according to the different cross-section or different part shape. Therefore, it is necessary to make some assumption in order to simplify the problem:

1. The temperature is the same in each built layer and is different between different layers.

2. In a currently being built layer, the temperature is the same in each deposited line and is different between different lines.

§4-3 BASICS OF SIMULATION

4-3-1 Thermal Conduction Equations

The Fourier differentiation equation, a general heat transfer equation is given by [61]:

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$$\rho(T)c(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}(k_x\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(k_y\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(k_z\frac{\partial T}{\partial z})+\dot{Q} \qquad (4-2)$$

where $\dot{Q}$= the internal thermal sources density, $\rho(T)$, $c(T)$ are the density and specific heat of a material, respectively, k_x, k_y, and k_z are the coefficient of thermal conductivity along the X, Y, Z, directions, respectively. If the material is isotopic, k_x= k_y= k_z= k.

Equation (4-2) is a thermal balance equation, in which the left hand side is the needed heat quantity for a unit temperature increment. On the right hand side, the first, second and third terms indicate the inputted heat quantity from the *X*, *Y*, and *Z* directions, respectively, and the last term is the heat quantity generated by the internal thermal source. If only the 2-D problem is considered, and assuming no inside thermal source and material being isotropic, then Equation (4-2) can be simplified to

$$\rho\cdot c\frac{\partial T}{\partial t}=k(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}) \qquad (4-3)$$

The equation governs the heat transfer behavior of a system. Further, the thermal field inside the material is determined by a specific boundary condition for a given situation.

$$T(x,y,z,t)_{t=0}=T_0(x,y,z) \qquad (4-4)$$

There are four types of boundary conditions:

1. The first boundary condition is that the temperature on surface S_1 is already known. The condition is:

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$$T(x, y, z, t) = T_0(x, y, z, t) \qquad (4-5)$$

2. The second boundary condition is the density of a thermal flow on surface S_2:

$$k\frac{\partial T}{\partial n} = -q \qquad (4-6)$$

where $\frac{\partial T}{\partial n}$ is a directional derivative of a temperature, T, along the normal line direction.

q is the density of thermal flow.

3. The third boundary condition:

a. S_3 is a convection thermal exchange boundary:

$$k\frac{\partial T}{\partial n} = -\alpha(T - T_0) \qquad (4-7)$$

where a is the thermal exchange coefficient, T_0 is the outside temperature.

b. S_4 is a radiating thermal exchange surface:

$$k\frac{\partial T}{\partial n} = -\sigma\varepsilon F(T^4 - T_\infty^4) \qquad (4-8)$$

where σ is the Boltzmann constant, 1.380662×10^{-23} J/K, ε is the radiation ratio (thermal emissive), F is a shape coefficient, and T_∞ is the temperature of the thermal radiating source.

4. The fourth boundary condition is that a surface S_5 is a heat insulation boundary:

$$\frac{\partial T}{\partial n} = 0 \qquad (4-9)$$

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where n is the outside normal direction of the surface S_5.

For any system, the boundary condition should be S and

$$S = S_1 + S_2 + S_3 + S_4 + S_5 \qquad (4-10)$$

where S includes all the boundaries of the system.

4-3-2 Basic Assumptions

According to the existing CLM system operating in a self-anchoring mode, the following boundary conditions can be assumed:

1. At the bottom of the forming chamber, the surface is thermally insulated. Thus, it is the fourth boundary condition, and Equation (4-9) can be used.

2. Connecting thermal exchange exists between the deposited towpreg and the air of the inside chamber. Hence, the third boundary condition; Equation (4-7) can be used.

3. The temperature inside the chamber is set to be constant and uniform.

4. The radiation direction is along the longitude of the deposited towpreg line. The cross-section direction does not radiate. See Figure 4-4.

4-3-3 Basic Parameters

The most important parameters used for the present simulation work are listed in Table 4-1 (see Appendix A). In the Self-anchoring process, Kevlar-49 fiber and

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polyethylene matrix are used. The parameters listed in Table 4-1 are for these two materials. If other materials replace these materials, the simulation process does not need to be changed. Only the inputted parameters need to be changed [62, 63].

4-3-4 An Analytical Solution for a Single Towpreg

An analytical solution should be used to describe the results of the simulation study.

A unit cube is shown in Figure 4-5. Assume that

1. The temperature inside the cube is uniform, and is not a function of the X, Y, and Z coordinates.

2. There is no heat source inside the cube and only the heat quantity change on the cube surface influences the heat quantity change inside the cube.

3. Furthermore, only a change of the heat quantity could changes the temperature inside the cube.

4. The temperature change in the cube surface follows the third boundary condition. Equation (4-7) should be used.

5. No thermal exchange occurs on the bottom, front and rear surfaces. Only the top, left, and right surfaces experience thermal exchanges, (Figure 4-5).

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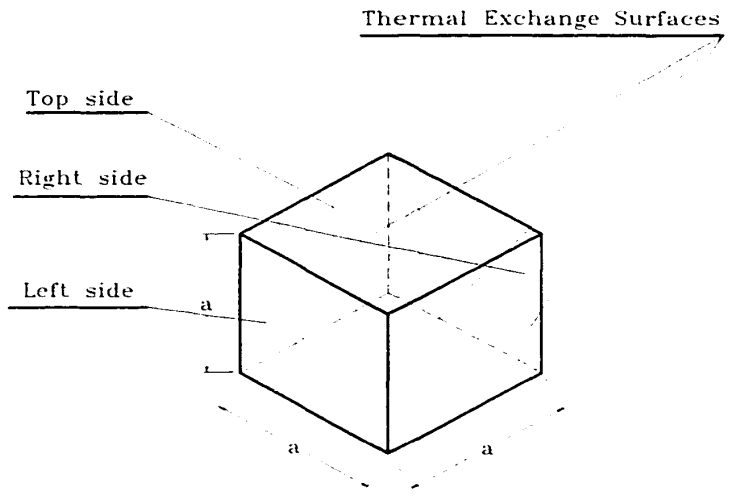

Figure 4-5 A Unit cube of thermal exchange.

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The area of the thermal exchange surfaces is $3a^2$, and the cube volume is a^3. According to the principle of energy conservation, one can establish an equation that describes the thermal exchange in the micro-cube:

$$\rho c \frac{\partial T}{\partial t} a^3 = -\alpha (T - T_c)(3a^2) \qquad (4-11)$$

where T_c is the temperature of the chamber, α is the thermal convection exchange coefficient.

In the left hand side of Equation (4-11), the item indicates the heat quantity varies with the temperature, which changes with the time inside the micro-unite. The right hand side item is related to the quantity of the thermal exchange at the boundary.

Simplifying and changing the order of Equation (4-11) we have Equations (4-12) and (4-13):

$$\frac{dT}{dt} = -\frac{3\alpha}{a\rho c}(T - T_c) \qquad (4-12)$$

$$\frac{d(T - T_c)}{T - T_c} = -\frac{3\alpha}{a\rho c} dt \qquad (4-13)$$

and upon integration of both sides of Equation (4-13), one obtains

$$T = Ae^{-\frac{3\alpha}{a\rho c}t} + T_c \qquad (4-14)$$

From an initial condition:

when $t = 0$, $T = T_0$, we have $A = T_0 - T_0$.

Substituting the value A into equation (4-14) results in:

$$T = (T_0 - T_c)e^{-\frac{3\alpha}{a\rho c}t} + T_c \qquad (4-15)$$

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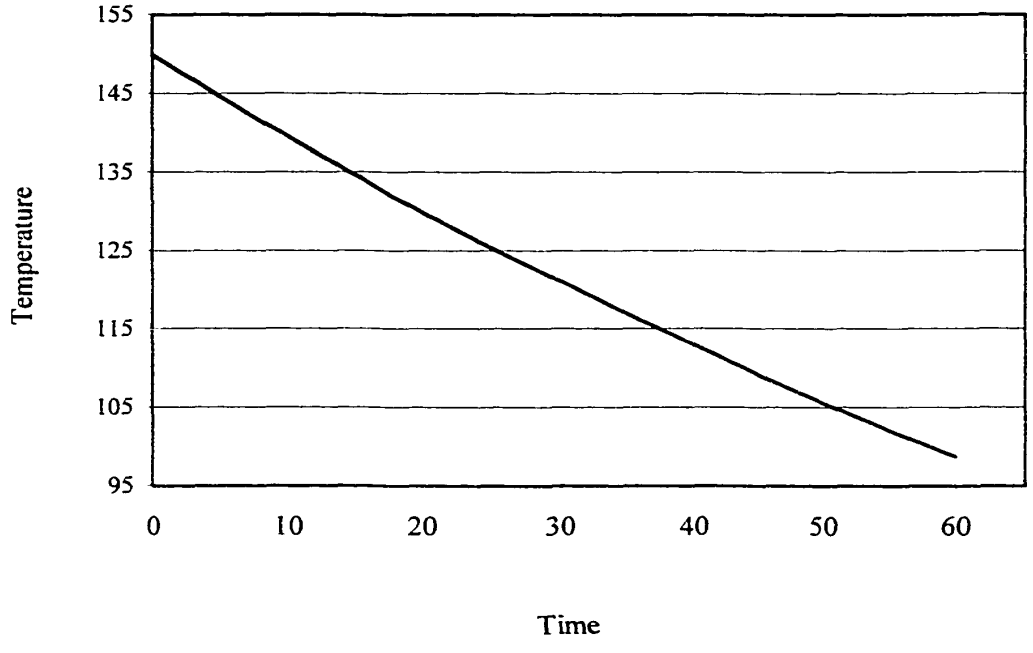
Figure 4-6 An analytical solution for the single- towpreg-line heat transfer.



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According to Equations (4-14), and (4-15) and the length of the cube $a = l^{-3}\ m$, a diagram of the temperature vs. the time is shown in Figure 4-6. By comparing Figure 4-6 with Figure 4-9 and Figure 4-10, we can find that the temperature change pattern is almost the same. The temperature change for a single towpreg can be simulated and calculated, but in a complicated problem, only the simulation is useful.

§4-4 TEMPERATURE SIMULATION FOR A SINGLE TOWPREG

4-4-1 Introduction to the ANSYS

It is hard to find an analytical solution to Equation (4-3), even if it is a 2D problem. For most of the thermal field problems, a numerical solution is used. Many software packages are commercially available for thermal field simulation. The ANSYS is one of the most successful software packages. ANSYS can be used to solve the problems such as structure analysis, thermal transfer, electromagnetic field and fluid flow analysis.

Conduction, convection, and radiation, the three basic heat transfer processes could be treated by the ANSYS program package, which can be used for linear, nonlinear, steady state, and transient thermal analysis.

According to the forming characteristics of the CLM process, the current problem requires nonlinear and transient thermal analysis. Thus, thermal conduction, convection, and radiation should be considered.

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4-4-2 Simulations for a Single Towpreg

First let us evaluate the influence of a towpreg's cross-section. A towpreg is dispensed from a nozzle, which has a circular cross-section. When the towpreg is deposited onto a surface, its cross-section could be changed into a square or other shapes, see Figure 4-3A, B, and C. Two shapes are shown in Figure 4-7. Figure 4-7A shows a shape with round corners. Figure 4-7B shows a square shape. Now, an error is evaluated when the shape effect is negligible.

Five points were selected for each shape (see Figure 4-7). It is assumed that the chamber temperature is *20℃* and the initial temperature of the towpreg is *150℃*. A calculation result is shown in Figure 4-8. Figure 4-8A shows the temperature changes with time at each point for the shape that has round corners, Figure 4-8B shows the same thing but for a square shape. As demonstrated in Figure 4-8, the shape does not influence the temperature variation too much. Therefore, in the following calculation the towpreg is treated as a square cross-section.

Second, consider the effect of fiber. Figure 4-8 shows the result for the case of a pure matrix in witch the fiber effect is not considered. for the case of a *50%* fiber volume fraction, the result is shown in Figure 4-9. By comparing Figure 4-8 and Figure 4-9, we can see that the temperature change trend is almost the same, but the value is different. The specific heat of the Kevlar fiber is lower than that of the PE matrix. When heat is lost, the temperature of the Kevlar-PE towpreg will fall faster than that of the pure material.

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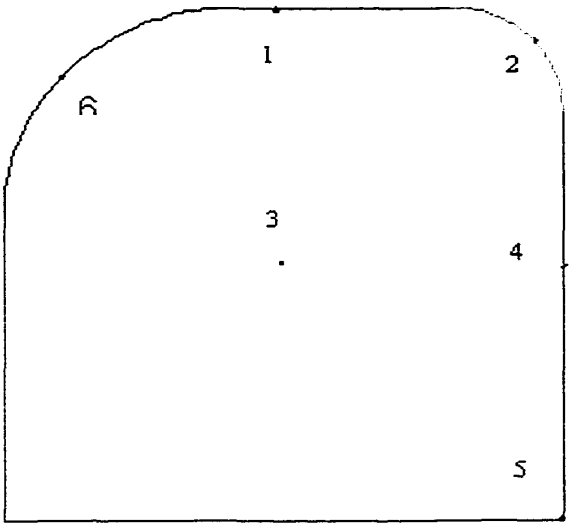

Figure 4-7A A cross-section of the towpreg has round corners.

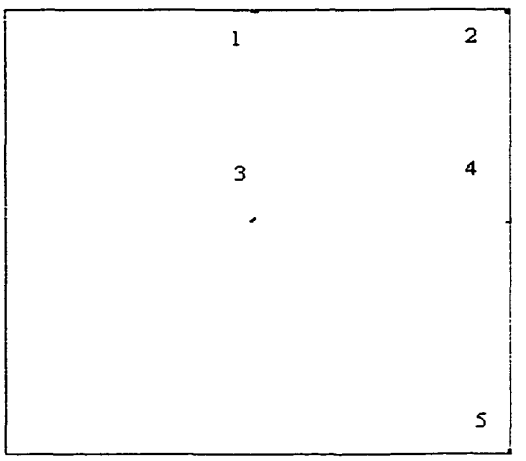

Figure 4-7B A cross-section of the towpreg has right-angle corners.

Figure 4-7 Cross-section shapes and the calculated points.

1, 2, 3, 4, 5 and 6 are the selected points for evaluation.

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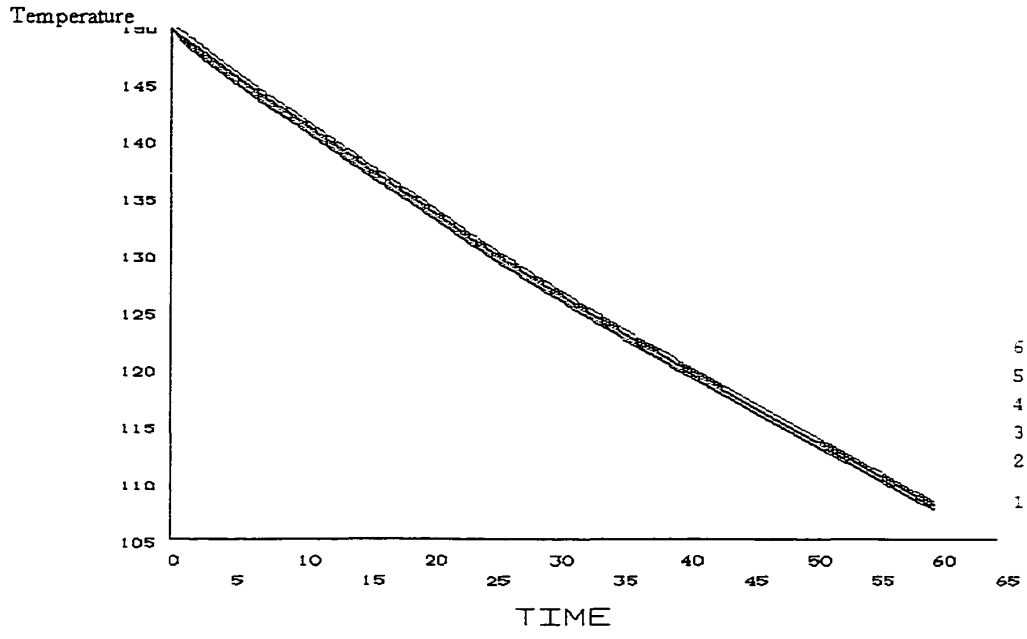

Figure 4-8A Temperature changing with time at each point for the round-corners shape.

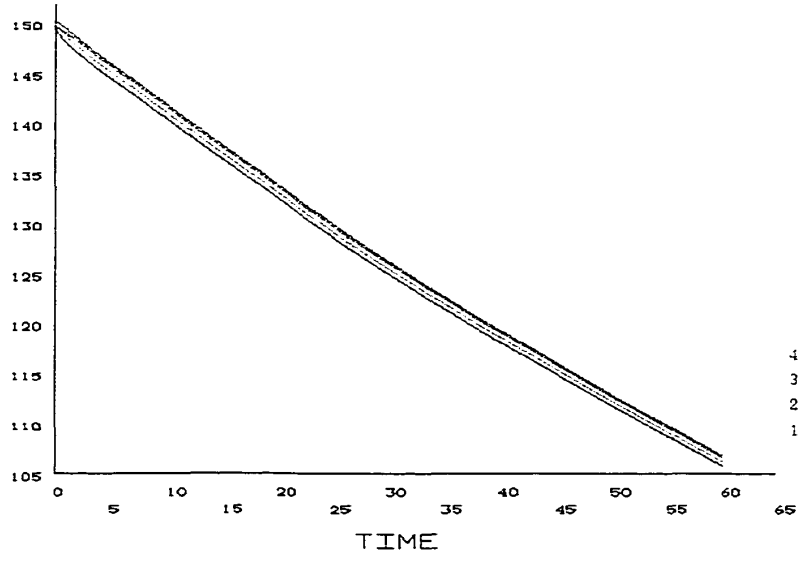

Figure 4-8B Temperature changing with time at each point for a square shape.

Figure 4-8 Temperature changing for each point.

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An ANSYS model for a composite material is complicated. The model is built up with two different components, the fiber and the matrix. These components are assumed to be evenly distributed inside the model. Through separate Boolean Operations, the fiber and the matrix properties were inputted to the units, respectively. Then, they were marked with different number to build the final model. If equivalent heat transfer properties of the material are found, the model can be readily built.

According to the heat transfer principle, the equivalent conductivity $\bar{k}$, specific heat $\bar{c}$, and density $\bar{\rho}$ of the composite are [64]:

$$\bar{k} = \frac{k_f k_m}{k_f V_m + k_m V_f} \qquad (4-16)$$

$$\bar{c} = c_f V_f + c_m V_m \qquad (4-17)$$

$$\bar{\rho} = \rho_f V_f + \rho_m V_m \qquad (4-18)$$

where K_f, K_m are the thermal conductivity of fiber and matrix, respectively, V_f, V_m are the volume fraction of the fiber and matrix, respectively, c_f, c_m are the specific heat of the fiber and matrix, respectively, and ρ_f, ρ_m are the density of the fiber and matrix, respectively.

Assuming that $V_f = V_m = 0.5$, and that the fiber is well dispersed in the matrix. according to Table 4-1 and Equations (4-11) ~ (4-13), the equivalent parameters are:

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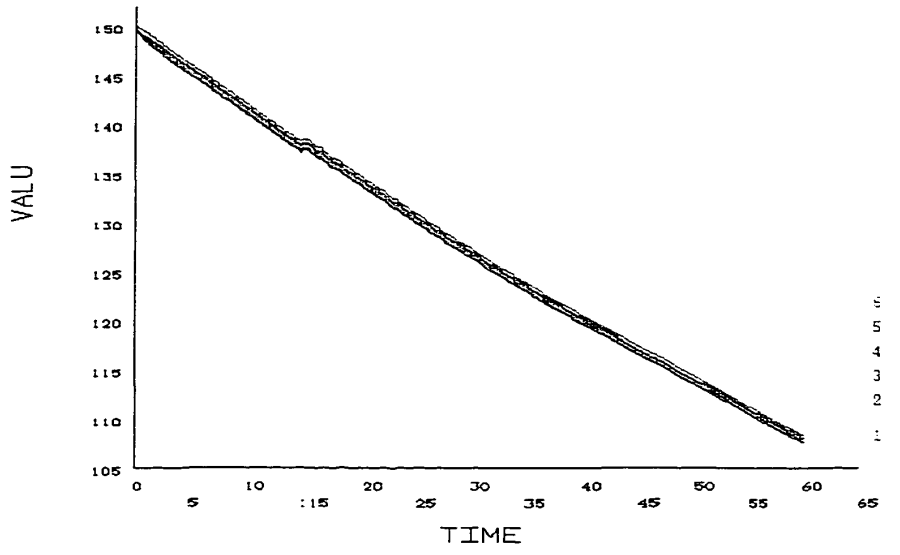

Figure 4-9 Temperature changes of the towpreg having a 50% by volume of fibers.

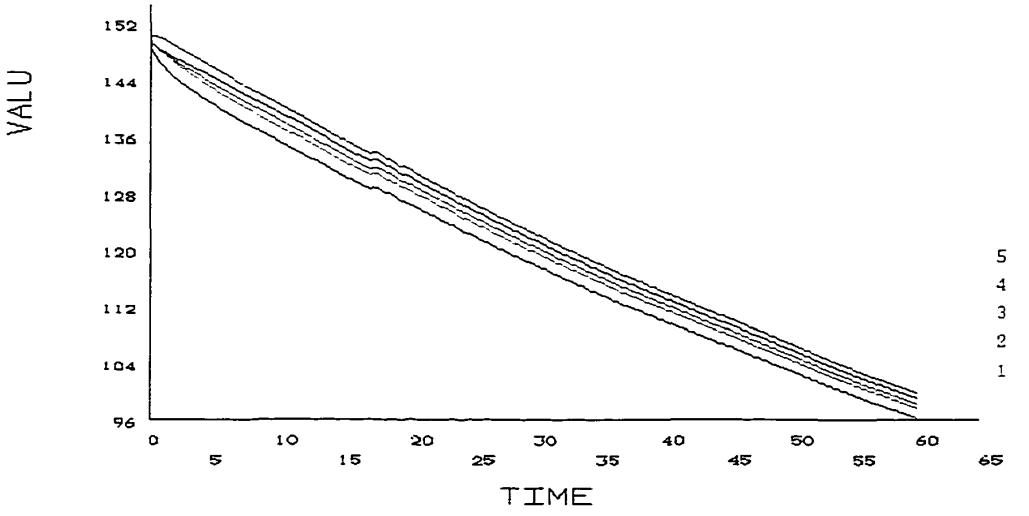

Figure 4-10 Temperature changes with time (with equivalent parameter values incorporated).

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$$\bar{k} = 0.07\frac{w}{mK}, \qquad \bar{c} = 1465\frac{J}{kg\,K}, \qquad \bar{\rho} = 1231\frac{kg}{m^3} \qquad (4-19)$$

According to the equivalent parameters, a simulation result is shown in Figure 4-10. The numbers 1, 2...5 indicate different investigation points in the towpreg cross-section (See Figure 4-7)

By comparing Figure 4-10 with Figure 4-9 on the surfaces and corners of the towpreg (points 1, 3, 4 and 5), we can see that the temperature change trend is almost the same. Only in the inside of the towpreg (point 3) the temperature change trend is a little different. During the forming process, a temperature change on the towpreg surface is a major effect for anchoring. Therefore, the equivalent parameters can be used to substitute for the composite parameters and make the simulation simple.

§4-5 TEMPERATURE SIMULATION FOR MULTIPLE TOWPREGS

4-5-1 Forming and Heat Transfer Model

As indicated in the analysis in §4-1, the temperature of the towpreg is influenced by many factors. During the earliest stage of the simulation, the influencing factors should be simplified. A part of a forming process is selected for the simulation to find a general regularity of the whole forming process. As an example, the structure of a part may be built with nine towpreg circles. A cross section of the nine-towpreg circles is shown in Figure 4-11. There are three towpreg lines in each layer and three layers in the structure. In Figure 4-11, the different colors indicate different lines and layers, and the depositing sequence is $A_1 \rightarrow A_2 \rightarrow A_3 \rightarrow \cdots\cdots \rightarrow A_9$.

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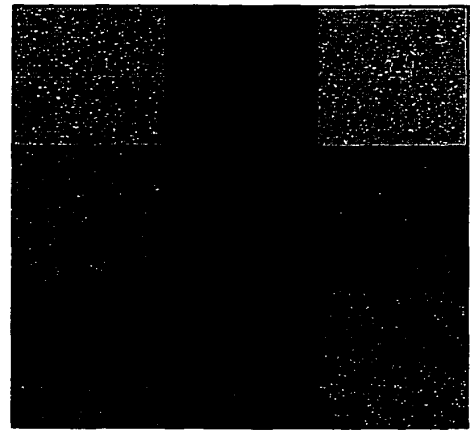

Figure 4-11 Deposition sequence of the nine towpregs (a cross-section).

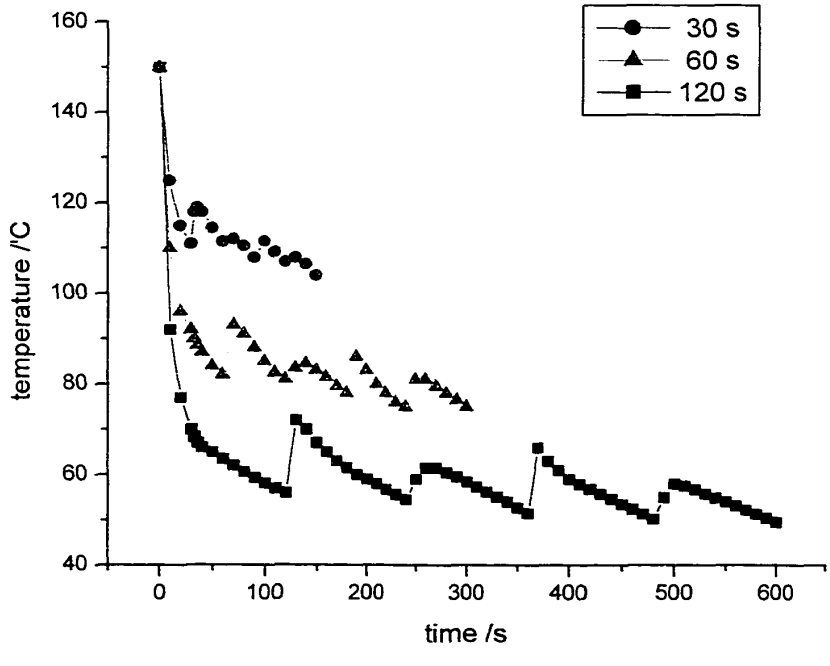

Figure 4-12 Temperature vs. depositing interval.

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The deposition interval between two towpreg lines is the same everywhere and the interval is in inverse proportion to the nozzle moving speed. Assume the temperature of the chamber is $20^{\circ}\ C$, and the convection coefficient is 5 N/m^2sk. Based on this forming and heat transfer model, the temperature change of the fifth towpreg is investigated under the different chamber temperature, nozzle moving speed, and convection coefficient conditions.

4-5-2 Temperature Field Simulations

The effects of depositing speed, chamber temperature, and convection coefficient will be simulated in this subsection. Figure 4-12 shows the fifth towpreg's temperature vs. different interval or depositing speed. The following observation are made:

1. At the beginning, the temperature decreases in a more drastic manner. With the towpreg is being added, the temperature is undulated. The temperature undulation is larger when the temperature is lower. The maximum fluctuation is up to approximately 16°C. After that, the temperature decrement is slower.

2. The sixth and eighth towpregs have the largest influence on the temperature of the fifth towpreg.

3. If the interval is longer, or the depositing speed is slower, the temperature falls faster.

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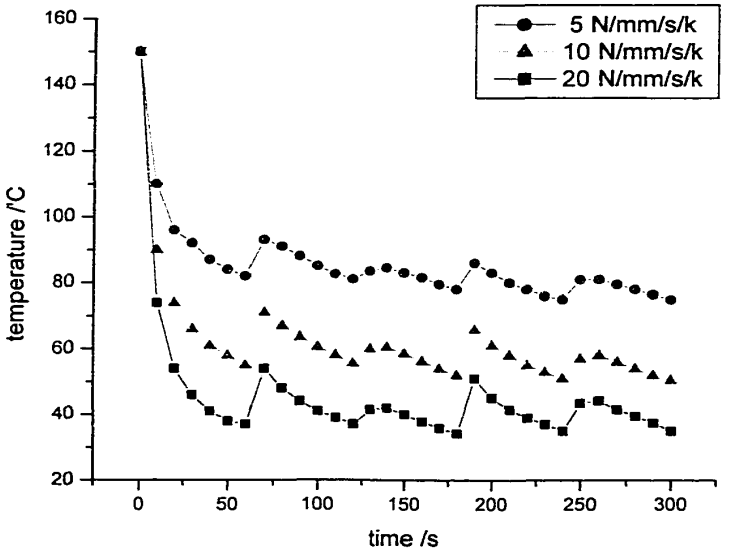

Figure 4-13 Temperature vs. convection exchange coefficient.

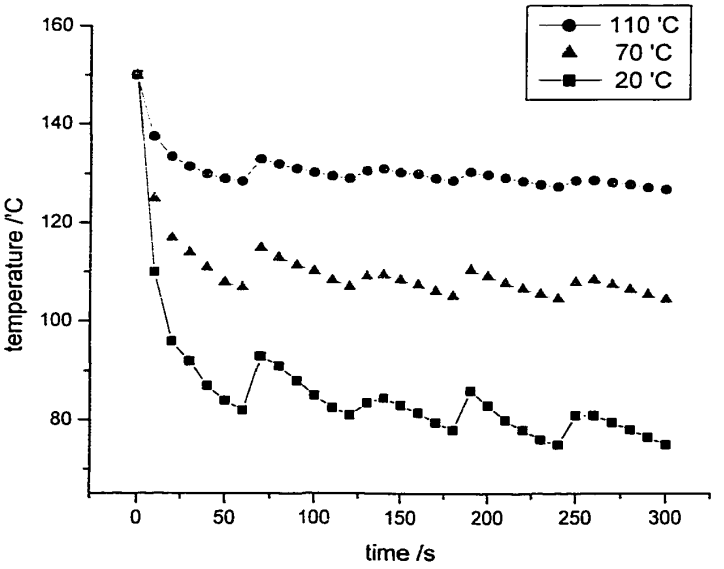

Figure 4-14 Temperature of the fifth towpreg vs. different chamber's temperature.

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When the chamber temperature is *20℃* and the interval is *60* seconds, the temperature vs. the convection exchange coefficient, α, is shown in Figure 4-13. The temperature undulation is not much different for the different convection conditions.

When the convection exchange coefficient is $5N/m^2\ s\ k$, and the interval is *60*, the temperature vs. the different chamber temperatures is shown in Figure 4-14. The undulation of temperature does not vary much with the different environment temperature.

In the preceding subsections, the temperature fields were simulated under different conditions. A future task should be to investigate the conditions of the towpreg's solidification speed in relation to the temperature fields, and then, according to the different towpreg's solidification degrees, to find the various bond strength of the towpreg, and finally to calculate the effect of the forming speed on the towpreg's bond strength. With this knowledge on hand, the max forming speed can be evaluated for different towpreg materials.

§4-6 ANALYZING AUTOMATIC EXTRUSION

4-6-1 Principle of Automatic Extrusion Method

The self-anchoring forming method was studied in the previous sections. It was found that the forming speed of the self-anchoring CLM method is limited. So, other effective forming methods are highly desired and must be investigated. The advantages

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of the one-step forming method and the Active Material Supply method were introduced in Chapter 2. One of the advantages is that the forming speed is not limited by the solidification condition of the towpreg during the forming process. But, a challenge of the one-step forming method mentioned before is to continuously deliver the fiber tow into a pressure vessel and to seal the fiber entrance to prevent leakage.

A one-step forming method is shown in Figure 2-20. In this system, an extrusion machine supplies melted thermoplastic material to an impregnating and depositing device. The device impregnates a continuously supplied fiber tow where the melt deposits the towpreg onto a work surface, which is located on a 3D-motion system. A key component in this forming system is the impregnating and depositing device. A layout of this device is shown in Figure 4-15. In the design, a flange joins the device to the extruder machine to receive a pressurized polymer melt there from; the fiber tow is drawn into the pressure chamber through a regulating rod and regulating head and is impregnated with the polymer melt inside the nozzle area. The regulating rod could be risen or lowered to adjust the distance between the regulating head and the nozzle. The nozzle and regulating head are changeable to match different towpreg requirements and to find the best shape and dimension.

A proposed fluid flow model is shown in Figure 4-16 [65, 66]. When the melted polymer is squeezed in the pressure vessel, in zone *A*, the fluid flow speed is steady and uniform, see Figure 4-16A. In zone *B*, the matrix impregnates the fiber tow, and the speed of the distributing matrix flow is complicated. However, a dead zone *C*, where the pressure is equal to zero, could be generated at the end of the regulating head. In zone *C*, the polymer flow speed is higher than that in zone *A*, and the towpreg is driven out of the

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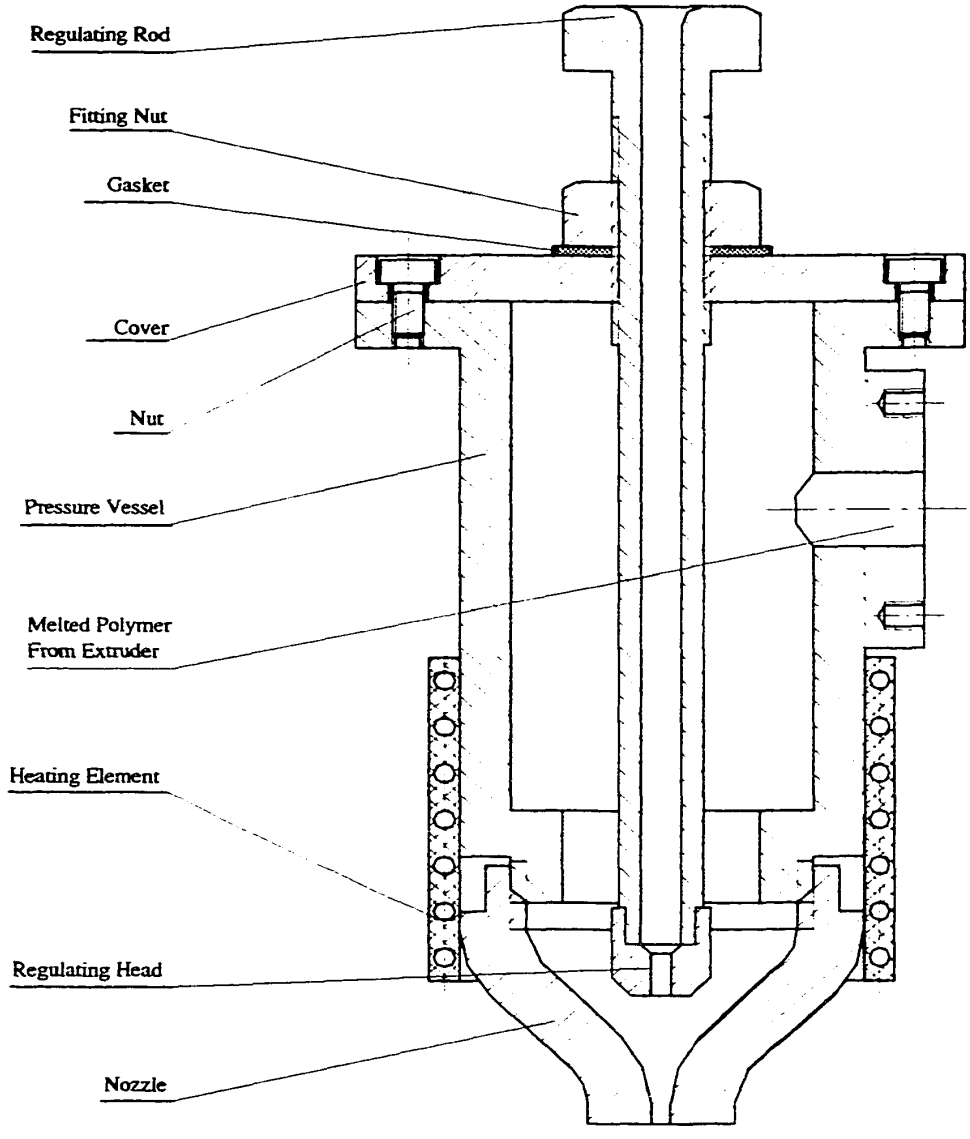

Fig. 4-15 An impregnation and deposition device.

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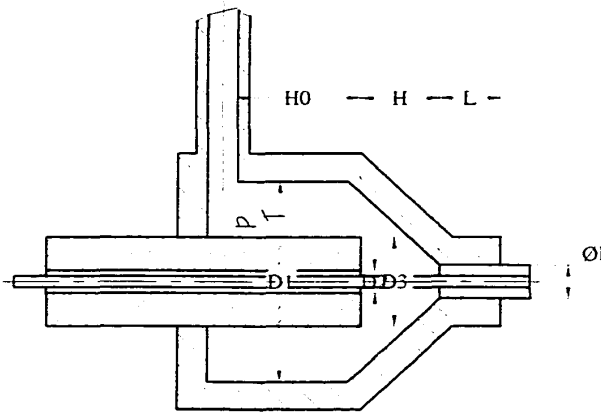

Fig. 4-16B

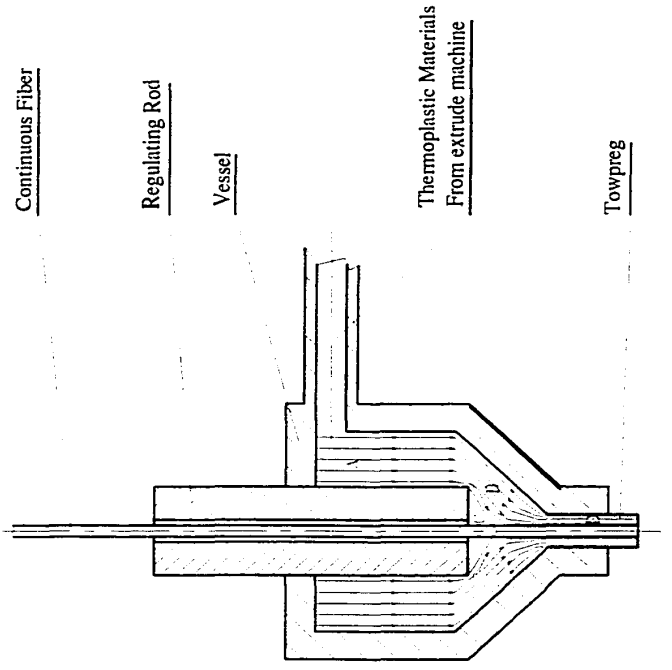

Fig. 4-16A

Fig. 4-16 The fluid flow model.

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nozzle by shear stress. Because a dead zone is formed near the entrance of the fiber tow, the melted polymer could not go up. Therefore, the fiber is drawn into the chamber for impregnation and is deposited onto the work surface continuously and automatically. This is the mechanism of the forming method, which is called Automatic Impregnation and Deposition Mechanism (AIDM).

The factors that influence the AIDM are shown in Figure 4-16B. Physical properties that are influencing are material viscosity μ, chamber pressure p, and temperature T. The geometry factors are the shapes of the regulating head and nozzle. The dimension factors are shown in Figure 4-16B. The following simulation and analysis procedures were used to study their factors for the purpose of determining the best parameters for the AIDM forming method. The feasibility of the AIDM method has been demonstrated by experiments.

4-6-2 Simplification and Estimation of the Best Parameters

Figure 4-16A shows a distribution profile model of the fluid flow lines. In zone A, the fluid flow could be treated as a non-Newtonian fluid inside coaxial cylinders. This is a commonly encountered situation in the industry. Therefore, many scientists have tried to solve the problem with an analytical solution. Bird [67-72] has done much investigation in this field. The results of Bird's work provide some solution to the AIDM problem. Before analyzing the fluid flow, the following assumptions are made:

1. The fluid is incompressible (constant density).
2. The flow is under steady state conditions (i.e. time-independent).

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3. Stationary boundary condition (the two cylinders do not slide or rotate during the simulation).

4. The cylinders are sufficiently long, so that the effect of the cylinder ends could be neglected.

5. The gravitational force is neglected.

The stress distribution for the axial laminar flow of an arbitrary inelastic, non-Newtonian fluid through a concentric annulus is known as:

$$\tau_{rz} = \frac{PR}{2}(\xi - \frac{\lambda^2}{\xi}) \qquad (4-20)$$

$$p = \frac{P_O - P_i}{L} + \rho g \qquad (4-21)$$

Where p = the total pressure loss per unit length L, τ_{rz} = the shear stress, $\xi = \frac{r}{R}$ and R = the Radius of the outer pipe of the annulus as illustrated in Fig4-17.

The constant of integration is chosen so that: when $r = \lambda R$, $\tau_{rz} = 0$.

In a laminar flow this corresponds to the location of maximum velocity. The power-low rheological model could be represented as:

$$\tau_{rz} = -m\left|\frac{dv_z}{dr}\right|^{n-1} \times \left(\frac{dv_z}{dr}\right) \qquad (4-22)$$

where: m, n are the parameters in power-low model and $s = 1/n$.

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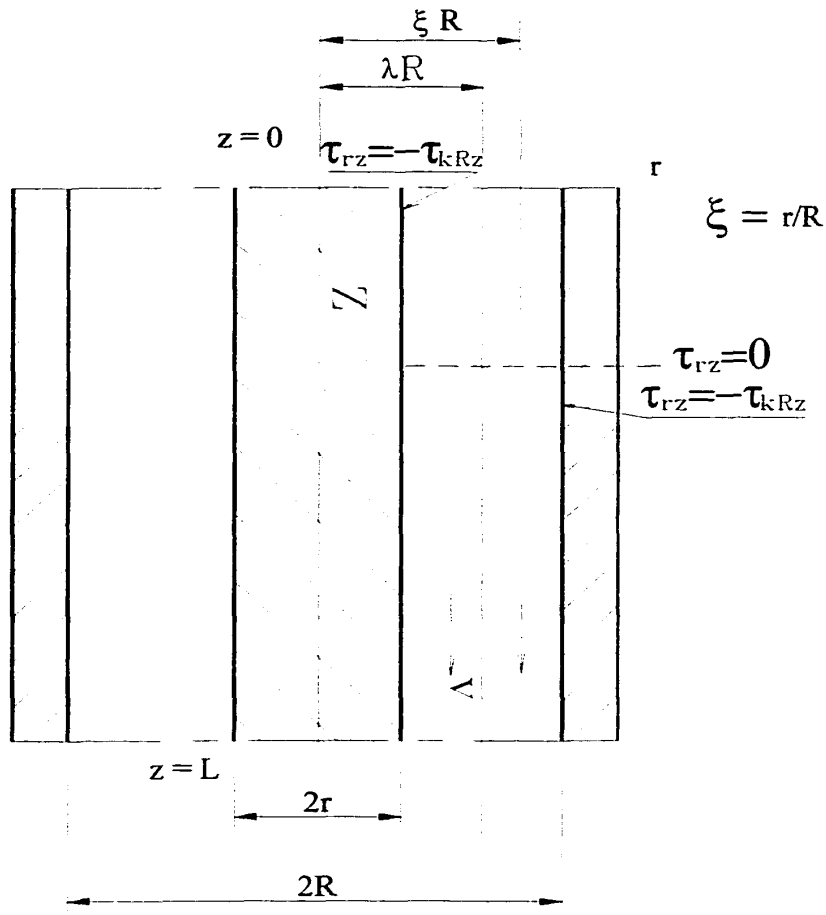

Figure 4-17 A fluid flow model.

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Combining Equations (4-20) and (4-22) and considering the boundary conditions that, when $\xi=K$, $v_z=0$, and when $\xi=1$, $v_z=0$, we obtain Equations (4-23) and (4-24):

$$-m\left|\frac{dv_z}{dr}\right|^{n-1}\frac{dv_z}{dr}=\frac{PR}{2}\left(\xi-\frac{\lambda^2}{\xi}\right) \qquad (4-23)$$

Or:

$$\begin{aligned} v_{zi} &= R\left(\frac{PR}{2m}\right)^s \times \int_K^{\xi}\left(\frac{\lambda^2}{x}-x\right)^s dx \qquad K\le\xi\le\lambda \\ v_{zo} &= R\left(\frac{PR}{2m}\right)^s \times \int_{\xi}^{1}\left(x-\frac{\lambda^2}{x}\right)^s dx \qquad \lambda\le\xi\le 1 \end{aligned} \qquad (4\text{-}24)$$

where: k = the ratio of the radius of inner cylinder to that of outer cylinder,

λ = a value of a dimensionless radial coordinate,

μ = Newtonian Viscosity,

μ_0 = "Plastic-viscosity" of the Bingham plastic.

The value of λ is determined by the condition:

$$v_{zi}(\lambda) = v_{zo}(\lambda)$$

Or: $$\int_K^{\lambda}\left(\frac{\lambda^2}{x}-x\right)^s dx=\int_{\lambda}^{1}\left(x-\frac{\lambda^2}{x}\right)^s \qquad (4-25)$$

A volume flow rate is

$$Q=2\pi R^2\int_K^1 \xi v_z d\xi \qquad (4-26)$$

Substitution Equation (4-24) into (4-26) yields:

$$\frac{Q}{\pi R^3}=2\left(\frac{CPR}{2m}\right)^s\left[\int_K^{\lambda}\xi d\xi\cdot\int_{\xi}^{\lambda}\left(\frac{\lambda^2}{x}-x\right)^s dx+\int_{\lambda}^{1}\xi d\xi\cdot\int_{\xi}^{1}\left(x-\frac{\lambda^2}{x}\right)^s dx\right] \qquad (4\text{-}27)$$

Integrating Equation (4-27) yields:

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$$Q = \frac{\pi n R^3}{1+3n}\left(\frac{PR}{2m}\right)^{\frac{1}{n}} Y \qquad (4-28)$$

Or: $$\frac{PR}{2} = \left(Q\frac{1+3n}{Y\pi n R^3}\right)^n \times m$$

where $$Y = (1-\lambda^2)^{1+\frac{1}{n}} - k^{1-\frac{1}{n}}\left(\lambda^2 - k^2\right)^{1+\frac{1}{n}} \qquad (4-29)$$

The value of λ can be calculated by Equation (4-25), or the Table of λ (n, k) [73].

Thus, Equation (4-28) shows the relationship between pressures drop and flow quantity. When the m, n values and the dimensions of the concentric annulus are known, Equation (4-28) can be used to compute *PR/2* if *Q* is given.

According to the design of the impregnation and deposition device, the parameters could be $R=15\ mm$, and $K \approx 0.3$. For polyethylene, values of $n=0.5$, $m=0.3$ can be assumed

From the values of the table for $\lambda(n, k)$, the value of λ can be obtained: $\lambda = 0.5970$. Substituting those parameters into Equation (4-29) we obtain $Y \approx 0.511$. If the extruder machine supplies a flow rate of melted polymer with

$Q = 0.001 cubic$ foot per second

$p = 2\left(Q\frac{1+3n}{Y\pi n R^3}\right)^n \times m / R = 0.125$ pound per square foot.

The above analytical solution can be used to describe the flow behavior in zone A of the impregnation and deposition device if the device is long enough (see Figure 4-16A). Several articles that introduced the analytical solutions for an Apex Tapered concentric annulus can be used to evaluate the wire coat and plastic blowing process. But for such

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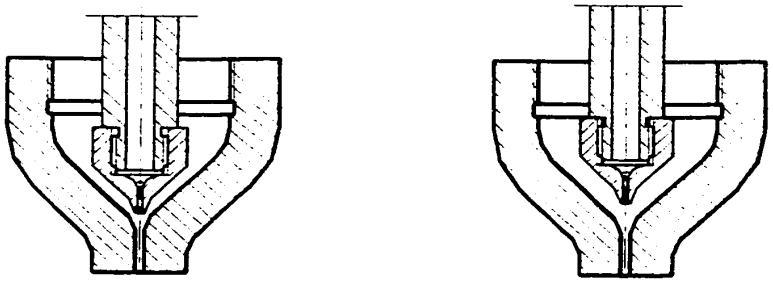

Fig. 4-18 A Different positions for tapered head.

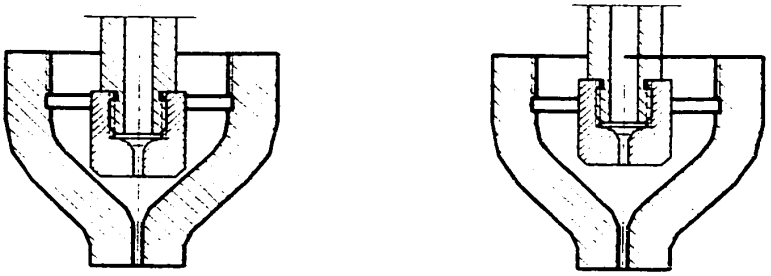

Fig. 4-18 B Different positions for flat head.

Fig. 4-18 The relative position of the heads and nozzles.

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complicated shapes in zone B, C and D it is impossible to get the analytical solutions; the numerical solution is useful in this situation.

§4-7 NUMERICAL SIMULATION OF THE AIDM METHOD

4-7-1 The Numerical Simulation Model

The fluid flow could be assumed to be nonlinear, and steady-state, and the assumptions concerning physical properties are the same as those made in the previous subsection period, In fact, no matter how one selects the parameters of the matrix, the simulation result will not change too much. Hence the simulation will be focused on the geometry and dimensions of the regulating head and nozzle.

1. Two regulating heads are selected to be studied, referring to Figure 5-11. Figure 5-11A shows a flat head, Figure 5-11B shows an apex-tapered head, called tapering head. The heads are positioned inside the nozzle as shown in Figure 4-18.

2. The distance between the regulating head and the nozzle is an important parameter. It is called h, and several h values are investigated.

3. The diameter of the nozzle bore ϕ and a depth ξ of the bore need to be evaluated. See Figure 5-10.

4-7-2 The Fluid Flow Simulation

In this subsection, several simulation tasks are discussed.

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1. The h effect: the tapering head is used with a nozzle of $\phi = 2$ mm. Figure 4-19 shows a pressure distribution diagram near the nozzle exit for $h = 1, 2, 3, 5$ mm, respectively.

2. The effect of the diameter of the nozzle bore ϕ: In this case, using the tapering head, and setting $h = 1, 2, 3, 5$ mm, for four positions, three ϕ values have been simulated. Figure 4-20, 4-21 and 4-22 shows the results for $\phi = 3, 4, 6$, respectively.

The simulation results show that when the regulating head is adjusted near the nozzle exit, h is shorter and a zero pressure zone appears near the end of the regulating head. With increasing ϕ, the h needed to build a dead zone is going to be longer. When ϕ is smaller, the pressure inside the nozzle will be higher. The regulating head needs to be closer to the nozzle exit to form a small environment in which the pressure is equal to zero.

This simulation result is consistent with the result of an experiment that will be introduced in Chapter 5.

3. The effect of the regulating head: Figure 4-23 shows the simulation results in which the flat head is employed. One can see that when the regulating flat head is adjusted closest to the nozzle exit and ϕ is larger than $8mm$, a zero pressure zone will be established around the fiber tow entrance. The result is a little different from the experiment at result. Because in the simulation, only the steady state is considered. Actually, once a steady fluid flow is formed and the flat regulating head is adjusted up to some distance, the flow is still stable, and no melted

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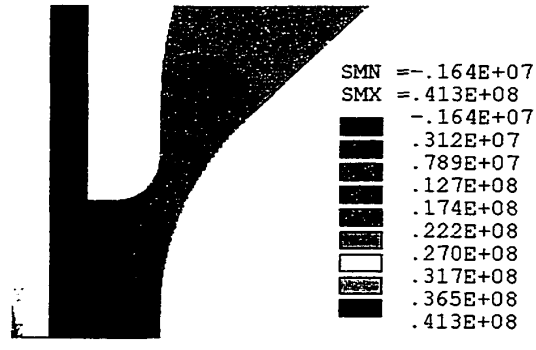

Figure 4-19A *h = 1 mm*

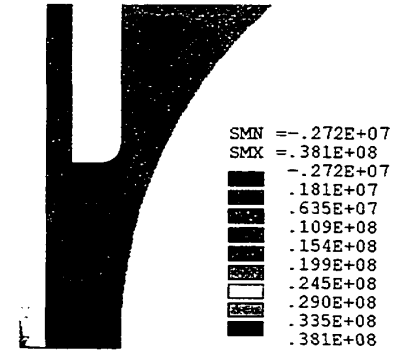

Figure 4-19B *h = 2 mm*

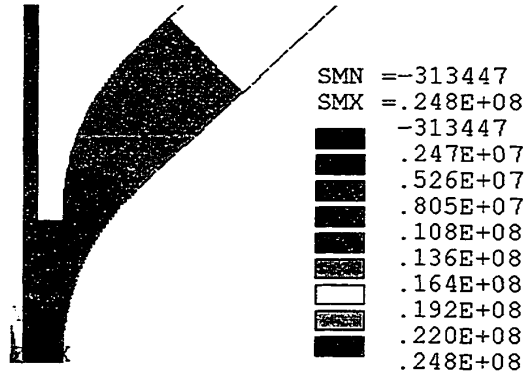

Figure 4-19C *h = 3 mm*

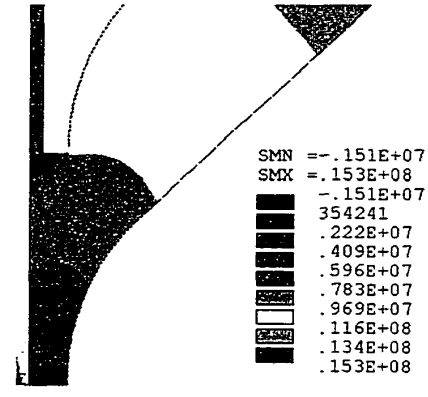

Figure 4-19D *h = 5 mm*

Figure 4-19 the pressure distribution with different *h* values.

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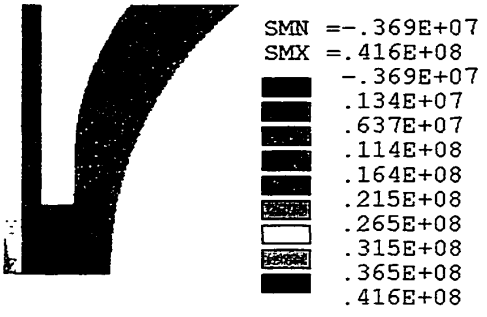

Figure 4-20A $h = 1\ mm$

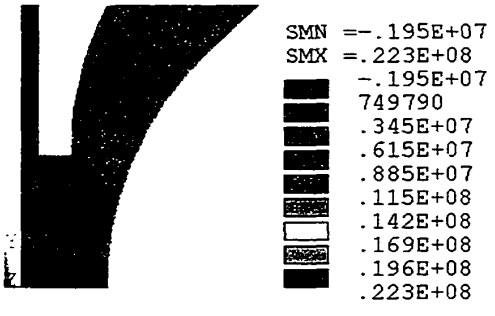

Figure 4-20B $h = 2\ mm$

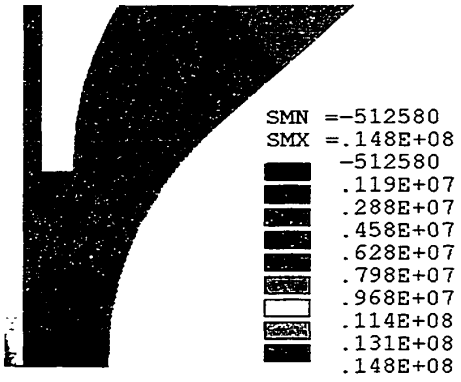

Figure 4-20C $h = 3\ mm$

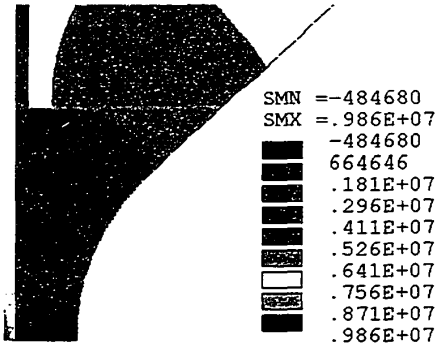

Figure 4-20D $h = 5\ mm$

Figure 4-20 the pressure distribution when $\phi = 3\ mm$.

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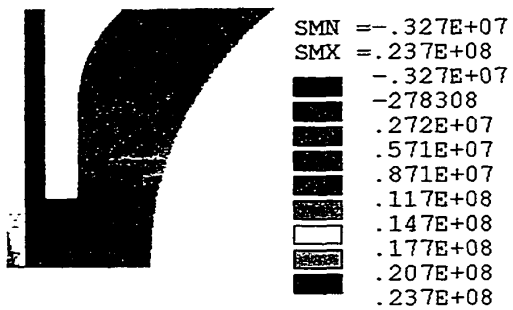

Figure 4-21A *h = 1 mm*

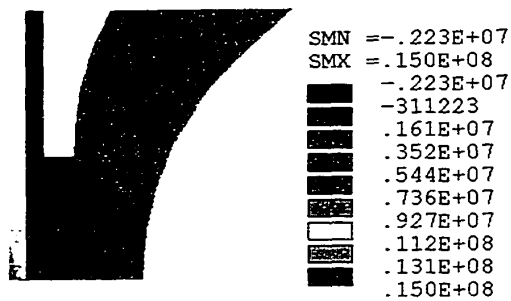

Figure 4-21B *h = 2 mm*

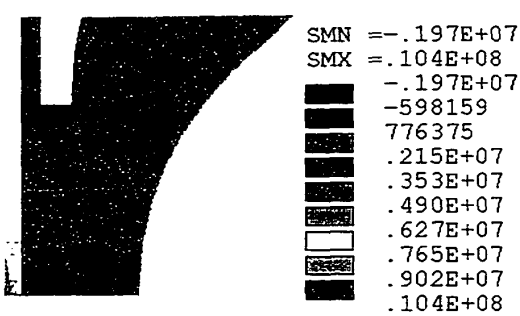

Figure 4-21C *h = 3 mm*

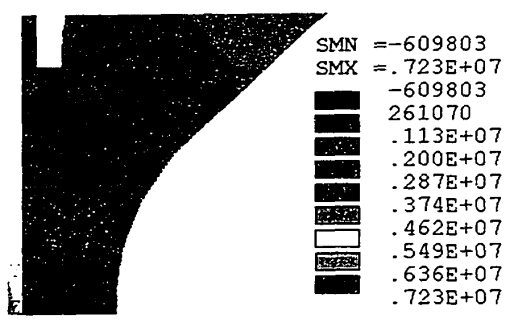

Figure 4-21D *h = 5 mm*

Figure 4-21 the pressure distribution when $\phi = 4$ *mm.*

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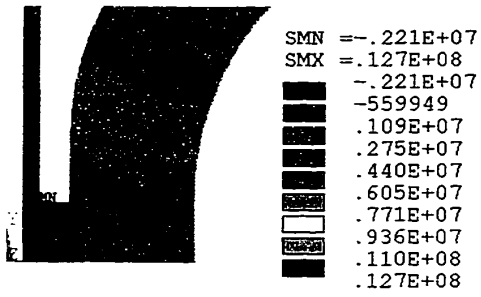

Figure 4-22A *h = 1 mm*

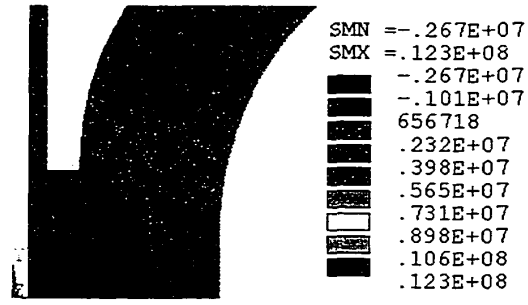

Figure 4-22B *h = 2 mm*

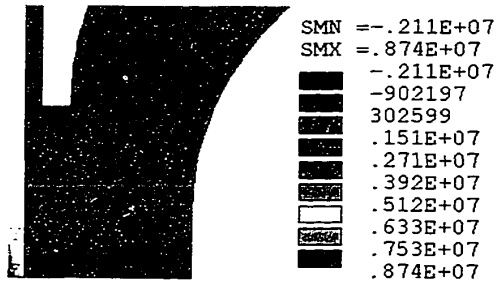

Figure 4-22C *h = 3 mm*

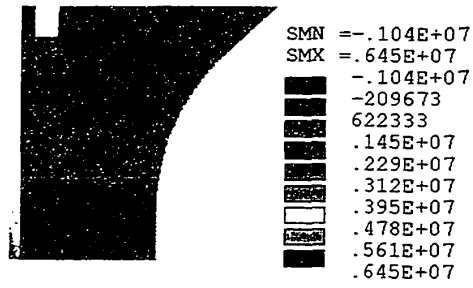

Figure 4-22D *h = 5 mm*

Figure 4-22 The pressure distribution when $\phi = 6$ *mm.*

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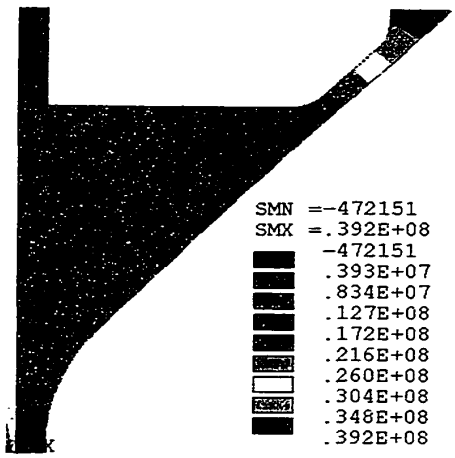

Figure 4-23A $\phi = 2\ mm$

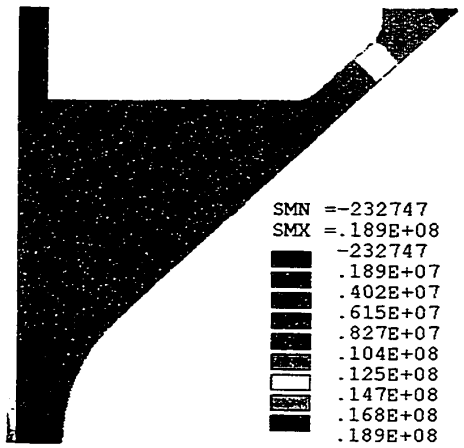

Figure 4-23B $\phi = 3\ mm$

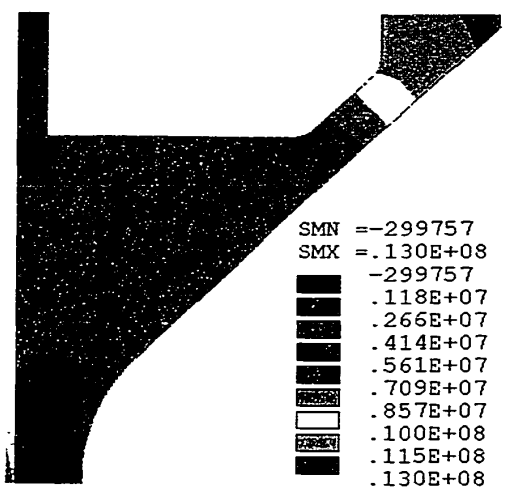

Figure 4-23C $\phi = 4\ mm$

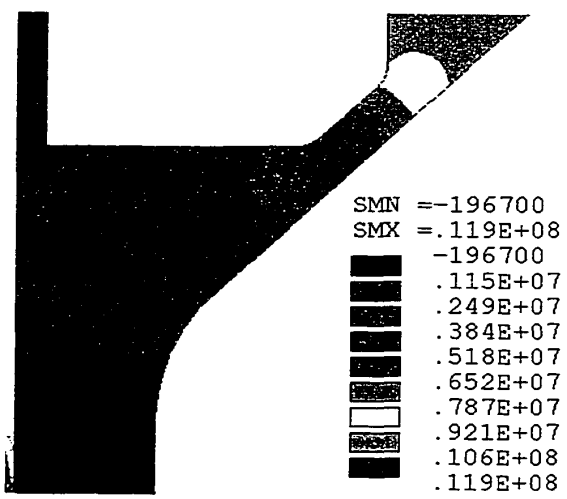

Figure 4-23D $\phi = 8\ mm$

Figure 4-23 the pressure distribution when $\phi = 10\ mm$ and using flatting head.

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Figure 4-23 the pressure distribution when $\phi = 10\ mm$ and using flatting head.

polymer goes up through the regulating rod. More detail will be introduced in Chapter 5.

§4-8 CHAPTER CONCLUSIONS

1. In this chapter, the Self-Anchoring Process and Automatic Impregnation and Deposition Mechanism have been analyzed in more detail and analytical solutions methods were obtained that describe simplified processes.

2. The temperature fields for the Self-Anchoring Process were simulated by using ANSYS. The results could be used in the future for optimizing the whole process.

3. Numerical simulations were also obtained for the Automatic Impregnation and Deposition process. Again, the results could be used to optimize the process.

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CHAPTER 5 CLM SYSTEM DEVELOPMENT AND EXPERIMENTAL ANALYSIS

§5-1 INTRODUCTION

The investigation of Composite Layer Manufacture (CLM) has been a four-year project, starting from the creation of original ideas, concept design demonstration, complete design for the CLM process, and the construction of the present prototype machine.

In this chapter, several important experiments, key part design principles, and CLM system components will be discussed. The mechanical properties of several parts fabricated through CLM will be analyzed in order to evaluate an important feature of this process.

A system developing process is a tedious procedure; the whole development process (including successes and failures) could not be completely covered in one chapter. Throughout the development process, no matter how big or small a component design is, several different plans were presented, analyzed, and compared to determine their pros and cons before making a decision.

Although the prototyping CLM system appears to work reasonably well, however, there is room for improvement and better systems will be coming in the future.

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§5-2 THE EXTREMUM EXPERIMENT

The methodology used in the development of the new CLM technology has been introduced in Chapter 2. Numeric analysis is an important method used in the development period. Hence, a great amount of concept design, numeric simulation, and analysis work has been done and the results have been presented in Chapter 3 and Chapter 4. These results could be used as a guide to direct the hardware and software development of a CLM machine. But some key problems were hard to study with a numeric method or a numerical solution was impossible to get. So, from time to time, experiments were carried out to provide additional insight into the CLM process. With the sole purpose of reducing the required amount of simulation and modeling work an "Extremum experiment" were conducted.

5-2-1 The Concept of Extremum Experiments

In the early stage of development for a new technology, when a design is carried out or a method is proposed, many parameters should be considered, and many possibilities need to be analyzed. So, a lot of experiments need to be done in this period. Given the requirements and characteristics of the technology, Extremum experiments could be used to get an initial result quickly so that the whole technology development procedure can be conducted efficiently and effectively.

An Extremum experiment is done to investigate the result under a certain situation in which all influencing factors and parameters are set on the maximal or minimal value.

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The Extremum experiment is one of the feasibility experiments, and it is used to yield a qualitative result to determine if the investigated object is possible or impossible. The Extremum experiment could be separated into two different experiments, which are Confirming Extremum Experiment and Denying Extremum Experiment:

1. Denying Extremum Experiment: To determine whether or not a design or a method could be employed, all parameters or positions are set in the best conditions. Then the experimented result is evaluated.

    a. If the result yields a negative conclusion, the design or method is not useful at all. Even in the best situation, the method is not workable, so it could not be used in a common situation. Therefore, the design or method should be discarded.

    b. If the result yields a positive conclusion, the design or method could not be rashly inferred as a good one in a common situation. Further experiments are required to determine the real conclusion.

2. Confirming Extremum Experiment: The experiment condition is set just opposite to the denying extreme experiment. All parameters and/or positions are set at the worst value or location.

    a. If a result yields a positive conclusion, the investigated design or method could be taken as a good one at once.

    b. If a result yields a negative conclusion, the investigated object could not hastily be regarded as a bad one.

The Extremum experiment could be used to find a correct research direction, or a region of parameter values only. But the direction could be modified, and the region

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could be compressed with a continuous Extremum experiment. When a series of Extremum Experiments is being done, the best point should be achieved, and/or the optimized value could be obtained. Several Extremum Experiments will be introduced in the following section.

5-2-2 Automatic Extrusions of Thermosetting Materials

The Extreme Experiment 1 was introduced in Chapter 2 briefly and is shown in Figure 2-6. In the concept design period, a material delivery method was proposed in which the fiber impregnation and towpreg deposition were meant to be done automatically and simultaneously. In order to test the designed method, a Deny Extremum Experiment was employed. All parameters and positions were set on the best conditions. If the towpreg could not be extruded out automatically, the design should be abandoned.

The influencing factors were simplified and the experiment was set up, as shown in Figure 2-6A. A segment of fiber tow was placed inside a hypodermic in where it was pilled out along with epoxy resin. The thermosetting resin was used as a matrix because its viscosity would not change too much at room temperature during a short period of time. When the plunger is pushed down, the impregnated towpreg could be squeezed out of the needle connecter. In such a set up, we assume that

a. A seal effect does not need to be considered,

b. Friction does not need to be considered,

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c. The viscosity, μ of the polymer is not changed, so the shear stress could be regarded as a constant.

Throughout the present study, Kevlar-49 was used as the reinforcing fiber. There were *12K* filaments in one tow. In this experiment, *1* tow, *2* tows, or *3* tows were jointed together, respectively in *3* separate runs. The result indicated that when *2* tows were combined together, the impregnated Kevlar-49 fiber tow was readily squeezed out of the syringe. The volume fraction V_f could be evaluated as:

$$V_f = \frac{S_f}{S_n} \qquad (5-1)$$

where: S_f = the total cross section area of fibers, and

S_n = the cross-section area of the needle.

The diameter of a Kevlar 49 filament was $9\mu m$, so

$$S_f = 2 \times 12000 \times \frac{9^2}{4} \pi\pi \times 10^{-6} = 1.53\ (mm)^2$$

The inside diameter of the needle connecter was around *1.8mm*, so,

$$S_a = \frac{1.8^2}{4}\pi = 2.54 \quad (mm)^2$$

$$V_f = \frac{1.53}{2.54} \approx 0.6 = 60\%$$

When *2* tows were used, V_f = *60%* is the best volume fraction for effecting the automatic extrusion. The viscosity μ of the thermoplastic is higher than that of the thermosetting materials, so *50%* volume fraction is chosen for the thermoplastic matrix composite.

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For the case of *3* fiber tows, the total diameter of the fibers was larger than the orifice diameter of the syringe and the friction force was too large for the towpreg to be squeezed out.

In the case of using *1* tow of Kevlar-49, the fiber volume fraction was around *30* percent, $V_f = 30\%$. The automatic extrusion process did not work well for this case. One specimen of the extruded towpreg is shown in Figure 5-1. The speed of resin extrusion was not uniform and excess amount of resin was extruded out intermittently.

The conclusion was that the method for impregnation and deposition implemented at the same time is possible in certain situations. But further experiments need to be done to well define these situations.

5-2-3 Automatic Extrusions with Thermoplastic Materials

In the previous experiment, a thermosetting resin was used for the matrix. In the case of using thermoplastic materials, the viscosity μ is $50 \sim 400$ times higher than that of a thermosetting resin [74]. A device for extruding a thermoplastic melt and a continuous fiber tow is shown in Figure 4-7. Because many parameters influence the final result, several experiments had to be done. The result had not been was satisfactory, so a different extremum experiment had to be conducted, explained as follows.

To simplify the attempt to identify identifying influencing factors, the device was re-designed, as shown in Figure 5-2. The regulating rod and regulating head were removed, and a seal screw was used to seal off the hole of the top cover. Then a small shaft, which was entwined with the fiber, was placed in the cylinder. The volume fraction was set

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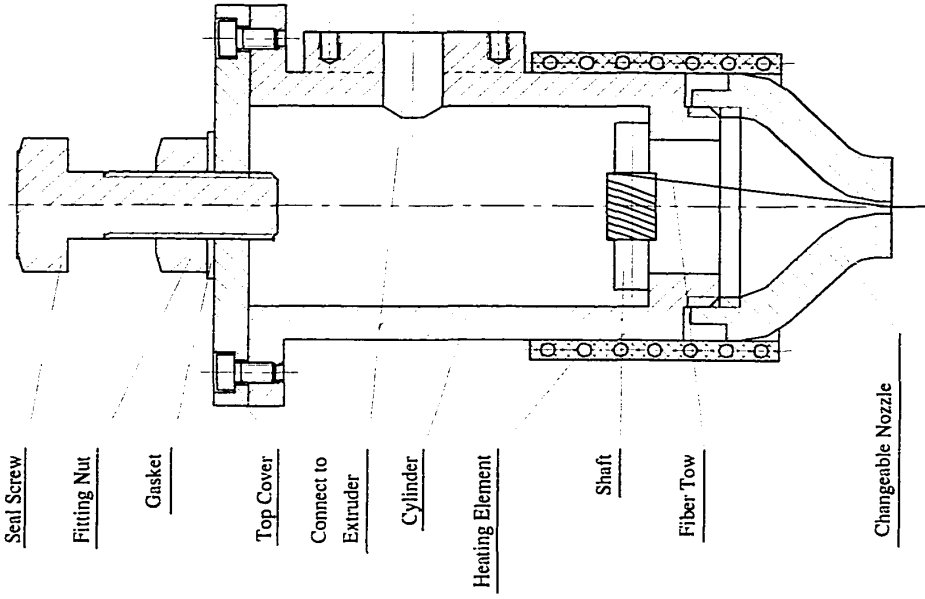

Fig. 5-2 An Extremum experiment.

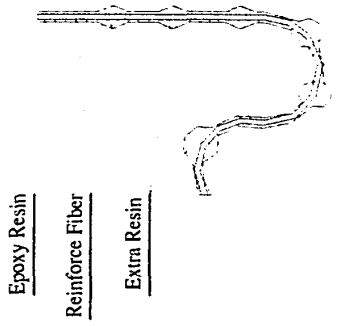

Fig. 5-1 The extrusion speed was not uniform.

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at *50%* by selecting a proper bore diameter of the nozzle. After that, the device was installed on the extruder machine that supplied the required melted thermoplastic. This configuration was operated to determine if the towpreg could be extruded. The extremum experiment was successful, which means the method was useful provided that proper processing parameters could be found.

In order to find a correct parameters range, an experiment similar to the extremum experiments was carried out, such as indicated in Figure 4-7. To find the best distance between the regulating head and the nozzle, other influencing factors were kept at the same values or positions, which were supposed to be in the right region. Then, the effect of this distance was investigated. Initially, when the distance was not set in a correct position, the melted polymer would climb up through the center hole of the regulating rod to sometimes block the channel for the incoming fiber tow, and the polymer could not be sent back to the cylinder. As a result, the experiment could not be continued. A series of operations had to be carried out before the experiment could be resumed. These included cooling the device, disassembling the regulating rod, cleaning the polymer from the channel, and re-installing the rod, etc. But, if the regulating rod was set at the extremum position before the thermoplastic was extruded in the device, the phenomena of melted polymer climbing up should not happen. If in this situation, the polymer still goes up, the effectiveness of the method could not be proven.

A portion of the device is enlarged and shown in Figure 5-3. Figure 5-3A shows the setting position, with the regulating head being set in the lowest position and the end of the regulating head being at the exit of the nozzle to ensure no melted polymer could enter into the regulating head. But in this position, the impregnating time is very short,

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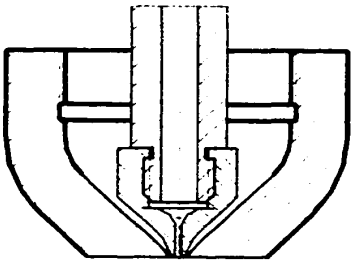

Fig.5-3A The original position.

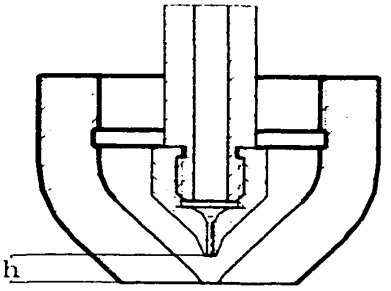

Fig.5-3B The head was ride.

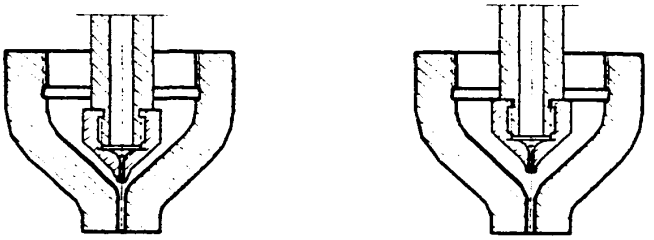

Fig.5-3C The two positions for a long-nozzle with the tapered head.

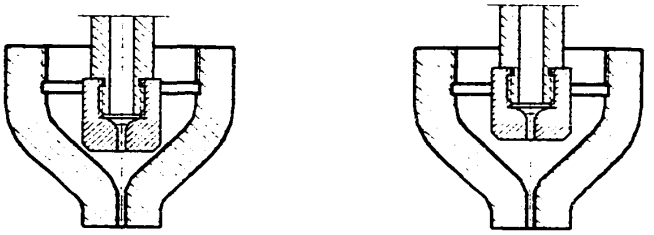

Fig.5-3C The two positions for a long-nozzne with the flat head.

Fig. 5-3 Extremum position experiment.

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because when polymer is extruded outside of the nozzle, no shear stress is exists to assist the fiber impregnation. So, the regulating rod was raised to have the regulating head back in the nozzle. During the experiment, the regulating rod was rotated and raised slowly until the fiber was driven down automatically while no polymer went up through the regulating head. The situation is shown in Figure 5-3B. It was observed that, when h = *1~3* mm, the fiber tow was driven out automatically.

§5-3 "PISTON EFFECT" EXPERIMENT

In the FDM process, a wire made of thermoplastic materials is driven by rollers to work as a piston to push the melted materials out of the nozzle to implement the deposition process. Inspired by this FDM concept, in the early stage of development for CLM, a method was proposed that involved a concept design as shown in Figure 2-14. Several devices have been designed for the concept and a series of feasibility experiments have been conducted.

5-3-1 Experimental Set Up

The proposed CLM process, as indicated in Figure 2-13 and Figure 2-14, is a two-step forming method. In the first step, a towpreg that is a composite wire made of continuous fiber, and a thermoplastic are pre-formed. A towpreg forming device is shown in Figure 5-4. In the second process step, the towpreg is deposited onto a work surface just like in the FDM.

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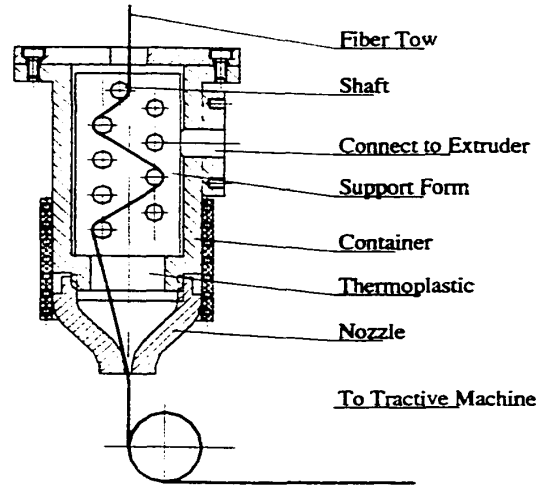

Fig. 5-4 A simple impregnating device.

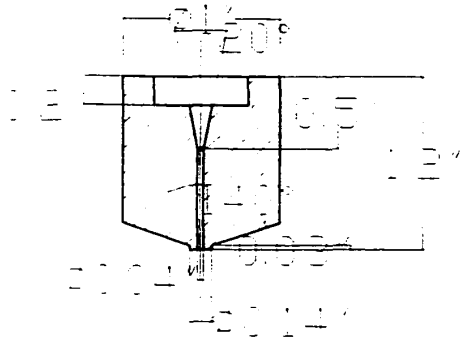

Fig. 5-5A

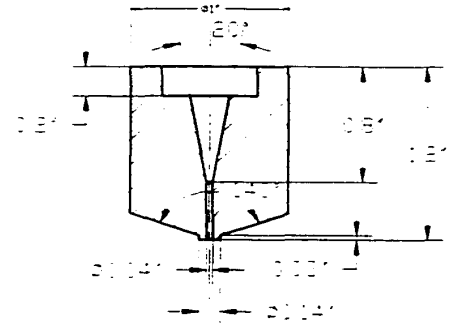

Fig. 5-5B

Fig. 5-5 The nozzles were designed for piston effect.

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The 3D motion device, work-platform, heating and cooling device are considered to be similar to those in the FDM. The selection of a towpreg delivery method and the design of an effective nozzle are the key tasks in the development of the CLM process. Two nozzle shapes and dimensions are shown in Figure 5-5. The differences between the two designs are the lengths of the heating zone, entrance shape of the nozzle and the guiding distance for the towpreg.

The diameter of the towpreg is *1mm*; it is a little bit smaller than the orifice of the nozzle in order to ensure the towpreg could be pushed into the nozzle first. It is considered that the towpreg is heated up to above the resin melting point in the nozzle and the solid towpreg in the rear is used like a piston to push the melted towpreg out of the nozzle.

During the experiment, the towpreg was hard to push into the nozzle. What happened was that when the towpreg was forced to enter the nozzle as shown in Figure 5-6. the towpreg was bent or zigzagged to avoid entering the nozzle. The phenomena were analyzed as follows:

1. The diameter of the towpreg was too small so that the rigidity of this materials is not sufficient for it to serve as a piston.
2. At the nozzle entrance, the towpreg was heated and softened and hence it lost its stiffness.
3. The dimension and shape of the towpreg are not uniform and the fiber tow was not well impregnated.
4. The surface finish of the nozzle orifice is too low to allow the towpreg to go through smoothly.

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Based on these considerations and experimental results, we believed that an improved design was much needed. Two such designs were layed out as shown in Figure 5-7 and Figure 5-8. These two designs were developed based on the following considerations:

1. A cooling sleeve may be used to keep the entrance at room temperature or lower.

2. The exit diameter of the nozzle is half of the entrance diameter. If the exit diameter is *1 mm*, a towpreg of *2 mm* diameter could be used.

3. In the FDM process, the entrance is three times larger than the exit diameter. The larger entrance ensures that the thick wire can be used as a piston, and a small exit is to ensure the precision of the deposited object. But, there are fibers inside a towpreg, and the fiber dimension could not be reduced. Because the towpreg is melted in the melting zone, segment by segment, and is supplied segment by segment, a branched-out orifice could be use to drain out the extra matrix materials.

4. Detailed designs of towpreg dispensing nozzles are shown in Figure 5-8. In order to evaluate the influence of shape and dimension, 12 different nozzles have been designed. The dimensions are shown in Table 5-1 and 5-2 (see Appendix B).

5. The fiber impregnation device was redesigned in order to make the towpreg uniform.

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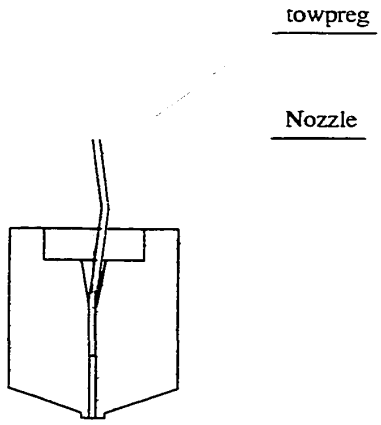

Fig. 5-6A The towpreg was bent.

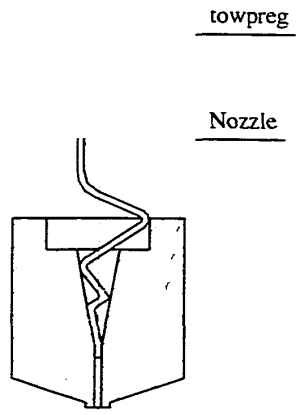

Fig. 5-6B The towpreg zigzagged.

Fig. 5-6 The towpreg can not be pushed into the nozzle properly.

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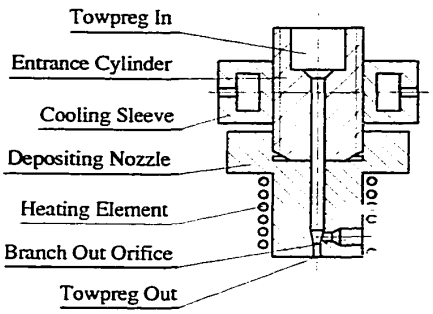

Fig. 5-7A The nozzle core was separated.

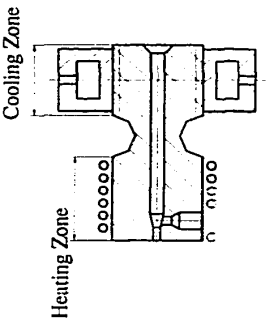

Fig. 5-7B The nozzle core has a groove.

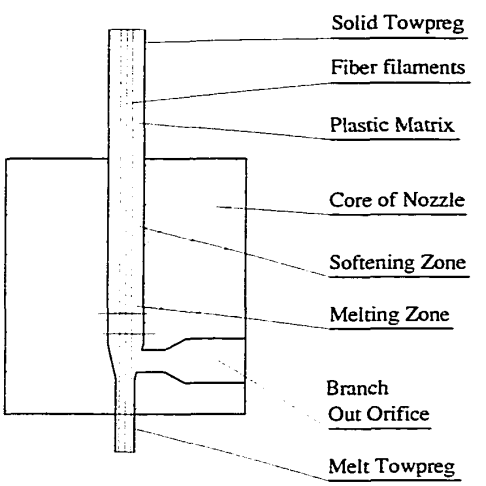

Figure 5-7C A divided exit for extra polymer.

Fig. 5-7 The nozzles designed for the "piston effect".

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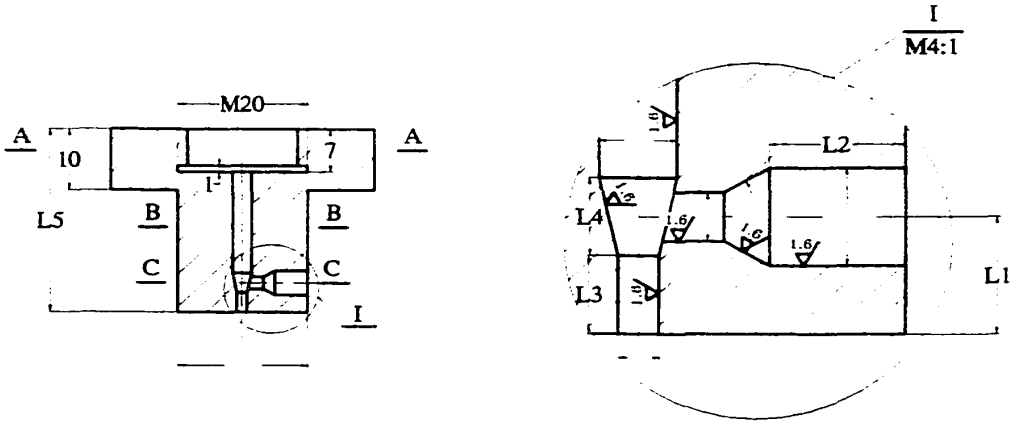

Fig.5-8A.

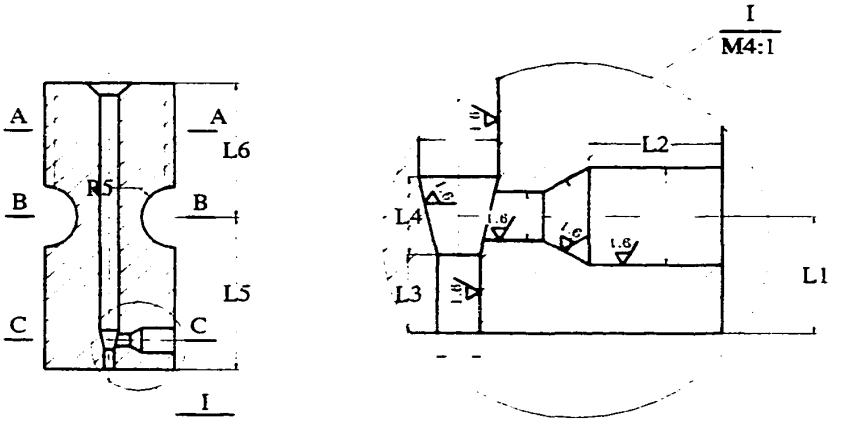

Fig.5-8B.

Fig. 5-8 Detailed Designs of the deposition nozzle shown in Fig. 5-7.

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5-3-2 Results and Discussions

After conducting a series of experiments with these nozzles, we obtained the following results:

1. The towpreg could be melted within the nozzle when the towpreg was carried into the nozzle through a distance.

2. The cooling sleeve cooled the entrance of the nozzle, so the towpreg was delivered through the entrance with enough rigidity.

3. The towpreg was supposed to branch out near the exit of the nozzle; but did not.

These results indicate that a challenge still exists in the case where a solid towpreg is used to provide the piston effect to push the melted towpreg out of the nozzle. Other parameters and shapes could be improved to achieve successful results.

1. The fiber volume fraction of the towpreg could be made smaller. If the diameter ratio of the nozzle entrance to exit is *3:1*, and the fiber volume fraction of the towpreg in the exit of the nozzle is intended to be *50%*, at entrance, the fiber volume fraction at the entrance could not be in excess of *5.5% (1/18)*.

2. The temperature of the nozzle could be raised to decrease the needed heating distance in which the towpreg is touched with the nozzle. The smooth surface finish of the bores of the nozzle could be improved to decrease friction.

3. For a large structure or part, the towpreg could be slightly larger, but still keeping a reasonable precision. In this case, the nozzle exit diameter

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could be made as large as the entrance, and the shape of the nozzle could be made very simple. The effect of the nozzle is only for heating up and guiding the towpreg to a certain location. Then, the diameter of the towpreg does not have to be reduced and the towpreg could be pushed straight through the nozzle.

§5-4 "AUTOMATIC EXTRUSION" EXPERIMENT

In Chapter 2, an Active Materials Supply method was introduced. See Figure 2-20 and Figure 4-7. The advantages of the one-step method have been analyzed in Chapter 2 and feasibility testing has been done successfully as discussed in §5-2. In order to find the best forming parameters, a numeric simulation procedure has been used to imitate the process of the one-step method with the results being analyzed in §4-3. To validate the method and to find the best range for the important parameters, a device that simulates a real system was set up and investigated.

5-4-1 Experimental Set Up

The experimental set-up was shown in Figure 2-20. The 3D motion device was not installed because the experiment was for testing the concept of automatic push-out in order to integrate the two processes, impregnating and depositing, into one step.

1. Pressure Control: The vessel pressure value is considered as an important parameter for this method, because the flow shape of the melted polymer fluid is influenced by the pressure directly. The extruder used in the

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present study was a Killion extrusion machine (*Series Number 10881*), the pressure was regulated by controlling the volume of the extruding material. A fine-tuning resistor is used to control the volume. Actually the pressure value depends on the load also. A digital pressure meter is installed on the connector between the extruder and the impregnating and forming device. The displayed number approximately reflects the pressure value inside the device. At a stable fluid flow, a value of *150 Psi ~ 250 Psi* was shown on the display screen.

2. Temperature Setting: Temperature is also considered as an important parameter, because the viscosity μ of the polymer fluid depends on temperature. The effect of viscosity is complicated for a non-Newtonian fluid. For shear thin plastic materials, its viscosity is influenced by the shear stress also. Viscosity has two effects on the movement of a towpreg in this method. If the viscosity increases, the shear stress near the exit of the nozzle could also increase. That is an advantage for pushing automatically towpreg out. But if the viscosity μ is increased too much, the fiber could not be impregnated very well or could not be impregnated during a short period.

The above considerations led us to set the temperature at a certain value, which did not change during the experiment. A temperature of was selected *360°F* for the extrusion machine, and the temperature setting for the device was *370° F*.

3. The distance h between the regulating head and the nozzle: the distance could change continually (See Figure 5-4). Determination of the distance h was one of the targets for the experiment and it was set at three different values to evaluate its effect.

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4. Shapes and dimension of the nozzle: The shape of the nozzle was not varied by much. But the ratio between the diameter and depth of the nozzle orifice was considered an important parameter because the stress distribution depends on the ratio:

$$R = \frac{D_n}{L_n} \qquad (5-2)$$

where: D_n = diameter of the nozzle and

L_n = depth of the nozzle.

In the experiment, R was set at eight different values, respectively.

5. The shape and dimension for the regulating head: Two different head shapes were designed in order to determine a preferred shape. The two designs are shown in Figure 5-9 and 5-10.

6. The fiber volume fraction: Each Kevlar fiber tow has *12,000* filaments and could not be separated, but several tows could be combined together. In the experiment, *1, 2, 3,* and *6* tows have been employed in *4* separate runs. The cross sectional area for each tow is around *1.53* mm^2. The volume fraction is determined with the number of fiber tows and the orifice diameter of the nozzle.

5-4-2 Results and Discussion

This experiment had many different effects. If each and every combination of items *3 - 6* above is evaluated, there would be *128 (4 × 4 × 4 × 2)* different experiments that must be done, and it could take a long time. Instead, only representative combinations have been studied, which led to several significant findings or observations.

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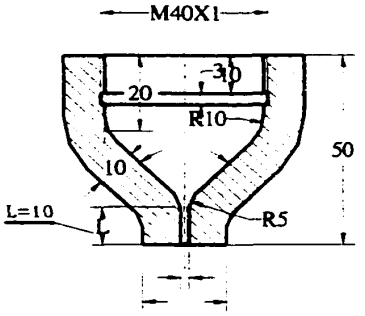

Fig.5-9A The long nozzle.

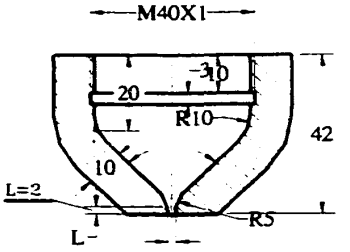

Fig.5-9B The short nozzle.

Fig. 5-9 The dimensions of the long and short nozzle.

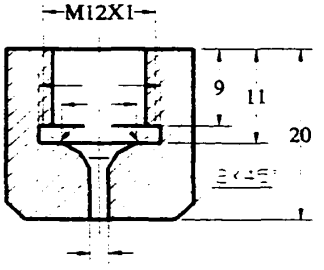

Fig. 5-10A The flat head.

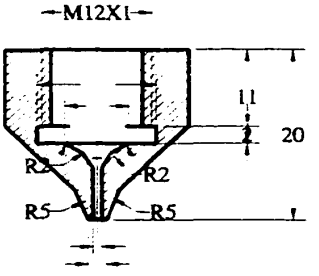

Fig. 5-10B The apex tapered head.

Fig. 5-10 The dimensions of the regulating heads.

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The conditions for these experiments are listed in Table 5-3 (see Appendix C) and key observations shown are as follows:

1. The proposition that the towpreg could be delivered automatically was achieved under certain situations.

2. Some positions and parameters are not critical; a stable fluid flow could be established under a wide window of parameter values. For example, the distance between the regulating head and the nozzle was discussed before; actually the head was initially set outside of the nozzle, as shown in Figure 5-10. In this position, the fiber was readily guided through the device and it was ensured that the melted polymer would not go up into the regulating rod. When the regulating head is raised slowly, the melted polymer should be squeezed out by the vessel pressure. At the beginning, a gap between the head and the nozzle was small, so not much polymer was extruded out, and there was not enough force to push the towpreg out of the nozzle just yet. But, when the head was raised, the gap was larger and the volume of polymer flow was also larger. When the distance reached a certain value h, the polymer flow had enough shear stress to drive the towpreg out. Depending on the different ratio R, the distance h could be varied over a wide range. Some times, even when the head was still outside of the nozzle, the towpreg was driven to start moving.

3. The established stable flow: Once a stable flow is established, even if some conditions are later changed, the flow remains stable.

For example, when the head was raised to a distance h, say $h = 3mm$, the towpreg was driven downward. During this situation, if the head is raised up by

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additional *3~5 mm* more, no polymer is going up through the regulating rod. In another direction, if the head is lowered down by *1~2 mm* more, the towpreg was still driven downward by the polymer flow.

But, if the head was set at the same stable position $h = 3mm$, before the polymer was extruded, then even after the polymer was extruded, with the pressure slowly getting larger, the towpreg was not driven down and some polymer was going up through the regulating rod.

4. The ratio *R*: The ratio *R* between the diameter and the depth of the nozzle orifice was an important parameter. For the polymer fluid flow, the larger *R* is the more stable the flow is. But if *R* is smaller than a certain value, say $R<0.5$, a stable flow state is never reached.

5. The minimum diameter of the nozzle: In this experiment, the nozzle bore diameter ϕ was selected at $\phi = 4mm$, $\phi = 2.5mm$, $\phi = 2$, and $\phi = 1mm$, respectively. If $\phi > 2mm$, with the different depth of the nozzle and the ratio *R* not smaller than *0.5*, a stable flow is observed.

6. The fiber volume fraction: The fiber volume fraction did not influence the stable flow too much. But, in general, when the fiber volume fraction is larger the flow is more stable.

7. The regulating head: the shape of the regulating head did not have a significant effect on the stable flow. A flat head shown in Figure 5-10A could not be set outside of the nozzle. If the flat head was set at the lowest position in the beginning, the bottom edge of the flat head was touched the nozzle inside surface to

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be service as the function of a seal, the polymer did not goes up. Then a similar operation that like conducted in the apex tapered head could establish a stable flow.

5-4-3 Design Features and Further Improvements

The "two in one" method (impregnation and deposition being integrated in one process step) was demonstrated by the experiments as a viable method. Compared with the "two in two" method (impregnation and deposition being conducted in sequence), the features of the "two in one" method are summarized as follows:

1. Advantages:
    a. The process is simple, and the time and cost will be saved.
    b. It is an Active Materials Supply method. The forming condition of the current layer being deposited is not influenced by the quality of a previous layer.
    c. The deposition speed is higher.
    d. The towpreg diameter is equal to the diameter of the nozzle bore. When the depositing toolpath turns at an angle or follows an arc, the errors analyzed in §3-3 and §3-4 could be neglected.
2. Disadvantages:
    a. A pressure is requires to drives the towpreg out of a vessel, but the pressure is hard to control, especially at the beginning of the forming process.

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b. The bore or orifice diameter of the nozzle could not be too small and the deposited towpreg is somewhat thick. As a result, the part precision could not be high.

3. Improvement:

a. Redesign the "two in one" devices. The volume of the cylinder could be reduced, and a flow balance should be maintained; i.e., the polymer-entering rate equals to the polymer-exiting rate. The cylinder, the shape of the regulating rod, and other parts could be optimized to let the polymer flow more fluently and to let no extra polymer cumulate inside the cylinder.

b. The operating parameters of the extruder machine could be improved. The volume flow rate could be smaller and steadier.

c. One should select different matrix materials to impregnate Kevlar quickly and completely during a short period of time.

At the end of this section, another design will be introduced, which is supposed to improve the stability of the "two in one" method. A concept design is depicted in Figure 5-11. The melted polymer is supplied into a container by an extruder machine, which is used for shear thinning the viscosity μ. The container is divided into a top region and a bottom region by an annular seal that is made of rubber or some material that could not damage the fiber. In the top region, the pressure is higher than the atmospheric pressure. In the bottom region, there is a circulating pressure region. An annular Pulse Air Bag could be blown up or shrunk down by a circular pressure source to induce a circular pressure in the container. The annular seal could be controlled to open and close just like

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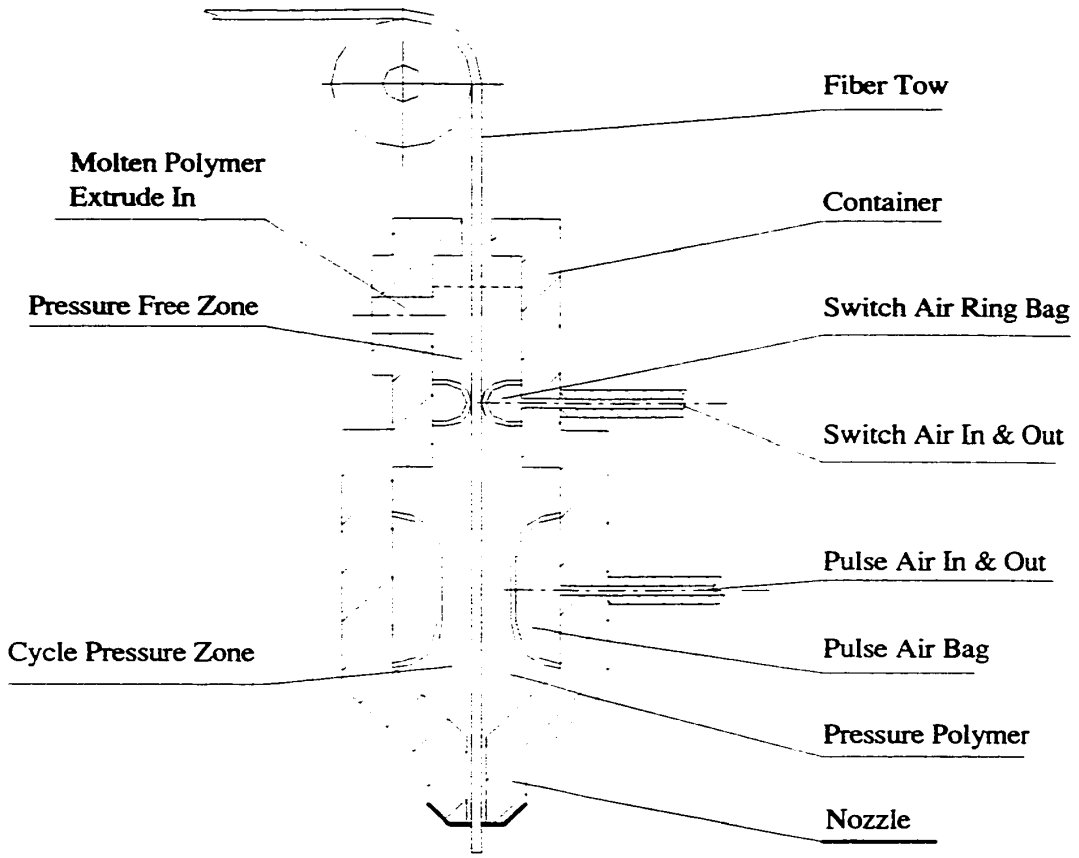

Fig.5-11 A proposed pulsating air method.

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a door could be opened and closed. When the door is open and the Pulse Bag shrinks, a negative pressure is induced in the circular pressure region. Then the fiber tow and matrix materials, which are in the pressure free region, could be drawn into the circulating pressure region. When the door is closed and the Pulse Bag is blown up, a positive pressure is induced in the bottom region. The fiber is gripped and the polymer in the bottom region could not go up but could go out of a nozzle due to the positive pressure.

If the frequency of the circulating pressure is *100~ 200* times per second, the continuous towpreg will be delivered smoothly. Actually, other means could be employed to get the same function.

§5-5 SYSTEM DEVELOPMENT OF THE CLM WITH SELF-ANCHORING

The concept of self-anchoring was introduced in §2-5. Potential of this method capability were analyzed in §3-2 ~ §3-4, and the forming mechanism was studied in §4-2. A system for this forming method has been developed, and various simple parts and structures have been produced with this system.

This is a two-step method with thermoplastic materials: a towpreg making system was used to form the towpreg, a semi-finished composite product. Then, another machine system was used for deposition process.

5-5-1 The Towpreg Making System

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The towpreg forming system is schematically shown in Figure 5-12. Four main units were lined up from right to left. An impregnating die fixed on the extruder machine was the first unit. A cooling water trough and a position trimmer constituted the second unit. A drawing machine and the winding machine were the third and fourth unit, respectively.

A towpreg made with the unsophisticated device mentioned before (See Figure 5-4) had many defects:

1. The geometric defects:
    a. The diameter of the towpreg was not uniform.
    b. Defects of creases, tumors, and ripples were induced sometimes because the extruder-supplied pressure fluctuated, and the impregnating device was designed roughly.
2. Impregnation defects:
    a. The fiber tow was not fully impregnated with the matrix in some sections because the viscosity μ was too high. The affinity between the fiber and the matrix was low.
    b. The fiber was not uniformly soaked.
3. Eccentric defect: The fiber tow filaments were not well dispersed in the matrix, even in segments where the fiber was soaked completely. This defect happens especially when the fiber volume fraction is lower. The filaments were not located at the center of the towpreg, as shown in Figure 5-13. The eccentric defect shown in Figure 5-13A has the characteristic that the impregnated filaments were pulled to one side of towpreg and,

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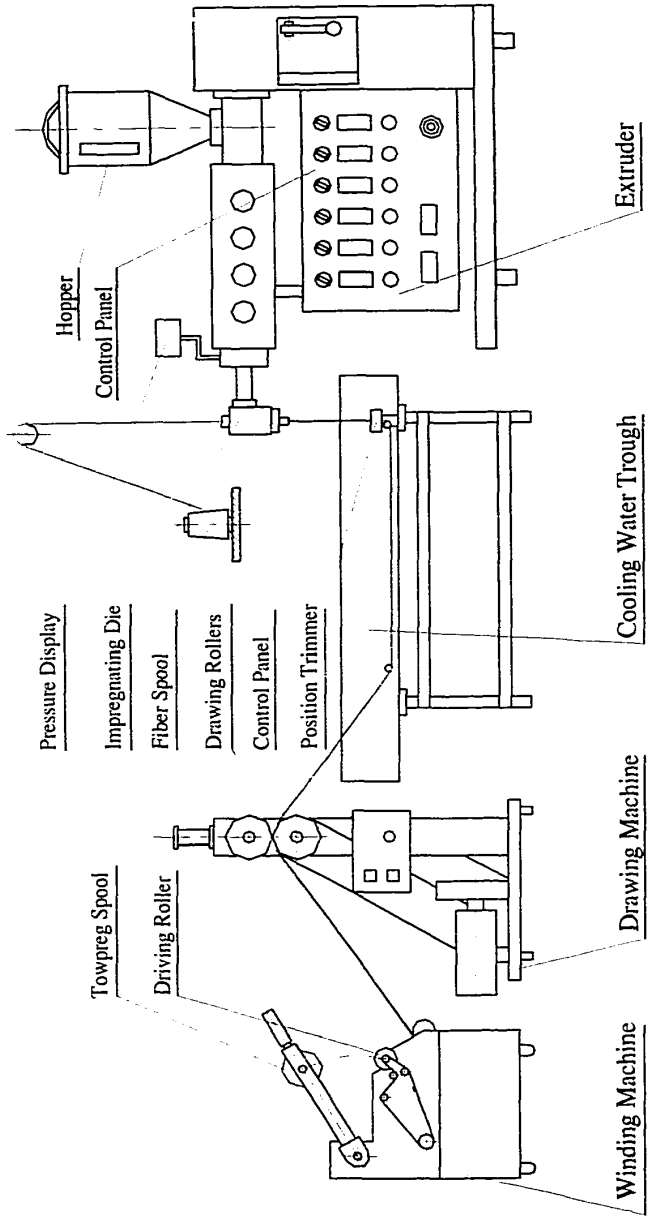

Fig.5-12 The towpreg forming system.

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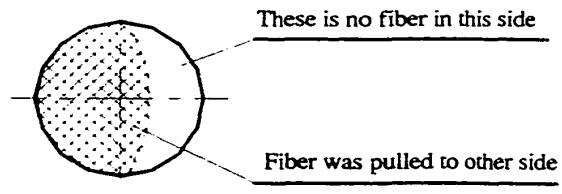

Fig. 5-13A A cross-section of the towpreg.

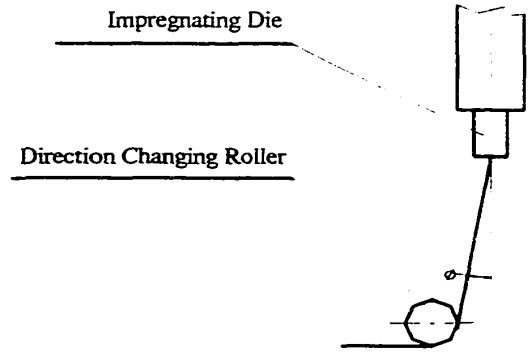

Fig. 5-13B The device was alignment properly.

Fig.5-14 An analysis diagram of the towpreg eccentric.

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in another side, there was no filament.

A cause for the defect was that an angle ϕ existed between the impregnating die and the drawing device. The angle ϕ is shown in Figure 5-13B. In order to eliminate the angle ϕ, a position trimmer was designed, fabricated, and installed to align the towpreg line with the central axis of the impregnating die. The position trimmer is shown in Figure 5-14. Where the position trimmer is located in the whole impregnation system can be found in the Figure 5-12. The trimmer was fixed in the water trough first, and its position was roughly adjusted. Next, the core was aligned with the impregnating die by meticulously turning the three core-adjusting pins in order to ensure the towpreg be pulled concentrically with the impregnating die.

The device in the system was the impregnating die, which is shown in Figure 5-15. The die was designed and built based on the experience and knowledge acquired from previous experiments on polymer fluid flows. The design principle and the required calculations for the impregnating die are too complicated to be described in a short paragraph [75,76].

The main parts, which are the guider tip, and the cores of forming die, were designed into different dimensions and shapes so that the effects of shape and dimension could be readily accommodated. With this system, towpreg samples with a dimension range from *0.8 mm* to *2 mm* have been successfully formed with different forming dies. The linear forming speed was from *20* to *50* meter per minute (*20m/min. ~ 50m/min*).

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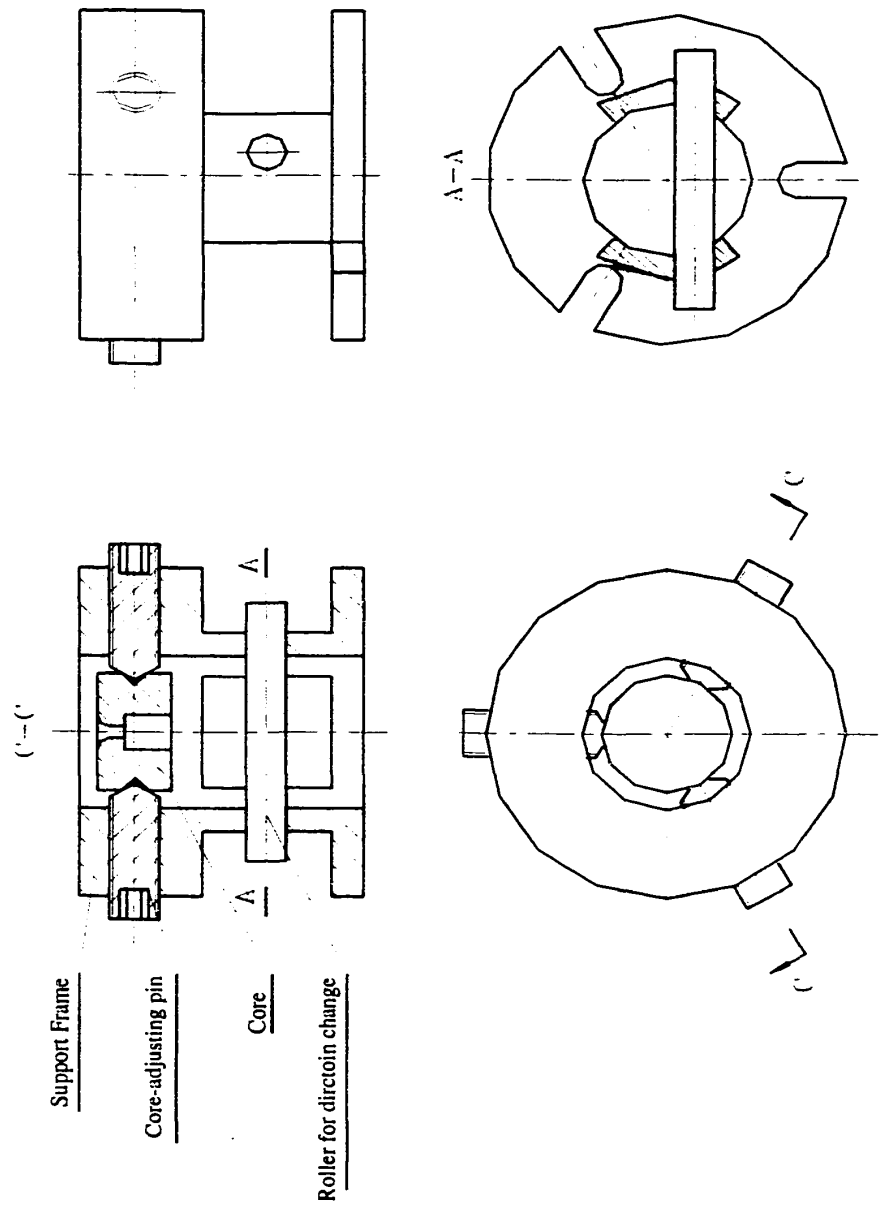

Fig. 5-14 The towpreg alignment device.

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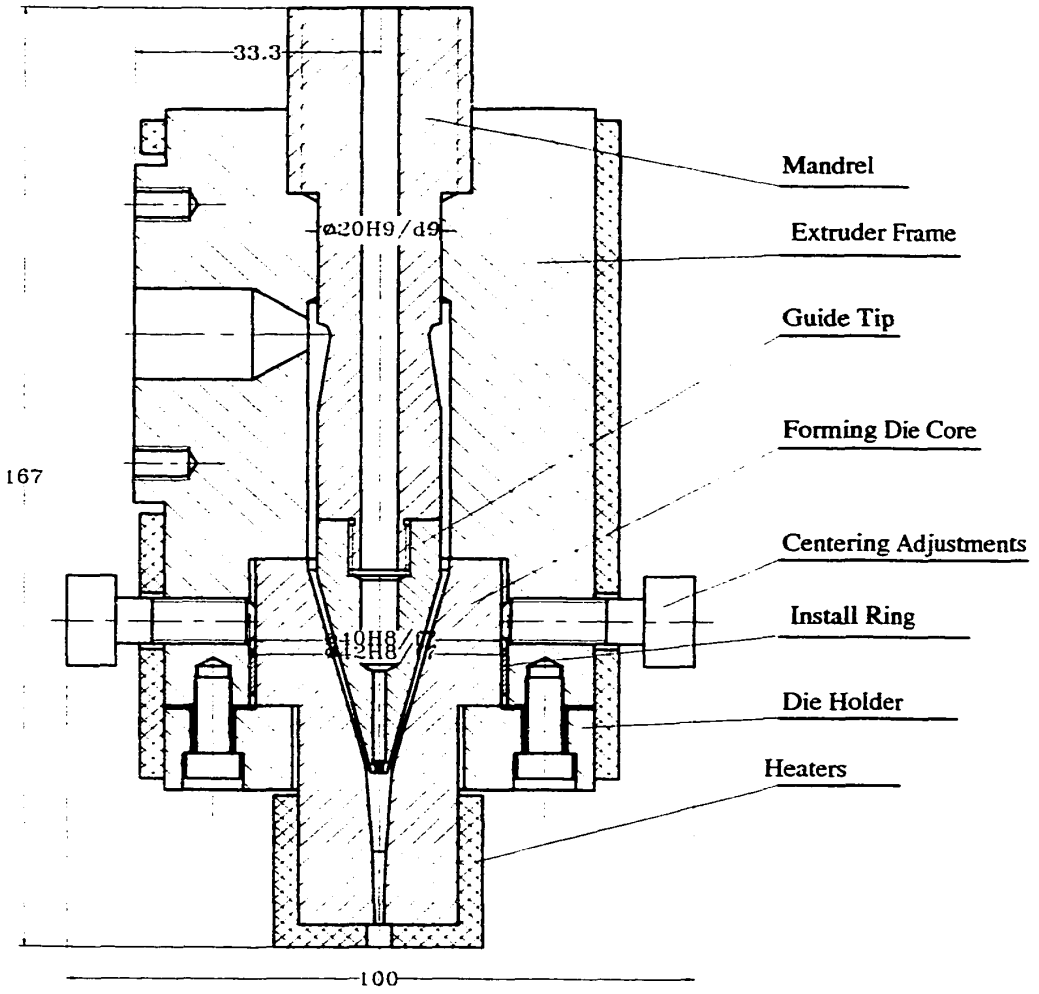

Fig. 5-15 The towpreg forming die assembly.

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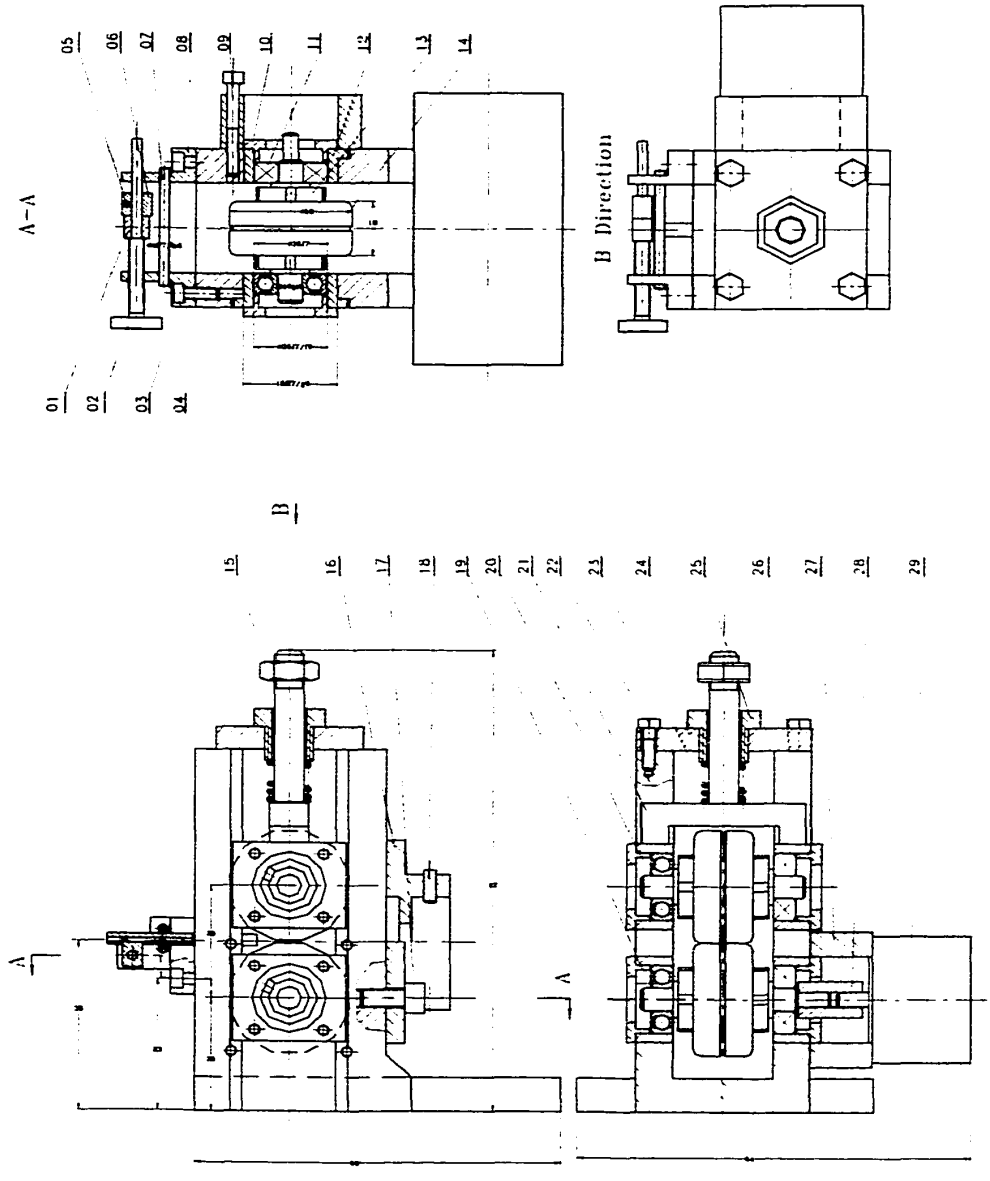

Fig. 5-16 The towpreg deposition device.

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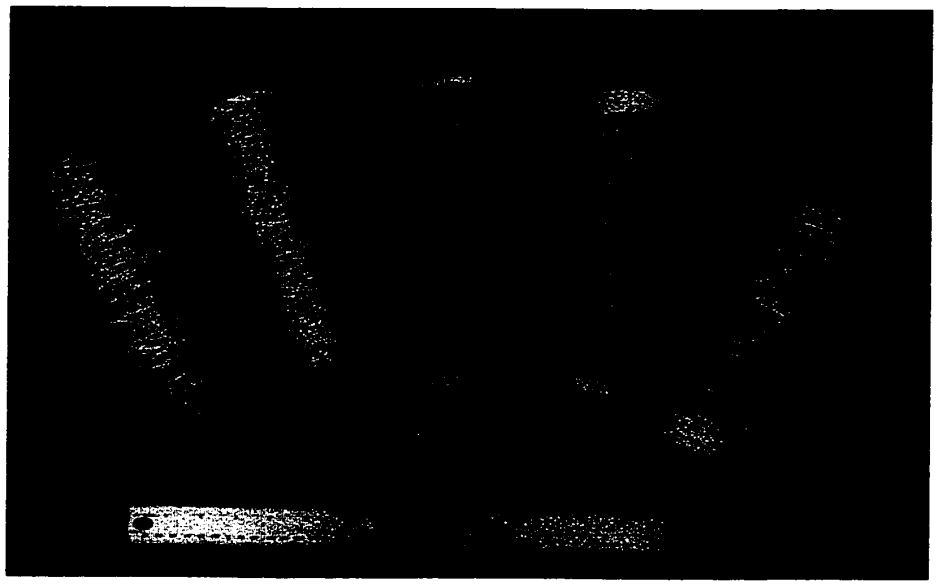
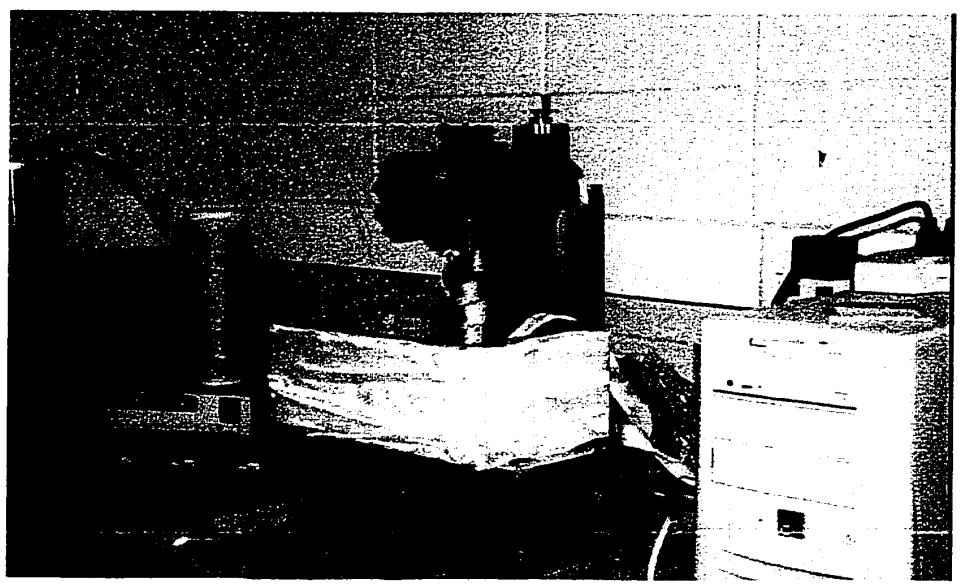


Picture 5-1 Formed towpregs.



Picture 5-2 One of the CLM system.

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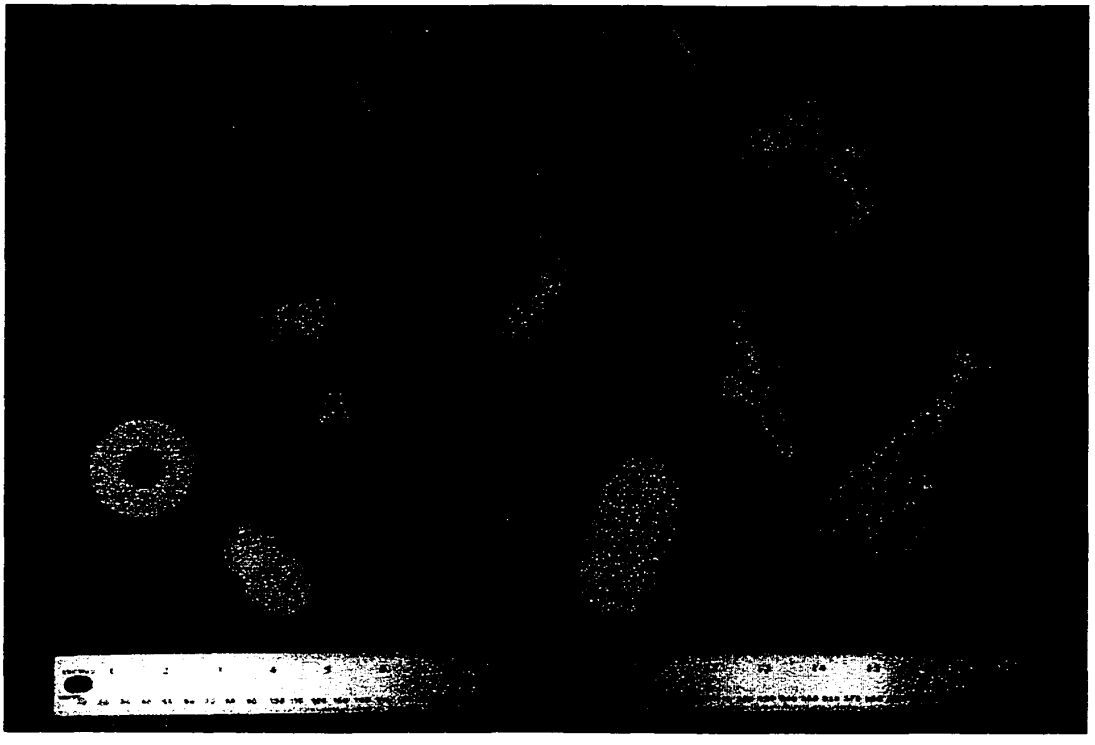

Picture 5-3 Parts made by the CLM system.

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Picture 5-1 shows the towpreg produced by this system. The towpreg was found to satisfactorily meet the subsequent deposition requirements.

5-5-2 Depositing Systems

A depositing system is shown in Picture 5-2. The deposition former, a main unit of the system, is shown in Figure 5-16. The list of parts table is given in Appendix D. The structures produced by this system are shown in Picture 5-3.

§5-6 EVALUATION OF MECHANICAL PROPERTIES

The mechanical properties of selected parts produced by the CLM method were measured and compared with those of corresponding parts produced by a traditional composite fabrication method, compression-molding.

5-6-1 Three Point Bending Test

To measure the elastic modulus of a composite material, on may choose to conduct the three-point bending test as recommended by ASTM. The test was done with a universal testing machine. The three-point bending set up is shown in Figure 5-17. Delamination strength is a very important index for a part or structure that is made of a

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composite material. So, the delamination strength was tested with a three-point bending mode. This test is also referred to as a "transverse bending" method.

5-6-2 Specimens from the CLM

A structure like a box formed by the CLM process is shown in Figure 5-18. The structure was built line by line and layer by layer with the self-anchoring method. The towpreg was deposited continuously, so each layer of this structure was unidirectional. The specimen was cut off from the structure. Where these specimens were cut from and the orientations of the specimens are shown in Figure 5-18B and 5-18C.

5-6-3 The Specimens from Compression-Molding (Hot Press)

In order to evaluate the mechanical properties of a part made from the CLM, a baseline structure should be made with a common composite method. The flow chart for this process is pictured in Figure 5-19. In this forming process, a slab was made from the same fiber and matrix, which was used in CLM, and a fiber volume fraction was almost maintained at the same percentage. Shown in Figure 5-22 A, B and C, this process is called FWPM (Filaments Winding and Press Molding). This process begins with the formation of laminar layers or " prepregs" by a filament winding type procedure, which is followed by prepreg cutting and lay-up.

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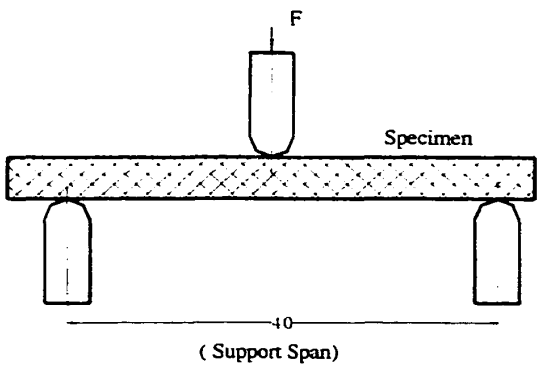
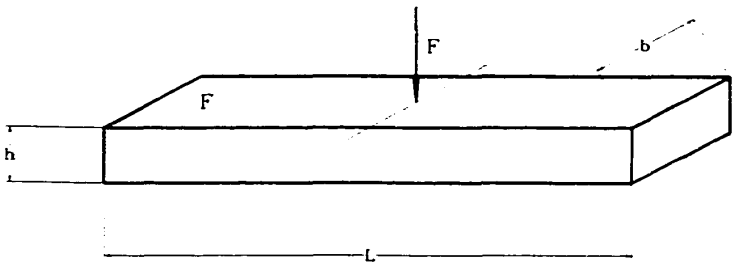


Fig 5-17A Three Point Bending.



For flexural modulus and strength:	For delamination testing:
L=60 mm	L=50 mm
h=6 mm	h=10 mm
b=10 mm	b=12 mm

Fig 5-17B Specimen dimension.

Fig 5-17 The three point bending set up.

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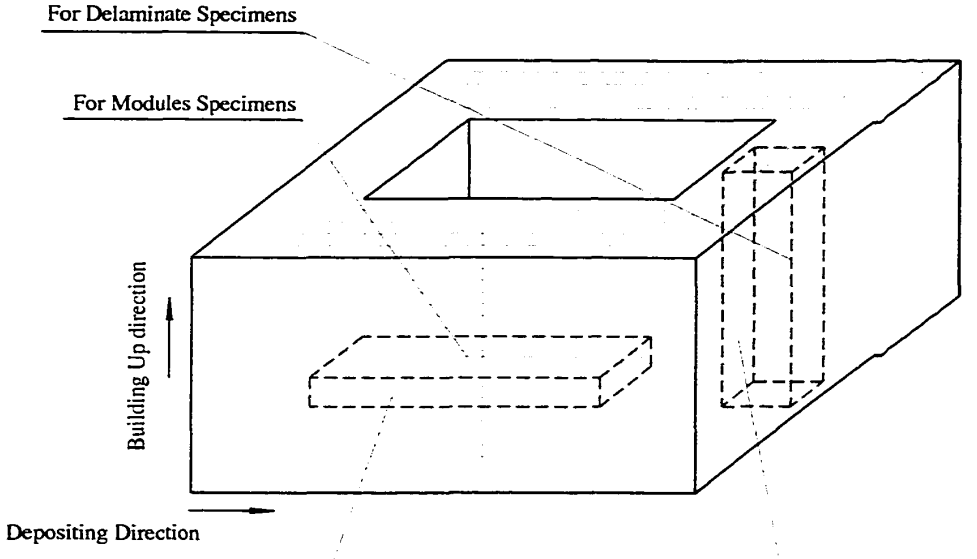

Fig.5-18A The specimens cutting off location.

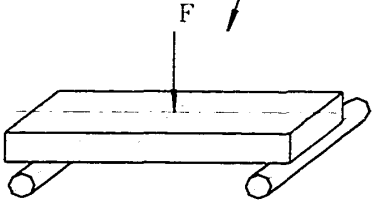

Fig.5-18B Modules test.

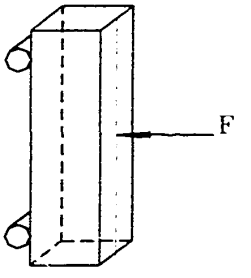

Fig.5-18C Delamination test.

Fig.5-18 The orientations of the specimens

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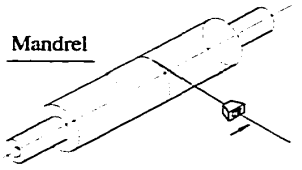

Fig.5-19A Laminar layers made by Filament Winding.

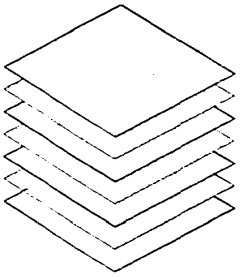

Fig.5-19B Layer-up with unidirection.

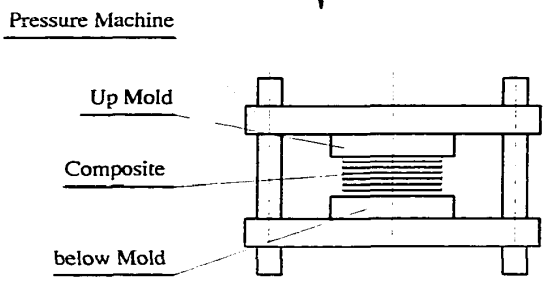

Fig.5-19C The hot press.

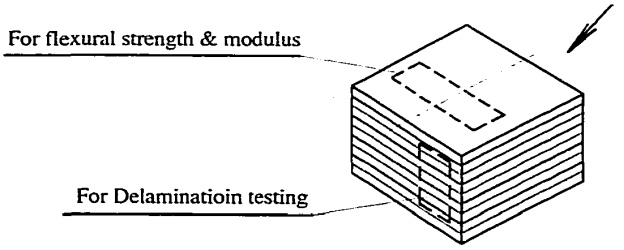

Fig.5-19D Specimen cut off.

Fig.5-19 The Specimen made by compression molding.

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The laid-up prepreg assembly, placed in a mold, was then heated to a temperature above the melting point of the thermoplastic matrix, compressed under a pressure, and then allowed to solidify to form a slab. Then, specimens with proper fiber orientations and rectangular dimensions were cut off this slab.

5-6-4 Three-Point Bending Test for Flexural Strength and Modulus

Flexural properties and delamination strength of both CLM and FWPM samples were measured by using the three-point bending and transverse bending test, respectively. Five specimens were tested for each sample to get an average value.

The calculations for elastic modulus and flexural strength are given by Equation 5-2A and 5-2B:

$$E_B = \frac{\sigma}{\varepsilon} = \frac{W^3 F}{4\, d\, b\, h^3} = \frac{W^3}{4\, b\, h^3}\left(\frac{F}{d}\right) = \frac{W^3}{4\, b\, h^3}(m) \qquad (5\text{–}2A)$$

$$\sigma_{fl} = \frac{3\, W\, F_{max}}{2\, b\, h^2} \qquad (5\text{–}2B)$$

where: E_B = modulus of elasticity in bending, P_a,

m = slop of the load-deflection curve,

W = support span,

b = width of beam,

h = depth of beam,

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d = deflection of the beam,

F = Force, N.

A record of the 3-point bending test is shown in Figure 5-20. According to the strain-stress curves, the modulus can be solved by Equation 5-2. As shown in Figure 5-20A and 5-20B, five specimens were tested for each of the CLM and FWPM samples, respectively. The modulus was an average value of the five specimens.

According to the data and a simple calculation, the modulus is:

For CLM: $E_{CLM} = (E_2 + E_3 + E_4 + E_5 + E_6)/5$

$= (1594.3+1151+1460+1815+1675)/5=1539$ MPa

For FWPM: $E_{FWPM} = (E_7 + E_8 + E_9 + E_{10} + E_{11})/5$

$= (1611+1276+1506+1171+1130)/5=1249$ MPa

Where E_{CLM} = modulus for the CLM sample,

E_{FWPM} = modulus for the FWPM sample,

$E_2, E_3, \cdots\cdots$ modulus for each specimen.

This result could be normalized with respect to the fiber volume fraction. The modulus of a composite is a function of the fiber volume fraction:

$$Ec = E_f \times V_f + E_m \times (1- V_f) \qquad (5\text{–}3)$$

where Ec = modulus of composite

E_f = modulus of fiber, for Kevlar–49, 125GPa,

E_m = modulus of matrix, the range being around 1~6 GPa for most thermoplastic materials,

V_f = fiber volume fraction.

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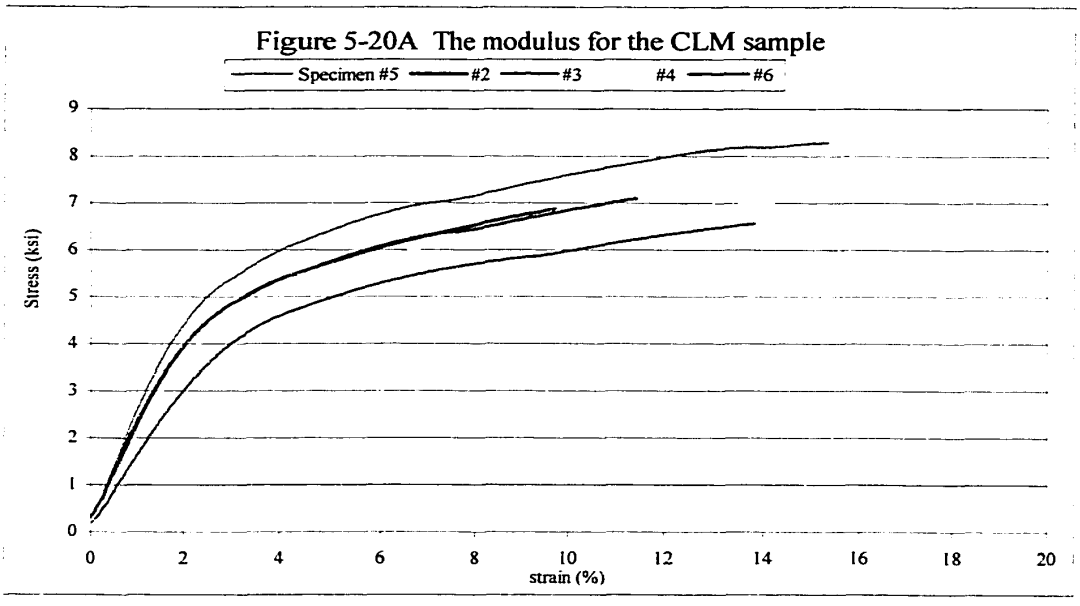

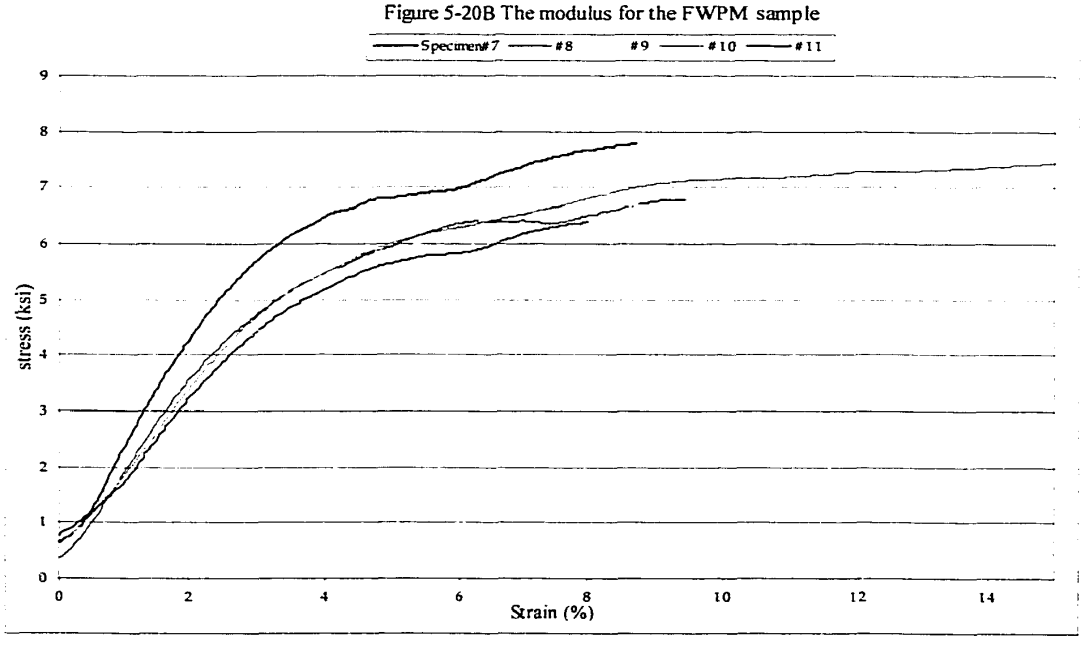

Figure 5-20 Flexural test results.

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Figure 5-21A Delamination test for the CLM sample

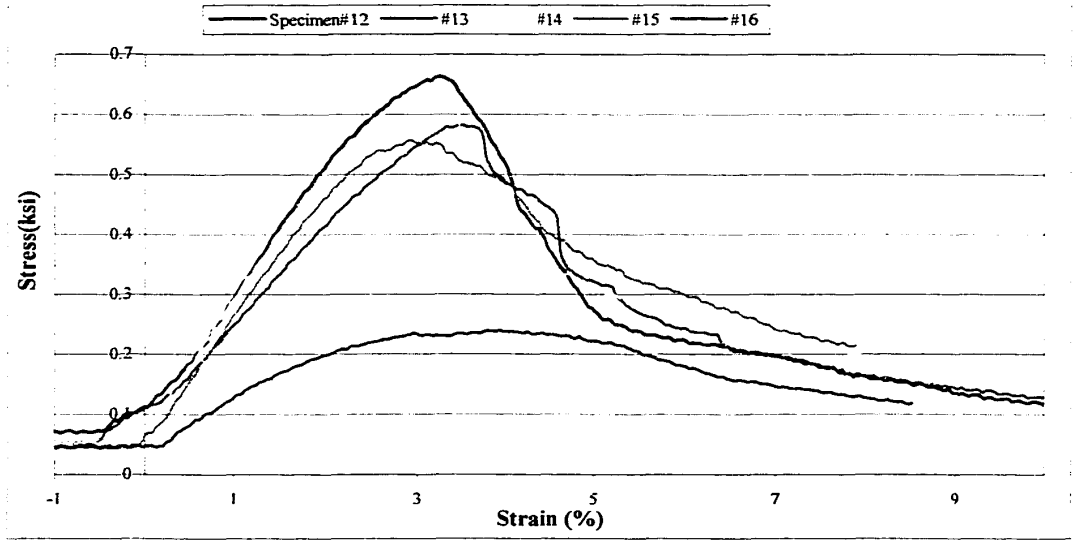

Figure 5-21B Delamination for the FWPM sample

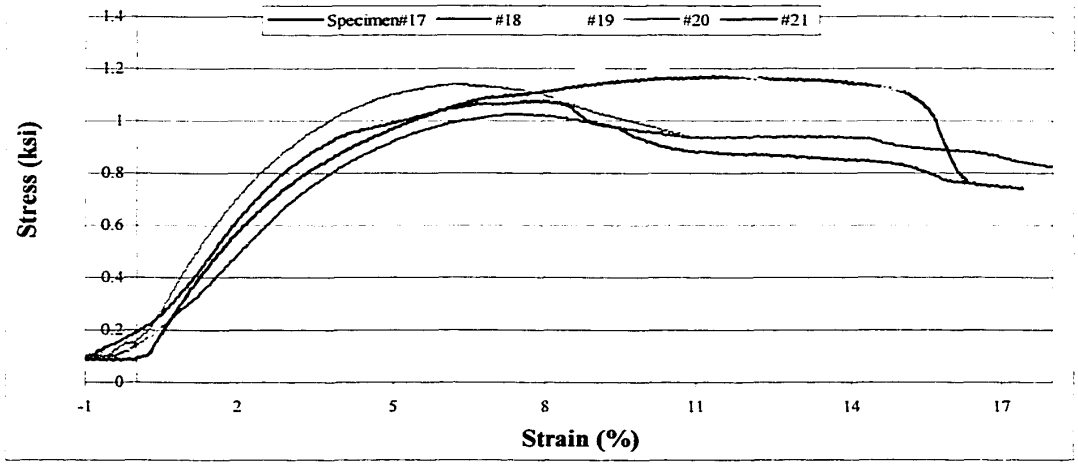

Figure 5-21 Delamination test results.

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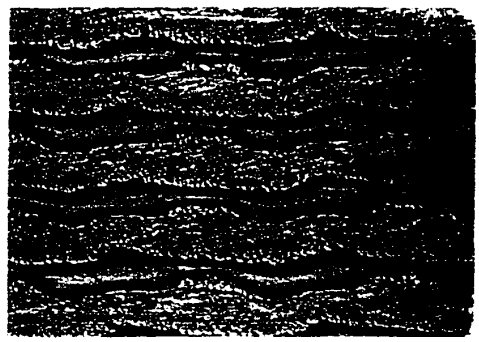
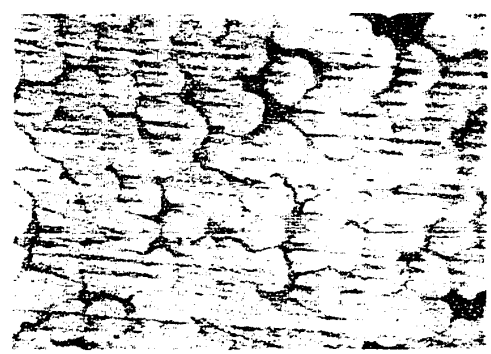


Picture 5-4 A CLM sample, *40X*
"fiber phase" was *65%* .

Picture 5-4 B FWPM sample *40X*
"fiber phase" was *78%*.

Picture 5-4 C CLM sample *400X*
Inside the "fiber phase", the fiber was *94%*.



Picture 5-4d FWPM sample *400X*
Inside the "fiber phase", the fiber was *94%*.

Overall fiber volume fraction in the CLM sample: 60%,
Fiber volume fraction in the FWPM sample: 80%.

Picture 5-4 Pictures made by a metalloscope to analyze the matrix volume.

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Equation 5-3 can be rewritten as:

$$Ec \approx E_f \times V_f \qquad (5\text{–}4)$$

According to a microscopic analysis, the fiber volume fraction is V_f = 78% in the FWPM specimens and 59% in the CLM specimens (Picture 5-4). From Equation (5-4), we realize that the fiber fraction of the FWPM specimen is higher than that of the CLM specimen by *20%*. So, if the fiber fraction in CLM process is the same in FWPM process, the modulus would have been increased by *20%*. After the revision, the modulus based on a 78% fiber volume fraction basis could be:

$E_{CLM} = 1847$ Mpa

$E_{FWPM} = 1249$ Mpa

The modulus of the CLM process is larger than that of FWPM by almost 30%.

5-6-5 Transverse Bending Test for Delaminatoin Strength

The ability against delamination is defined as:

$$\sigma_{flex} = \frac{3\,L\,F_{max}}{2\,b\,h^2} \qquad (5\text{–}5)$$

where: σ_{flex} = the max stress,

L = support span

b = width of beam,

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h = depth of beam,

F_{max} = Maximum Force.

A record of the delamination testing is shown in Figure 5-21. An average value for the CLM sample is:

σ_{flex} = 3.66 Mpa

For a transverse test, the composite modulus

$$F_c = F_m = F_f$$
$$\sigma_c = \sigma_m V_m = \sigma_f V_f$$
$$\sigma_{c\,Max} \approx \sigma_m V_m \qquad (5\text{–}6)$$

where V_m = matrix volume fraction,

V_f = fiber volume fraction,

σ_m = matrix stress,

σ_f = fiber stress,

σ_{cMax} = max composite stress.

Revising the value with the fiber volume fraction yield an answer of:

σ_{flex} = 3.66 × (1+20%) = 4.39 (Mpa)

For FWPM process:

σ_{flex} = 7.76 (Mpa)

The ability against delamination of the FWPM sample is larger than that of the CLM sample by *43%*.

5-6-6 Result and Discussions

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1. Elastic modulus of the part that is made from the CLM process is higher then that of the part made by the FWPM process.

2. The ability against the delamination is much lower for the CLM sample. From Picture 5-4A, we can see that a pure matrix interface is placed in each layer, and the mechanical properties of the interface are lower. During the CLM deposition procedure, very little pressure was exerted on the towpreg layers resulting in poorer contacts between the fiber and the matrix.

§5-7 PROPOSED FUTURE WORK

1. To optimize the existing system and method.

2. To develop a forming method to deposit the towpreg not only in the X-Y plan but also in the Z direction.

§5-8 CHAPTER SUMMARY

1. Experimental data have further validated the viability of the proposed CLM process.

2. The two primary forming methods in CLM have been tested and proven very effective in forming a part layer by layer.

3. The self-anchoring method and the required system have been developed. Composite parts have been successfully made using this method.

4. The mechanical properties of the part, were tested and analyzed.

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CHAPTER 6 CONCLUSIONS

A novel solid freeform fabrication (SFF) technology, Composite Layer Manufacturing (CLM), has been developed. The CLM process is capable of building a continuous fiber reinforced composite part on a point-by-point and layer-by-layer basis. This computer-automated process converts a computer-aided design file of a part directly into a 3-D physical object of a complex shape and good mechanical integrity. Most of the conventional SFF technologies are limited to the fabrication of a concept model, a prototype, or a master pattern for casting and, therefore, are at best considered to be for "rapid prototyping". In contrast, the present dissertation study has laid down a solid foundation for a new SFF technology that provides "rapid tooling" as well as "rapid manufacturing" capabilities. Although the present study, due to time constraints, has been limited to the fabrication of polymer matrix composites, the same process can be readily adapted for the fabrication of other types of continuous fiber reinforced composites.

Specifically, in the present dissertation study, the technical feasibility of the CLM process has been demonstrated with a bench-top CLM machine constructed that is capable of fabricating both thermoplastic and thermoset resin matrix composites. This CLM machine rapidly dispenses, deposits and consolidates pre-impregnated fiber tows or towpregs to form a 3-D advanced composite component of a complex shape without

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using a mold or process tooling. Two CLM forming methods, the "self-anchoring" and the "automatic-extrusion", have been designed and developed based on the selection and evaluation of various forming theories.

Related part forming theories and material selection issues for the CLM have been studied during the earliest development stage of the CLM. Several innovative process strategies have been proposed and tested, including "active and passive material supplying", "one step forming method", and "multiple step forming method". These strategies were introduced to help categorize and create a deposition method for different matrix materials. Over ten CLM forming methods have been designed and analyzed. Based on comparison comparisons of their advantages, shortcomings and feasibility, two designs were considered as part of the best forming plans for CLM and were further investigated.

The sources, values, and governing factors of process errors in the CLM technology have been analyzed and evaluated. A series of equations have been derived to evaluate the magnitude of errors in different forming situations. When the parameters of the towpreg, nozzle and toolpath are inputted to these equations, the error could be calculated and the error diagrams could be drawn. The method for *a priori* design of mechanical properties of a composite made by CLM and the method for reducing the towpreg-cutting time during the towpreg deposition process were proposed and studied. These results of these studies could be used in the development of the required software for future commercialization of the CLM technology.

Self-anchoring and automatic extrusion methods have been analyzed in detail. Some analytical solutions were obtained to describe the mass and heat transfer processes

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involved. According to the studies, the self-anchoring forming speed has an effect on the towpreg bending strength. The bending strength is correlatable with the towpreg solidification, but the degree of solidification depends on its surrounding temperature. The initial and boundary conditions of the temperature fields for the self-anchoring process were considered and a modeling study was carried out by using ANSYS. The results could be used in the future for optimizing the whole process.

Numerical simulations were also obtained for the automatic extrusion process. Again, the results could be used to optimize the process directly. The simulation results were consistent with the experimental data, which further validated the viability of the proposed CLM process.

The two primary forming methods in CLM have been tested and proven very effective in forming a part layer by layer. The self-anchoring method and the required system have been developed. Composite parts have been successfully made by using this method.

The mechanical properties of the part were tested and analyzed. The modulus of the samples, which were cut from the CLM formed samples are greater than that of the part made by the FWPM process by almost 30%. But the ability against delamination of the FWPM sample is better than that of the CLM by 43%.

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APPENDIX A

Table 4-1 Parameters for the temperature field simulation.

	Polyethylene matrix	Kevlar fiber
Thermal Conductivity, k	*0.26 N/s k*	*0.04 N/s k*
Density, ρ	*976 kg/m^3*	*1450 kg/m^3*
Specific Heat, c	*2260 J/kg k*	*670 J/kg k*
Convection Exchange coefficient, α	*5 N/m^2 s k*	

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APPENDIX B

The dimension table for the nozzles (see Figure 5-7 and 5-8).

Table 5-1

Dimensions	Symbol									Qty
	ØA	ØB	ØC	ØD	L1	L2	L3	L4	L5	
Dimension1	Ø3±0.01	Ø1.6±0.01	Ø2±0.01	Ø4±0.01	4.8	5	3.2	3.2	30	2
Dimension2	Ø2±0.01	Ø1.0±0.01	Ø1±0.01	Ø2±0.01	3	6	2	2	25	2
Dimension3	Ø1±0.01	Ø0.6±0.01	Ø1±0.01	Ø2±0.01	3	6	2	3	20	2

Table 5-2

Dimensions	Symbol										Qty
	ØA	ØB	ØC	ØD	L1	L2	L3	L4	L5	L6	
Dimension1	Ø3±0.01	Ø1.6±0.01	Ø2±0.01	Ø4±0.01	4.8	5	3.2	3.2	25	22	2
Dimension2	Ø2±0.01	Ø1.0±0.01	Ø1±0.01	Ø2±0.01	3	6	2	2	20	15	2
Dimension3	Ø1.6±0.01	Ø0.6±0.01	Ø1±0.01	Ø2±0.01	3	6	2	3	15	10	2

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APPENDIX C

The results of the automatic extrusion experiment.

Results G: Good F: Failed Blank: None			Nozzle Diameter ØD																	
			Length of Orifice L=9.9289				Length of Orifice L=1.9289				Length of Orifice L=0.4298				Length of Orifice L=0.1716			
			Ø1	Ø2	Ø2.5	Ø4	Ø1	Ø2	Ø2.5	Ø4	Ø1	Ø2	Ø2.5	Ø4	Ø1	Ø2	Ø2.5	Ø4
Number of Fiber Tows	Flat Head	1	F		F		F	F	G	G	F	G	G	G				G
		2							G	G								
		3					F					G	G	G				
		6								G				G				
	Taper Head	1								F								
		2			F			F	G			G	G	G				
		3								G								
		6								G				G				

Table 5-3 The result of automotive extrusion experiment.

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APPENDIX D

The Parts list for the deposition device (see Figure 5-16).

	Name	Material	Quantity	
01	Alignment Tube	A3	1	
02	Regulator shaft	45	1	
03	Nut M5X15	45	4	GB70-85
04	Regulator lift Stand	A3	1	
05	Locking Bolt M2 X 6	45	1	GB77-85
06	Tube Locking Nut	45	1	
07	Balance Shaft	A3	2	
08	Regulator Right Stand	A3	1	
09	Bolt M5 X 40	45	4	GB70-85
10	Bearing Cover	A3	4	
11	Bearing 200		4	GB276-89
12	Bearing Support	A3	4	
13	Locking Nut M16X1.5	45	4	GB812-88
14	Roller	A3	2	
15	Nut M12	45	1	GB41-86
16	Depositing Holder	45	1	
17	Bolt M8X 25	45	4	GB70-85

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18	Locking Bolt M5X12	45	3	GB77-85
19	Driving Shaft	45	1	
20	Driven Shaft	45	1	
21	Pushing Rod	A3	1	
22	Bolt M5X20	45	4	GB70-85
23	Compression Spring	50CrVA	1	
24	Front Cover	A3	1	
25	Compression Nut	45	1	
26	Main Support	A3	1	
27	Motor Support	A3	1	
28	Shaft Clipper			Existing
29	Stepping Motor			Existing

* GB China Standard

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New Metal/Polymer Composites for Fused Deposition Modelling Applications

By

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A thesis submitted in fulfilment of the requirements for the degree of

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May 2011

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Abstract

Fused Deposition Modelling (FDM) has been a leading rapid prototyping process but it has been mostly limited to use in making prototypes for design verification and functional testing applications. The commercial process can currently fabricate parts only in limited types of thermoplastics such as ABS and Polycarbonate. Very little efforts have been made to increase the range of FDM materials to include metals or metal based composites for wider application domain beyond just design and verification. This thesis presents new research in this direction by developing novel metal based composites for use in FDM technology.

The principal objective of this research is to develop new metal/polymer composite materials for direct use in the current Fused Deposition Modelling rapid prototyping platform with long term aim of developing direct rapid tooling on the FDM system. Using such composites, the direct rapid tooling will allow fabrication of injection moulding dies and inserts with desired thermal and mechanical properties suitable for using directly in injection moulding machines for short term or long term production runs. The new metal/polymer composite material developed in this research work involves use of iron particles and copper particles in a polymer matrix of ABS material, which offers much improved thermal, electrical and mechanical properties enabling current Fused Deposition Modelling technique to produce rapid functional parts and tooling. Higher thermal conductivity of the new metal/polymer composite material coupled with implementation of conformal cooling channels enabled by layer-by layer fabrication technology of the Fused Deposition Modelling will result in tremendously improved injection cycles times, and thereby reducing the cost and lead time of injection moulding tooling.

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Due to highly metal-particulate filled matrix of the new composite material, injection tools and inserts made using this material on Fused Deposition Modelling, demonstrate a higher stiffness comparing to those made out of pure polymeric material resulting in withstanding higher injection moulding pressures. Moreover, metallic filler content of the new composite allows processing of functional parts with electrical conductivity and in case of using ferromagnetic fillers, namely as fine iron powders, it introduces magnetic properties, which will make FDM-built components suitable for electronic applications specifically whereby electro-magnetic shielding is of high interest.

In this research project, a full characterization of the newly developed metal/polymer composites including rheological, thermal, mechanical and electrical properties has been investigated. Mathematical models have been employed in order to predict and optimize the viscous behaviour of metal/polymer composite during the course of deposition through the FDM nozzle.

In order to predict the main flow parameters of the metal/polymer composites including pressure, temperature, and velocity fields through the FDM liquefier head, 2-D and 3-D numerical analysis of melt flow behaviour of acrylonitrile-butadiene-styrene (ABS) and Iron composite as a representative metal/polymer material has been carried out using ANSYS FLOTRAN and ANSYS CFX commercial codes. Results of numerical analysis have been verified by the developed empirical mathematical models.

A variety of advanced techniques have been employed to fully characterize the newly developed metal/polymer composites in order to successfully process filaments for fabrication of injection mould tooling inserts. Morphological effects of metallic fillers and surfactants as well as variation of volume fractions of constituents on the viscoelastic properties of the new composite material

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have also been investigated. Filaments of the filled ABS has been fabricated and characterized to verify the possibility of prototyping and direct tooling using the new material on the current FDM machine.

Major contributions of the thesis include:

- Development of a new metal/polymer composite material for functional parts and rapid tooling solutions on Fused Deposition Modeling platform.
- Development of mathematical models for predicting viscous behavior of three-component composite flow through capillary extrusion process.
- Full rheological, thermal, mechanical and electrical characterization of the new metal/polymer composites.
- Combining experimental and numerical methodology (tools) to predict melt flow behavior of metal/polymer composite through Fused Deposition Modeling.
- Fabrication of stiff and flexible filaments of the metal-polymer composites as feedstock material for direct rapid tooling via Fused Deposition Modeling.
- Fabrication of functional parts and inserts of new metal/polymer composites successfully and directly on the FDM3000 system.
- Production of plastic parts using injection moulding tools made by Direct FDM-based Rapid Tooling Process.

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Acknowledgment

First of all, I would like to express my deepest gratitude to my principal supervisor Professor S.H. Masood for his continuous support and valuable guidance throughout my research work. I would like to also thank my second supervisor, Dr. Igor Sbarski, for his valuable inputs especially on rheological studies, and overall arrangement of experimental works. Initial support of my external supervisor, Dr. Andrew Groth from CSIRO, is also highly appreciated.

I acknowledge the financial support in the form of scholarship provided by Swinburne University of Technology and the Commonwealth Scientific and Industrial Research Organisation (CSIRO).

My thanks are extended to the people for their help at various stages of my PhD work. Assistance of John Thomas, Adam Webb from Autodesk Moldflow; Dr. Ruether and Dr. Shekibi from CSIRO Energy Technology division; Mike Dundan from Chisholm TAFE; Pejman Hojati from Monash University; Brian Dempster, Mehdi Miri, Girish Thipperudrappa, Dr. Ismet Ilyas, Dr. Wei Song, and Dr. James Wang, from Swinburne University of Technology is highly appreciated.

I wish to express my eternal gratitude to my Mum, Dad and Siblings for their endless support, love and encouragement throughout my entire schooling.

Last but not least, I would like to thank all my friends and fellow postgraduate students, especially A.B.M. Saifullah and Barbara, whose sincere friendship made the course of my PhD studies fun and enjoyable.

Thank You!

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DECLARATION

This thesis contains no material which has been accepted for the award of any other degree or diploma at any university and to the best of my knowledge and belief contains no materials previously published or written by another person or persons except where reference is made.

Mostafa Nikzad

May 2011

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Chapter 1 Introduction

1.1. General Background

Rapid prototyping (RP) describes the physical modelling of a design using digital data-driven, additive processes. Also recognized as additive manufacturing (AM), it is a solid freeform manufacturing process that allows users to fabricate a real physical part directly from a CAD (computer aided design) model. The CAD model is sliced into many thin horizontal layers by a software package that can also prepare the part for whichever layered-manufacturing machine to be used to transform materials into physical prototypes. The part is then built layer by-layer without the need for external tools (Kamrani & Nasr 2006; Liou 2008; Wohlers 2004-2008). Before the application of RP, computer numerically controlled (CNC) equipment were used to create prototypes either directly or indirectly using CNC program or CAM software. In CNC process, material is removed in order to achieve the final shape of the part as opposed to RP operation where models are built by adding material layers after layers. Figure1.1 demonstrates the typical procedure of an RP process (Kamrani & Nasr 2006).

RP processes enjoy numerous advantages in a variety of applications compared to conventional subtractive processes such as milling, and turning. Some major advantages include (Grenda 2007):

- Formation of objects with any degree of geometrical complexity without the need for any tooling or computer programming;
- Fabrication of objects potentially from a variety of materials and any composites, and the ability to even vary feed materials in a controlled fashion at any location in an object;

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- Opening new horizons in design and manufacturing not conceivable before, such as functionally graded materials, designed materials with engineered properties;
- Greatly enhancing the scope of product development with reduced cost and time in specific areas such as biomedical engineering, tooling development, and consumer products, etc.

These advantages have resulted in their wide use as a way to reduce time to market in manufacturing (Grenda 2007; Hopkinson, Hague & Dickens 2006; Kucklick 2007).

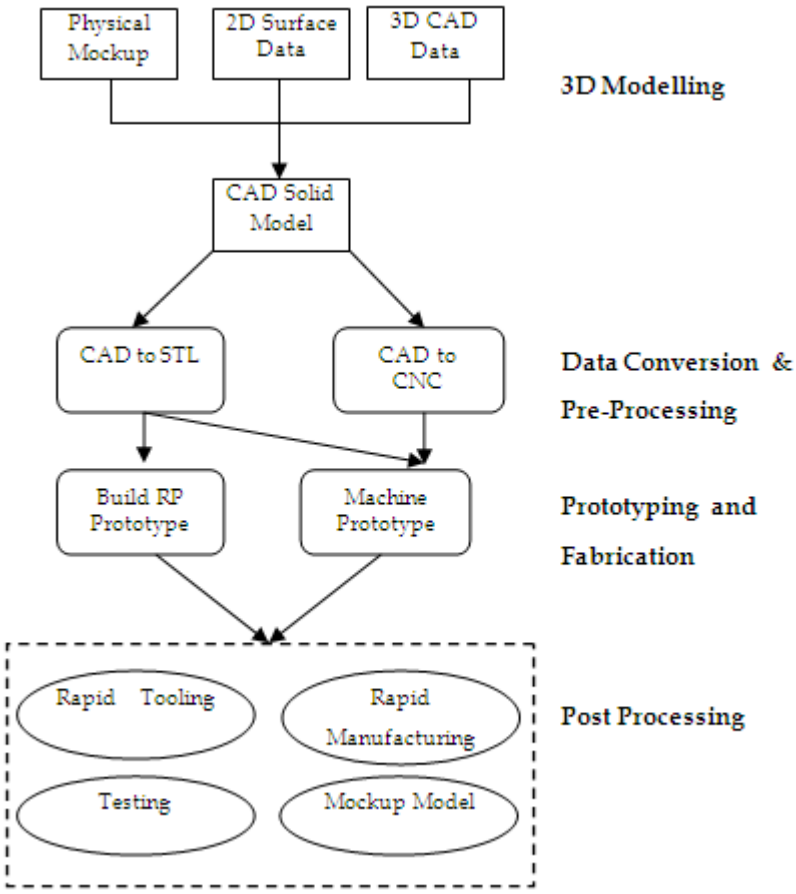

Figure 1-1: Generic Flow of RP Process (Kamrani & Nasr 2006)

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There are over 20 different RP processes recognized today which are divided into three categories of liquid-based, powder-based, and solid-based systems according to the raw materials used in the process (Chua, Leong & Lim 2003; Hopkinson, Hague & Dickens 2006). Out of these existing processes, the most widely used include Stereolithography (SLA), Fused Deposition Modelling (FDM), Selective Laser Sintering(SLS), 3D Printing (3DP), and Laminated Object Manufacturing(LOM) (Grenda 2007; Liou 2008; Wohlers 2004-2008). Nowadays, Rapid Prototyping processes are extensively applied in areas of conceptual design, fabrication of functional parts, making patterns for metal casting, fit and assembly checking as well as prototype tooling. While yet not fully evolved, more and more areas of applications are emerging due to the vast and ever growing need of design and manufacturing industries to meet the demands of market in a shorter period of time. Nonetheless, challenges are still remaining in major areas of rapid tooling through implementing RP techniques, rapid manufacturing in batches of medium to high volume, and also application of such techniques in medical implantations.

Furthermore, there has been a high degree of demand for development of rapid tooling solutions for the stages of bridge and short-run production.

In this context, Rapid Tooling (RT) by making use of currently-established Rapid Prototyping processes has offered a great potential for reduction of lead-time and fabrication of very intricate tools in small volumes. Demand for faster, reasonably low-cost and high performance tooling has driven development of a dozen of such methods worldwide (Chua, Leong & Lim 2003; Jacobs & Hilton 2000; Wohlers 2004-2008). Alongside, some of the radically improved emerging Rapid Prototyping techniques have promised dramatic increase in speed of mould fabrication and new product development (Knights 2005). Particularly, their superiority in building geometrically complicated models as well as enhancement of their earlier technologies has proved that

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they can be used not only for prototyping but also for commercial production tooling since traditional mould manufacturing is costly and time consuming.

However, capabilities of these RP systems are plagued with questions about accuracy, surface finish and specially their limited range of materials which demand a lot of research in terms of physical, thermal and electro-mechanical properties of newly developed prototypes, and tools.

In order to address the shortcomings of current RP systems in improving properties of new product, and tooling development, and diversifying applications of these processes, there is a growing interest towards development of new materials. As well as cost and time reduction, by development of new composite or functionally graded materials for use on current RP platforms, there is a high potential of developing tooling solutions with benefit of improved thermal, electrical and mechanical properties.

Existing Rapid Tooling (RT) processes are categorized in two classes of direct and indirect processes. Direct Rapid Tooling involves fabrication of rapid tooling inserts directly from CAD model on an RP machine whereas indirect Rapid Tooling method uses RP master patterns to build a mould which requires additional down stream work such as RTV silicone rubber mouldings, epoxy-based tooling, and spray metal tooling. Direct Rapid Tooling processes are much faster and significantly reduce cost and time-to-market for new products (Chua et al. 2005; Luo & Tzou 2007; Wohlers 2008). Therefore, current research mainly focuses on development and expansion of such methods.

Numerous researchers have conducted research worldwide on development and employing RP-based rapid tooling processes (Ferreira, Mateus & Alves 2007; Ingole et al. 2009; Rahmati & Dickens 2007; Salmoria et al. 2008; Wu et al. 2009b; Yan et al. 2009). Despite all the setbacks, extensive research is being conducted with a variety of strategies, specialised materials and new processes

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to overcome the problems and enjoy the significant benefits of RP patterns (Cheah et al. 2005).

In a pioneering work by 3D CAD/CAM systems, it was shown that a resin mould produced by Stereolithography could be directly used for injection moulding of thermoplastic parts (Tsang & Bennett 1995). Known as Direct AIM, the technique was based on SLA process in which layers of liquid photopolymers were solidified one after another as a result of exposure of the monomers to ultraviolet radiation. Achieving a very high level of accuracy and considerable reduction of time was reported by use of this technique. However, the resin mould suffered from a low strength and poor thermal properties.

Later on, direct SL composite tooling method was developed whereby a solid thin resin mould built by SLA was backed with aluminium-powder filled epoxy resin (Atkinson 1997). Addition of aluminium powder increased the thermal conductivity of the mould tremendously, and improved the mould strength.

Venus et al (Venus, Crommert & Hagan 1996) used silicone rubber to make a mould around a master pattern fabricated by RP process to build a cavity. Silicone rubber is a multi-purpose material available both in transparent and opaque forms. Silicone rubber poured around the master prototype, contained in a box, solidified and a parting line was created. By parting the rubber mould in two halves, male and female sections of mould were produced. Then a variety of material, namely as polyurethane, could be poured into the resultant rubber cavity and moulded. Using this technique about 20 numbers of polyurethane parts could be produced before silicone rubber mould broke away.

Selective Laser Sintering (SLS) process has also been one of the most extensively used RP platform for rapid tooling solutions (Cheah et al. 2005) in which powders of metal, ceramic or polymer is fused selectively layer by layer as a

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result of exposure to CO_2 laser to form the required parts. The key advantage of SLS is the variety of materials it can process. But due to porosity of moulds produced by this technique, they are mechanically weaker than conventional ones and a further infiltration is needed to improve the properties of final parts. Sachs et al (Sachs et al. 1997) employed 3D Printing to produce some metallic moulds. Different components were made by depositing very small droplets of binder onto thin layers of steel powders successively through an electrostatic inkjet head. Then the "green" porous moulds were put into a furnace to burn the binder out resulting in a half-dense skeleton. By infiltrating the left-over porosities via some metallic bonding materials, moulds were finally densified completely. The process was relatively simple and hereby resulted in a faster fabrication time, but the brittleness of mould prototyped by this technique was a key weakness. In addition, due to need of post processing, parts accuracy was reduced(Radstok 1999).

Laminated Object Manufacturing (LOM) has also been used by a few researchers to produce some functional parts and tools (Chartoff et al. 1996; Mueller & Kochan 1999; Prechtl, Otto & Geiger 2005; Wang, Conley & Stoll 1999). LOM creates solid prototypes by cutting and laminating adhesive layers of wood sequentially. Chartoff (Chartoff et al. 1996) et al employed LOM to fabricate functional composite laminates, such as composite tools and moulds using a variety of material systems including monolithic ceramics (SiC), ceramic matrix composites (SiC/SiC), and polymer matrix composites (glass/epoxy). Some realistic tools and moulds were developed, however post processing (ceramic densification, polymer post cure) was necessary to obtain objects with good mechanical properties. There also technical solutions needed to be developed to enhance the geometrical accuracy of the final parts which compromised the speed of process.

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In recent years, Fused Deposition Modelling (FDM) has become one of the most widely used rapid prototyping technologies for various applications in engineering (Chua, Leong & Lim 2003). The fused deposition modelling (FDM) rapid prototyping systems, developed by Stratasys Inc., can fabricate parts in a range of materials including elastomer, acrylonitrile- butadiene-styrene (ABS) and polycarbonate with the layer by layer deposition of extruded material through a nozzle using feedstock filaments from a spool. Among these, ABS is the most commonly used material for part fabrication on the FDM because of its superior engineering properties.

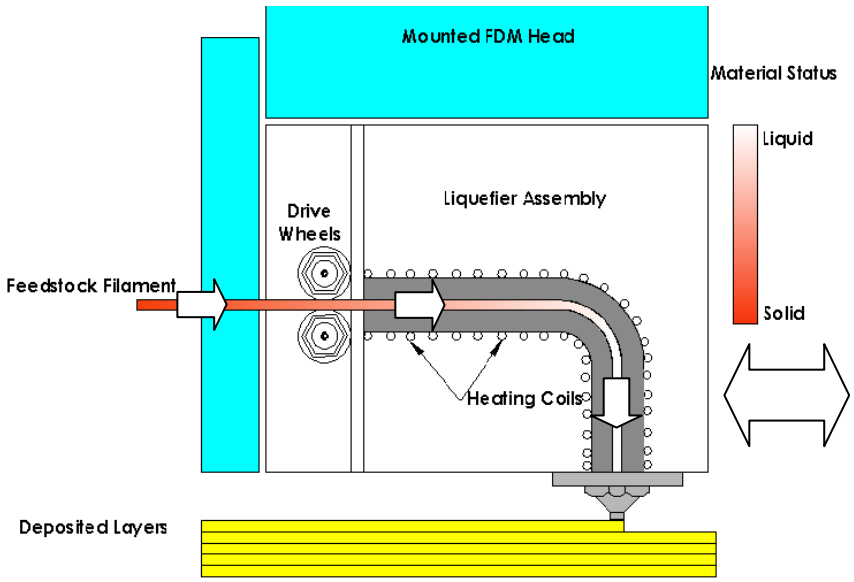

Figure 1-2: Schematic of Stratasys FDM Process

Most of the parts fabricated in current materials can be used for design verification, form and fit checking and some as patterns for casting processes and medical applications. For a shift from "rapid prototyping" to "rapid tooling and manufacturing" using fused deposition modelling, both flexibility and improvements in the properties of the current feedstock material is necessary. New materials for FDM process are needed to increase its application domain

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especially in rapid tooling and rapid manufacturing areas. The basic principle of operation of the FDM process, as shown in Figure1.2, offers great potential for a range of other materials including metals, ceramics, and composites to be developed and used in the FDM process as long as the new material can be produced in feedstock filament form of required size, strength, and properties.

1.2. Outline of Research Project

This research work presents a unique application of Fused Deposition Modelling rapid prototyping system used in the direct rapid tooling for producing injection moulding dies and inserts using a newly developed metal/polymer composite. The other RP techniques such as SLA and SLS have been extensively used for direct rapid tooling, but few attempts have been made to apply the FDM RP platform to fabricate injection moulding tools directly.

The principal objective of this research is to develop a new metal/polymer composite material for direct rapid tooling solutions based on the current Fused Deposition Modelling rapid prototyping platform. Using such composite, a new direct rapid tooling technique can be developed to fabricate appropriate tools and dies for injection moulding applications. The existing Fused Deposition Modelling process is only capable of producing prototypes from pure polymeric/plastic materials resulting in their limited use for design verification, fit and assembly checking. The new metal/polymer composite material developed in this research work, offers much improved thermal, electrical and mechanical properties enabling current Fused Deposition Modelling technique to produce rapid functional parts and injection moulding tools. Higher thermal conductivity of the new metal/polymer composite material coupled with implementation of conformal cooling channels enabled by layer-by layer fabrication technology of the Fused Deposition Modelling will result in

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tremendously improved injection cycles times, and thereby reducing the cost and lead time of injection moulding tooling.

Due to highly metal-particulate filled matrix of the new composite material, injection tools and inserts made using this material on Fused Deposition Modelling, demonstrate a higher stiffness compared to those made out of pure polymeric material resulting in withstanding higher injection moulding pressures. Moreover, metallic filler content of the new composite allows processing of functional parts with electrical conductivity and in case of using ferromagnetic fillers as fine iron powders it introduces magnetic properties, which will make FDM-built components suitable for electronic applications specifically whereby electro-magnetic shielding is of high interest.

In this research project, a full characterization of the newly developed metal/polymer composite including rheological, thermal, mechanical and electrical properties has been investigated.

Comprehensive rheological properties of different compositions of the new material have been studied using both capillary and parallel plate rheometry. Mathematical models have been employed in order to predict and optimize the viscous behaviour of metal/polymer composite during the course of deposition through FDM nozzle.

In order to predict the main flow parameters of the metal/polymer composites including pressure, temperature, and velocity fields through FDM liquefier head, 2-D and 3-D numerical analysis of melt behaviour of acrylonitrile-butadiene-styrene (ABS) and Iron composite as a representative metal/polymer material has been carried out using ANSYS FLOTRAN and ANSYS CFX commercial codes.

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Morphological effects of metallic fillers, and surfactants as well as variation of volume fractions of constituents on the viscoelastic properties of the new composite material have also been investigated.

Filaments of the filled ABS has been fabricated and characterized to verify the possibility of prototyping using the new material on the FDM machines.

The major issues of die swell phenomenon, and viscosity variation in regards to FDM processing of the new filaments have also been investigated. Normal viscoelastic forces have been measured using parallel plate rheometry, and amounts of swelling has been optimized using appropriate addition of surfactant to prevent intermittent flow of filament material during deposition process.

The new material developed for the FDM process has a large potential for direct rapid tooling technique that could lead to direct fabrication of injection-moulding dies or inserts and considerable reduction of cost and time in tooling production.

A variety of advanced processes and techniques have been employed to carry out extensive experimental investigations reported in this thesis. A multi-variable speed mixer and homogenizer together with a single/twin screw extruder have been used to compound a homogenous metal/polymer composite. Initially through a cryogenic grinding using similar technique in liquid-nitrogen atmosphere, pellets of polymers have been ground into suitable micro-sized particles for mixing. Modulated Differential Scanning Microscopy (MDSC), Dynamic Mechanical Thermal Analysis (DMTA), Electrochemical Impedance Spectroscopy (EIS), and Thermal Conductivity Analysis (TCA) have been used to study melt and glass transition temperature (T_g), specific heat (C_p), viscoelastic properties such as storage and loss modulus, AC, and DC electrical

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conductivity and thermal conductivity (TC) of the new composite material respectively.

Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) have been used for analysing distribution of filler particles, particle shape and the elemental composition in the matrix as well as examination of fracture surfaces and understanding cohesion and bonding mechanisms of filler-matrix in the metal/polymer composite which are necessary to prevent interphase crack growth.

Quasi-static mechanical properties were measured on the samples of the new metal/polymer composite using a Zwick tensile test machine according to ASTM D638. Finally, the composite filaments have been successfully used for fabrication of injection mould tooling inserts. To improve surface finish of the parts made by FDM-based rapid tooling, mould release coating was applied to the cavity surfaces of these composite injection moulding dies (inserts). Some functional thermoplastic parts have been successfully produced using the new FDM-based rapid moulds on a commercial injection moulding machine.

Major contributions of the thesis include:

- Development of a new Fe/ABS composite material for Fused Deposition Modeling platform.
- Development of mathematical models for predicting viscous behavior of three-component composite flow through FDM type capillary extrusion process.
- Full rheological, thermal, mechanical and electrical characterization of the new metal/polymer composite.
- Combining experimental and numerical methodology (tools) to predict melt flow behavior of metal/polymer composite through Fused Deposition Modeling.

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- Fabrication of stiff and flexible filaments of the metal-polymer composites as feedstock material for direct rapid tooling via Fused Deposition Modeling.
- Production of plastic parts using injection moulding tools made by Direct FDM-based Rapid Tooling Process.

1.3. Outline of thesis

To accomplish the aforementioned objectives:

Chapter 2 reviews the literature on material development and rapid tooling solutions based on the existing rapid prototyping platforms. It presents state-of-the-art in RP field, and most recent directions of research in Fused Deposition Modeling as well as the direction of research. A background is given on the metal-polymer composites, some fundamental theories, and delineating concept of applying such materials to improve the properties of parts and tools made by RP-based rapid tooling.

Chapter 3 demonstrates steps taken for development of a new metal-polymer composite, as well as fabrication of filaments of suitable geometry for Fused Deposition Process. Effects of morphology of metallic fillers, and coupling agents on polymer-metal interface have also been explored. It also establishes effects of mixing and dispersion techniques on homogenous properties of the composite material.

Chapter 4 presents a comprehensive rheological study of the new metal/polymer composite material developed for fused deposition modelling. Empirical mathematical models have been established for such composites in order to control and predict their viscous behavior as a function of volume fraction of fillers, surfactant, and temperature. Die swell phenomenon in extrusion of the new material through capillary nozzle of FDM has also been addressed.

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Chapter 5 contains full characterization results of mechanical, thermal and electrical properties of the metal-polymer composite. Quasi-static and dynamic mechanical properties as well as morphological, thermal and electrical properties of the new filament material have been presented for various volume fractions and size of fillers.

Chapter 6 presents numerical analysis of melt flow behaviour of metal-Polymer composite through Fused Deposition Modelling Process.

Chapter 7 offers a direct rapid tooling method using the new metal-polymer composite material on Fused Deposition Modelling system. Conclusions to total work effort and future directions of research in this field are also presented.

Chapter 8 summarizes the general conclusions of this research and also points out the limitations and future directions.

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Chapter 2 RP/RT/RM and Materials Development

2.1. Introduction

An overview of the latest developments in rapid tooling, and manufacturing technologies using primary rapid prototyping systems are given with the most recent directions of research in Fused Deposition Modelling (FDM). Focus is given to the development of new materials as the outstanding gap in the current rapid prototyping based tooling (RPT), and manufacturing methods for the production of functional parts and tools with tailor-made properties, and long-term use in diverse applications. A background will be given on the metal-polymer composites as the representative new materials for developing rapid tooling, and manufacturing solutions using Fused Deposition Modelling process, their fundamental theories, and delineating concept of applying such materials to improve the properties of parts and tools made by RP-based rapid tooling (RPT), and manufacturing (RPM).

RPT and RPM are referred to the new types of processes which employ the currently established Rapid Prototyping concepts to transform a rapid prototype into a *functional*, *material* or *production* part depending on the phase of product development process. Rapid prototyping-based tooling techniques (RPT) allow the fabrication of production tools offering a high potential for a faster response to market demands and creating a new competitive edge. The purpose of RPT is not the manufacture of final parts, but the development of the means to produce final parts i.e. mass production tools including moulds, dies, etc with the most notable advantage of integrating production planning and testing within the product development cycle (Hans, Gideon & Ralf 2001; Karapatis, Van Griethuysen & Glardon 1998).These processes can be classified into two categories of Direct Rapid Tooling and Indirect Rapid Tooling,

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Figure2.1, based on the number of intermediate steps taken along with the normal RP operations to build the final tool (Karapatis, Van Griethuysen & Glardon 1998; Levy, Schindel & Kruth 2003). As mentioned earlier, Direct Rapid Tooling involves fabrication of rapid tooling inserts directly from CAD model on an RP machine whereas Indirect Rapid Tooling method uses RP master patterns to build a mould, which requires additional down stream work. In Indirect methods RP model will be used to make the tooling using some secondary or reproduction processes such as investment casting, and are alternatively referred to as "*Pattern Making for Casting Processes*"(Dimitrov, Schreve & De Beer 2006).

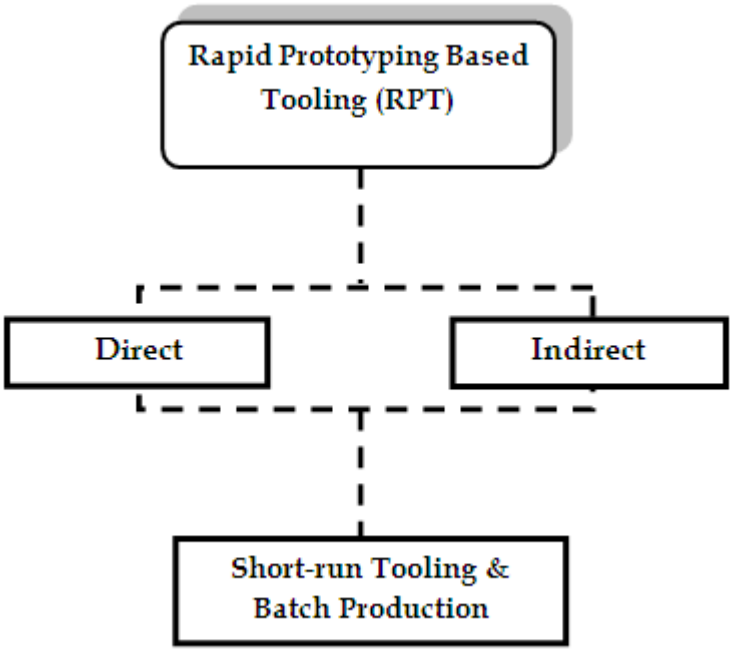

Figure 2-1: Classification of the current RP-based Tooling

In order to guarantee the long-term consistent use of components made using current RP-based tooling technologies, and create the means for Rapid Manufacturing(RM), there is a demand for the most significant role of materials in such technologies. In this regard, four main basic material categories have

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been identified, which fulfil the required physical, mechanical, thermal and geometrical properties as shown in Figure2.2 (Levy, Schindel & Kruth 2003). Processability of new materials on the current RP platforms has been a major challenge in developing and introducing them for RP-based rapid tooling solutions, which in turn has resulted in extremely small choice of materials towards each process (Kruth, Leu & Nakagawa 1998). However, in the past years, some dispersed research works have been tried to develop and improve the materials for Rapid prototyping systems. (Abe 2000; Kloke 1998; Kruth 2001b; Laoui 1999; Laoui, Froyen & Kruth 1999b)

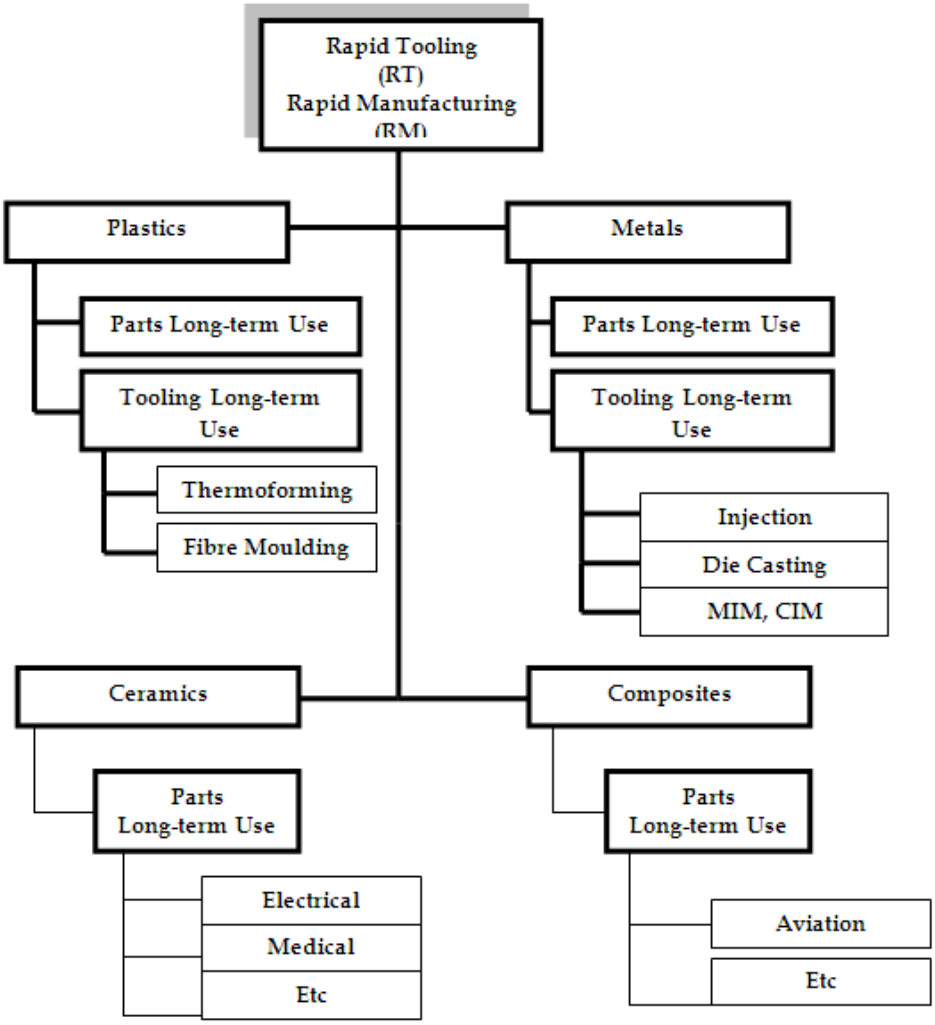

Figure 2-2: Material-dependent Rapid manufacturing and Tooling (reproduced from Levy, Schindel & Kruth 2003)

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In the following section, an overview of the primary rapid prototyping processes is given followed by an investigation of the emerging Rapid Tooling and Manufacturing processes. RPM or simply Additive Manufacturing (AM) at this stage is being defined as the future path for the developments of freeform technologies (Bourell, Leu & Rosen 2009).

2.2. Overview of the Traditional RP Processes

2.2.1. Stereolithography

Stereolithography (SLA), patented in 1986, is the first commercialized process introduced by 3D Systems. It relies on the principle of solidifying a photosensitive resin using UV (ultraviolet) laser light to build a three dimensional object. The energy provided by UV light acts like a catalyst helping polymerisation of small molecules into larger chains or polymers. The laser light is moved within X-Y plane using a CNC positioning system tracing the cross-sectional tool-paths generated from slices of the CAD model of the prototype, and transformed into STL file format (Crowell 1989; Hull 1988).

A typical SLA machine comprises a platform submerged in a vat of resin, and a UV laser light as shown in Figure2.3. An optical scanning system controlled numerically by computer focuses the UV beam onto the photosensitive polymer liquid solidifying a cross-section at a time corresponding to that of a slice of the CAD model. Once the scanned cross-section has solidified, the platform is lowered down to submerge the solidified layer in the liquid resin. A leveling wiper sweeps across the surface to make sure that exactly one layer thickness remains above the just-solidified cross-section. The laser sequentially scans the next layers, and therefore builds the part layer-by-layer.

Owing to the liquid properties of the photopolymer resin, SLA can make prototypes with good surface finish (glass-like), and good dimensional accuracy

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(±0.1mm). It is a very stable process, and a fully automatic one which can be unattended until the building process is complete.

Of its disadvantages is the one that the water absorption into the resin over time in thin areas creates curling and warping. The system cost is relatively high, and the only available material is the expensive photosensitive polymer. Prototypes made by this technique cannot be used for durability and thermal testing as often they are not fully cured by the laser inside the vat due to the fact that when a laser (UV light) is curing a spot, the energy is spread over a cone shape which leaves some uncured areas during the processing throughout the prototype (Liou 2008).

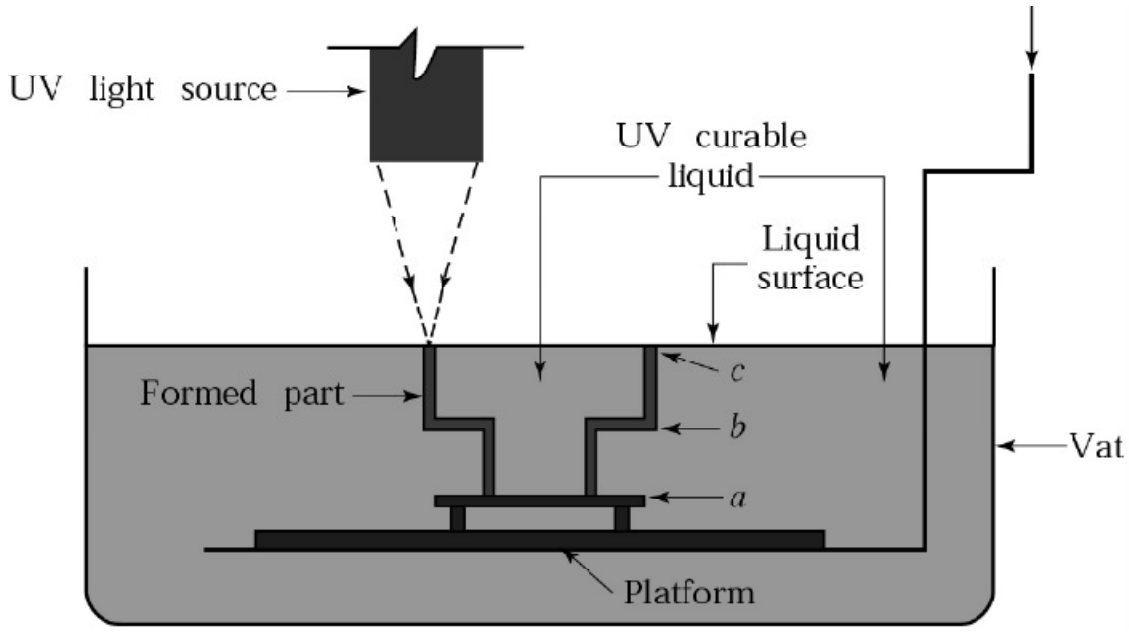

Figure 2-3: Schematic of Stereolithography process (Source: Ultra Violet Products, Inc)

Perhaps Direct ACES (Accurate Clear Epoxy Solid) Injection moulding is one of the most established direct rapid tooling processes based on Stereolithography developed by 3D system. The process is capable of building low volume tooling prototypes (up to 50 parts) quickly and economically for injection moulding applications. Both cavity and core pieces of the injection mould is built directly on a SLA machine from the photopolymer resin (Dickens & Ruggley 2001;

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Jacobs & Hilton 2000). Due to poor thermal conductivity of the SLA polymer, after the cavity is made, it would be backfilled using a verity of materials such as aluminium-filled epoxy, low melting metals and ceramic to improve thermal properties of the Direct AIM built moulds. A better heat dissipation through thermally conductive backfilling material can reduce the cooling time, and hence total injection moulding cycle. Figure2.4. shows cavity and core pieces of an injection mould built using this technique.

An investigation by Li et al (Li, Gargiulo & Keefe 2000) has demonstrated that the development of advanced materials with better thermal properties, or an optimized cooling channel design could help to promote the use of SLA rapid tooling moulds for fabrication of production parts. They suggested that the direct SLA based tooling would be suitable for the final moulded parts with desirable tolerance of ±0.15 mm.

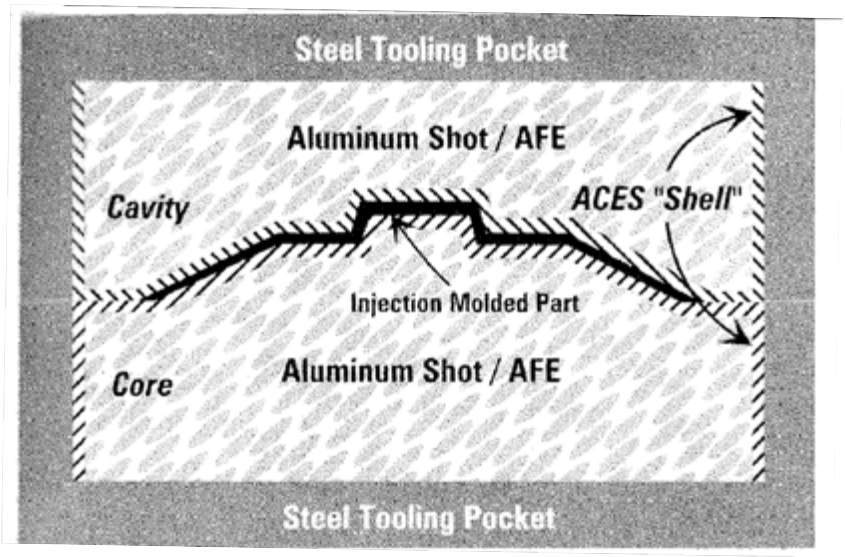

Figure 2-4: Illustration of Direct AIM "Shelling" backfilled with Al-filled Epoxy (Jacobs 2000)

Silicon RTV is an indirect rapid tooling method which uses SLA components as pattern for the preparation of rubber mould. SLA- generated pattern is placed in a frame, and then the moulding compound is poured into the frame taking

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up the shape of the pattern. Once the compound is solidified, the pattern is removed, and the mould would be ready for use (Grenda 2006; Karapatis, Van Griethuysen & Glardon 1998). Figure2.5. illustrates the room temperature vulcanizing (RTV) moulding process. The process is inexpensive, and provides a good surface finish. It is suitable for production of small to medium quantities of some polymeric materials namely Epoxy, Polyurethane, Investment casting wax, silicon rubber, and low melt metal alloy (Grenda 2006; http://www.efunda.com/processes/rapid_prototyping/lom.cfm Retrieved 2008).

SLA-generated patterns have also been used in the other direct rapid tooling processes such as QuickCast by 3D systems (Jacobs 1993) and indirect rapid tooling solution such as 3D KelTool(Inc. 1994) . In a case study for Ford Motor Company, QuickCast was used to prototype an investment casting tool (both core and cavity) on a SLA 250 system resulting in a 45% reduction in the costs and saving more than 40% of production time compared to the previous subtractive tooling method (Denton & Jacobs 1994). Becton Dickenson & Company (Connelly 1998) have successfully used 3D-KelTool, a *production-grade* tooling technique based on SLA, to produce injection moulds for precision medical components. In a similar study, Maisel (Maisel 2001) has demonstrated 3D KelTool as the shortest way from prototyping to mould construction for fabrication of eroding electrodes or some complex mould components.

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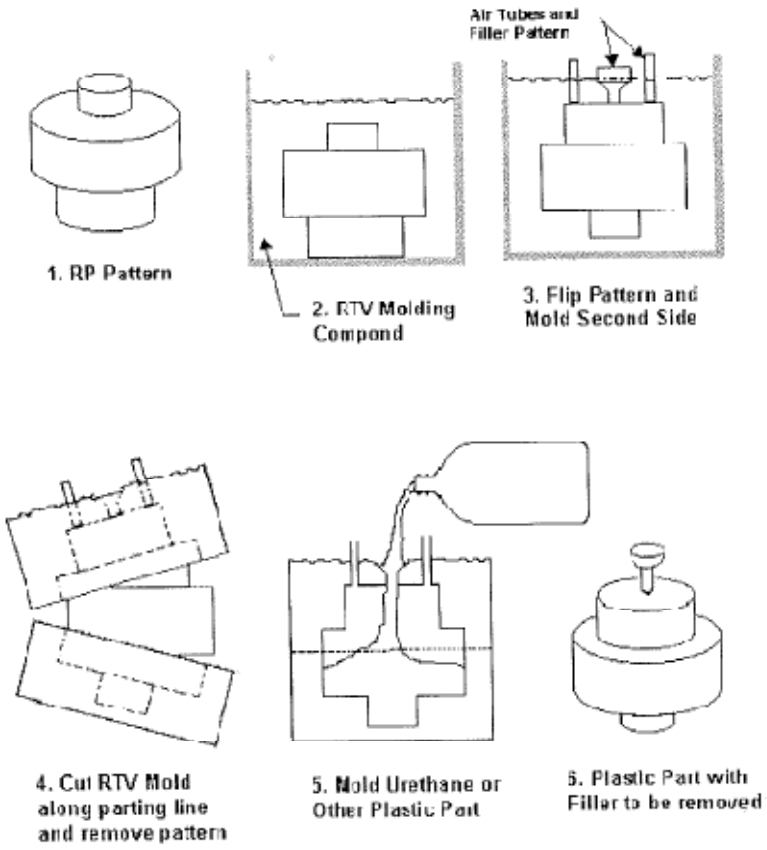

Figure 2-5: Illustration of Silicon RTV moulding process (Grenda 2006)

Weiss et al. have used an integration of SLA and thermal spraying for rapid tool manufacturing. By thermal spraying of various metals onto the SLA-built models they were able to fabricate a range of tooling including injection molds, forming dies, and EDM electrodes.

2.2.2. Selective Laser Sintering

Selective Laser Sintering (SLS), developed and patented by Deckard and Beaman (Deckard & Beaman 1988) of the University of Texas, is a powder based RP process in which a high power Carbon Dioxide Laser fuses powdered materials selectively by tracing the cross-sections of CAD solid model to create a layer. Once a cross-section is scanned and fused by the laser beam, the piston over which tightly packed powder material is laid, moves down by one layer-

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thickness and a levelling roller spreads a new layer of material on top. This procedure is repeated until a full prototype of the CAD model is built as shown in Figure2.6. It is necessary that the whole powder bed chamber to be heated prior to the start of the process in order to avoid thermal distortion and improve the bonding of subsequently fused layers. Left-over powders can easily be brushed away and reused.

Contrary to SLA process, prototypes featuring overhangs and undercuts would require no support to be built using this method as the solid powder bed provides such support during the processing. SLS can build objects from relatively wide choices of materials available in powder forms. However, surface finish is poor, and requires extra machining to improve. Due to sintering natural of the process, prototypes are porous. Therefore, based on the application, varying degrees of infiltration might be necessary to improve the mechanical properties of the prototypes built by this method. Extensions of Selective Laser Sintering have been used for direct fabrication of metals and ceramic objects and tools (Grenda 2007).

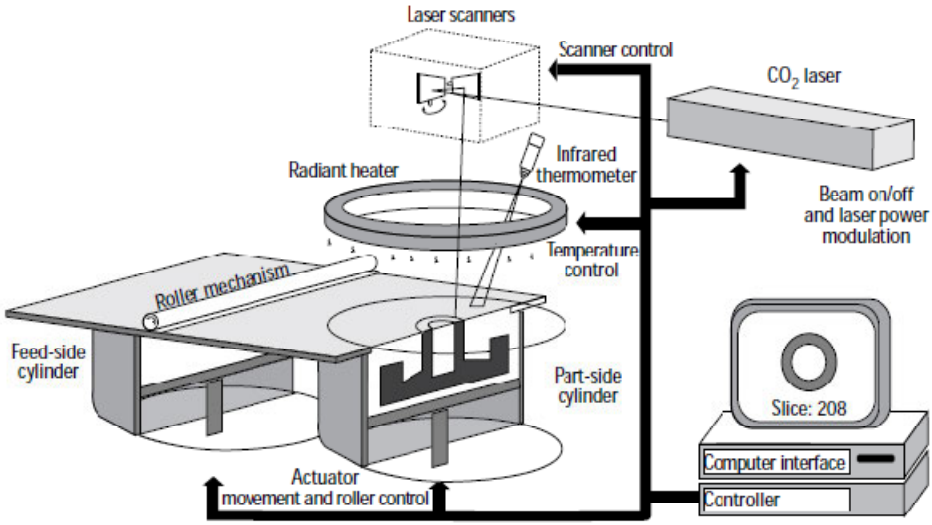

Figure 2-6: Illustration of the SLS process (Subramanian et al. 1995)

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2.2.3. Three Dimensional Printing

As shown in Figure2.7, Three-Dimensional Printing (3DP) lays up thin spreads of powders on a substrate and sequentially joins them by spraying droplets of a binder through inkjet nozzle. The successive layers are deposited according to the tool-paths generated from 2-dimenstional cross sections of computer aided design (CAD) models. As-printed prototypes by this technique might need subsequent sintering and infiltration in order to burn out the polymeric binder and produce denser structure depending on the applications.

Developed by MIT, and commercialized by Z Corp in 1993, 3DP is more affordable, faster, and easy to use. The modern 3D printers can produce full-colour models that imitate exactly the look, feel, and functionality of product prototypes(Sherman 2009).

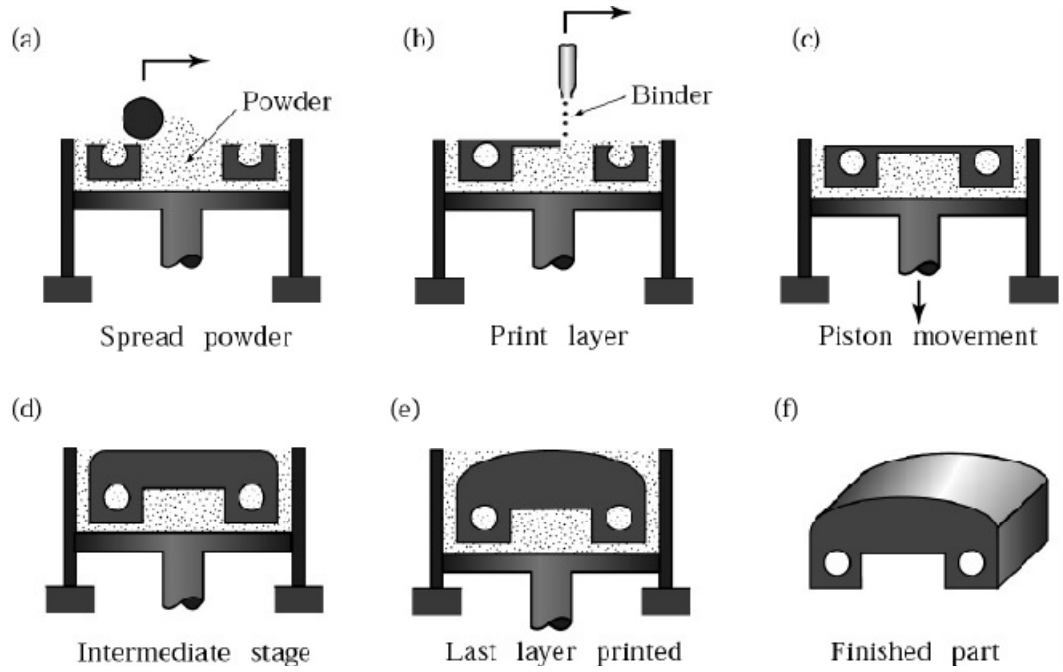

Figure 2-7: Illustration of 3DP process (Source: after E.Sachs and E.Cima)

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Direct Shell Production Casting(DSPC) that works on the same principal as 3DP is the a common tooling process developed by Soligen (Gebhardt & Petschke 1996)

2.2.4. Laminated Object Manufacturing

Laminated Object Manufacturing (LOM) is a rapid prototyping technology developed originally by Helisys, and succeeded later-on by Cubic Technologies which builds three dimensional objects from laminates of adhesive-coated paper, plastic and composites. In principle, the sheets of raw material are glued together and then cut out corresponding to the cross-sections generated from CAD model on a PC. A CNC driven knife or a laser cutter traces out the cross-sections one after another. The excess material is cross-hatched heavily by laser so that it can be removed easily. Once the first layer is cut to the desired shape, the substrate is lowered down one thickness of a layer so that a fresh sheet can be rolled in for the next cut, as shown in Figure 2.8. The process is considered a hybrid of additive and subtractive fabrication technologies in that the objects are made from stacks of sheets in a layered fashion, and the leftover material is cut to the shape by laser similar to a removal process. Paper models fabricated by this method need to be sealed with paint or epoxy resin to avoid the ingression of moisture and subsequently the compromise on the dimensional stability.

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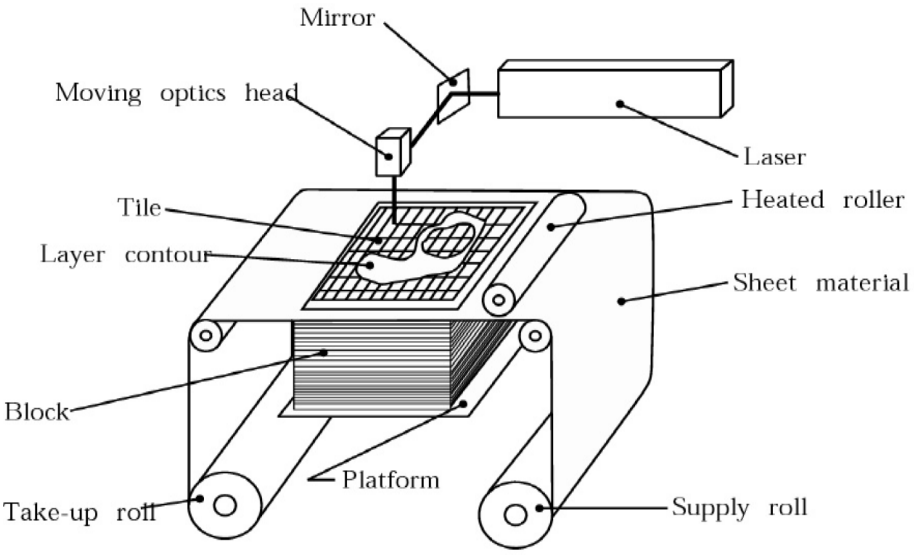

Figure 2-8: Illustration of the LOM process (Source: Helisys, Inc)

The advantages of LOM include a relatively wide range of inexpensive materials, large working volume, and therefore fabrication of large-size prototypes comparing to the other RP methods. But generally, the finish, accuracy, and stability of paper models are not as good whereas, the objects made reflect the look and feel of wood, and can be worked and finished accordingly which drives applications such as pattern-making for die castings. (Grenda 2007). Work has been done to develop ceramic, metal, and composite materials for this technique to improve the process. In an effort, sheets of powder metal have been bound by adhesive and cut to produce the "green" part and subsequently sintered to the final form (efunda Retrieved 2009).

2.2.5. Fused Deposition Modelling Process

Fused Deposition Modelling (FDM) is an extrusion based rapid prototyping process, which is capable of building objects from filaments of polymeric materials such as Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC),

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Polyphenylsulfones (PSSF) and waxes. The process was developed by Scot Crump of Stratasys in the late 80s and was commercialised in 1990, and currently is one of the most used rapid prototyping technologies.

In FDM, the prototyping process begins with unwinding the feedstock filament from a reel and feeding it through the liquefier located inside the system working envelop, as shown in Figure2.9, where it gets gradually heated by temperature gradient provided by a number of coils wrapped helically about the axis of the liquefier .

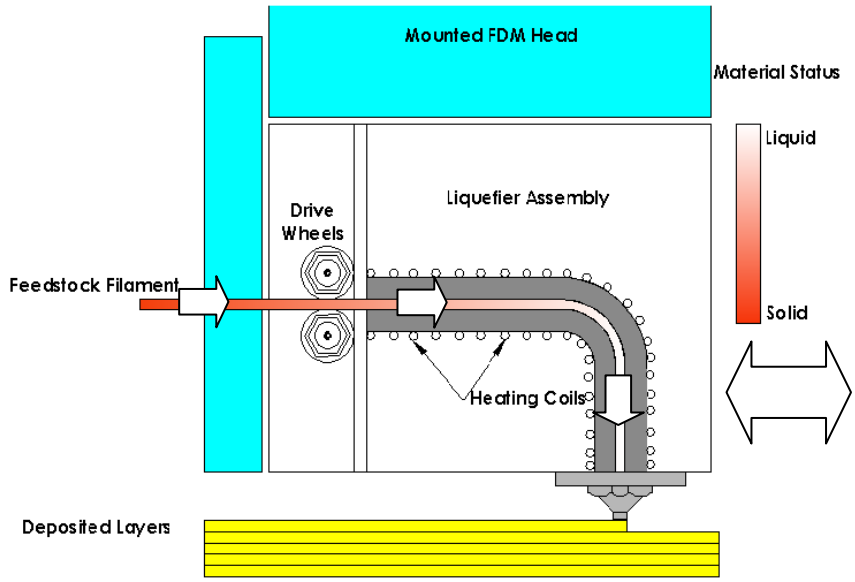

Figure 2-9: Fused Deposition Modelling process

The heated liquefier melts the plastic filament and deposits the melt through a nozzle attached at the exit controlling the diameter of final extrudate. Two step motors at the entrance of liquefier make sure a continuous supply of material during the model build-up. The nozzle and liquefier assembly is mounted onto a mechanical stage numerically controlled in X-Y plane. Upon receipt of precise tool paths prepared by the Insight software, the nozzle moves over the foam substrate depositing a thin bead of thermoplastic model material along with any necessary support structure. Deposition of fine extruded filaments onto the

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substrate produces a layer corresponding to a slice of the CAD model of the object. Once a layer is built the substrate moves down in z direction in order to prepare the stage for the deposition of next layer. The deposited filaments cool down immediately below the glass transition temperature of the polymer and get hardened. The entire build system is contained within a temperature-controlled environment with temperatures just below the glass-transition temperature of the polymer to provide an efficient intra-layer bonding.

There are two designs used for the liquefier assembly on the commercially produced FDM machines, one with straight tube and the other with 90-degree bent tube. The latter design, Figure2.9, provides less dimensional inaccuracy on the extruded strands due to the improved die-swell phenomenon whereas the former design, Figure2.10, design brings about more continuous and smooth flow of the filament extrusion. While most configurations use filament form of the feedstock materials, some other have used pellets fed from a hopper offering certain advantages (Bellini, Shor & Guceri 2005). Where applicable, support structures are deposited along with the model material for overhanging geometries and are later removed by breaking them away from the model. A water-soluble support material is also available which can be washed away in a water-based sodium hydroxide solution contained within a mechanically agitated tank (Grenda 2007).

The Fused Deposition Modelling process is a bench-top and office friendly technology. It is fairly fast for small parts, or those that have tall, thin shape-factors. Currently, it can build durable, accurate and strong models from Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), and Polyphenylsulfones (PSSF). The feedstock material is fed in the form of filament with diameters of 1.75± 0.05 mm and a range of nozzle tip sizes are used to produce fine to medium slices with different trade-offs between accuracy and lead time of the final prototype as shown in Table 2.1.

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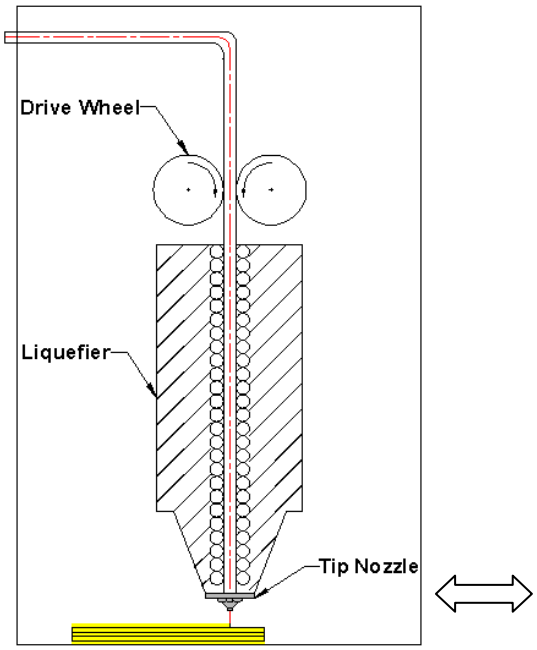

Figure 2-10: FDM Liquefier Straight Nozzle

Materials used in FDM are non-toxic and inert, synthesised from commercially available thermoplastics and waxes. They all vary in strength, rigidity and surface finish providing a wide range of testable models (Stratasys Retrieved 2009).

Table 2-1: Different Nozzle Tip Sizes and Thicknesses Used in FDM (Courtesy of Stratasys Inc.)

Tip	Slice	Default	Min Road	Max Road
T10	0.007	0.014	0.010	0.028
	0.010	0.020		
T12	0.007	0.014	0.012	0.038
	0.010	0.020		
T16	0.010	0.020	0.016	0.038
	0.012	0.024		

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Application areas of the Fused Deposition Modelling cover various industries including automotive, aerospace, business, commercial machines, medical, consumer products, architecture, etc (Liou 2008). Main advantages of this extrusion-based process comprise fabrication of functional models from real thermoplastic materials such as ABS and medical ABS, investment casting wax and elastomer as well as multiple colour materials. Due to non-toxicity of the feedstock materials the process is office-friendly. The material can be easily changed, and the waste is negligible. Since the size of strands produced as building elements of the prototypes is limited to the nozzle tip size, the process can have limited accuracy compared to the liquid-based processes such as SLA. Limited materials, limited size, and unpredictable shrinkage are of disadvantages of FDM rapid prototyping technology.

2.3. Overview of Emerging Rapid Manufacturing Processes

Rapid Manufacturing (RM) or alternatively digital direct manufacturing refers to the new series of additive fabrication processes currently being developed for the volume part production based on the same concept of Rapid Prototyping. Likewise, it uses computer aided design data to produce solid objects which can be directly used as finished product or components with no tooling required. The additive manufactured parts might need post-processing of some sorts using techniques such as infiltration, bead blasting, paining, etc (Hopkinson, Hague & Dickens 2006). RM differs from RP in that most of RP systems have not been designed for manufacturing, and therefore, suffer from issues of surface finish, accuracy, materials range, and repeatability to name a few.

By elimination of tooling phase, as the most costly and time consuming part of the conventional manufacturing process, using RM, the designers will be able to think more freely and creatively without the limitations previously imposed by the "design for manufacture" concept. This also justifies application of RM not

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only for low volume production but also for the manufacturing of a single product (Eyers & Dotchev 2010; Hopkinson, Hague & Dickens 2006).

In the following, some of the current commercially available RM processes is reviewed. Based on the raw material use, these processes are classified in three groups of liquid based, powder-based, and solid-based processes.

2.3.1. Liquid-based RM Processes

These entail processes in which a photosensitive polymer is solidified as it gets exposed to a UV laser light.

2.3.1.1. *Stereolithography*

As a successful pioneering Rapid Prototyping technique, SLA offers a great potential as a Rapid Manufacturing process thanks to its reliability, very high accuracy and resolution, and material range (Eyers & Dotchev 2010).

Viper Pro is the most recently introduced SLA machine, by its developer 3D System, with building envelop size of 1500 mm X 700 mm X500 mm; capable of manufacturing multiple parts with the same surface finish as "normal CNC machining" (LeGault 2009).

Introduction of MicroStereolithography by Bertsch et al (Bertsch et al. 2000; Bertsch et al. 2003) has added completely new dimensions to the existing SLA process. Using this new technique based on SLA, fabrication of very small and very complex components have been viable which previously were not possible for replication on the Stereolithography apparatus. In addition, choices of material have been extended to new series of polymer/composite photosensitive resins to be used in the process for the manufacturing of complex 3D parts and tools. Biomedical applications, in particular tissue engineering and scaffolding, have also been a major target for SLA-based rapid

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manufacturing (Arcaute, Mann & Wicker 2006; Greil et al. 2007; Lee et al. 2007; Peltola et al. 2008; Sodian et al. 2005; Stoner et al. 2005; Winder & Bibb 2005).

Further developments and improvement of Stereolithography process in micro/nano scale and introduction of a wider range of materials is the major drive towards its new applications in the horizon of rapid manufacturing (Arcaute, Mann & Wicker 2010; Crandall et al. 2008; Lee et al. 2008; Singare et al. 2009; Wu et al. 2009a).

Another successful RP technique which has outgrown into RM process is Envisiontec Perfactory system. Similar to SLA, based on Photopolymerisation, it creates three dimensional resin molds directly from 3D CDA data through a patented Digital Light Processing System (DLPS)(Envisiontec 2010). Using a projector, instead of laser, sequential Voxels (volume pixels) are projected into liquid resin causing it to solidify plane by plane. Layers with dimensions as small as (16 um x 16 umx15 um) in X, Y, Z directions can be built. It is a flexible, high throughput and low cost RM process capable of producing superb detail and accuracy for medical and dental applications as well as jewellery industry as shown in Figure2.11.

Figure 2-11: Production of Jewellery and Hearing Aid by Envisiontec Perfactory©

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PolyJet from Object Geometries is a photopolymer based jetting technology which deposits 16 um layers of photosensitive liquid resin and support material simultaneously to fabricate fine-featured parts. It is a non-laser based RM system offering a high production speed, accuracy and resolutions. Due to absence of laser, the part cleaning is easy and the process has a good reliability (Eyers & Dotchev 2010).

2.3.2. Powder-based RM Processes

Due to material properties, part stability as well as wider range of materials including polymers, ceramic and metals, these processes are more suitable for RM compared to their liquid counterparts (Hopkinson, Hague & Dickens 2006). In particular, the potential of producing functionally graded materials, as a result of combining powder mixtures with layer additive manufacturing, offers a unique functionality of rapid manufacturing for these processes.

Figure2.12 presents a classification of powder-based RM processes based on whether or not the feed powder is melted during the process to manufacture the final components.

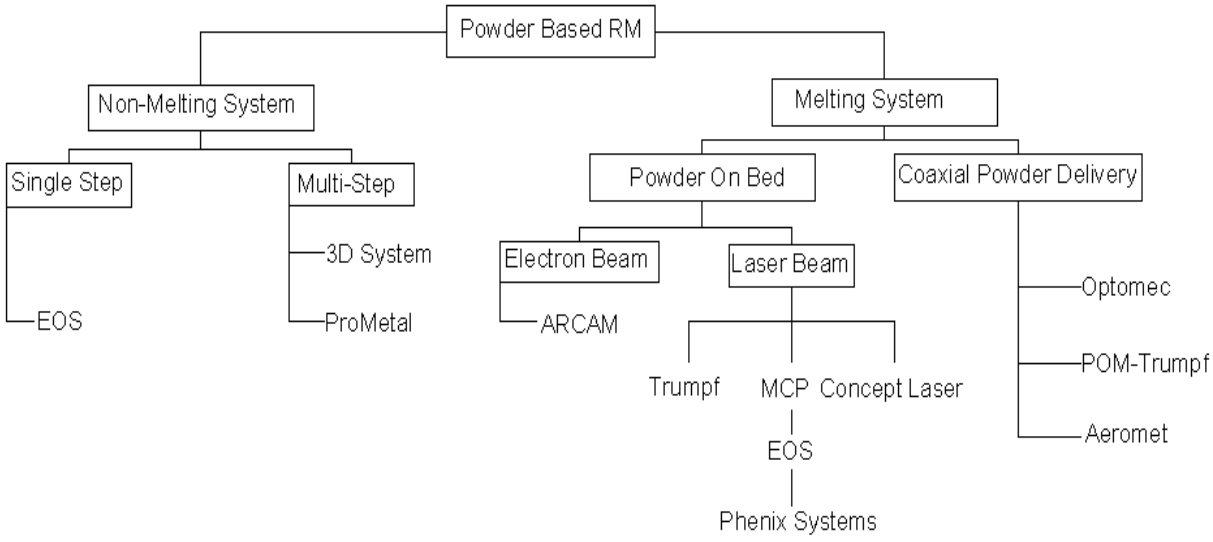

Figure 2-12: Powder-based RM Processes and the Current Commercial Providers (Santos et al. 2006)

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2.3.2.1. Direct Metal Laser Sintering

Direct Metals Laser Sintering (DMLS) is an SLS based(Santos et al. 2006) RM technology, commercialised by EOS of Germany, which can directly produce metallic parts by fusing metal powders using a high-power laser beam. At least two types of metal powders with significantly different melting temperature are used. By fusing the powder with lower melting temperature it infiltrates into the body of main powder mixture, and therefore creates a dense part upon solidification (Lu, Fuh & Wong 2001). It is a net-shape process capable of producing parts with a good detail resolution of 20-50 micron, accuracy of ±50 micron, and surface finish of 3-6 micron. A wide range of metal powders are available for various RM applications including injection/die casting moulds, medical devices and implants, biomedical functional parts as well as heavy duty moulds (Eyers & Dotchev 2010). Finer powder size results in a thinner layer thickness, and higher quality of the finished part (Santos et al. 2006). Table 2.2 shows the range of materials used by SLS/DMLS process. Figure2.13 shows some parts produced by DMLS.

Table 2-2: Materials Used for Processing by SLS/DMLS(Levy, Schindel & Kruth 2003)

Material	Particle size (μm)
DTM RapidTool 1	50
DTM RapidSteel 2.0	34
DTM LaserForm ST 100	23
DTM LaserForm ST 200	20
EOS Ni–Bronze Sn60Pb infiltrated	100
EOS (Electrolux) DMLS DirectMetal™ 50-V3	100
EOS (Electrolux) DMLS DirectMetal™ 50-V2	50
EOS (Electrolux) DMLS DirectMetal™ 50-V1	50
EOS (Electrolux) DMLS DirectMetal™ 20-V2	20
EOS (Electrolux) DMLS DirectMetal™ 50-V1	20
Inconel 625 superalloy (SLS+HIP)	16-44
Ti–6Al–4V (SLS+HIP)	37-74

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Figure 2-13: Rapid Manufactured Parts by DMLS (Source: Morris Technologies Retrieved 2010)

2.3.2.2. Selected Laser Melting

Selective Laser Melting (SLM) is similar to SLS, but the laser used has a much higher energy density to fully melt the powders, and achieves fully dense parts without the need for post-process densification (Kruth et al. 2003; Santos et al. 2006). Solid state fibre or disc laser is used, namely diode pumped Nd:YAG , instead of Co_2 laser. Full melting has the advantage of producing dense products in single step; however, internal stresses or part distortions are also expected due to high temperature gradients. In addition, due to *balling and dross formation* in melt pool there is a risk of poor surface finish (Kruth et al. 2007). Currently four German vendors are offering dedicated SLM machines(M3Linear, EOSM250X, Vangaurd HS, MCP-HEL) (Ghany & Moustafa 2006).

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2.3.2.3. Direct Metal Deposition

Direct Metal Deposition (DMD) is a rapid manufacturing process which employs the principal of blowing metal powders into a melt pool, created by computer controlled lasers, to build custom parts, and fabricate moulding tools. A representative of this process is Laser Engineered Net Shaping (LENS) developed by Optomec Inc, and a similar version commercialised by POM as shown in Figure2.14 (Hopkinson, Hague & Dickens 2006). Typically powdered metal particles are fed into the focus of laser beam through a stream of gas to create a molten pool of metal.

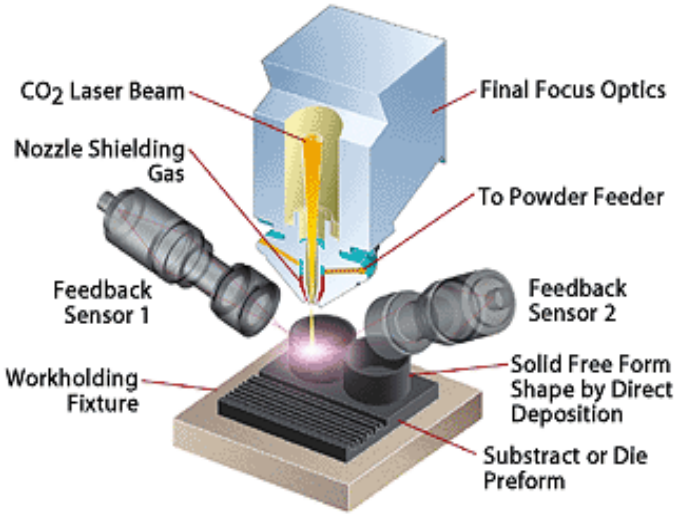

Figure 2-14: Direct Metal Deposition (Courtesy of the POM Group Inc.)

The high-power laser beam moves back and forth across the part while a precise stream of metal powder is added to the molten pool to increase its size. This process combines several technologies namely as lasers, CAD/CAM, sensors, and powder metallurgy(Liou 2008). Objects made by this technique are near net shape with a requirement for a finish machining stage. They are fully dense with good grain structure, and have properties similar to, or even

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better than the intrinsic materials. Material limitations are fewer than SLS with no need for secondary firing processes. DMD can be used for various applications ranging from materials research to functional prototyping, and volume manufacturing. A unique benefit of this process is its ability to add material to an existing structure for repair and service applications. The drawbacks are relatively slow deposition rates, and poor surface finish.

2.3.2.4. Electron Beam Melting

Electron Beam Melting (EBM), Figure2.15, is a rapid manufacturing process developed by ARCAM AB based on RP technology. It manufactures parts and tools using a focused electron beam within a vacuum chamber from thin layers of powders with accuracy of ±50um. The focusing high power electron beam (4KW) ensures a very fast scanning of powder layers, and minimum heat distortion, and hence fabrication of parts with excellent physical and mechanical properties (Thundal 2008). Vacuum chamber coupled with high power energy source helps achieving a controlled chemical composition, and a fully dense material with fine microstructure. It makes the process also suitable for highly reactive materials such as titanium which is widely used in biomedical implants. EBM is capable of building highly efficient cooling channels from hard tooling steel with reduced manufacturing time and cost compared to other RP-based tooling methods such as 3D Keltool, and 3D printing (Gibbons & Hansell 2005).

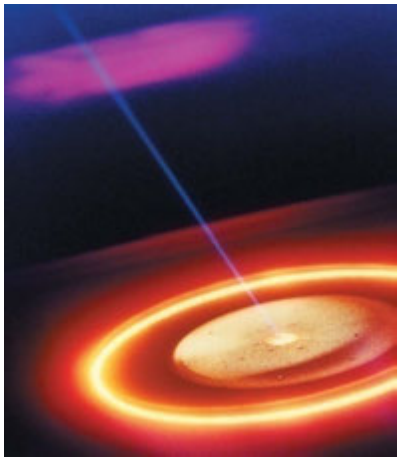

Figure 2-15: Arcam Electron Beam Melting Process (Thundal 2008)

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A wide range of metal powders can be used including steel, aluminium, and copper powders as well as Arcam own developed titanium, and cobalt-chromium based powder mixtures for optimized processing parameters on EBM.

2.3.3. Solid based RM Processes

Predominant solid-based RP techniques offering a potential for use as Rapid Manufacturing process include fused deposition modeling (FDM) and laminated object manufacturing (LOM) (Hopkinson, Hague & Dickens 2006), described in details in sections 2.2.4, and 2.2.5.

2.3.3.1. Laminated Object Manufacturing

A few LOM-based processes have been developed and used for direct manufacturing of functional metal parts(Chiu, Liao & Hou 2003; Guo 2006; Pereira et al. 2007), and composite parts(Windsheimer et al. 2007). In a similar manner to other layered additive manufacturing technologies, LOM creates three dimensional parts by cutting and stacking two-dimensional sheets of various materials. As mentioned earlier, one of its major drawbacks is the tedious, and time consuming post processing, involving the disposal of unwanted materials using hand tools, and its limited range of materials. However, some improvements have been made such as Bridge-LOM by Chiu et al (Chiu & Liao 2003) resulting in reduced laser-cutting time, and waste disposal time by proposing new building algorithm. In addition, employment of different materials such as polyvinyl chloride (PVC) by Solidimension, and development of new and more environmentally friendly polymers (Hopkinson, Hague & Dickens 2006) can increase its potential for Rapid Manufacturing(RM). A very successful variation of solid-based Rapid Manufacturing process is the ultrasonic consolidation of Shape Memory Alloy (SMA) fibre-embedded aluminium matrices by Kong et al (Kong, Soar & Dickens 2004) as shown in

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Figure2.16. Their proposed method has been capable of fabricating adaptive structural composites for advanced aerospace applications (Kong & Soar 2005).

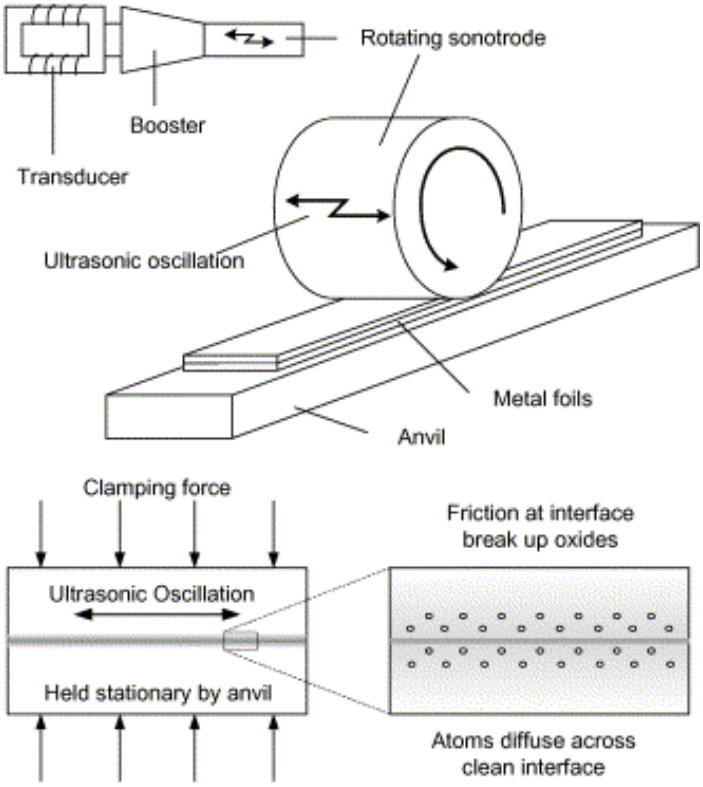

Figure 2-16: Ultrasonic Consolidation of Metal-Matrix Composites (Kong, Soar & Dickens 2004)

CerLOM is another variation of LOM process which has been used for rapid production of ceramic parts with both homogenous and multilayered composite structures(Griffin, Mumm & Marshall 1996), and continuous fibre ceramic matrix composites (CMCs) (Klosterman et al. 1997).

2.3.3.2. Fused Deposition Systems

Fused Deposition Modeling (FDM) and Contour Crafting are the two established extrusion based layered manufacturing processes currently capable of manufacturing parts from a wide range of thermoplastic and structural ceramics respectively.

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Contour Crafting(CC) developed by Dr. Khoshnevis of the Southern University of California (Khoshnevis 1998) couples the FDM extrusion concept, to deposit and crafts the contours of the part, with a filling process to build the core. It replaces the tip nozzle of Fused Deposition Modeller with a bladed trowel to fabricate very smooth and accurate surfaces with complex features as shown in Figure2.17. Its major potential applications include fabrication of turbine blades, large tooling for automotive and aerospace industries as well as construction of civil structures such as houses and bridges (Khoshnevis et al. 2001). Khoshnevis has also presented a very interesting variation of CC system called Lunar Contour Crafting designed for automated fabrication of integrated structures using high-strength concrete on the Moon (Khoshnevis et al. 2005).

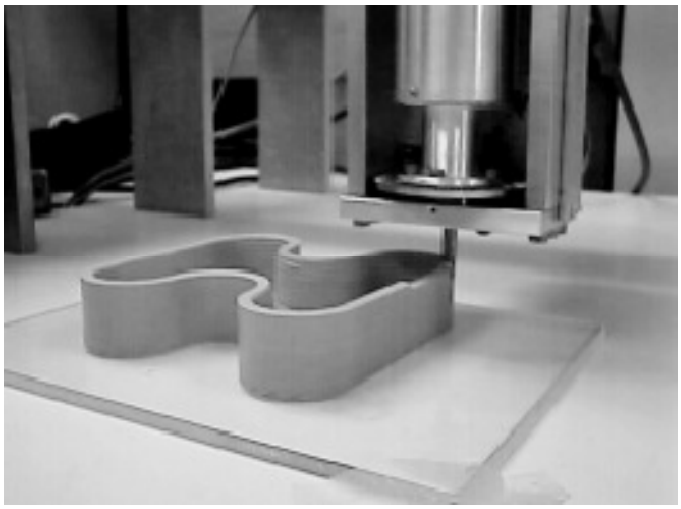

Figure 2-17: Contour Crafting of Structural Ceramic (Khoshnevis et al. 2001)

Another variation of FDM is the fused deposition of ceramics (FDC) patented by Danforth in the New Jersey University of Rutgers (Danforth 1995). It is primarily used to manufacture piezocomposites for applications in piezoelectric censors and actuators (Safari, Allahverdi & Akdogan 2006). The process has been further developed by Bellini et al (Bellini, Shor & Guceri 2005) where a

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new feeding system is introduced to intake the bulk material in granulated form, and overcome the limitations imposed through use of feedstock in filament form. The developed mini extruder deposition system creates new opportunities for the use of a wider range of materials in FDM, and therefore makes it a more viable manufacturing process for specialty products.

Stratasys as the commercial provider of FDM machines has recently introduced its Fortus 3D Production System for the short-run production of manufacturing tools, and end-use parts. Fortus FDM technology is capable of producing accurate and durable parts using advanced production grade thermoplastic materials (Stratasys Retrieved 2009). With a large envelope size of 914 x 610 x 914 mm, the system is offering an accuracy of ±0.0015 mm at multiple layer thicknesses. However, the feedstock materials in the filament form can only be made of engineering plastics limiting the properties of parts and tools made by this technology.

2.4. Material Issues in RP & RM

As outlined in the section 2.1, materials play a fundamental role in the improvement of existing RP techniques and development of Rapid Tooling and Manufacturing processes using such techniques. Developing new materials and their long-term consistent availability is the key to the success of RM or layered manufacturing processes, in particular, with the incentives of geometrical complexity and smaller part size (Levy, Schindel & Kruth 2003). But, the material requirements are influenced by the need to produce feedstock that can be processed successfully by a particular additive manufacturing process. Despite the varying limitations of each of the RP/RM processes imposed by

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such requirements, there is a potentially wide range of materials that may be processed by these technologies(Bourell, Leu & Rosen 2009).

For new product development, product functionality, appearance, and shape or geometry are considered as the main criteria(Eyers & Dotchev 2010) which are all driven by the material to be used in the manufacturing phase. This further demonstrates the importance of materials in developing a viable rapid manufacturing process, and facilitating the product development. Figures2.18 & 2.19 show the classifications of homogeneous and heterogeneous materials, respectively, which may be processed using AM/RM processes.

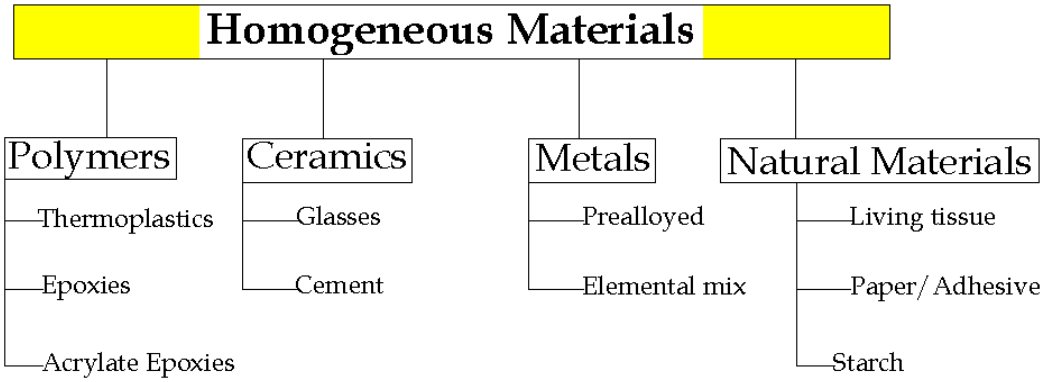

Figure 2-18: A hierarchy of homogeneous materials system for additive manufacturing (Bourell, Leu & Rosen 2009)

The use of transient and permanent binders is central to heterogeneous materials. This class of materials can be further varied by the potential in many cases to employ post processing steps such as infiltration of porous AM parts.

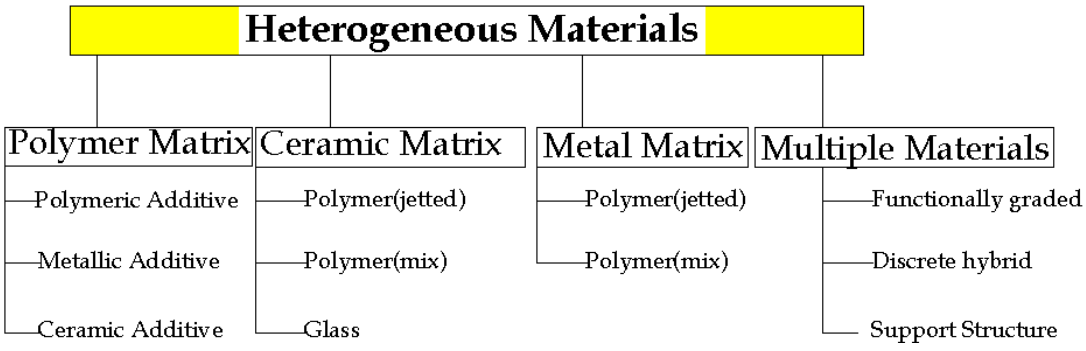

Figure 2-19: A hierarchy of heterogeneous materials system for additive manufacturing (

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Along with the advent of rapid Additive Manufacturing processes, research is being conducted to develop and enhance the properties of materials to improve the viability of such processes.

So far a variety of photo curable epoxy-based and acrylate-based monomers have been used for Stereolithography by its commercial developer 3D systems. However, there is still need for introducing a wider spectrum of materials, which can be routinely processed (Stampfl et al. 2008).

One major requirement for development of new materials for SLA process is the photopolymerisation characteristics i.e. the material should solidify when scanned by a UV laser, making it a more challenging task. It has been shown that polymers obtained from acrylates with urethane units, mostly dialkylacrylamide and especially trimethylolpropane triacrylate can provide such a base with outstanding biocompatibility in tissue engineering applications (Schuster et al. 2007).

Stampfl et al have processed photopolymers with modifiable mechanical properties through a new high resolution μSLA system (Stampfl et al. 2008). Various hybrid sol-gels, hydrogels, and photo-crosslinked elastomers have been screened. By tailor making the formulation of the suitable resins, they have been able to adjust the viscosity, and therefore tune the elastic moduli of the macroscopic parts by several orders of magnitudes. It has also been shown that biocompatible and biodegradable monomers can be developed by carefully selecting their constituent monomers which can be used in SLA (Anseth & Quick 2001; Schuster et al. 2005).

Most of the existing photopolymers demonstrate similar mechanical properties to plastics such as ABS and PC. However, due to demand of superior mechanical and thermal properties by the market, new materials are expected to appear (Eyers & Dotchev 2010).

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Quite a few numbers of materials have been developed for the advanced SLS/SLM metal deposition systems although some haven't yet reached the industrial maturity (Kruth et al. 2003; Levy & Schindel 2002). These include IN 718, $ZrSiO_4$, SiO_2 by the IPT Aachen (Kloke 1998); WC-Fe-Ni, SiC, WC-9Co and WC-12Co cermets by (Kruth 2001a; Laoui, Froyen & Kruth 1998, 1999a, b).

Abe et al (2000) have used titanium, aluminium and copper to manufacture medical devices, and metallic and hard tools by selective laser melting. Partee et. al have introduced polycaprolactone (PCL), one of the most widely used biocompatible and bioresorbable materials for tissue engineering applications to manufacture test scaffolds with designed porous channels. Using the optimal SLS process parameters, they have successfully fabricated bone tissue engineering scaffolds based on the actual minipig and human condyle scaffold designs (Partee, Hollister & Das 2006). Chung and Das (Chung & Das 2006) have investigated the fabrication of functionally graded materials (FGM) by introducing Nylon-11 composites filled with different volume fraction of glass beads (0-30%). The results showed an increase of tensile and compressive modulus and decrease of strain at break as a function of filler. They have also experimented processing of functionally graded polymer nano-composites by incorporating silica nano fillers in the Nylon-11 matrix, and subsequently fusing it by an SL process (Chung & Das 2008).

In a recent work by Yang et al (Yang, Shi & Yan 2010) a composite of potassium titanium whiskers (PTWs) reinforced plastic has been tried for processing in selective laser sintering. Using a new dissolution-precipitation method they have prepared PA12/PTWs composites suitable for use in SL process with reasonably improved mechanical properties. A complete list of composite materials by SLA has been discussed by Kumar and Kruth(Kumar & Kruth 2010).

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Despite developments of a wide range of materials for SLS/SLM processes, there are still some critical issues to be addressed by research including the porosity and microstructures. It has been shown that with the existing materials, pore-free parts cannot be obtained by SLM process, and neither heat treatment nor infiltration can be used to decrease the porosity of the parts, however, Hot Isostatic Pressing could be a solution (Kumar & Kruth 2008) which will compromise the time and cost of the process instead. Additional problems limiting the palette of usable materials in laser and powder based layered manufacturing have been discussed by Kruth et al through invoking different consolidation mechanisms (Kruth et al. 2007).

Developing new materials and improving the existing materials have also been identified as the two research areas to further develop 3D printing into rapid manufacturing process (Dimitrov, Schreve & De Beer 2006).While the producers of 3D printers have been the up runners of improving the existing materials, some research institutions lead by MIT, as the inventor of the 3DP, have also been involved in developing suitable material combinations for the process (Kaczynski 2000). Z Corp has been continuously upgrading its starch powders for 3D printers by offering zp11, zp14, and zp15e with new binders and infiltrants as well as introducing new ZCast 500, and ZCast 501 materials to expand its manufacturing applications in sand casting technology.

Seitz et al have successfully used a modified hydroxyapatite (HA) powder to fabricate implantable bio-compatible scaffolds using 3D printing. Manufacturing of fine internal features (down to 450 μm) have been demonstrated (Seitz et al. 2005). Suwanprateeb and Suwanpreuk have used a mixture of Polymethyl methacrylate(PMMA) powders with maltodextrin binders as a raw material in 3DP process to produce translucent and strong models(Suwanprateeb & Suwanpreuk 2009). In a work by Anderson et al, a combination of steel powder and a low viscous polymer binder have been used

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as stock material for rapid manufacturing of metal matrix composites. The requirement for a subsequent thermal sintering and infiltration has been a major obstacle in expanding the materials for this process (Anderson, Lembo & Rynerson 2002; Johnston & Anderson 2002).

Similarly to the other RP/RM processes, some of the key issues hampering further development of Laminated Object Manufacturing have been related to its lacking or inefficiencies of the materials including the adhesives used for interlayer bonding (Li 1997) and warping of the laminates due to variations in the temperature and viscosity of the adhesives (Lin & Sun 2001). However, some of these issues have been addressed by finite element analyses of bonding process in LOM considering the effects of material properties and resulting internal stresses, load deformation as well as interlaminar shears during the process which influence the quality of interlaminar bonding (Park, Kang & Hahn 2001). Pereira has investigated the effects of surface heat treatment, thickness of the adhesive layer, and the applied pressures during the process on the joint strength, and quality of parts made of aluminium layers (Pereira et al. 2007). Some researchers have focused on developing new materials to addressee such issues, and enhance the process for production purposes. These include introduction of a styrene-acrylic based binder for making green tapes using water-based tape casting for LOM process(Cui et al. 2003), metal matrix, and adaptive composites using ultrasonic consolidation (Kong & Soar 2005), and colloidal processing of a new glass-ceramic material (LZSA) to produce laminates of higher tensile strength (Gomes et al. 2009). Table 2.3 lists the currently most viable commercial RM technologies and their available materials.

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Table 2-3: Material type and the most viable commercial RM technologies (Eyers & Dotchev 2010)

Materials Type	RM Technology	Manufacturer	Materials
Photopolymer resin	SLA	3D systems	Variety of epoxy resins and nano-composite resins
	Envisiontec Perfactory(2D mask)	Envisiontec	Epoxy-acrylic resins, nano-composite resins and acrylic resin(investment casting)
	PolyJet(3D printing)	Object Geometries	Proprietary photopolymers and biocompatible resins
Plastic	SLS	3D systems	Polyamide 12, GF polyamide, aluminium filled polyamide, composite plastics and CastForm (polystyrene/wax system for investment casting)
	LS	EOS GmbH	Polyamide 12, GF polyamide, aluminium filled polyamide, flame retardant polyamide, carbon fibre filled polyamide and polystyrene (investment casting)
	FDM	Stratasys	ABS, PC-ABS, PC and biocompatible ABS
	MJM(3D printing)	3D systems	Polymer (wax-like)
	Multi jet Modelling	Solidscape	Polymer (wax-like)
Metal	DMLS	EOS GmbH	Stainless steel GP1 and PH1, cobalt chrome SP1 and SP2, titanium Ti64, Ti64 ELI and Ti CP, maraging steel MS1, AlSi20Mg and EOS Inco718
	SLM	MTT	Stainless steel and titanium
	Laser Cusing	Concept Laser	Stainless steel, hot-work steel, titanium TiAl6V4, aluminium AlSi12, AlSi10Mg and nickel-based alloy (Inconel 718)
	EBM	Arcam AB	Pure titanium, Ti6Al4V, Ti6Al4V ELI and cobalt chrome

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In general, improving the quality, process consistency, repeatability and reliability in a ***broader diversity of materials*** at a lower material, machine, processing and finishing cost is the main challenge facing the future of AM/RM processes (Bourell, Leu & Rosen 2009). RM processes should eventually provide the best material choices in order to be able to address the design requirements (Eyers & Dotchev 2010). Despite a wide range of materials processed by AM/LM/RM technologies, a lot remains to be achieved in terms of developing better materials with properties equal or superior to those used in traditional processes. While extensive researches so far have been devoted to introducing new metallic and plastics materials, especially in case of powder based processes, there is a need for focusing more research towards development of ceramics and composites in the future research.

2.5. Research Direction in Fused Deposition Modelling

Fused deposition modelling is among the fastest growing prototyping techniques with its potential for the emerging tool-free manufacturing era. It has already established itself as an ideal conceptual and functional modelling method with great stability of the parts, processing reliability, and reasonable accuracy. Recently, with introduction of large building envelope by its developer Stratasys, even shorter throughput can be yielded. However, further research and developments are required to widen its application domain, and fully enable its potentials as a viable manufacturing method. In this context, two major areas can be recognized, from the literature, as the frontiers of research which can possibly promote the process for rapid manufacturing purposes. These include process improvements in particular improving the accuracy and surface finish of the parts and tools made by this method, and more crucially, development of new production grade materials.

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Development of novel materials ideally will result in the production of parts with excellent electro-mechanical, thermal, chemical or magnetic properties as well as high definition and surface finish. Certain challenges need to be overcome in this regard which have been addressed earlier. However, the simple structure and fabrication technique of FDM is a great advantage in opening up more opportunities for introducing new materials and turning it into a reliable and agile manufacturing process. In the following, state of the art of literature, and attempts made regarding the new materials development and process improvements for Fused Disposition Modeling are presented. FDM assisted medical and rapid tooling as its most important manufacturing applications have also been reviewed.

2.5.1. New Materials & Process Improvements in FDM

Some pioneering work in regards with developing new materials and system improvements have been conducted by the researchers from the Rutgers University (Agarwala et al. 1996b; Allahverdi et al. 2001; Bandyopadhyay et al. 1997; Safari & Danforth 1998; Subramanian et al. 1995). Their focus have been given to the development of new sets of binders to vehicle high loads of ceramic powders through the Fused Deposition process and fabricate green ceramic parts. Compounding of powder/binder mixtures through a single screw extruder to produce feedstock filament has been followed by processing them on a modified Stratasys 3D Modeler ™ system, and removing the binder to achieve the green parts. A further stage was needed to sinter the green parts into fully dense functional parts.

Agarwala et al(1996b) have demonstrated the possibility of fabricating ceramic and metal parts by applying a variety of ceramic and metal particulate systems

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through the processes called Fused Deposition of Ceramic (FDC), and Fused Deposition of Metals (FDMet) as variants of the commercial Fused Deposition Modelling system. The ceramic and metallic materials used were SiO_2, Si_3N_4, PZT, and stainless steel powders respectively. Despite the practicality shown for the processing of ceramic and metallic systems, further improvements were needed to tackle some serious surface and internal defects, and hence produce functional parts. Later on (Agarwala et al. 1996a) some strategies were suggested in order to eliminate most of the defects. A detailed investigation of issues related to processing 'green ceramic prototypes' by Lombardi et al (Lombardi et al. 1997) revealed some very important parameters influencing the robustness of Fused Deposition of Ceramic to produce high strength, and dimensionally accurate ceramic components. Some of these include the high degree of compositional homogeneity; reproducible rheology, facile binder removability, and the capacity for sintering into fully dense part after debinderisation (Lombardi et al. 1997).

McNulty et al have processed filaments of a thermoplastic binder loaded with 55% volume fraction of lead zirconate titanate(PZT) powder to fabricate functional piezoelectric ceramic devices using Fused Deposition of Ceramic (McNulty et al. 1998). Formulation of the binder had been based on a compromise of resultant mechanical, rheological and thermal properties in the final filaments. A combination of tackifier, wax, and plasticizer along with base binder have been used to trade off between the required stiffness and flexibility of the filaments to successfully process them through fused deposition modeller to achieve the final components.

In a collaboration between researchers of the University of Illinois and Rutgers University (Venkataraman et al. 2000), property-process relationship of the feedstock filaments have been studied to understand the causes of failure of the filaments during the FDC process. It was observed that filaments with lower

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buckling load tolerance than the pressure required to push them through the FDC liquefier would fail, and interrupt the prototyping process. Therefore, a critical value for the ratio of compressive modulus of elasticity to the viscosity of the feedstock material has been proposed. It has been stated that a ratio $\left(\frac{E}{\eta_a}\right)$ greater than value of ($3x10^5$ to $5x10^5 s^{-1}$) would prevent buckling of the filaments. Based of these findings, a verity of advanced electroceramic components have been processed by another team from Rutgers (Allahverdi et al. 2001). Included were alumina structures with photonic bandgap and bismuth titanate parts for high frequency applications.

Gray IV et al. (Gray Iv, Baird & Bøhn 1998) have investigated the feasibility of using thermotropic liquid crystalline polymers (TLCPs) in FDM 1600. Using a dual extrusion process proposed by Sabol (Sabol, Handlos & Baird 1995), fibrils of TLCP were injected into the molten 4018 grade polypropylene to produce the TLCP/PP composite strands. Then the strands were chopped and re-extruded through a single screw extruder to achieve monofilaments of TLCP/PP. Some basic prismatic shaped parts were processed on FDM 1600, and the mechanical properties of those parts were compared to that of parts produced from neat ABS provided by Stratasys. It was shown that 40 Wt% TLCP reinforced polypropylene composites were 100 percent stronger than those of ABS and 150 percent stronger than pure Polypropylene (Gray Iv, Baird & Bøhn 1998). When filaments of pure TLCPs were processed on FDM, delamination of cross-sections in the part occurred which was due to poor adhesion between adjacent layers and roads, and therefore resulted in weaker mechanical properties.

Zhong et al have attempted to process glass-fibre(GF) reinforced composites through a locally modified FDM system (Zhong et al. 2001). Initially they have tried to use a commodity ABS polymer as the carrier for commercially obtained GF-reinforced ABS. But due to brittleness, the composition could not be made into filament form which is an indispensable requirement for processing of

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parts on Fused Deposition platform. In their second try, matrix has been replaced by a linear low density polyethylene (LLPDE) to provide a better ductility and flexibility. However, this also proves not feasible for filler contents of more 10% due to severe delamination between LLDPE-rich phase and ABS matrix used for incorporating the glass fibres. Therefore a compatibilizer namely Buta-N has been used to improve the linking between molecular chains of ABS on one end and LLDPE on the other end. This way the incompatibility is overcome and short fibre reinforced composites with glass fibre contents of 10.2 Wt% and 13.2Wt% have been processed to produce filaments. There were no details of monofilament processing (Zhong et al. 2001). However, some samples have been made on FDM machine to compare the mechanical properties of GF-reinforced LLDPE with those of the neat ABS. While addition of glass fibres adversely affected mechanical properties of ABS, stacks of GF-reinforced ABS deposited through FDM nozzle, showed improved tensile strength. It was speculated that this could be the result of 'bridging' established between the adjacent glass fibres in the stacked layers prior to the solidification of matrix during FDM processing.

A bioresorbable filament of PCL (Poly ε-carbonate) has been used by Zein et al to produce fully interconnected scaffolds with controlled porosity and channel size on 3D FDM modeller (Zein et al. 2002). By studying the compression mechanical properties of the fabricated scaffolds using PCL biodegradable material, it has been shown that the porosity of the scaffolds were the main determining factor influencing their mechanical behaviour. Contrary to the non-biodegradable materials, build patterns of FDM have not influenced the mechanical properties of such scaffolds (Zein et al. 2002).

Researchers from Rice and Texas Universities in the United States have studied the application of reinforced thermoplastics containing carbon nano fibre (CNF) and carbon nano-tube as the feedstock materials in fused deposition modeling

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process (Shofner et al. 2003a; Shofner et al. 2002; Shofner et al. 2003b). A very small amount by weight percentage of Vapour Grown Carbon Fibres(VGCF), and Single Wall Nano-Tube(SWNT) have been added to the commercially available ABS material to produce filaments for use on Fused Deposition Modeling in order to create functional parts. Some issues have been addressed regarding the dispersion, porosity, and alignments of fibres in the matrix. Scanning Electron Microscopy of the VGCF-reinforced thermoplastics produced by high hear mixing has shown a good dispersion of fibres in the matrix, and minimal porosity. Possessing of such composites through FDM has further improved the alignment of fibres and resulted in their improved mechanical properties compared to the unfilled ABS commercially used on FDM machines. Dynamic Mechanical Analysis has revealed an increase of storage modulus of the matrix by 68% resulting from reinforcing effects of nano fibres (Shofner et al. 2003a). Poor fibre/matrix interface has hindered collection of data for X-ray diffraction and Raman spectroscopy to further investigate the alignment of nano fibres in the filament or measure the electrical resistivity of the samples.

In the most recent work, a medical grade polymethylmethacrylate (PMMA) has been used in order to fabricate some customized porous implants via Fused Deposition Moulding (Wicker et al. 2010). To successfully use filaments of PMMA through a FDM 3000 machine, a trial and error method has been adopted to vary the liquefier and envelope temperature. By closely observing the building process, while varying the temperature of building envelope and liquefier head, suitable temperatures have been found to be 235 ^{o}C , and 55 ^{o}C for the modelling head and the envelope ,respectively, under which optimal raster surface, and minimum material residue were created (Wicker et al. 2010). Tip wipe frequency, layer orientation, and air gap have been considered as the variables for building the implant structures and the experimental design by which mechanical properties and the porosity of scaffolds made out of PMMA have been evaluated. It has been shown that a higher tip wipe frequency, and

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transverse raster building direction resulted in higher compression strength and modulus of the porous implants. Compression strength of the scaffolds were approximately in the range of 13-16 MPa corresponding to the lower tip wipe frequency (one wipe per ten-layer), and higher tip wipe frequency (one wipe per layer) respectively. Higher porosities resulted in decreased compression strength of the implants. The possibility of using PMMA on FDM has been demonstrated by fabricating replacement model for a cranial defect and a femur.

Along with the efforts to develop new feedstock materials for Fused Deposition Modelling, there have also been a few works on the process improvements of the system. Local adaptive slicing procedures have been proposed to further reduce the fabrication time, and improve the surface smoothness (Pandey, Reddy & Dhande 2003b; Tata et al. 1998; Tyberg & Bøhn 1998, 1999). These procedures allow for continuously varying the build layer thickness in order to maximize the overall deposition rate. One such a procedure is to increase the thickness of intermediate layers in the part while satisfying the local surface deviation tolerance (Sabourin, Houser & Bøhn 1997). In another approach for adaptive slicing of parts with complex features, Tyberg and Bohn have developed a procedure in which parts and part-features can be built independently of each other (Tyberg & Bøhn 1999). This method has been implemented, and proven more effective than conventional adaptive methods. However, build temperature, and manufacturer calibration tables needed to be revised to avoid delamination of thin layers. In a similar context, optimization of topology of FDM built parts has been proposed using a 'narrow-waisted internal structure' which creates internal voids with no supports (Galantucci, Lavecchia & Percoco 2008). The approach improves the process speed and reduces cost by reducing material consumption with a trade-off on the density of the final parts.

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Tong et al have suggested a software error compensation method to improve the mechanical error of FDM process by correcting the slice file format (Tong, Joshi & Lehtihet 2008). It has been shown that the proposed method considerably improves the dimensional accuracy of the parts build on FDM. Li and associates (Li et al. 2002) have proposed some predictive models using locally controlled properties offered by FDM which can be used to build functionally graded structures such as bones. Such models were helpful in predicting the mechanical properties of FGM materials produced by varying the deposition density and build orientation during the fused deposition process (Gu & Li 2002; Li et al. 2002).

In order to improve the surface quality of parts produced by fused deposition, important related issues such as surface roughness, dimensional inaccuracy, arising from the stepwise nature of the process, and developed thermal stresses due to temperatures gradients have been also investigated (Luis Pérez 2002; Pandey, Reddy & Dhande 2003a; Wang, Xi & Jin 2007). PEREZ has extensively analysed the uncertainty of roughness, and dimensional parameters in FDM by taking into account the manufacturing process variability and measurement variability. It has been shown that layer height is the most influencing parameter affecting surface roughness, and therefore, by applying smaller value for it, surface quality can be improved. Considering the diameter of material deposition nozzle in FDM, the precision of final parts has been concluded as 'quite good'. In an attempt by Pandey et al. (Pandey, Reddy & Dhande 2003a) a semi-empirical model has been developed to predict the surface roughness of the parts built by FDM. A hybrid RP process has been implemented in which a further machining step by a hot cutter was coupled with layer-by-layer deposition process to cut and flatten the surface of the deposited layers. The developed methodology has enhanced surface finish of the parts with plane surface, but it will require additional numerically controlled axes for free form surfaces which will increase overall machine costs. Wang et al. have addressed

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the factors underlying warp phenomenon which detrimentally affects the quality of the parts in FDM (Wang, Xi & Jin 2007). These included the material characteristics, build parameters setup, and topography of the CAD model. Incorporating these parameters, a mathematical model has been developed to control and adjust the warp deformation of prototypes.

2.5.2. Metal-Polymer Composites in FDM

Layered Manufacturing methods so far used for fabrication of ceramic and metallic parts are invariably using a combination of a thermoplastic binders mixed with metallic or ceramic powders to provide necessary bonding between the particles. This requires a further burn-out stage to make functional parts available for end-use. The additional step can involve further cost and time increasing the overall fabrication cost and time. This partly is due to the nature of ceramic compounding, and hence is unavoidable.

Metal-polymer composites, however, are required due to the synergism offered by them for simultaneously providing polymeric and metallic properties. Intermediate properties of metal-polymer composites can serve for unique applications where use of no other class of materials is justifiable due to time and cost involved. Employing such materials in layered manufacturing technologies couples the further advantage of design flexibility, mass customisation, and lower cost as well as shorter time-to-market delivery.

Moreover, as the RP processes mature towards Rapid Manufacturing, performance validation of parts made by RP techniques requires that the models be made from the same materials as the final product for full scale production (Galantucci, Lavecchia & Percoco 2008). A representative area of applications is where metal-polymer structures are needed to produce electro-conductive polymers, thermally stable plastic, plastic coated metals, radiation

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shielded composites (EM & RF), and micro electronic devices. Currently there is no rapid prototyping process which can serve for such purposes due to lack of appropriate materials.

Fused Deposition Modelling, as detailed earlier, due to its simple structure, easy-to-change hardware, low cost and maintenance; much faster building process compared to traditional methods, and more importantly extrusion based processing nature offers a great potential for a blend of wide range of metals and polymers to be used to fabricate models fulfilling aforementioned areas of application. However, there are certain challenging issues need to be addressed for a successful processing of metal-polymer materials in fused deposition process. These include developing a homogenous composition of such materials by appropriate distribution and dispersion of the fillers in the matrix, rheological investigation in order to understand the proportionality of filler volume content with a trade-off on the resulting thermo-mechanical and electrical properties, need of coupling agents for interfacial bonding, as well as understanding the effects of temperature field on the shear viscosity through mathematical and computational tools.

2.5.3. Medical Applications & Rapid Tooling in FDM

Medical applications of FDM can be found in three areas of bio-implantation (biomedical implants), Scaffolding, and Drug delivery devices.

A major focus of research in material development for FDM has been in the area of tissue engineering scaffolds. Attempts have been made to develop biocompatible materials for processing in FDM for fabrication of scaffolds for tissue engineering applications. Researchers at the National University of Singapore have processed PCL and several composites (PCL/HA, PCL/TCP etc) on the FDM systems (Zein et al. 2002). Endres et al (Endres et al. 2003) and

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Rai et. al. (Rai et al. 2004) have used PCL and CaP composite scaffolds developed by FDM for bone tissue engineering. Woodfield et. al. (Woodfield et al. 2004)have used FDM process for making scaffolds made of PEGT/PBT composites with a range of mechanical properties for articular cartilage application. Kalita et al. (Kalita et al. 2003) have developed particulate-reinforced polymer-ceramic composites using polypropylene (PP) polymer and tricalcium phosphate (TCP) ceramic for scaffolds fabrication on the FDM system.

Although FDM seems to have a large potential for applications in rapid tooling, both indirect and direct RT, very little research has been done. Masood et. al (Masood 1996; Masood & Song 2004) in Swinburne have worked on developing rapid tooling solutions using a nylon/Iron composites.

2.6. Summary

RP methodology has been discussed as the new paradigm in manufacturing processes. With a shift from mass production concept towards mass customisation, due to socio-economical changes in the future society; such paradigm will be revolutionising the current traditional manufacturing industry. In particular it will change the way we think about design and manufacturing.

In this review, commercial RP processes have been discussed with a focus on advantages and disadvantages of four major processes i.e. SLA, FDM, SLS, and 3DP. Current research in RP is directed towards tackling main obstacles which will make them as future viable manufacturing processes. A considerable amount of research is focused on metal-based RP techniques for tooling developments and applications in biomedical engineering. However, the key issue to the success of shifting RP towards RM is the development of new materials.

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The most recent material development areas for RP in the field of polymer, ceramic, composites, metals, and nano-composites have been critically reviewed. It has been shown that while extensive research has taken place in developing materials for powder based processes namely SLS and 3DP, very little research has been done on new material development for FDM process.

FDM being an inexpensive, non laser based process offers big potential for new materials for specific applications such as rapid tooling and biomedical implantation. Research efforts in development of new materials in FDM have been discussed with a little work on using ceramic, biopolymer, and composites. Composites are particularly desirable materials for use with FDM, as its unique technology allows producing tools and parts with unique properties based on synergism of multiple components in such materials, in a way much simpler and faster than the traditional methods.

A previous work by (Shofner et al. 2002) has shown that reinforcing extrusion based SFF polymeric feedstock materials with fillers such as glass fibre and nanofiber can improve the functionality of such materials by employing solid free form (SFF) technology to achieve fibre alignment . However, issues of fibre distribution and dispersion, fibre/matrix interaction, and processing viscosity are keys to the development of the starting.

This research focuses on the development of a novel metal based polymeric composite for Fused Deposition Modelling. Acrylonitrile-Butadiene-Styrene (ABS) terpolymer has been chosen as the vehicle for this new composite because it is the most widely used FDM material for functional part, and no work has been done in developing metal-based ABS composite. The new composite will have a wide range of applications not only in functional parts, but also in making tooling inserts directly on the FDM process for injection moulding application.

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Chapter 3 New Metal/polymer Composites for FDM

3.1 Introduction

As detailed in the previous chapter, the fused deposition modelling (FDM) is an extrusion based rapid prototyping platform that can build prototypes from a range of polymeric materials such as ABS, PC, and PSSF. The prototypes are excellent for functional testing, and form/fit checking. However, for a shift from "rapid prototyping" to "rapid tooling and manufacturing" using fused deposition modelling, both flexibility and improvements in the properties of the current feedstock material is necessary. New materials for FDM process are needed to increase its application domain especially in rapid tooling and rapid manufacturing areas including the production of injection moulding dies and inserts with the desired thermo-mechanical characteristics.

The basic principle of operation of the FDM process offers a great potential for a range of other materials including metals, ceramics, and composites to be developed and used in the FDM process as long as the new material can be produced in feedstock filament form of required size, strength, and properties.

Selection of a metal-polymer composite to be developed as a representative new tooling material in Fused Deposition was based on, but not limited to, a variety of considerations leading to the improvement of thermal, mechanical, and electrical properties. Mechanically strong and stiff materials will help produce prototypes and tooling with higher working life, and dimensional stability. Due to presence of metal content, thermal properties such as thermal conductivity improves which will lead to a shorter cooling time, and production cost. This coupled with the design of the conformal cooling channels by taking the advantage of FDM layered fabrication technology, will tremendously improves the lead time, and thermal stability of the final parts. In addition to the low density, strength, and impact resistance of the polymeric matrix, induced

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electrical conductivity owing to the metal particle contents will help production of housing and casing in electronic devices which can be shielded against the electromagnetic radiation and hence be protected from broadcasting signals. This will be achieved by attenuating the interfering signals with a particular region of spectrum (Bigg 1987a, 1995).

This chapter describes the procedure, and methodology implemented to develop a new metal-polymer composite for use in the Fused Deposition Modelling process. A formulated mixture of the constituent elements and required additives to achieve the final properties is presented. Comprehensive characterization tests have been conducted to reveal the new and improved properties of the developed composite material. Finally, feedstock filaments have been fabricated for direct use in the current Fused Deposition Modelling platform without a need for hardware modification.

3.2 Composite Materials

Nowadays many advanced technological processes require materials with unusual combinations of properties that cannot be provided by the traditional polymers, ceramics, and metal alloys. This is particularly true in the case of applications in aerospace, underwater, and transportation industries with an ever-growing demand for special materials. For example, aerospace industry is increasingly looking for structural materials with low density, high strength, stiffness, and abrasion as well as impact resistance properties. The combination of these characteristics brings an extremely challenging front for engineers and materials scientists. Very often, strong materials are relatively dense whereas further increase of strength and stiffness generally leads to a decrease in impact strength (Callister 1940 & c2007). Materials with such contrasting properties and ranges are being extended by the development of new composite materials.

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In general terms, a composite is referred to any multiphase material that demonstrates significant properties of both constituent phases in such a way that an improved combination of properties is achieved. Based on the "*principle of combined action*" better property combinations are being realized by the well thought-out combination of two or more distinctive materials. Albeit property trade-offs are also expected for many composites. In the context of the present work, a composite is a multiphase material "*made artificially"* in contrary to the one that forms naturally. Furthermore, the constituent phases are chemically distinct with dissimilar interface.

A few classifications of the composite materials have been suggested based on the size, shape and distribution of the phases used (Agarwal & Broutman 1980; Hull 1985). One simple classification of the composite material is shown in Figure3.1, comprising three main categories: particle-reinforced, fibre reinforced, and structural composites. The metal-polymer composite developed in this project is categorized within division of particle-reinforced composites. For particle-reinforced composite the dimensions of particle are approximately the same in all directions whereas in the fibre reinforced composites the distributed phase i.e. fibres, have a large length-to-diameter ratio. A combination of homogenous materials and composites makes up structural composites.

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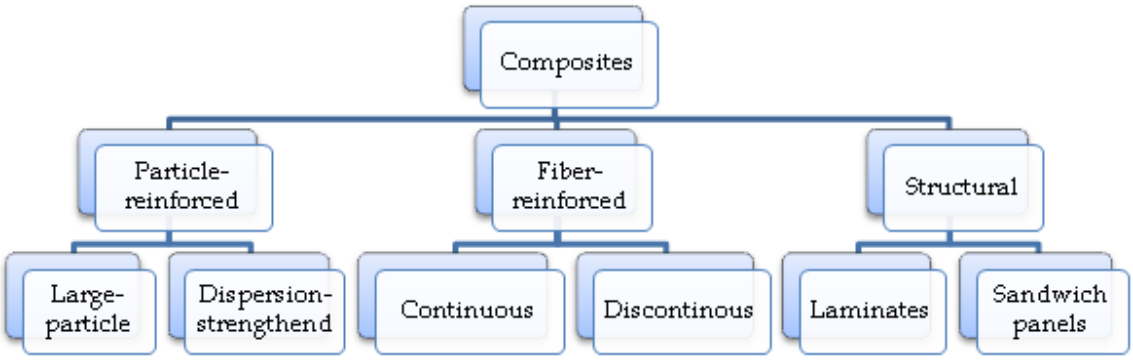

Figure 3-1: A simple classification of various types of composites

The properties of the composites are driven by the properties of their constituent components such as the filler shape, its morphology, and interfacial bonding mechanism. Through alteration of these properties, a variety of functionalities and applications can be achieved for the formulated composites. One such a property is the mechanical properties which is highly dependent on the strength of interfacial bonding between the filler and matrix of the composite(Harry 1987; Sheldon 1982) .

3.3 Metal/Polymer Composites

Traditionally metal/polymer composites have been formed by compounding of metallic fillers in polymeric matrices. Both thermoplastic and thermosetting polymers have been used as matrix to enhance the processing conditions, adhesive properties, corrosion resistance and strength-weight ratio of the composites. However, polymers intrinsically exhibit insufficient number of delocalized charge carriers which detrimentally affect their applications where thermal and electrical properties are required (Kusy 1986). Metallic fillers have been primarily used to modify and improve thermal and electrical properties as well as increasing the density, inducing magnetism, and thermal stability.

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Metallic fillers have been used in the form of fibres and particulates. Particulates fillers have low aspect ratio approximately equivalent to those of spheres or plates. With a compromise on the ultimate tensile strength of the polymeric matrix, use of particulate fillers improves the hardness, heat deflection temperature, and surface finish making them more attractive for applications as representative new materials in RP-based tooling process. Tremendous improvement of stiffness as a result of addition of higher volume fractions of particulate loading in the polymeric matrix is perhaps the most mechanically advantageous factor to be named (Bigg 1987b). Reduction of thermal expansion, mould shrinkage, extensibility, and creep (Bhattacharya 1986) are of the most influential applicable properties of particulate fillers when mixed with polymeric matrices to make up the new class of metal-polymer composites for use in the Fused Deposition Modelling.

3.3.1 Thermoplastic Polymeric Matrices

Polymeric matrices are classified in two subdivisions of thermoplastic and thermosetting based on their response to the mechanical forces at elevated temperatures (Callister 1940 & c2007). Thermosetting polymers are network polymers which can be permanently hardened during formation and do not soften upon heating. Because of the covalent bonds between the adjacent molecular chains in thermosetting polymers, when heated these bonds *anchor* together to resist the vibrational and rotational chain motions.

Thermoplastic polymers are the simplest linear molecular structures with independent macromolecules which can be softened or melted by heating, and be formed, moulded, and solidified when cooled. Contrary to thermosetting polymers, this class of polymeric material can be repetitively heated and cooled

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without physical deterioration (Biron 2007). These give them advantages over the other structural materials for a prolonged use in applications with a wider temperature range, mechanical stresses for severe chemical and physical conditions.

Thermoplastic polymeric materials are extensively used in the various composite applications due to their attractive room-temperature properties, ease of manufacturing, and low cost. Some of the important advantages for processing purposes include their shorter processing time due to absence of the chemical reaction of crosslinking, very high formability, ease of monitoring, and minimal waste. Thermoplastic wastes can be partially reused as a virgin matter owing to the *reversibility* of their physical softening or melting.

Low density of polymeric matrices in the range of (0.9-1.45) g/cc leads to the light weight and low inertia in the moving parts made out of them. Their good corrosion resistance is complementary to the behaviour of the metals. However, lower thermal conductivity and high thermal expansion of the polymers are typical of organic materials which can be modified by the metallic fillers (Birley 1974). Unreinforced thermoplastics have lower stiffness and strength due to existence of weak interchain forces (Van der Waals) between their molecules. Orientation and reinforcement of polymeric chains can significantly increase tensile modulus and tensile strength by increasing the interchain forces. Reinforcing fillers can very well be used in accordance with the macromolecular mixtures to increase the modulus and strength of polymeric matrices.

Based on their consumption, thermoplastics can be categorized into commodities such as polyethylene (PE), polypropylene (PP), polystyrene (PS) and technical thermoplastics such as polyamide (PA), polyacrylics (PMMA), polyacetal (POM), polycarbonate as well as specialty thermoplastics namely polysulfone (PSU), PPS, flouroplastics, PEEK, PEI, liquid crystal polymers (LCP) (Biron 2007).

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3.3.2 Particle-reinforced Polymer Composites

Synergism of materials combinations have been the focus of attention yielding advanced composites with unique properties (Delmonte 1990). In this context, addition of finely divided particles to plastic polymers to create properties and qualities not found in the plastic products has been extensively employed in increasing quantities in the various high-tech industries such as automotive and aeronautics (Jerabek et al. 2010; Markarian 2004; Morieras 2001). Control of density, improvement of electro-thermal properties, and aesthetic effects have also been of the obvious emphasized characteristics.

A wide range of fillers, including pigments and other additives have been used in the formulation of polymeric composites. The facility of many polymers to accommodate additional materials without any unnecessary deterioration in properties or even upgrading their behaviour, and ability to become competitive with other structural materials such as metals has resulted in considerable supplementary demand for new types of fillers (Dasture & Kelkar 2007; Sheldon 1982). Table 3.1 shows some of the common fillers used in the reinforced polymer composites.

Selection of fillers is primarily determined by the particle size distribution and the particle shape and, as a consequence of both, the way in which the particles pack together. This is fundamentally true whether or not a particular class of filler is required because of a systematic requirement such as electrical properties. Table 3.1 presents a general classification of the filler particles, and, Table 3.2 shows their geometrical characteristics (Harry 1987).

For the most of particle-reinforced composites, the particulate phase is harder and stiffer than the matrix. The reinforcing particles control the movement of the matrix phase in the vicinity of each particle. Essentially, the matrix transfers some of the applied stresses to the particles, which bear a fraction of load. The

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degree of reinforcement or improvement of mechanical properties will be heavily dependent on the interfacial bonding of the matrix and particles.

Table 3-1: Fillers for Polymers (Sheldon 1982)

Particulates		Fibrous	
Organic	Inorganic	Organic	Inorganic
Woodflour	Glass	Cellulose	Whiskers
Cork	Calcium carbonate	Wool	Asbestos
Nutshell	Alumina	Carbon/graphite	Glass
Starch	Beryllium oxide	Aramid fibre	Mineral wool
Polymers	Iron oxide	Nylons	Calcium sulphate
Carbon	Magnesia	Polyester	Potassium titanate
Protein	Magnesium carbonate		Boron
	Titanium dioxide		Alumina
	Zinc oxide		Metals
	Zirconia		Sodium aluminium
	Hydrated alumina		Hydroxy carbonate
	Antimony oxide		
	Metal powder		
	Silica		
	Silicates		
	Barium ferrite		
	Barium sulphate		
	Molybdenum disulphate		
	Silicon carbide		
	Potassium titanate		
	Clays		

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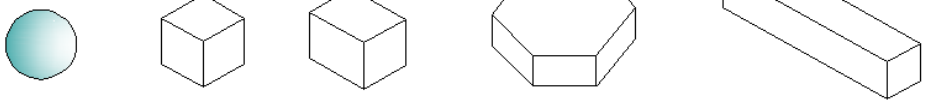
Table 3-2: Particulate Filler Geometry (Harry 1987)

Idealised Shape Class					
Particle Class	sphere	cube	Block	Flake	Fibre
Descriptor	spheroidal	cubic prismatic rhombohe-dral	tabular prismatic pinacoid irregular	platy flaky	acicular elongated fibrous
Surface area equivalent	1	1.24	1.26-1.5	1.5-9.9	1.87-2.3

Particles can have a variety of geometries, but they should be approximately the same in all directions. For effective reinforcements, the particles should be small and evenly distributed in the matrix. In addition, the behaviour of the composites is influenced by the volume fraction of the two phases i.e. mechanical properties improve with the increasing particle contents (Callister 1940 & c2007).

Two equations have been used to observe the relation of particle volume fraction with elastic modulus for the composite constituting two-phase composite. These are based on rules of mixtures and fall between the upper (u) and lower (l) limit represented by (Callister 1940 & c2007),

$$E_c(u) = E_m.V_m + E_p.V_p \quad (3.1)$$

$$E_c(l) = \frac{E_m.E_p}{E_m.V_p + E_p.V_m} \quad (3.2)$$

In these expressions, E and V denote the elastic modulus and volume fraction respectively, the subscripts c, m and p represents composite, matrix and particulate phase.

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3.4 Processing of a New Metal/Polymer Composite

3.4.1 Preparation of Iron-particulate filled ABS Composite

To develop the new metal-polymer composite, mixtures of iron (Fe) powders and ABS powders, as representative metal-polymer elements, were chosen with varying volume fractions (10%, 20%, 30%, and 40%) of iron with the aim of producing appropriate feed stock filament for FDM processing. The main reasons for selection of iron powder as short fibre fillers were its reasonably good mechanical and thermal properties as well as its capabilities of mixing and surface bonding with polymer and with other required additives in case of improving the composite melt flow(Bigg 1987b). Iron powders were purchased from Sigma-Aldrich in Australia. Table 3.3 shows two types of metallic fillers used in the processing of the new ABS-Fe composites.

Table 3-3: Types of fillers used in metal-polymer composite

Particulate	Purity	Size (μm)	Shape	Density (g/mL)	Melting point (^{0}C)
Carbonyl-Iron	≥99.5%	6-9	Spherical	7.86	1535
Iron	97%	~45	Flake	7.86	1535

The matrix polymer used was P400-grade Acrylonitrile Butadiene Styrene (ABS) supplied by the Stratasys Inc. This ABS is the FDM-grade polymer recommended by the Stratasys for use in the fabrication of prototypes on their FDM machines. The specific gravity of ABS was 1.05 g/mL. Acrylonitrile Butadiene Styrene is an amorphous thermoplastic made up of three monomers comprising commonly 15-35% of acrylonitrile, 5-30% of butadiene, and 40-60% of styrene as shown in Figure3.2. Its properties can vary according to the

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volume fractions of monomers used in the blend. While acrylonitrile is responsible for binding the neighbouring chains and resultant strength of the ABS terpolymer, styrene gives it a shiny and impervious look. The rubbery butadiene provides ductility and impact strength of the ABS (DesigninSite Retrieved May 2010).

The FDM grade ABS is an environmentally stable thermoplastic with no appreciable warpage, shrinkage or moisture absorption. It is 40% stronger than standard ABS with a greater impact and flexural strength. Its significantly stronger layer bonding makes it an ideal material to build durable parts for form, fit, and functional applications. Due to these advantages, ABS-P400 was selected as the matrix in the development of the new metal-polymer composite. Table 3.4 shows the mechanical characterization of FDM ABS-P400 (Stratasys 2001).

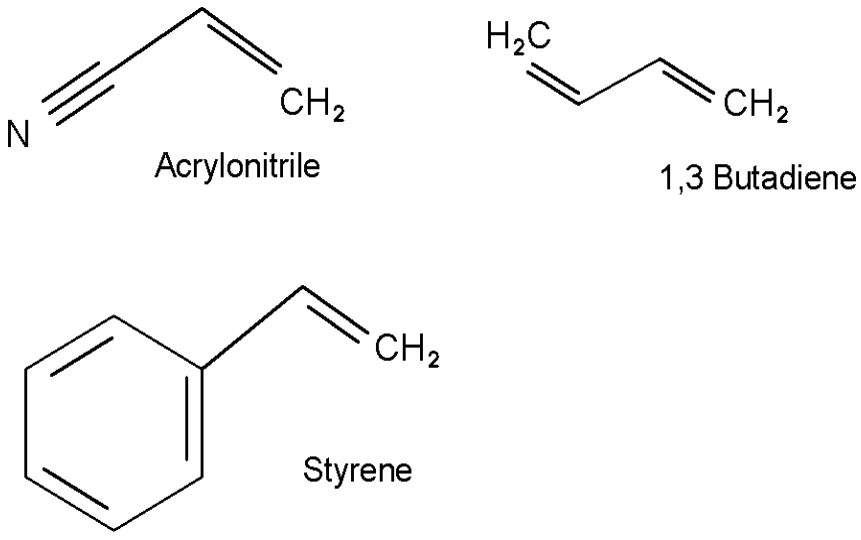

Figure 3-2: Monomers used in thermoplastic ABS

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Table 3-4: P400 ABS Specifications (Stratasys 2001)

Tensile Strength(MPa)	22	Unnotched impact(J/m)	214
Flexural Strength(MPa)	41	Elongation (%)	50.00
Tensile Modulus(MPa)	1627	Hardness(Shore D)	R105
Flexural Modulus(MPa)	1834	Softening Point (^{0}F)	220
Notched Impact(J/m)	107	Specific Gravity	1.05

To produce ABS micro particles, sufficient amount of P400 filament was first pelletized on a mechanical chopper. Then the ABS pellets were ground to fine powders using the cryogenic grinding technique. The machine used for this purpose was a SORVALL OMNI high speed grinder operating at temperatures well below glass transition temperature of the polymer (see Figure3.3). During this process, the ABS pellets were frozen by the surrounding liquid nitrogen which resulted in lower molecular energy of the pellets. Simultaneously, high speed rotation of stainless steel blades within the chamber containing the ABS pellets could easily break them below the glass-transition temperature. This process does not damage or alter chemical composition of material making it a very efficient polymer powder production technique.

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Figure 3-3: Cryogenic grinding of ABS polymer

In order to achieve a homogeneous mixture with higher packing factor when mixed with iron particles an ABS/Iron particle size ratio of approximately 10 to 1 was required (Tsai, Botts & Plouff 1992). Therefore, the ABS pellets were ground to a particle size of approximately 450-500 μm. To get the same size for ABS particles, grinding process was done in three time-interval of 45 minutes between which the particles were sieved to the required size. This helped uniform screening of the particles with different size range than 450-500 μm. The composite mixtures were then loaded in a multi-variable speed homogenizer to achieve maximum possible homogenous-distribution of iron powder in ABS matrix. Scanning electron microscopy (SEM) images of the prepared samples were analysed to make sure a homogenous matrix of metal-polymer composite is achieved as shown in Appendix A. At the end, a small percentage by volume of a surfactant was added to the mixtures. According to the previous studies carried out at Swinburne regarding composition of metal and nylon particulates (Masood & Song 2005), addition of surfactant increased

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homogeneous dispersion of metal particles in polymer matrix. The surfactant powder is coated on the iron particles and it reduces the high free energy surfaces of the iron fillers, and that in turn results in much lower interfacial tension between composite particles in melt stage. The coated iron particles give good link to lower free energy surfaces of polymer particles.

In order to investigate the effect of filler, and surfactant/plasticizer loadings on the final properties of parts made on Fused Deposition Modelling technology, various sets of ABS-Iron mixtures were prepared using the rule of mixture. Table 3.4 and Table 3.5 present the ABS-Iron mixtures along with the additives in terms of volume and weight fractions of each constituent respectively.

Table 3.5: Constituents of the new composite materials in volume fractions

ABS/Iron Sample Identifier No.	**Metal filler(Fe) Loading**	**Polymeric Matrix(ABS) Loading**	**Surfactant/Plasticizer**
1	10%	85%	5%
2	10%	82.5%	7.5%
3	10%	80%	10%
4	20%	75%	5%
5	20%	72.5%	7.5%
6	20%	70%	10%
7	30%	65%	5%
8	30%	62.5%	7.5%
9	30%	60%	10%
10	40%	55%	5%
11	40%	52.5%	7.5%
12	40%	50%	10%

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Table 3.6: Weight equivalent of the constituent particulates in the new composites of Table 3.5.

ABS/Iron Sample Identifier No.	W_{Fe} (g)	W_{ABS} (g)	$W_{Additive}$ (g)	Total (g)
1	46.41	50.59	2.97	99.97
2	46.41	49.10	4.46	99.97
3	46.41	47.61	5.95	99.97
4	66.06	31.77	2.11	99.94
5	66.06	30.71	3.17	99.94
6	66.06	29.66	4.23	99.95
7	76.90	21.37	1.64	99.91
8	76.90	20.55	2.46	99.91
9	76.90	19.73	3.28	99.91
10	83.85	14.78	1.34	99.97
11	83.85	14.11	2.01	99.97
12	83.85	13.44	2.68	99.97

3.4.2 Extrusion of the Metal-polymer Composite and Die Swell Phenomenon

For optimized compounding of the ABS-Fe composite, both single screw and twin screw extruders were considered. Rheological measurement of the melt flow behaviour, presented in detail in chapter 4, showed that both techniques provide consistent compounding and flow behaviour of the new material. A single screw extruder was used, due to its relatively lower cost, to process filaments of the new composite material as shown in Figure3.4.

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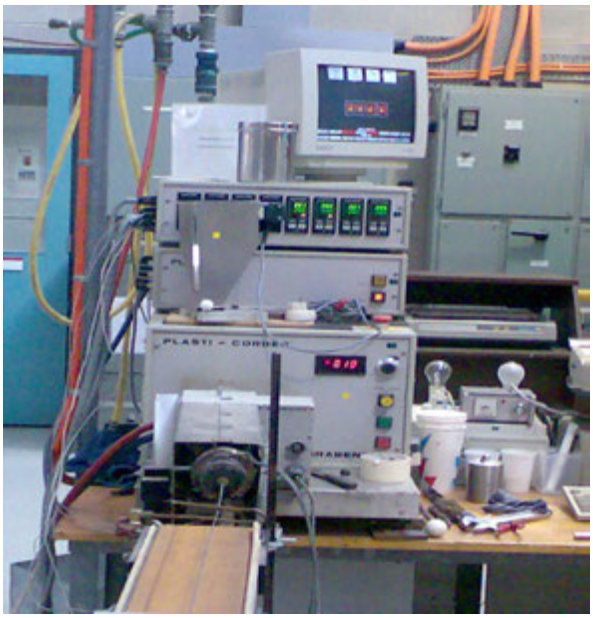

Figure 3-4: Single screw extrusion of the ABS-Fe filaments

The filament used in FDM process needs to be of a specific size, strength and properties. Due to die swell phenomenon, presented in Figure3.5, during the extrusion process of polymeric materials, there is a varying difference between dimensions of the extrusion die and those of the extrudate. Main causes of this phenomenon is the intrinsic elastic property of the polymer melts, and the wall shear rate (Rauwendaal 2001).

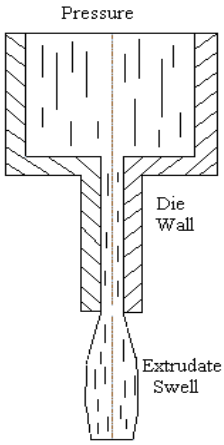

Figure 3-5: Schematic of Polymer Melt Swell

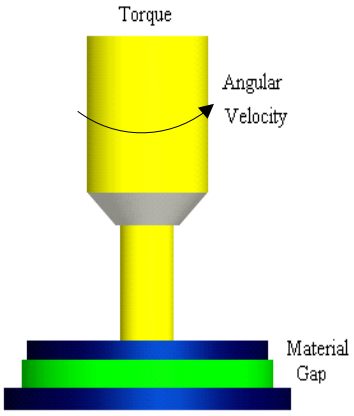

Figure 3-6: Parallel Plate Rheometry

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To minimize this effect and achieve a consistent diameter on the extrudate in such a way that the produced filament could be fed into the FDM machine smoothly, different operational variables including screw speed, pressure and temperature as well as optimization of wall shear stresses during extrusion process were considered. Parallel plate rheometry, depicted by Figure3.6, was used to work out the normal forces applied on the disc-shape samples made of the ABS-Iron composite representing the elastic recovery of the melt during actual rapid prototyping processing. It was found out that since the elastic recovery in polymer based materials is dependent on time; therefore a longer *time allowance* of pressurised melt before its exit through the capillary nozzle would lead to relaxation of the extrudate and less swelling as the result. Thus, new die nozzle were designed and fabricated with long "land length" as shown in Figure3.7.

Figure 3-7: Long land length die for suppressing extrusion swell

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The extrusion parameters for fabrication of ABS-Fe filament is shown in Table3.7.

Table 3-7: Single screw extrusion parameters for filament processing

Processing Temperature (^oC)	Screw Speed (RPM/Min)	Extrusion Torque (N-M)	Extrusion Die Diameter (MM)	Extruded Filament Diameter (MM)
205	20	10-15	1.75±0.05	1.75-1.8

3.5 Fabrication of FDM filament and test samples

In order to create a part on the FDM system using the new composite material, a certain amount of this composite is required to create the filaments for FDM machine. This amount of required composite material must have exact amount of its constituent elements, which include ABS, iron, and surfactant. The amount of each of these elements will depend upon the volume of the filaments required for FDM processing. In this experiment, the exact amount of constituents was determined by considering the CAD model volume. The weight of the composite was calculated by the following relationship:

$$Wc = \frac{W_{Fe} + W_{ABS}}{(1 - W_s\%)} \tag{3.3}$$

where W_c, W_{Fe}, W_{ABS} are the weight of composite, iron, ABS respectively, and W_s is the weight percentage of surfactant used.

Figure3.8 shows the final filament produced by this process. Figure3.9 shows some test samples produced from the new composite material on the FDM3000 system. More detailed discussion on the fabrication of parts and tools are presented in a separate chapter 7.

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Figure 3-8: FDM filament produced from Iron/ABS composite material.

Figure 3-9: Test samples produced on FDM3000 from the new Iron/ABS composite and unfilled ABS material (white).

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Chapter 4 Rheological Properties of Fe/ABS Composites for Fused Deposition Process

4.1. Introduction

Rheology is the science of dealing with materials whose properties cannot be explained by the classical models of Newton-Stokes and Hooke-Bernoulli. It is used to determine mechanical properties of various solid-like and liquid-like materials having continuous media. More specifically, it is concerned with study of stress versus deformation relationship for various technological and engineering materials in order to address the macroscopic problems related to continuum mechanics of these materials(Malkin 1994).

When polymers are softened or melted, they naturally undergo deformation and flow. All the softened and molten polymers are viscoelastic materials in that they respond to the external loads with a varying degree between that of viscous liquid and elastic solid (Shenoy 1999). It is necessary to study the viscosity and elasticity as the two fundamental rheological properties of polymer melts in order to understand and control the manufacturing process of the final product made of such materials as well as to be able to predict the performance of compounds primarily composed of these materials. A study of rheological properties of the new Fe/ABS composite will be the subject of this chapter. In particular, this chapter focuses on the investigation of viscosity of the metal-polymer composite system prepared for use in the fused deposition modelling.

Moreover, the combined effect of metallic fillers and additives on the viscosity of the matrix polymer will be discussed with the objective of developing optimum volume fractions of filler, matrix and appropriate additives which are indispensible to the successful flow of feedstock filament through the extrusion nozzle of existing FDM machine.

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4.2. Classification of Fluids and Rheological Properties

Rheological properties of materials can be defined in terms of how their *shear stress* (force per unit area) is related to their *shear rate* (described as the relative displacement). In the case of shear flows, as shown in Figure4.1, the response of the shear strain (γ) to the shear stress (τ) defines the mechanical or rheological behavior of the flow (Darby 2001).

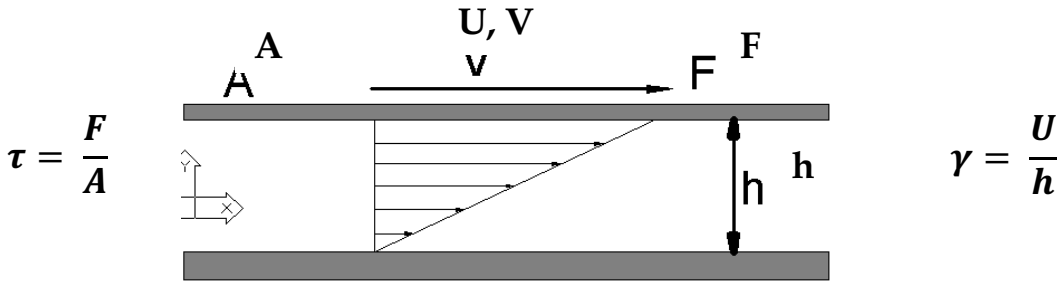

Figure 4-1: Simple Shear Flow

Fluids in which applied shear stress is proportional to the shear strain rate are called *Newtonian* fluids, such as water, whose behavior is described by the following equation (Darby 2001):

$$\tau = \mu\dot{\gamma} \tag{4.1}$$

where $\dot{\gamma}$ is the rate of shear strain or shear rate :

$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{dv}{dy} = \frac{V}{h} \tag{4.2}$$

and μ is the fluid viscosity, and represents the resistance to shear flow. It is expressed in Pa.s (Pascal. second) or poise (1 Pa.s = 10 poise).

Non-Newtonian fluids do not exhibit proportional shear stress versus shear rate

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relation. Contrary to Newtonian fluids, the viscosity of non-Newtonian fluid is not constant, and is a function of shear rate or shear stress; sometime referred to as the apparent viscosity η_a (Darby 2001; Yamaguchi 1952). Various polymeric liquids and molten plastics are examples of non-Newtonian fluids (Vlachopoulos & Wagner 2001; Yamaguchi 1952) .

Non-Newtonian fluids are characterized primarily based on experimental measurements through which the fluid is deformed through specified channel geometries and subsequently generated stresses in the flowing fluid is measured. Most of the non-Newtonian fluids used in engineering applications are *pure viscous fluids* in the sense that they can be fully reversed without time-lag; exhibiting time-independent properties(Yamaguchi 1952) . Shown in Figure4.2(a) & Figure4.2(b), these fluids are divided into the following groups (Rauwendaal 2001; Yamaguchi 1952):

- Pseudoplastic fluids (Shear thinning fluids)
- Bingham plastic and viscoplastic fluids
- Dilatant fluids (shear thickening fluids)

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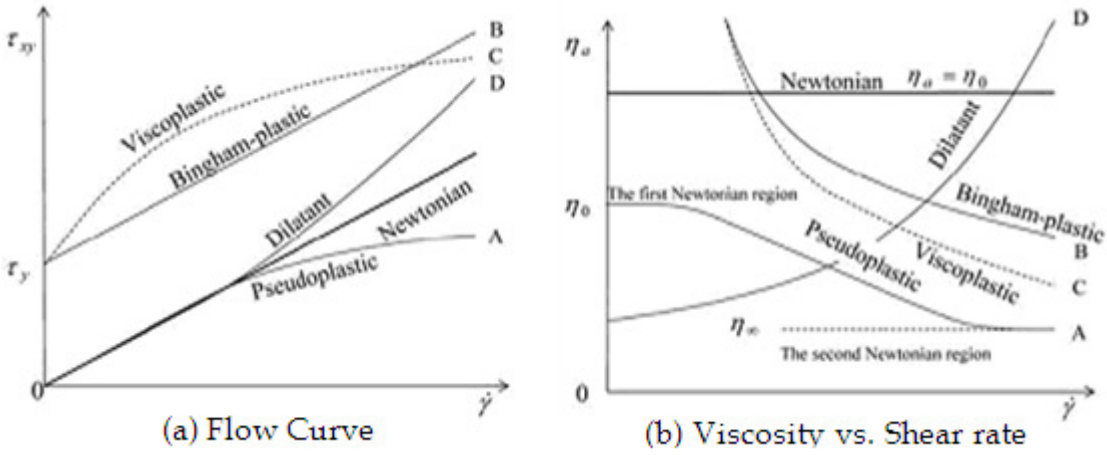

Figure 4-2: Pure viscous non-Newtonian fluids (Yamaguchi 1952)

In pseudoplastic fluids, as indicated on curve A in Figure4.2(a) and (b), flow curve appears with a decreasing slope; equivalently the apparent viscosity, η_a, decreases with increasing shear rate on viscosity vs shear rate curve. At very low shear rates, viscosity is independent of shear rate, and thus the behavior of fluid becomes Newtonian. The same behavior is observed at very high shear rate, where flow curves are straight and apparent viscosity is constant. Viscosities at these two regions, known as the first and the second Newtonian plateaus, are denoted as η_0 (called zero-shear viscosity), and η_∞ respectively (Rauwendaal 2001; Yamaguchi 1952).

Bingham plastic is referred to those non-Newtonian models of fluids in which viscosity is the function of shear stress. As shown by the curve B in Figure4.2 (a) and (b), flow curve of Bingham plastics is a straight line with an initial yield stress value. Viscosity is infinite below the initial yield stress. Paint, pastes, and slurries are examples of materials behaving like Bingham plastics. Viscoplastic fluids, curve C in Figure4.2, are characterized by a generalized model of Bingham plastic model (Yamaguchi 1952). In Dilatant or shear thickening fluids such as mixture of starch and water, the flow curve has an increasing slope, and

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correspondingly viscosity increases by the increase of shear rates. The rheological behavior of these fluids is represented by curve D in Figure 4.2 (a) and Figure4.2 (b).

Other two classes of non-Newtonian fluids are thixotropic and viscoelastic fluids. Viscosity of thixotropic fluids is dependant not only on the shear rate, but also on the time. These fluids are different from shear thinning fluids (Pseudoplastic) in that their viscosity changes *over time* at a constant shear rate (Reiner & Blair 1967; Yamaguchi 1952). Viscoelastic fluids have both viscous and elastic behavior. They deform under stress, but upon release of stress, the internal stresses do not disappear immediately as their molecular structure sustains part of the applied stresses due to their fading memory effect.

4.3. Rheological Behaviour of Polymer Melts

Behaviour of polymers generally is of viscoelastic nature. In the molten state, they exhibit primarily viscous properties with some degree of elasticity. In order to study the rheological phenomena which are characteristics of polymer melts, three types of viscometric flows are used(Tadmor & Gogos 2006) : Steady simple shear flows, dynamic(sinusoidally varying) simple shear flows, and extensional, elongational or shear-free flows.

4.3.1. Steady Simple Shear Flows

Steady simple shear flows can be obtained either by the relative motion of the rheometer surfaces inducing simple drag flow on the fluid or by an externally created pressure drop, which induces pressure flow on the fluid as shown in the capillary viscometer in Figure4.3. Rotational viscometer, which is shown schematically in Figure 4.4 is one of the common methods to measure simple shear of low magnitude. The maximum shear rate achieved in the simple shear

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flows are very low, below one reciprocal of a second, which is due to secondary flow induced instabilities generated at the melt sample periphery edges resulting from the second normal stress difference whereas the pressure-induced flows created in capillary rheometer undergo a wide range of shear,$1 < \dot{\gamma} < 10^4 s^{-1}$, coinciding with the most processing flows (Debbaut et al. 1997; Macosko 1994b; Tadmor & Gogos 2006).

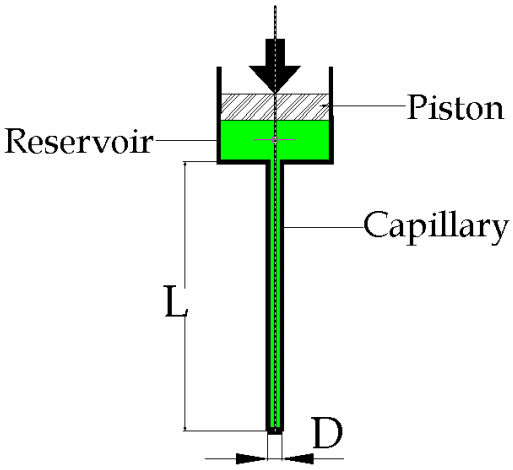

Figure 4-3: Capillary Viscometer

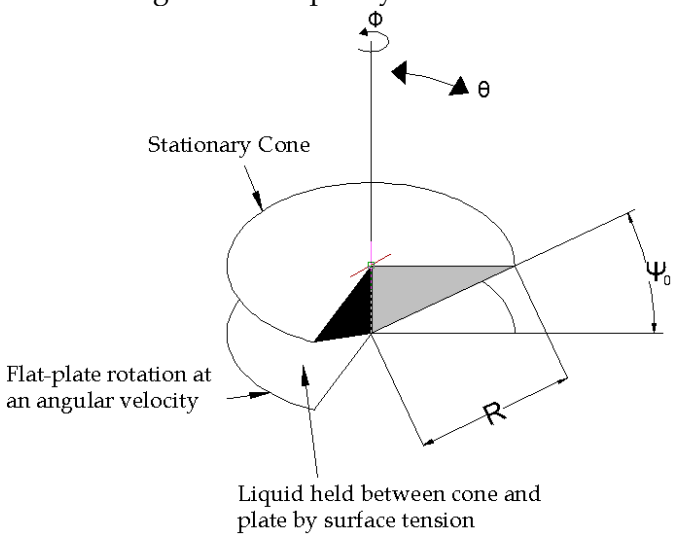

Figure 4-4: Rotational Viscometer

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4.3.2. Dynamic Drag Simple Shear Flows

Dynamic (sinusoidally varying) drag simple shear flows are obtained by applying a sinusoidally varying angular displacement in the same rheometers that generate steady simple shear flows. Time varying shear stress induced, in the case of polymer melts, has both an in-phase and out-of-phase components measuring the viscous and elastic properties of viscoelastic polymer melts. Rheological properties measured with the help of these types of flows can be related to the macromolecular structure of polymer melts. Since very small strains and shear rates induced do not take the macromolecular polymer melt conformation far away from their equilibrium, therefore, whatever measured, is the result of the response of not just a portion, but whole macromolecule (Macosko 1994b; Tadmor & Gogos 2006).

4.3.3. Shear Free Flows

Extensional, elongational or shear free flows are studied in the post die-forming step, such as stretching of melt strands in spinning, uniaxial stretching of molten films or biaxial stretching of a tubular films to measure the resistance of fluid to extend. The measurement involves extruding the polymer melt from capillary and subsequently stretching it with the help of two rollers to break. The maximum force recorded at breaking the extrudate filament is called *melt strength* (Tadmor & Gogos 2006; Vlachopoulos & Wagner 2001).

4.4. Filled Polymer Melts

There are a number of parameters affecting the rheological properties of filled polymer melts including type, size, shape and amount of the fillers. Effects of these parameters have been extensively researched (Abbasi et al. 2009; Ai Wah, Yub Choong & Seng Neon 2000; Anderson & Zukoski 2008, 2009; Araki, Kitano

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& Hausnerova 2001; Bar-Chaput & Carrot 2006; Bigg 1983; Boutelier, Schrank & Cruden 2008; Carreau 1992; Cassagnau 2003; Choi et al. 2003; Collins, Fahey & Hopfinger 1984; Dae Han 1974; Darwish, El-Aal & El-Megeed 2007; Dealy & Wissburn 1996; Fisa & Utracki 1982; Ghosh & Maiti 1997; Goel 1980; Gu, Ren & Wang 2004; Han, Sandford & Yoo 1978; Han et al. 1981; Hausnerova et al. 2008a, b; Hristov & Vlachopoulos 2008; Isayev, Wong & Zeng 1990; Jahani 2010; Kader, Lyu & Nah 2006; Kamal & Mutel 1985; Kao, Chandra & Bhattacharya 2002; Kaully, Siegmann & Shacham 2007; Kauly et al. 1996; Kulichikhin et al. 1997; Lakdawala & Salovey 1987; Lee, Kontopoulou & Parent 2007; Lévai, Ocskay & Nyitrai 1989; Li & Wolcott 2004; Liang 2010; Macosko 1994a; Maiti & Hassan 1989; Malkin 1990; Markov 2008; Montmitonnet & Delaware 1982; Muksing et al. 2008; Osman & Atallah 2006; Pipe, Majmudar & McKinley 2008; Pisharath, Hu & Wong 2006; Poslinski et al. 1988a, b; Shashkina et al. 2005; Shaw 1983; Sobhanie & Isayev 1999; Solomon & Lu 2001; Souloumiac & Vincent 1998; Utracki 1984; Zhang & Yi 2002).

4.4.1. Metal-Polymer Composite Melt

Often mere addition of fillers, especially inorganic ones, to the polymeric matrix can detrimentally affect the final performance of product due to interfacial regions created between the fillers and matrix with poor bonding. Delamination at the filler-matrix interface can decrease the strength of filled polymer system to less than half of that of neat polymer (Bigg 1987b; Nielsen, Buchdahl & Levreault 1950; Shenoy 1999; Tavman 1996). To improve the interfacial bonding, coupling agents are required to establish good adhesion and cohesion between the fillers and the matrix (Ai Wah, Yub Choong & Seng Neon 2000; Bose & Mahanwar 2006; Collins, Fahey & Hopfinger 1984; Doufnoune, Haddaoui & Riahi 2007; Han 1980; Han, Sandford & Yoo 1978; Han et al. 1981; Hung et al. 1989; Kim & White 2009; Nourbakhsh, Karegarfard & Ashori 2010; Saini & Shenoy 1986). Moreover, in order to improve the mixing and uniform distribution of fillers in the polymeric matrix, they are surface treated by

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various additives (Bigg 1983; Chen et al. 2009; Dai et al. 2008; Gu, Ren & Wang 2004; Hristov & Vlachopoulos 2008; Leblanc 2002; White & Crowder 1974). Inclusion of fillers as well as additives such as surfactants, plasticizers changes the flow behaviour of matrix polymer during melt processing. Presence of filler-additive combination can have conflicting effects. Therefore, it is necessary to investigate the effect of such factors on the behaviour of final compound during the processing.

Viscosity is the most important rheological property(Vlachopoulos & Wagner 2001) which can determine the flow behaviour of filled polymer composite through the specific channel geometry as in the fused deposition modelling. Correlation of the resultant rheological properties such as viscosity, with the volume fractions of different components in the particulate-filler-matrix system, is essential for optimization and prediction of final product performance made on FDM tooling/manufacturing system from such composites.

4.5. Experimental Work

In order to conduct rheological characterization of the new metal-polymer compound developed for this work, three methods are used: melt flow index (MFI), parallel plate rheometry and capillary rheometry. Various composites of Acrylonitrile Butadiene Styrene (ABS), iron powders (Fe), and Calcium Stearate were prepared by two techniques of dry centrifugal mixing and melt compounding as described in section 3.4.1 of the previous chapter. Both single and twin screw extruders were used in the stage of melt compounding in order to compare the effect of processing methods on the final product.

4.5.1. Capillary Rheometry

The capillary rheometry, as shown in Figure4.3, was used in order to measure the stresses, and shear viscosity of the metal-polymer compounds against a

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wide range of shear rates. The test batches of varying volume fractions of metallic fillers as well as an organic surfactant were sheared under high strain rates up to 10000 s^{-1}. A Davenport Ram Extruder supplied by RMPC was used for the rheological characterization of various samples. The instrument was equipped with a 2mm die (L/D=16) and a Dynisco® pressure transducer (0-70 MPa). Measurements were conducted at two temperatures of 250 °C and 270°C simulating the actual processing temperature range used in the Fused Deposition Modelling rapid prototyping technology. Capillary rheometry was conducted by measuring the pressure drop at the die while varying the extrusion speed. The linear velocity of the melt, V was calculated from the piston speed using the calibration given in the manual and the pressure drop, ΔP was calculated from the voltmeter readings using the calibration provided by transducer manufacturer. From the obtained data, apparent shear rate (8V/D) and shear stress were calculated using the following equations (Dealy & Wissburn 1996):

$$\gamma_w = \left(\frac{-dv}{dr}\right)_w = \frac{8V}{D}\left[\frac{3\acute{n}+1}{4\acute{n}}\right] = \frac{4Q}{\pi R^3} \quad (4.3), \qquad \sigma_w = \frac{\Delta PD}{4L} \quad (4.4)$$

The correction for non-Newtonian behaviour, known as Weissenberg-Rabinowitsch-Mooney equation (Macosko 1994b), was applied by calculating the slope of the *ln*(stress) *versus ln*(shear rate) relationship, according to eq.(4.5), in order to work out true wall shear rate and the corresponding rate-dependant viscosity(Pipe, Majmudar & McKinley 2008).

$$\acute{n} = \frac{d\ ln(\Delta \mathrm{PD}/4L)}{d \ln (8V/D)} \quad (4.5)$$

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4.5.2. Parallel Plate Rheometry

A controlled-stress parallel plate AR rheometer, Figure4.5, was used to measure the effect of first and second normal stress difference as an indication of elastic recovery of the melt in the capillary, which is responsible for die-swell phenomenon as shown in Figure4.6.

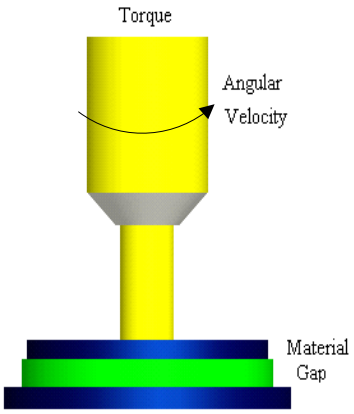

Figure 4-5: Parallel Plate Rheometry

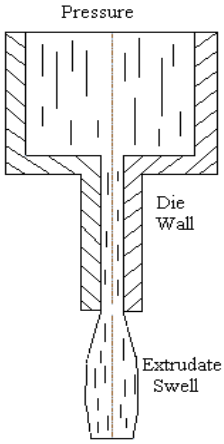

Figure 4-6: Schematic of Polymer Melt Swell

Composite samples were prepared in the shape of circular disk with diameter of 25mm, and thickness of 2mm by compression moulding (2500 ton LabTech Scientific) at 180^{o}C. A preheating, venting, heating and full pressing and cooling cycle of 5minutes were used to get the desired dimension and final shape.

4.5.3. Melt Flow Index

Melt flow index (MFI) or Melt Flow Rate was determined initially to study the melt behavior of the virgin ABS P400, and extract its rheological parameters namely Dynamic Viscosity (μ), Shear rate ($\dot{\gamma}$) and Shear stress (τ). From these data, power law index (n), consistency index (K), fluidity (φ) and flow component (m) were calculated to incorporate them in the simulation of the ABS P400 behavior through FDM nozzle. Details of these analyses are described in chapter 6. A CEAST Modular Melt Flow Tester, shown in Figure4.7, was

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used for this purpose, and procedure outlined in ASTM D 1238 was implemented. Effects of various temperatures and loads were studied.

Figure 4-7: CEAST Melt Flow Indexer

4.6. Results

Figures 4.8 and 4.9 show flow curves and in terms of the viscosity vs. shear rate relationship for the compounds of ABS and Calcium Stearate (Ca.St.) with volume fractions of 2.5, 5, 7.5, 10 and 15 percent respectively. While the shear stresses are increasing with increase of shear rate on the flow curves, the viscosity decays exponentially as the shear increases, demonstrating *Pseudoplasticity* or shear thinning behaviour. On the plots, CS denotes the calcium stearate. The test temperature used was 270^{o}C recommended as the processing temperature for ABS P400.

Figures 4.10 to 4.23 present the flow curves and viscosity vs. shear rate relationship for the Fe/ABS/Ca.St composites. Three volume fractions of metallic filler namely iron powders with 10, 20, and 30 vol% and organic filler,

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namely, calcium stearate (Ca.St) with 5, 7.5, and 10 vol% were tested. Iron fillers were used in two sizes of 9 μm and 45 μm in order to see the effect of filler size on the rheological properties. Total of 12 compositions were compounded and studied through capillary rheometry in order to extract sufficient data for conclusions on the appropriate formulation for the final products to be made on the fused deposition modelling process.

Figures 4.24 to 4.33 signify the effect of addition of varying volume fractions and particle sizes of iron powders as well as various volume fractions of surfactant on the viscosity of Acrylonitrile-Butadiene- Styrene (ABS) under low, medium, and high shear rates i.e. ($\dot{\gamma} = 1,\ 25,$ and $1000\ s^{-1}$) .

Finally, effects of varying processing temperatures on the viscosity of virgin and filled ABS are demonstrated by Figures 4.34, and 4.35 respectively.

4.6.1. Discussion

As shown by Figures 4.8, the variation of concentration of calcium stearate does not change the general trend of flow curves of acrylonitrile butadiene styrene (ABS) terpolymer in the sense that increase of shear rate induces higher shear stresses. A behaviour known as shear thinning or pseudoplasticity, is widely seen in the polymer melts, and is empirically characterized by power law equation (Rauwendaal 2001; Shenoy 1999; Yamaguchi 1952).

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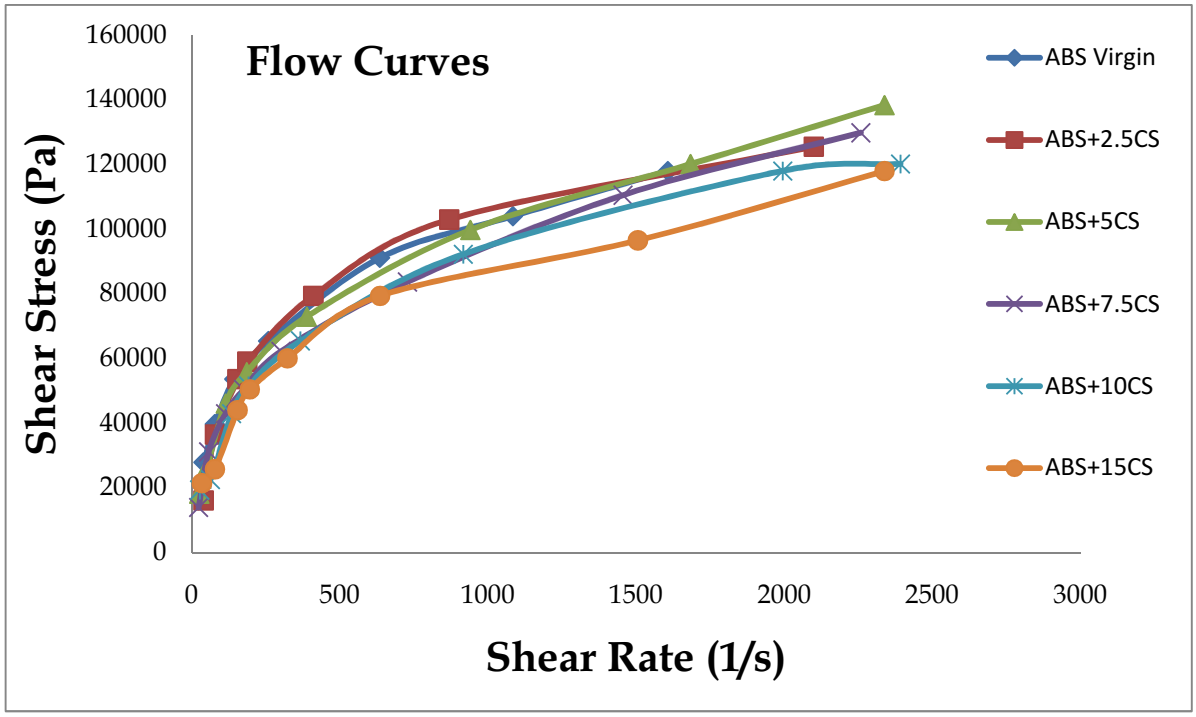

Figure 4-8: Flow curves of composites of ABS and varying volume fractions of Ca.St.

Despite concentration of up to 15 vol% filled calcium stearate, viscosity decreases with increase of shear rates as shown by the power law plateaus in Figure 4.8. Compared to the virgin ABS, however, the shear thinning effect is slightly higher in the presence of calcium stearate as seen by the downward shift in the power law curves.

Figure 4.9 shows the variation of shear viscosity with shear rate for various composites of ABS and Ca.St. From the graph, it appears that variation of different amount of Ca.St does not make any significant effect on the variation of shear viscosity with shear rate.

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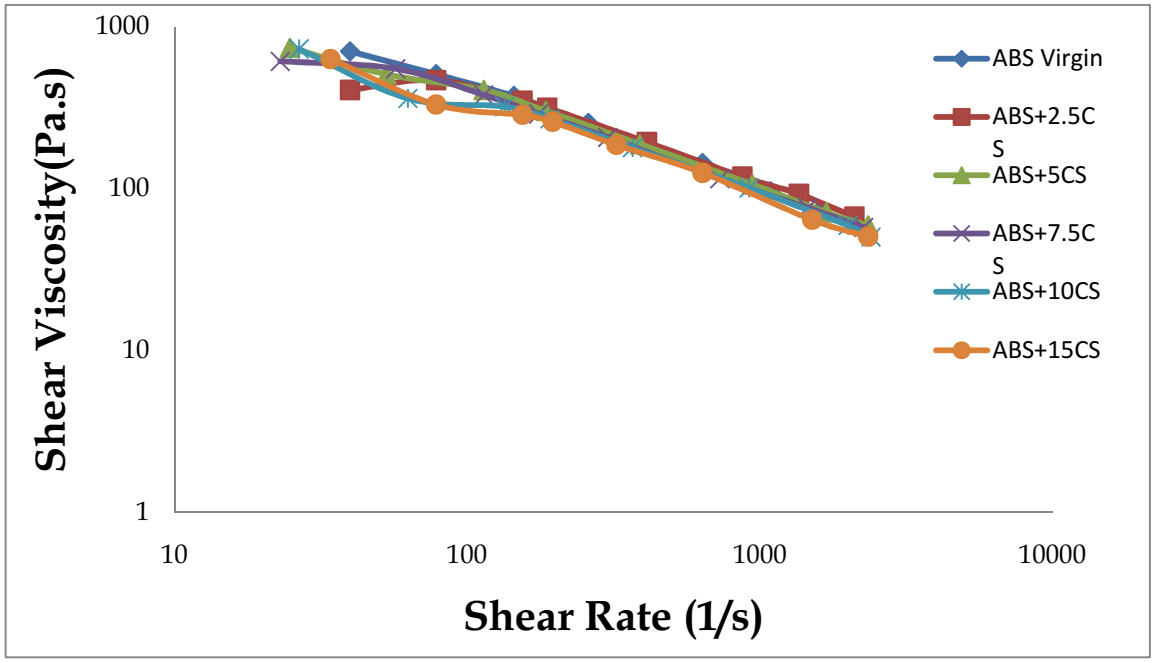

Figure 4-9: Effect of shear rate on the viscosity of various composites of ABS and Ca.St

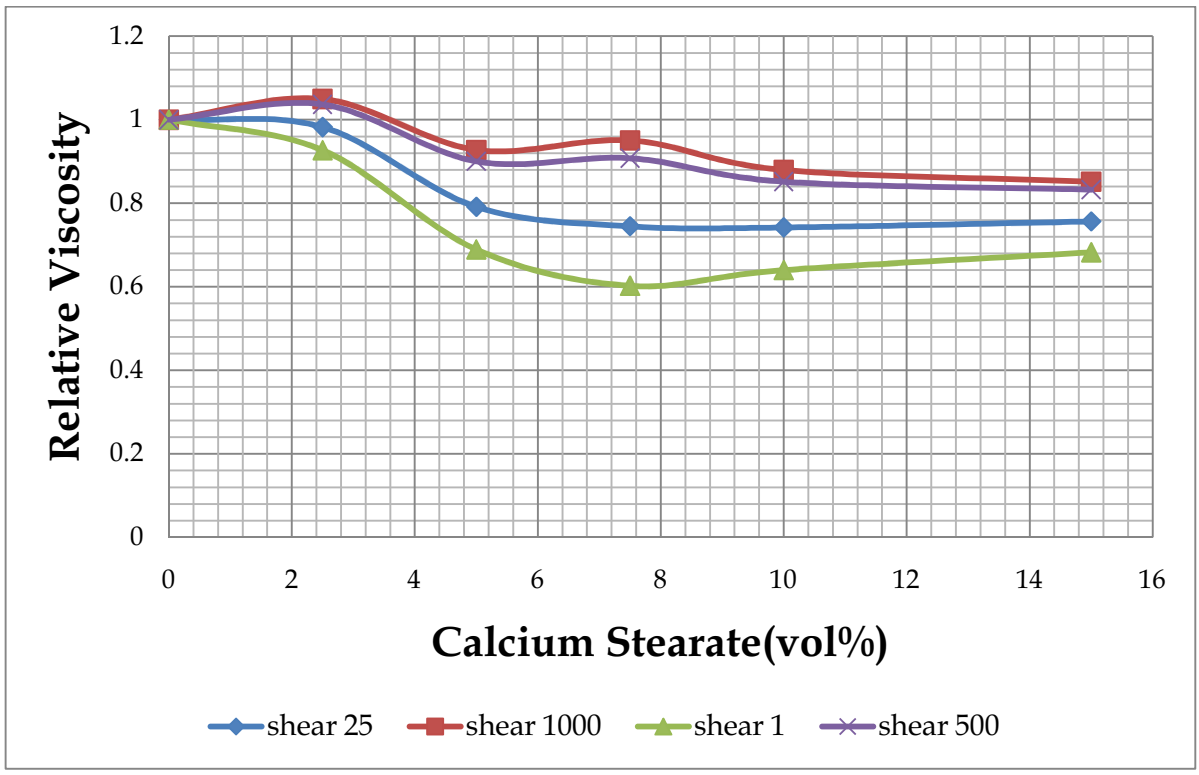

Figure 4-10: Relative viscosity of composites of ABS and varying volume fractions of Ca.St. at different shear rates

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Figure 4.10 shows the relative viscosity of ABS and calcium stearate under distinct low, medium, and high shear rates. Effect of reduction of viscosity of ABS as a result of addition of calcium stearate can be seen clearly. Such effect is attractive as it can compensate for the increase of viscosity of polymer melts as a result of addition of metallic fillers, and therefore can improve the extrusion of metal-polymer composites through the fused deposition process.

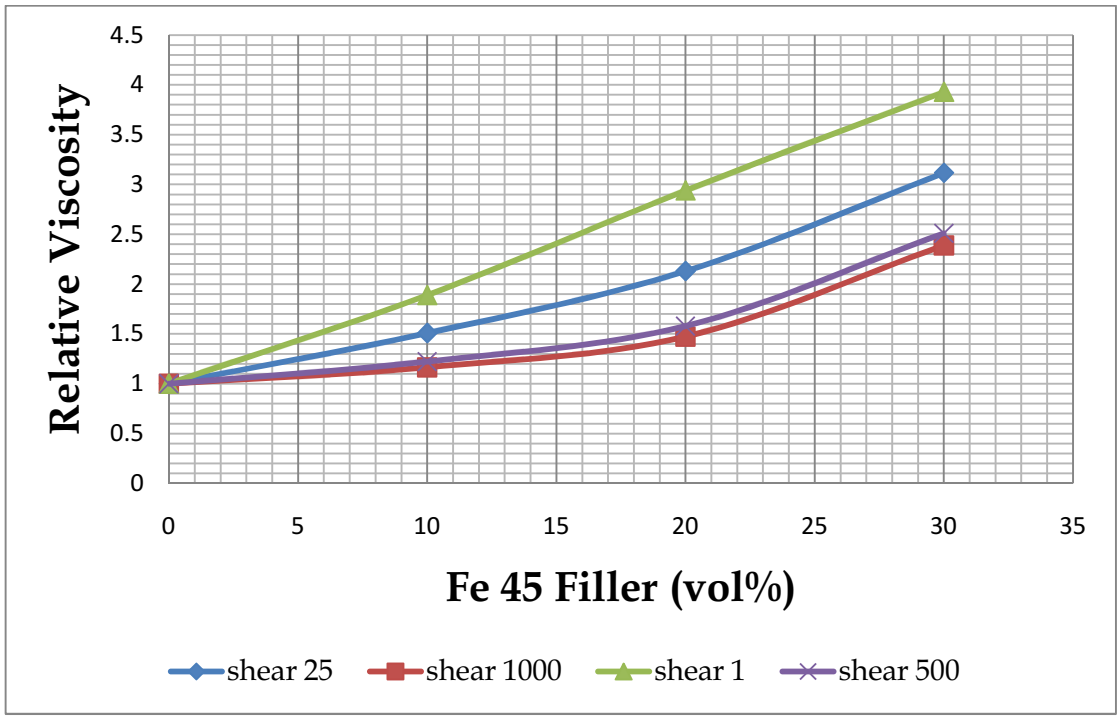

Figure 4-11: Relative viscosity of composites of ABS and varying volume fractions of 45 µm iron

Figure 4.11 demonstrates the relative viscosity of Fe/ABS composite, containing 10%, 20%, and 30% volume fractions of 45 µm iron powder, to that of the ABS matrix. The fillers were used without any surface treatment. It is seen that addition of metallic filler has substantially increased the viscosity of compound under various, but especially lower shear rates. This is generally seen for highly filled polymer melts which has been speculated to occur due to dependence of viscosity of such melts on the shear strength of inter-particle network (Bigg

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1983). However, such effect is a deterrent to the processing of metal-polymer composites by fused deposition modelling due to requirement for further increase of pressure at the entry of the FDM liquefier to push such highly viscous flow through to the deposition head.

Figures 4.12 and 4.13 show the effect of 10% filled iron powder with particle size of 6~9 um treated with different volume fractions of Ca.St. in the ABS matrix. Both flow curve and the viscosity vs shear relationship reveal a turning point in the general trend as is usually expected for filled polymeric systems. While addition of 5 percent Ca.St reduces the viscosity of Fe/ABS/Ca.St composite, further addition of 7.5, and 10 percentage concentration of Ca.St increases the induced shear stresses and viscosities. Similar trend can be seen in the case of 20% Fe-filled ABS with varying concentrations of calcium stearate as shown in Figures 4.14 &4.15. This suggests a correlation between the concentration of iron powder and calcium stearate for which the viscosity of Fe/ABS/Ca.St drops lower than that of the virgin matrix providing an optimum composition for processing through Fused Deposition Modelling prototyping platform.

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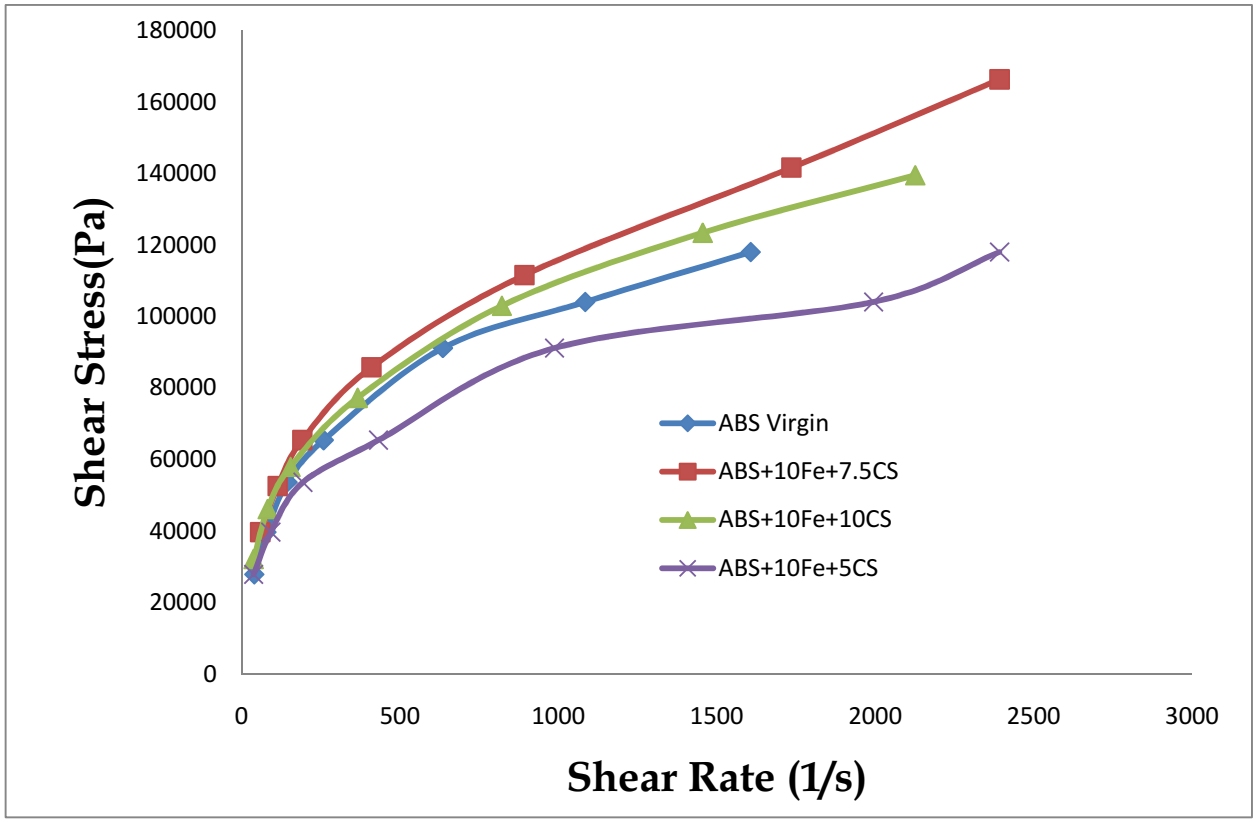

Figure 4-12: Flow curves of composites of ABS and varying volume fractions of Ca.St. in 10% filled iron with particle size <10um

Although the aforementioned change in the viscosity trend is not seen in the case of 30%Fe-filled ABS composite, as shown in Figures 4.16 & 4.17, however it is speculated that the concentration of calcium stearate is not enough to change the trend, and therefore, a further addition of Ca.St can possibly help repeating what is seen for the Fe/ABS composites with lower concentration of iron powders.

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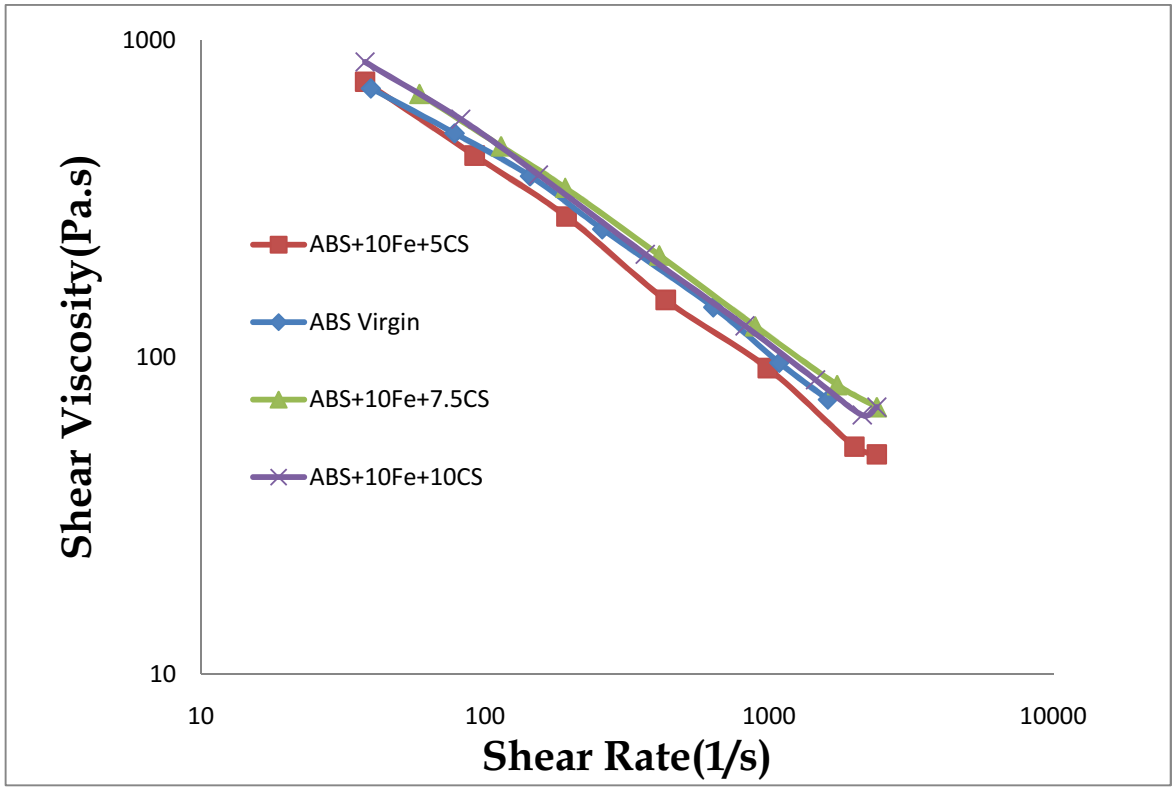

Figure 4-13: Shear rate versus viscosity of various composites of ABS and Ca.St in 10% filled iron with particle size <10um

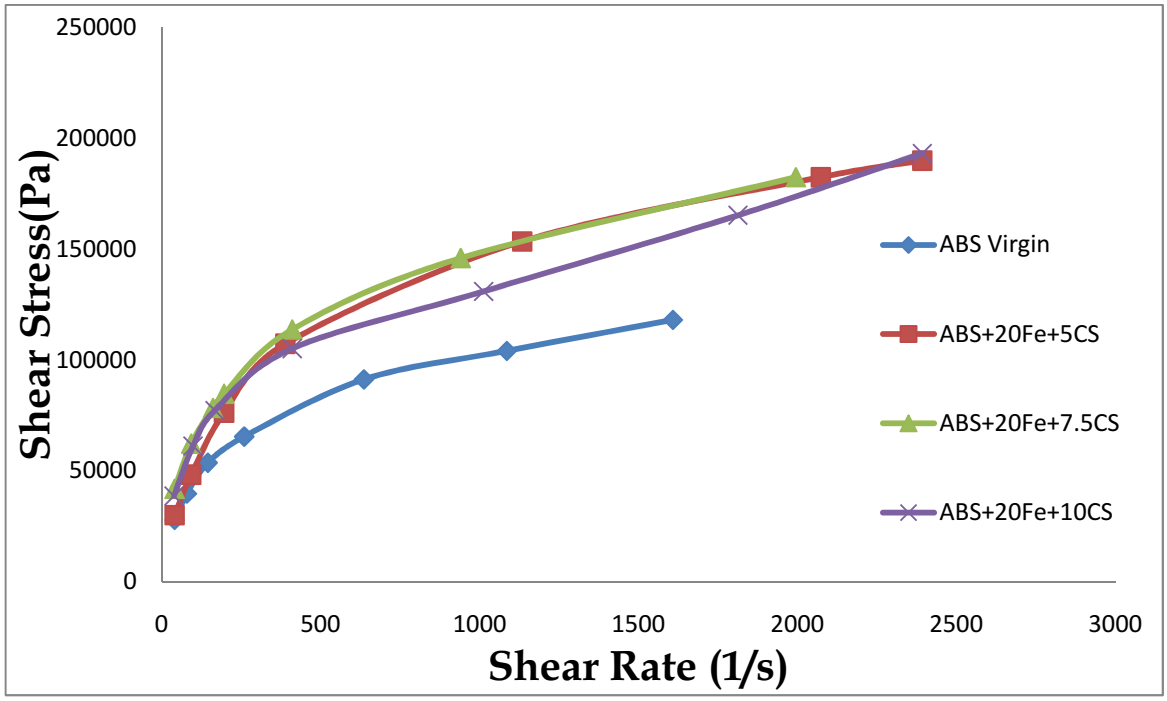

Figure 4-14: Flow curves of composites of ABS and varying volume fractions of Ca.St. in 20% filled iron with particle size <10um

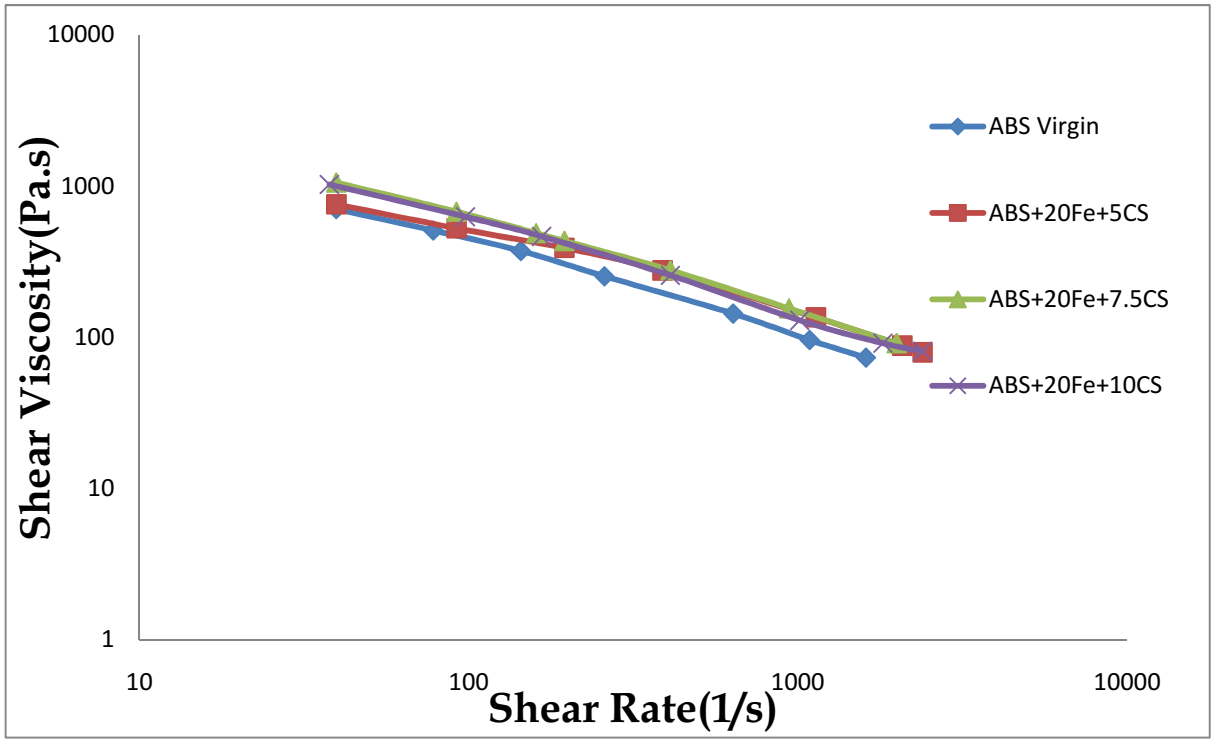

Figure 4-15: Viscosity vs. shear rate for various composites of ABS and Ca.St in 20% filled iron with particle size <10um

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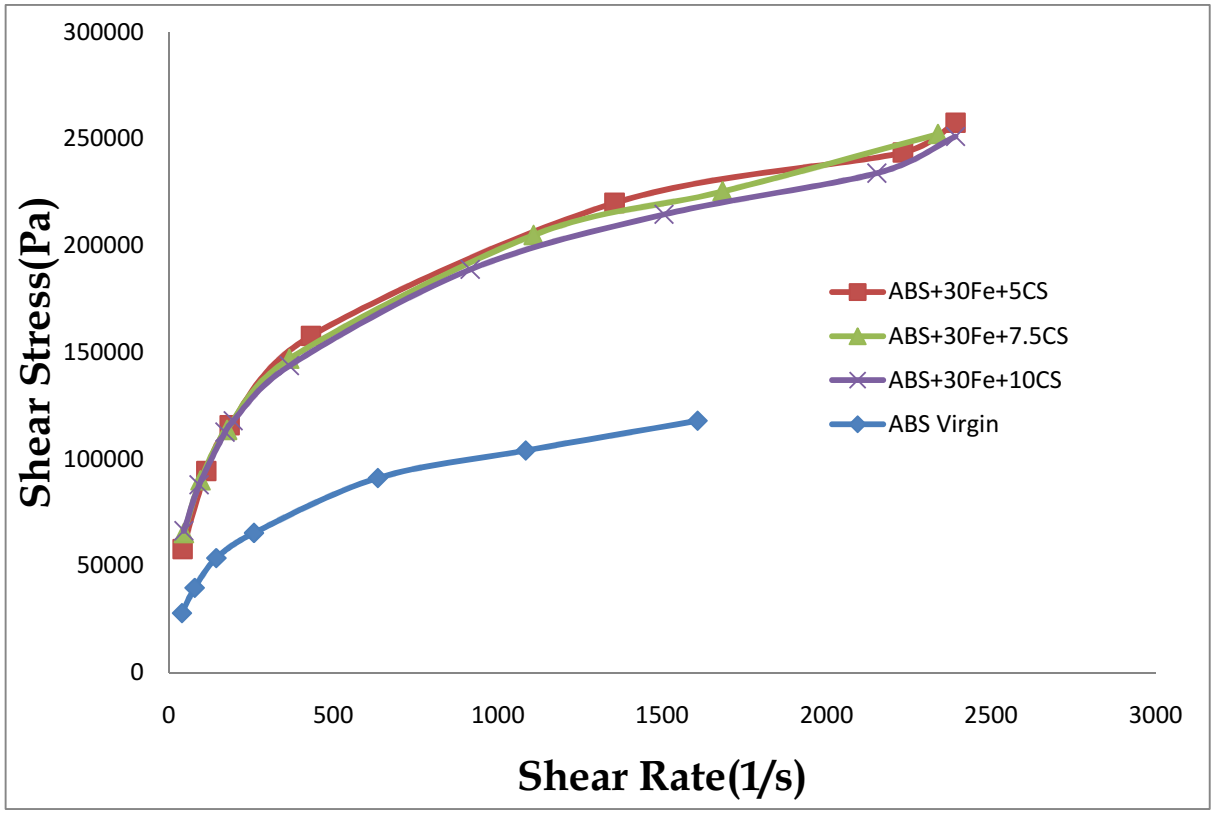

Figure 4-16: Flow curves of composites of ABS and varying volume fractions of Ca.St. in 30% filled iron with particle size <10um

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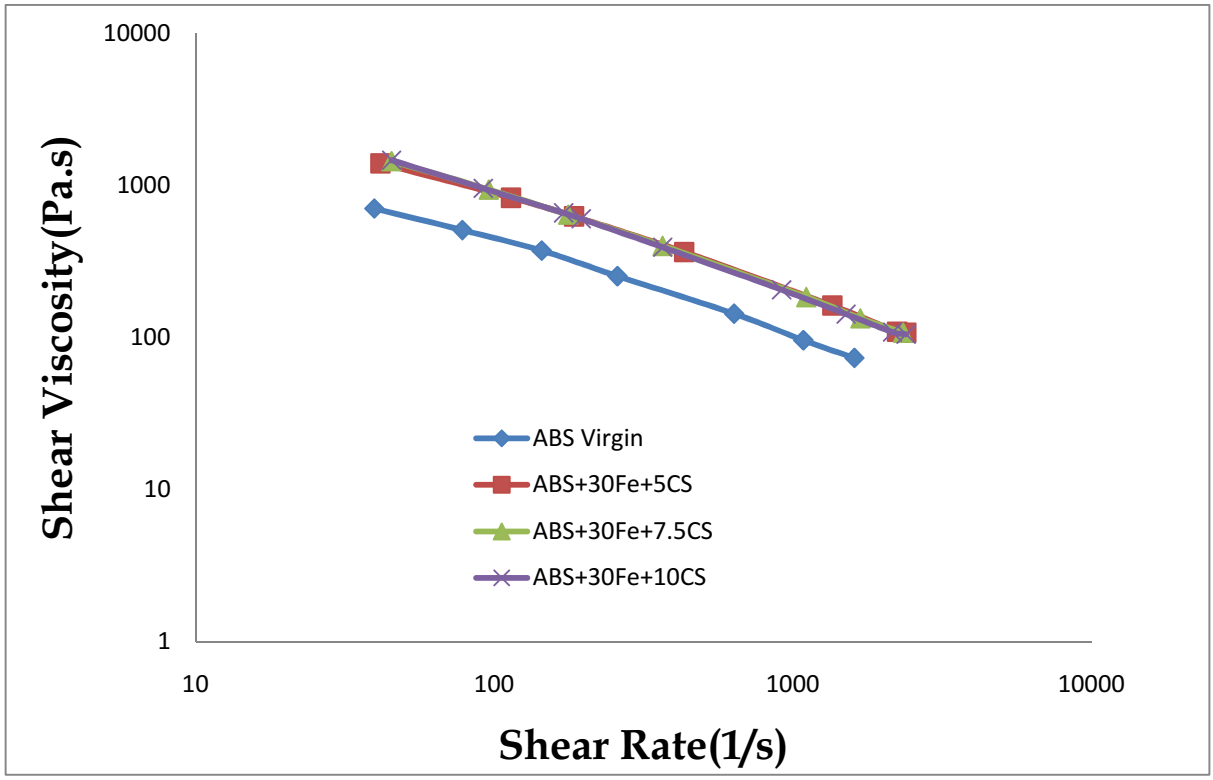

Figure 4-17: Shear rate versus viscosity of various compounds of ABS and Ca.St in 30% filled iron with particle size <10um

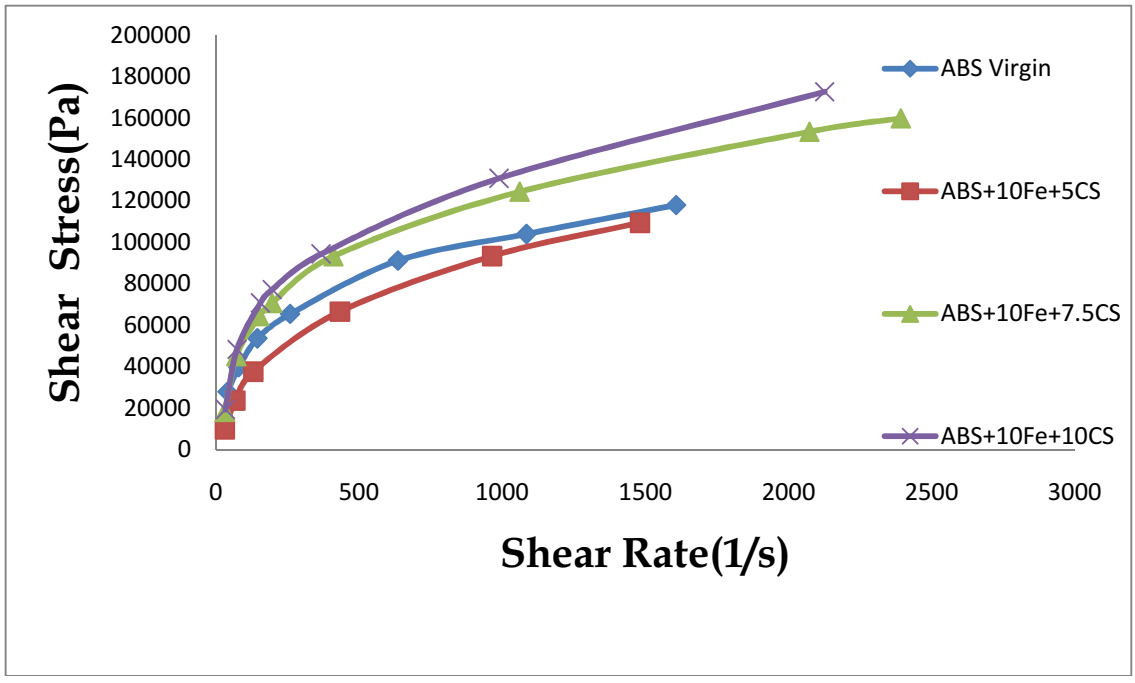

Figure 4-18: Flow curves of composites of ABS and varying volume fractions of Ca.St. in 10% filled iron with particle size <45um

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Figures 4.18 to 4.23 show the effects of varying Ca.St and varying iron content with particle size of 45 µm or less on the flow curves and shear viscosity for different strain rates. From these figures, a similar, but a pronounced phenomenon can be seen for the Fe/ABS/Ca.St composites with iron powder size of 45 µm in the sense that addition of calcium stearate reduces viscosity even further when appropriate volume fraction added corresponding to volume fraction of iron powder.

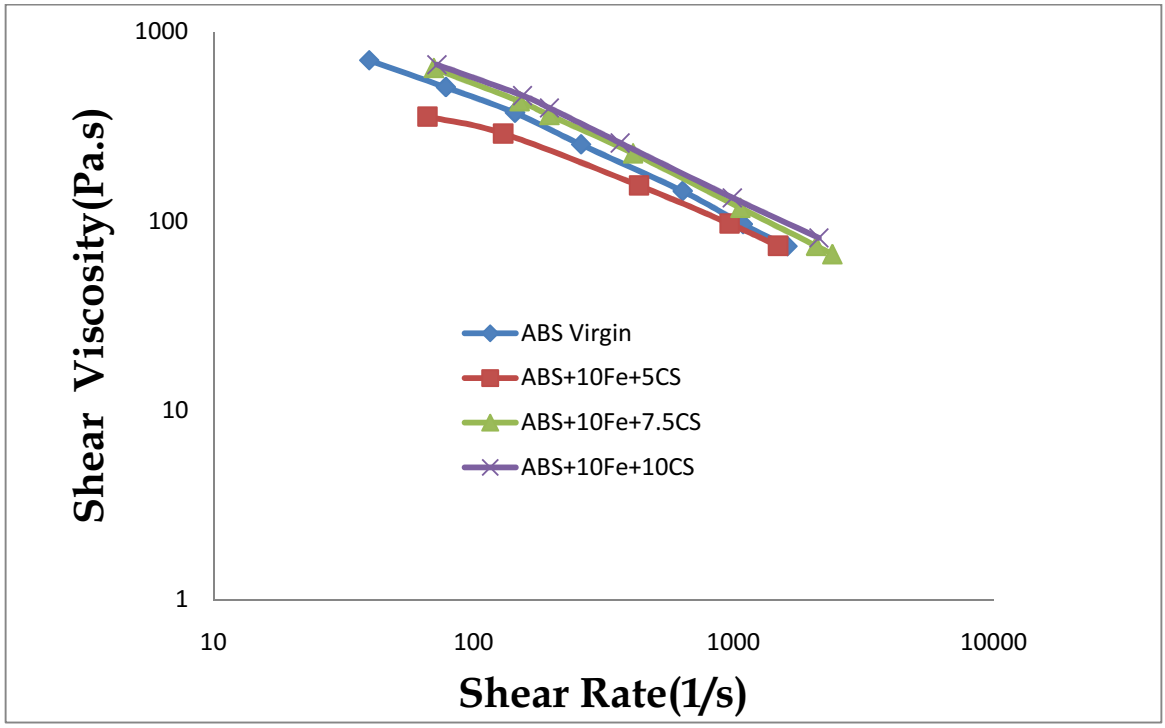

Figure 4-19: Shear rate versus viscosity of various composites of ABS and Ca.St in 10% filled iron with particle size <45um

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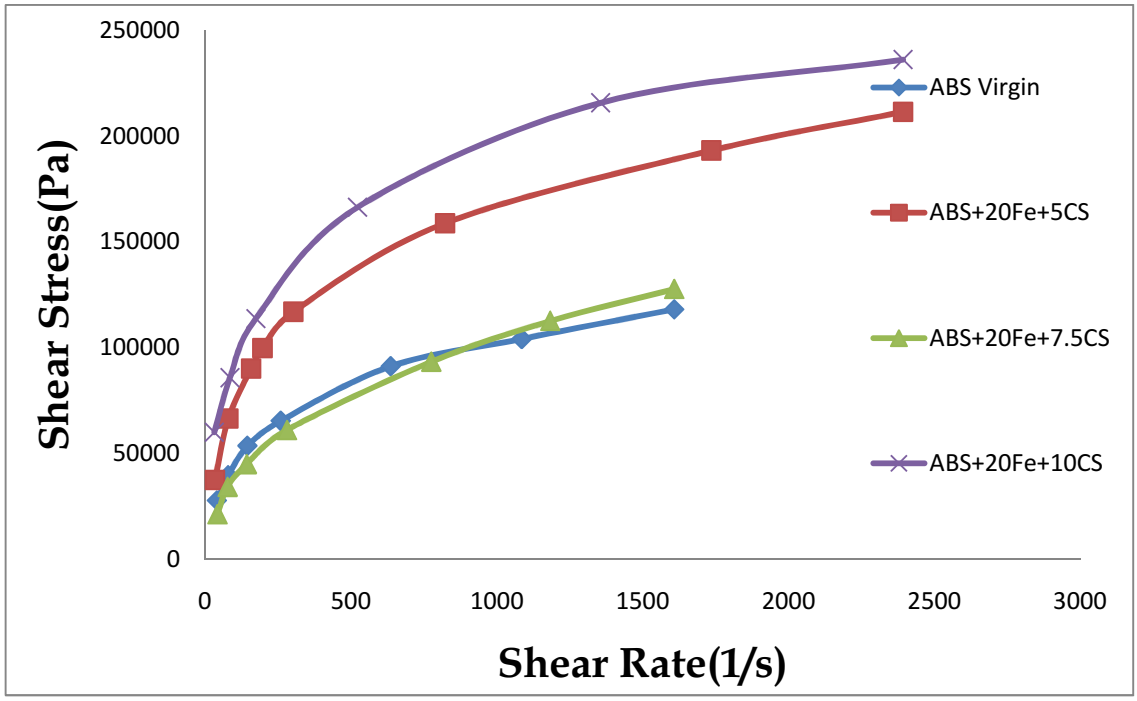

Figure 4-20: Flow curves of composites of ABS and varying volume fractions of Ca.St. in 20% filled iron with particle size <45um

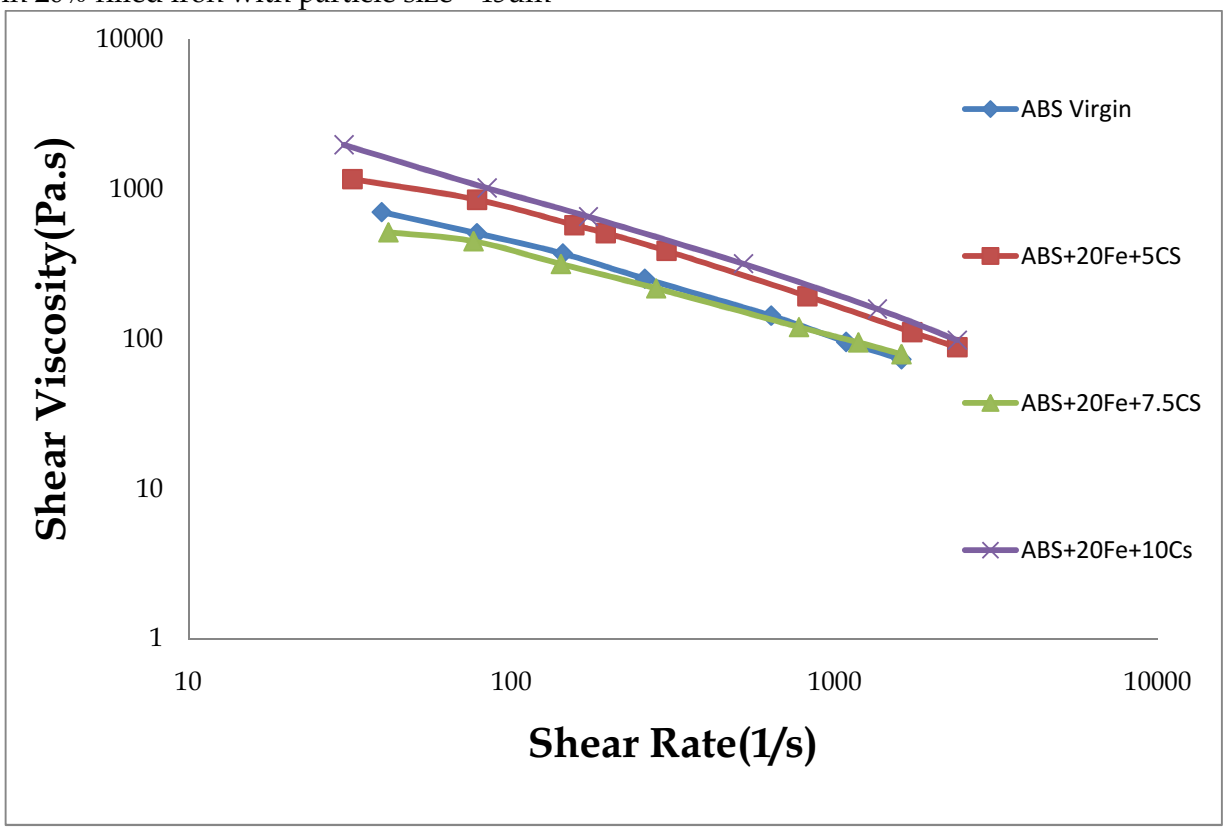

Figure 4-21: Effect of shear rate on the viscosity of various composites of ABS and Ca.St in 20% filled iron with particle size <45um

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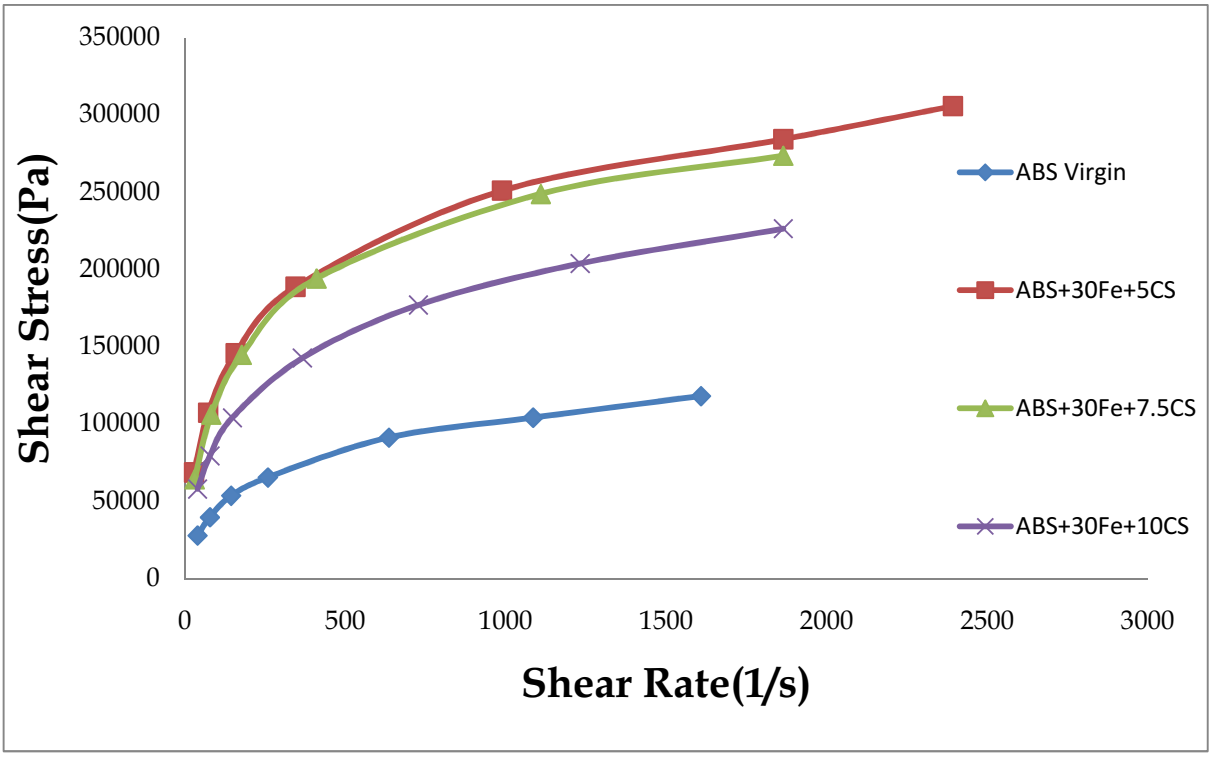

Figure 4-22: Flow curves of composites of ABS and varying volume fractions of Ca.St. in 30% filled iron with particle size <45um

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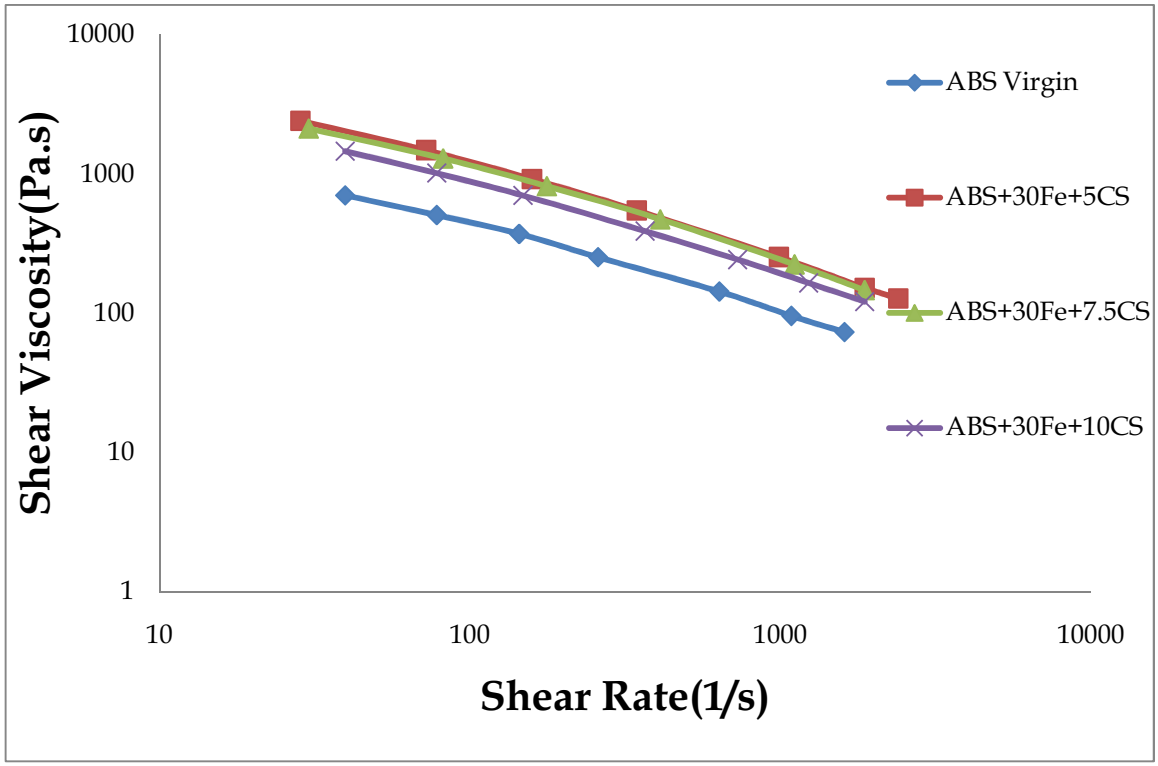

Figure 4-23: Viscosity vs. shear rate for various composites of ABS and Ca.St in 30% filled iron with particle size <45um

Figure 4.24 shows the effect of increase of 45 µm iron powder on the viscosity of Fe/ABS/Ca.St composites with only 5vol% concentration of calcium stearate at three shear rates. It is observed that despite increase of iron powder loading, the viscosity of composite reduces to some extent and only by further increase of Fe particles its trend changes and starts increasing. The effect is shear dependant in the sense that the lower the shear rate the higher loading of Fe particles can be added to the matrix without increasing its viscosity. For example for shear rates as low as 1 s^{-1}, it is seen that the relative viscosity of Fe/ABS/Ca.St containing Fe loading of up to 16 vol% is still lower than that of unfilled ABS. This is particularly important as the current FDM hardware has been designed for viscosities in the range of that of virgin ABS, and therefore not suitable for higher melt viscosities, in which case the constant-speed step motors provided with the machine cannot provide enough force to extrude continuous strands of

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feedstock for deposition on the substrates. Similar trend is observed for 7.5 vol% concentration of calcium stearate at different percentage loading of Fe particles. As shown in Figure 4.25, the optimum processablity of Fe/ABS/Ca.St through FDM nozzle is possible for the iron powder loading of 14~28% where viscosity of the melt composite is lower than that of the matrix.

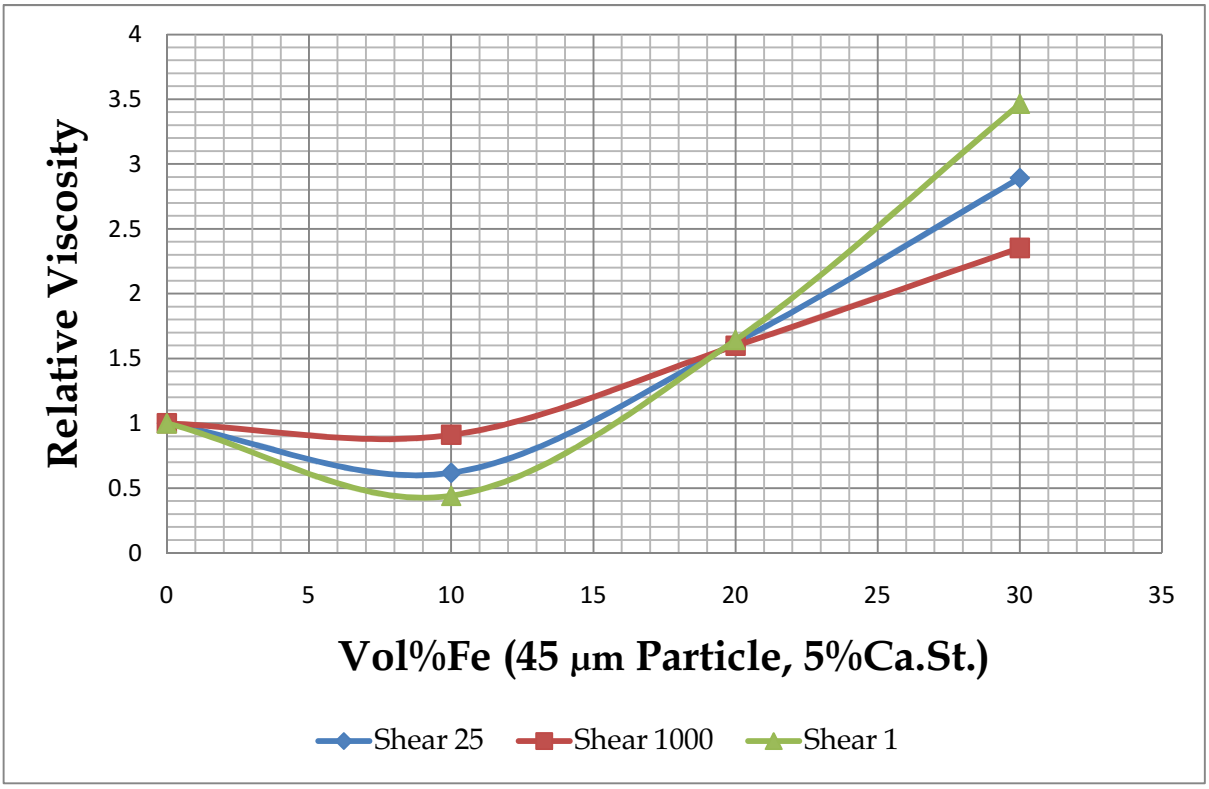

Figure 4-24: Relative viscosity of composites of ABS and varying volume fractions of Fe of 45 μm and 5%Ca.St.

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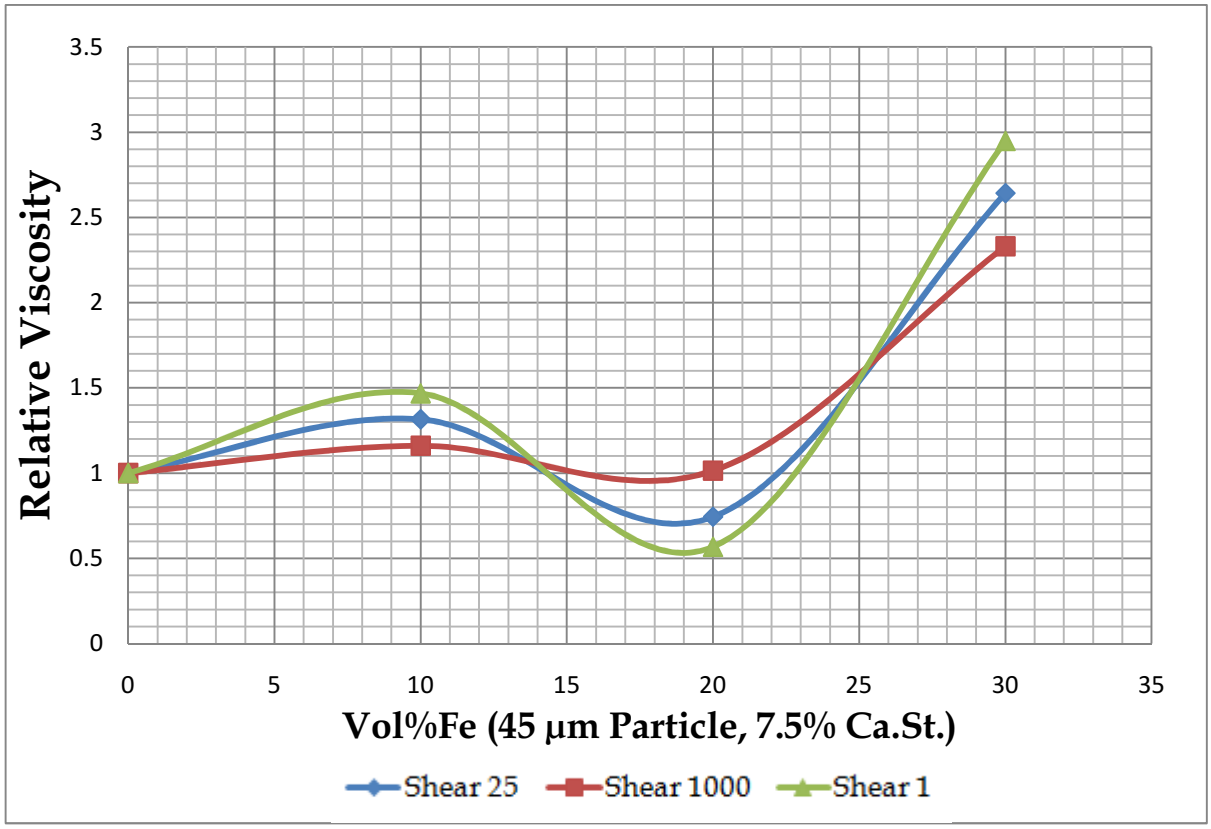

Figure 4-25: Relative viscosity of composites of ABS and varying volume fractions of Fe of 45 µm and 7.5%Ca.St.

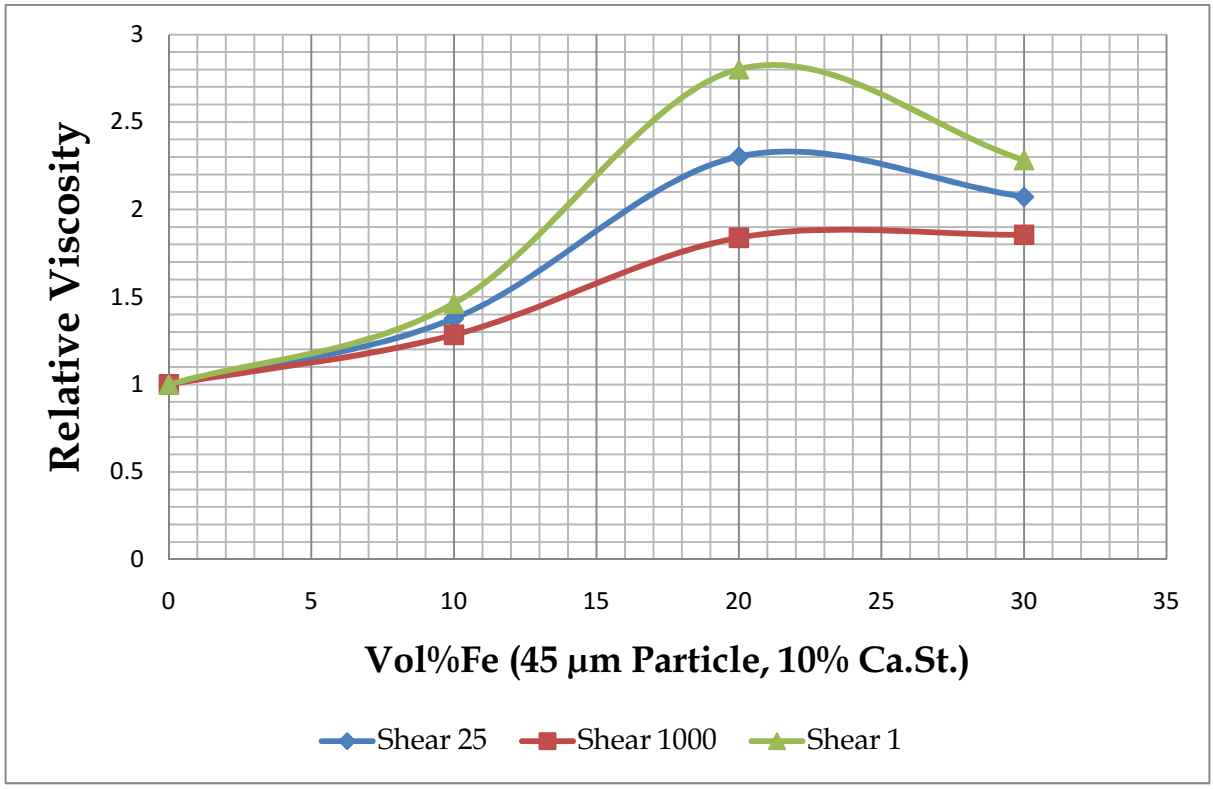

Figure 4-26: Relative viscosity of composites of ABS and varying volume fractions of Fe of 45 µm and 10%Ca.St.

As observed in Figure 4.26, for Fe/ABS/Ca.St composites containing only 10vol% calcium stearate, relative viscosity of the composite increases with increasing the iron powder content, and reaches to its peak at around 21% Fe concentration, after which the viscosity trend reverses and starts decreasing. The plotted trend for different shear rates suggest that further increase of calcium stearate could possibly reduce the viscosity of composites to the equivalent or less than that of the matrix.

It should be noted that the variation of viscosity of composites containing Fe particle size of 45 µm is consistent for low, medium, and high shear rates.

In the case of composites containing finer Fe particles (i.e. Fe<10 µm), however, the variation of viscosity for various Fe loading in the presence of calcium stearate is somehow sporadic, and not as consistent as the one seen for larger Fe

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particle size. For example, in composites containing fine particle size of less than 10 µm with 5 vol% calcium stearate, as shown in Figure 4.27, effective reduction of viscosity only is observed in the range of 14 to 22 percentage loading of Fe particles at low shear rates whereas at high shear rates the reduced viscosity is seen within 1 to 14 vol% of Fe.

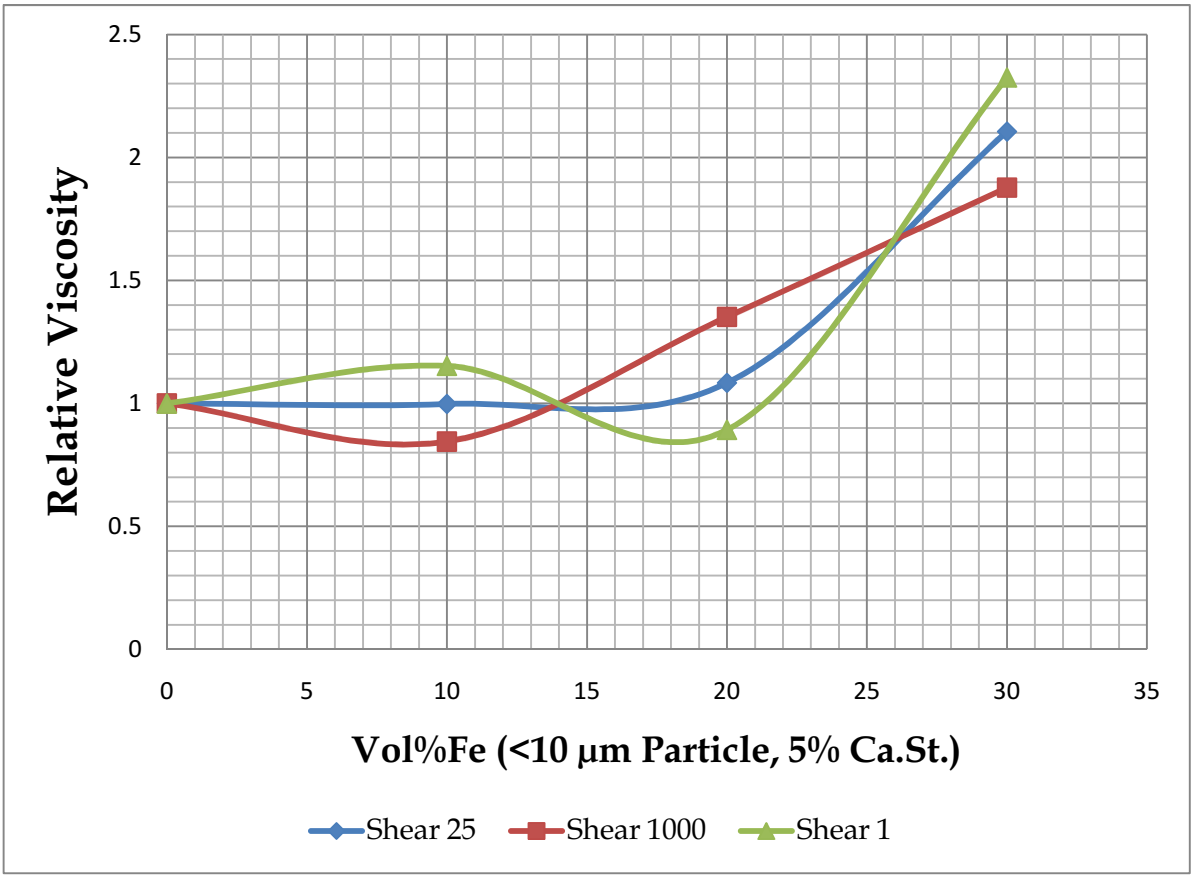

Figure 4-27: Relative viscosity of composites of ABS and varying volume fractions of Fe for 5% Ca.St.

Fe/ABS/Ca.St composites containing fine iron particles with Calcium Stearate concentration of 7.5vol% and 10vol% show monotonous increase of viscosity with increase of filler at various shear rates as depicted by Figures 4.28, and 4.29. It has been shown by several researchers that for the same concentration level; smaller particles have greater effect on the flow behaviour of particulate filled polymer composites, which is attributed to strong interactions of particle-

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particle within the composite (Han 1980; Hristov & Vlachopoulos 2008; Kauly et al. 1996; White & Crowder 1974). In presence of larger particles, the shear deformation of filled polymer composites is dominated by hydrodynamic interaction rather than particle-particle interaction (Shenoy 1999). It has been found that with decreasing average particle size, the ratio of area to volume of fillers increases, resulting in a strong tendency to agglomeration and aggregation, and thus imposing difficulties with regards to the processing of the composites (Osman & Atallah 2006).

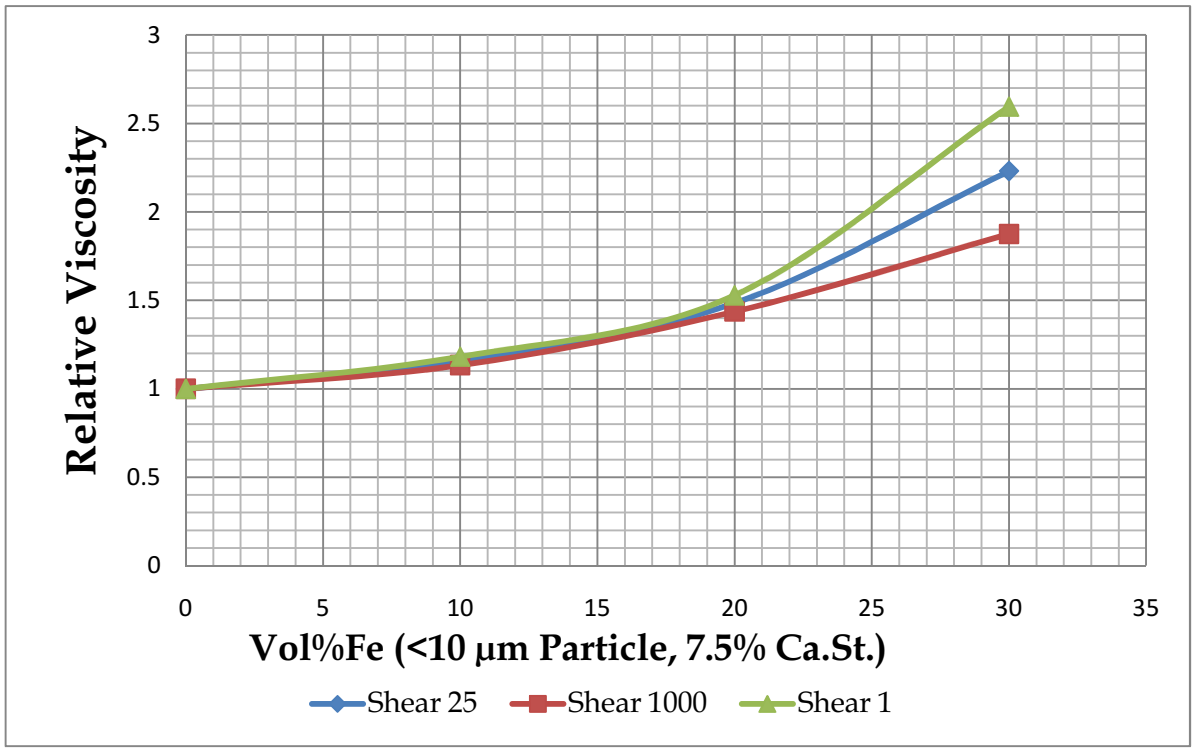

Figure 4-28: Relative viscosity of composites of ABS and varying volume fractions of Fe for 7.5 % Ca.St.

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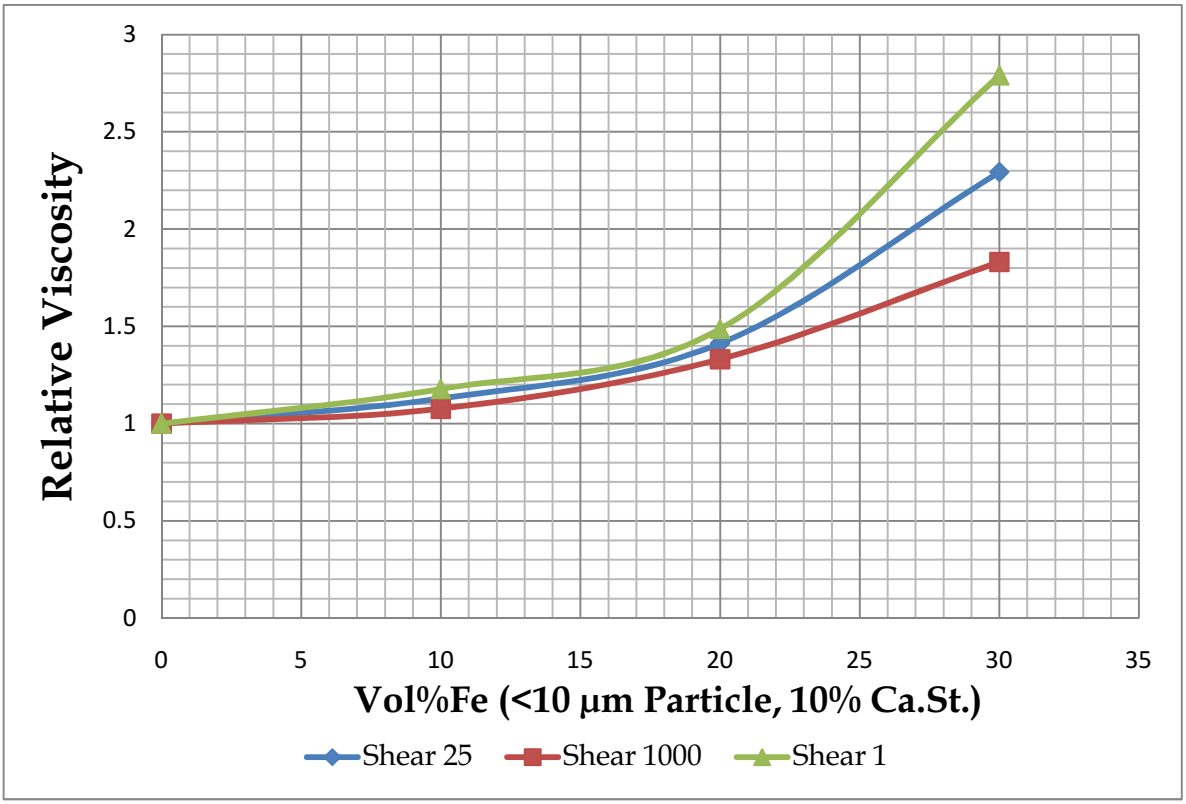

Figure 4-29: Relative viscosity of composites of ABS and varying volume fractions of Fe for 10% Ca.St.

Figures 4.30 to 4.33 show the superimposed plots of the relative viscosity of Fe/ABS/Ca.St composites versus concentration of iron powder. Given that two major shear rates are dominant in fused deposition modelling process i.e. low shear (=1 s^{-1}), and high shear (=1000s^{-1}), the plots have been produced for these two regions. Therefore the optimum compositions for processing ABS-Fe-Ca.St prototypes can be conveniently selected using these graphs. The compositions of interest are primarily those with viscosity lower than that of virgin ABS i.e. with relative viscosities equal or less than unity.

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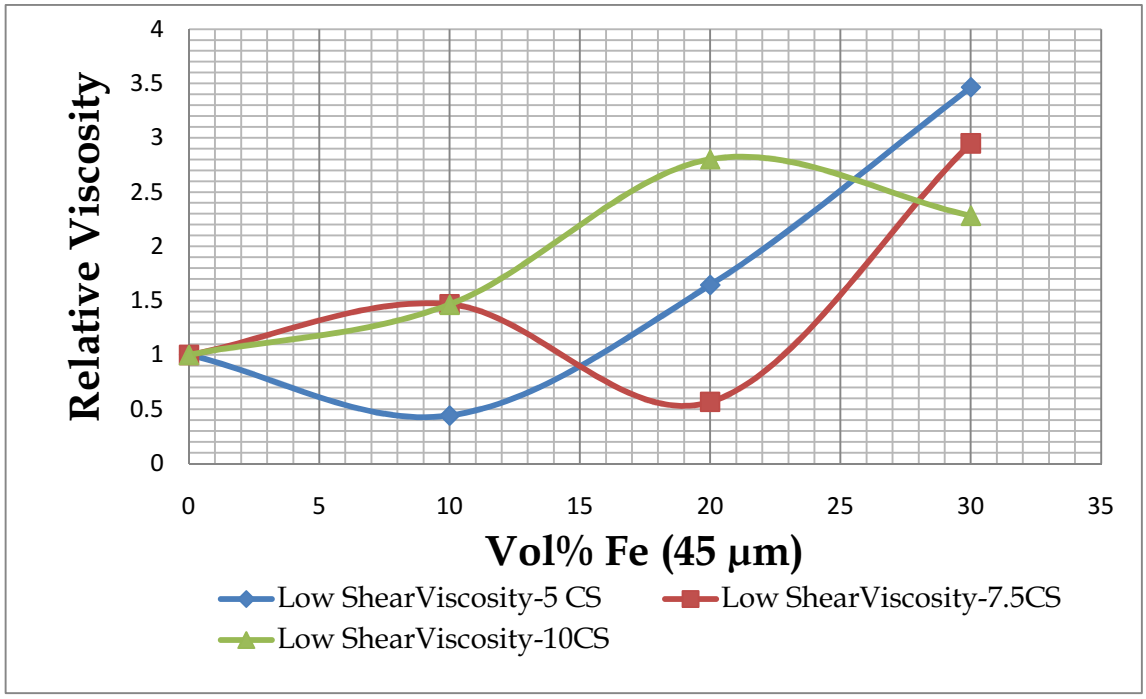

Figure 4-30: Relative viscosity of composites of ABS and varying volume fractions of Ca.St for low shear rate with iron particle size of 45 µm

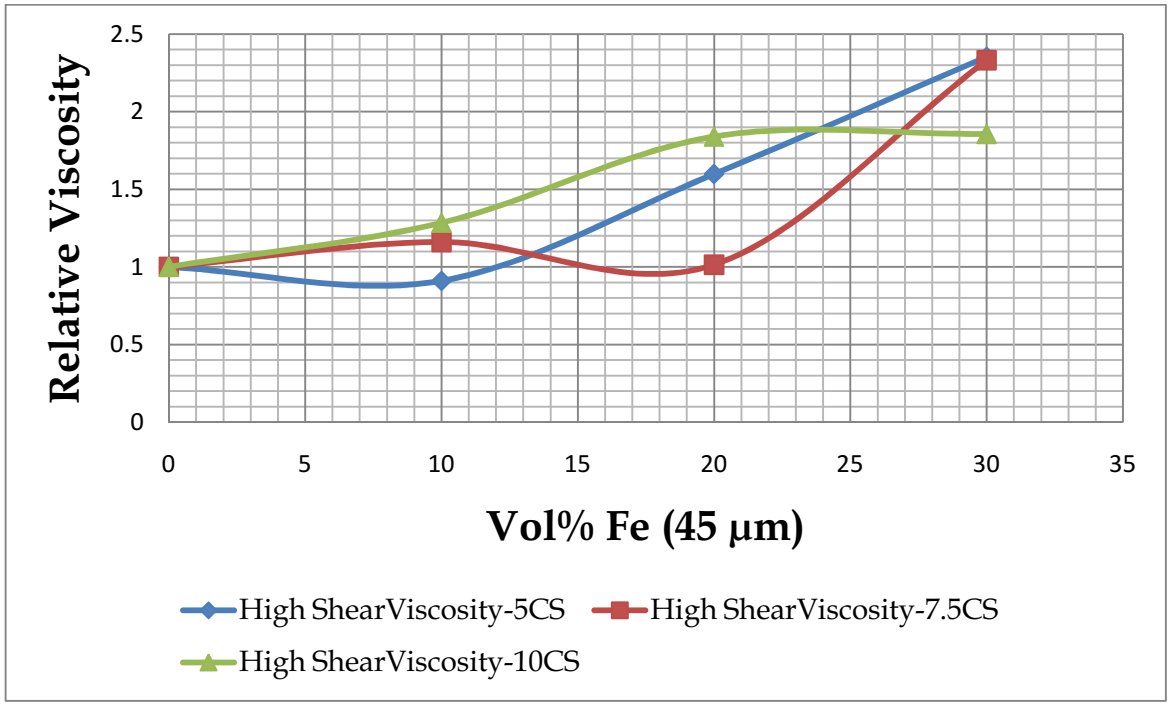

Figure 4-31: Relative viscosity of composites of ABS and varying volume fractions of Ca.St for high shear rate with iron particle size of 45 µm

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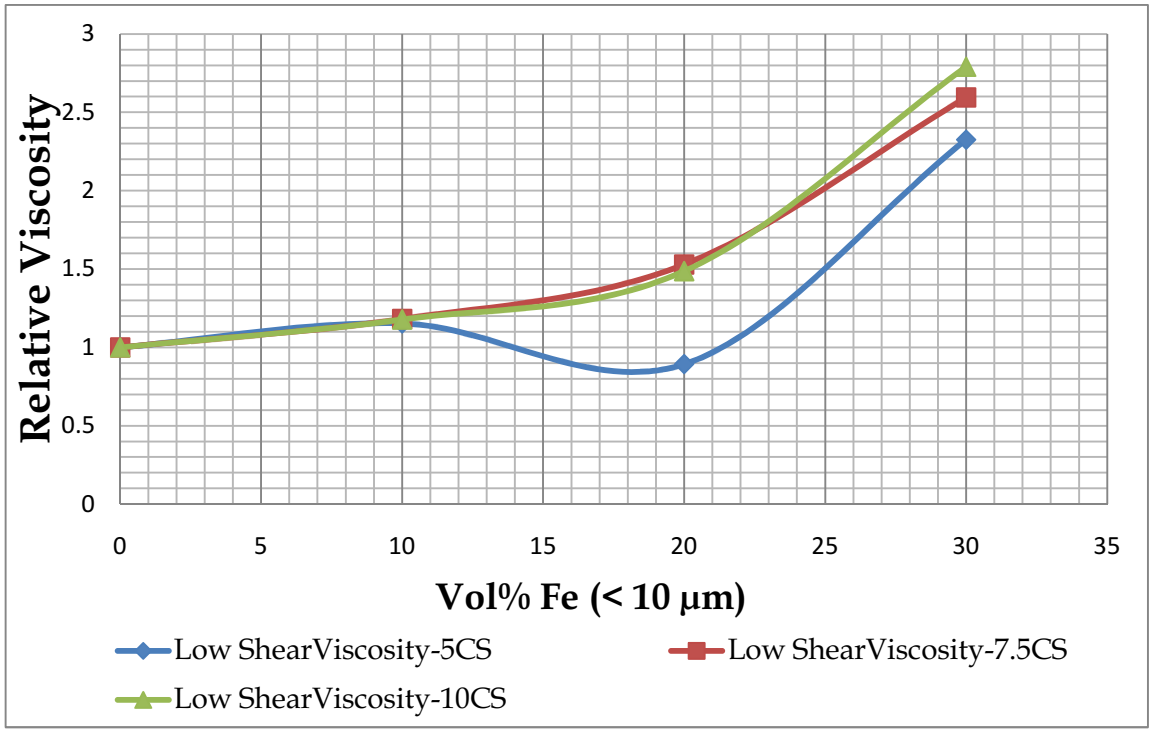

Figure 4-32: Relative viscosity of composites of ABS and varying volume fractions of Ca.St for low shear rate and iron particle size of <10 µm

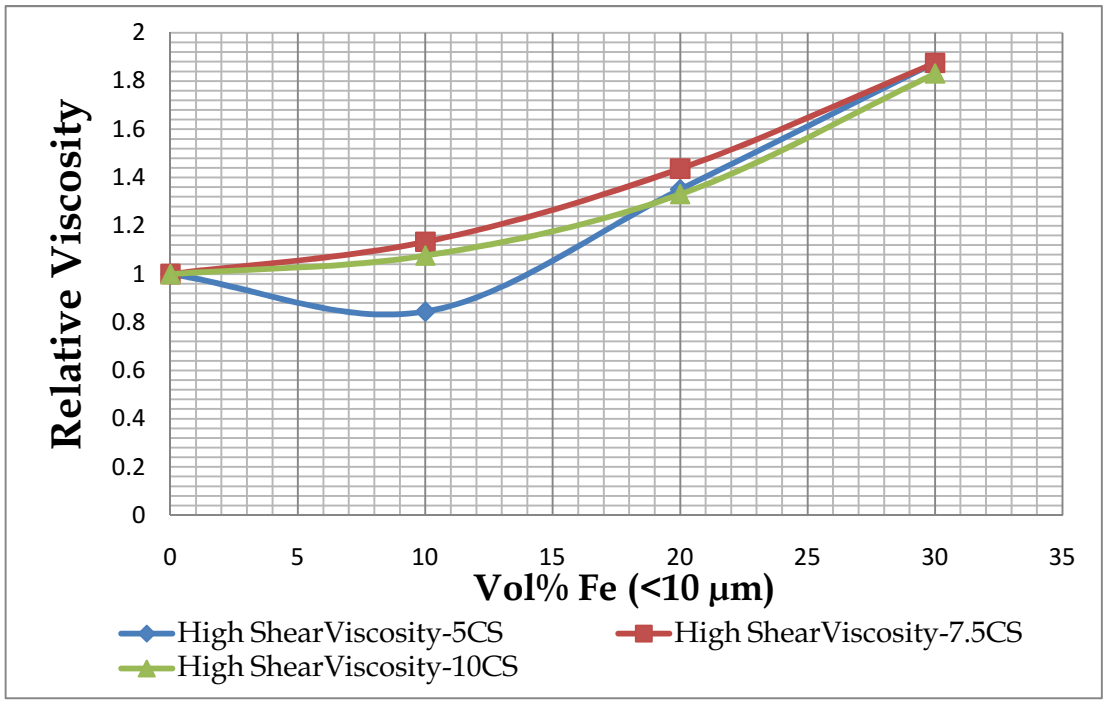

Figure 4-33: Relative viscosity of composites of ABS and varying volume fractions of Ca.St for high shear rate and iron particle size of <10 µm

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Figures 4.34 and 4.35 show that increase of temperature over a wide range of shear rates reduces the shear viscosity for both virgin and filled polymers. The effect has been argued to be due to the greater availability of free space for molecular motion as a result of thermal expansion of polymer melt (Saini, Shenoy & Nadkarni 1986). For the low and higher shear rates, temperature sensitivity of shear viscosity is identical. Temperature dependence of viscosity of ABS and Fe/ABS are both expressed by the Arrhenius equation (Li, Järvelä & Järvelä 1999) as given below:

$$\eta = A_o e^{E/RT} \tag{4.6}$$

where η is the melt viscosity, $A_o$is a constant, and E, R, T are the activation energy, universal gas constant, and the absolute temperature, respectively. From the comparison of temperature dependence of the filled and unfilled system, as demonstrated by Figures 4.34 and 4.35, it is seen that the former is more temperature sensitive than the latter one. This is consistent by the finding of other researchers in the case of polymer melts filled with inorganic filler (Gu, Ren & Wang 2004; Muksing et al. 2008). It is presumed that such effect is the result of further prevention of molecular chain motion by aggregated filler particles, and therefore increase of activation energy (Muksing et al. 2008). The increase of temperature sensitivity of the matrix due to addition of Fe particles should thus be taken into consideration in regards to the variation of temperature filed during the fused deposition processing of Fe/ABS composites as it can affect the deposition process.

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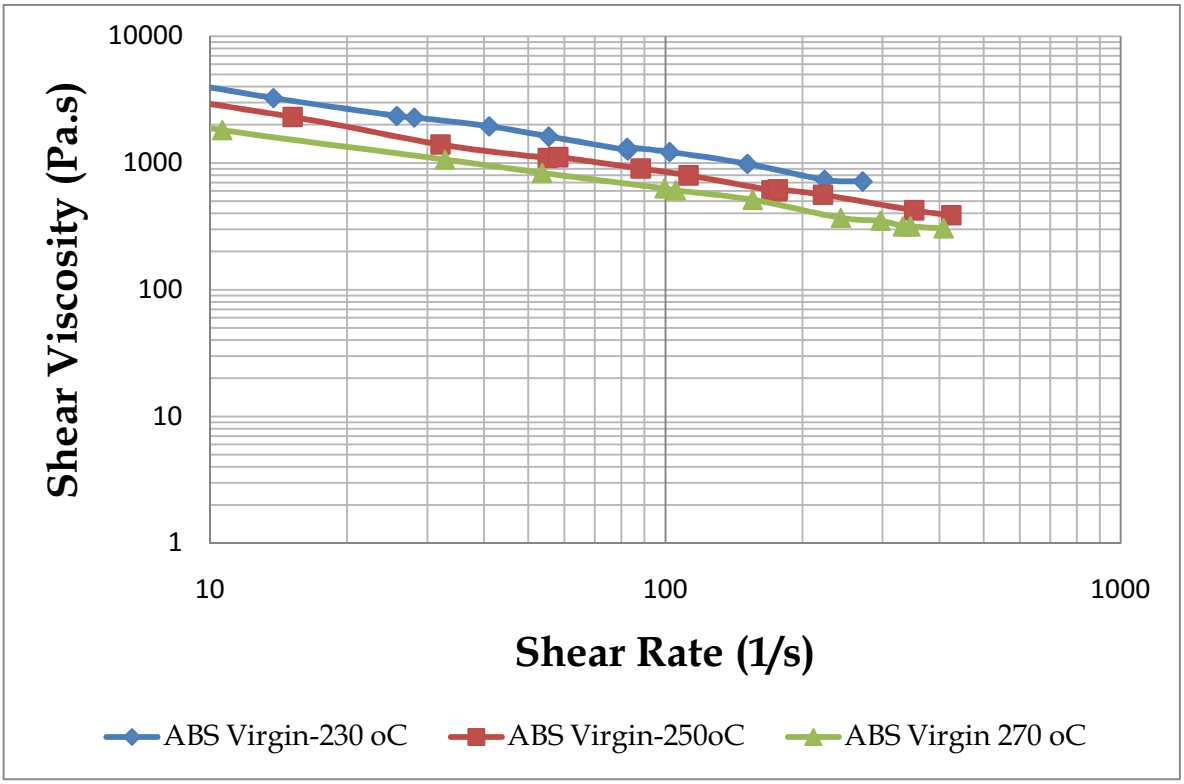

Figure 4-34: Effect of processing temperature on the viscosity of Fe/ABS composites

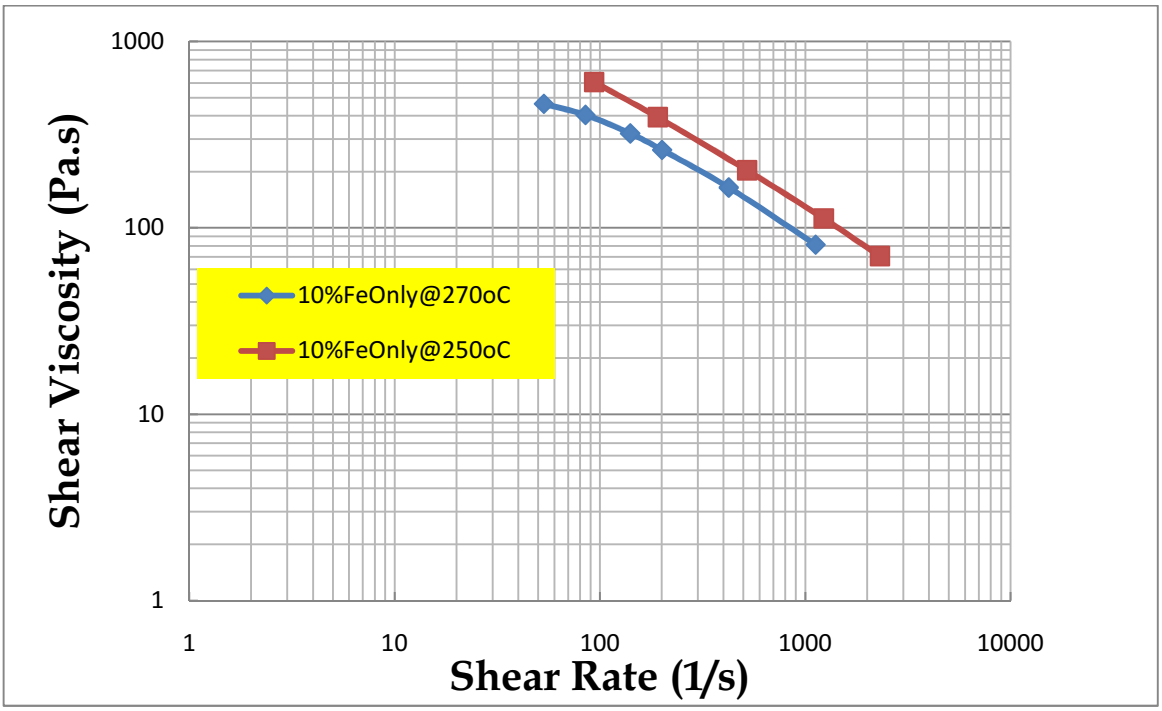

Figure 4-35: Effect of processing temperature on the viscosity of ABS P400

4.6.2. Normal Stresses and Die Swell Phenomenon

The filament used in FDM process needs to be of a specific size, strength and properties. Uniformity of the filament diameter is a crucial factor for continuous operation of the fused deposition process. Since the solid filament at the entrance of liquefier acts like a piston to provide sufficient load to push the materials for extrusion through the nozzle, any change in the diameter of the filament results in the variation of force applied on to the molten material inside liquefier head, therefore affecting the flow rate and final diameter of extrudate strands deposited on the machine platform. In extreme cases where initial filament diameter is radically changed, process fails to carry on continuously! Die swell phenomenon, as shown in Figure4.5, during the initial extrusion of Fe/ABS/Ca.St, is the major source of variation of filament diameter.

Viscoelastic properties of polymer melts have been reported to be responsible for die swelling of extrudate upon exiting the die (Rauwendaal 2001; Vlachopoulos 1981; Yamaguchi 1952). From macromolecular point of view, normal stress differences arising from shearing of polymer melts can be measured to predict extrudate swell (Goublomme, Draily & Crochet 1992; Vlachopoulos 1981). Therefore, parallel plate rheometry was used to work out the normal forces applied on the disc-shape samples made of the ABS-Iron composite representing the elastic recovery of the melt during actual rapid prototyping processing. As shown in Fig4.36, variation of surfactant alone affects the swelling of ABS, as by increasing the surfactant volume fraction to beyond 5%, normal stresses will increase resulting in higher die swell, and subsequently intermittent flow.

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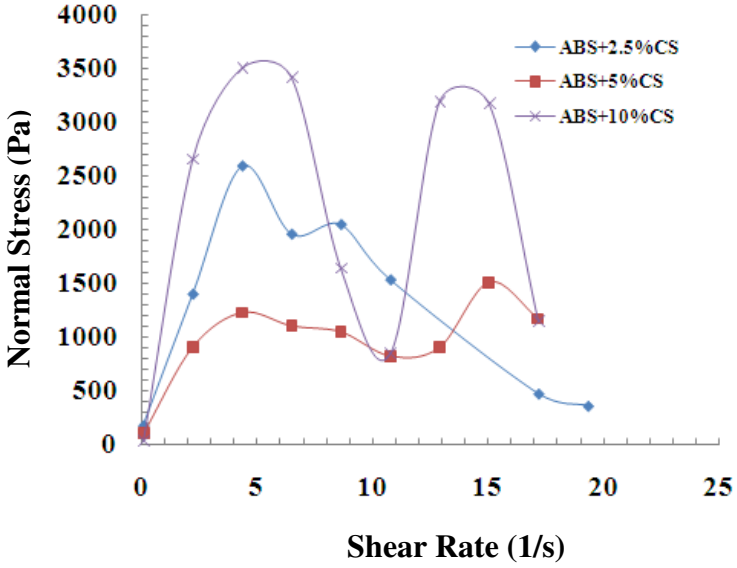

Figure 4-36: Normal Stress versus Shear Rate for ABS with varying %vol of Ca.St.

4.7. Viscosity Models for the Composites

As it can be seen clearly from the rheological data presented in Figure 4.8 and Figures 4.12 to 22, contrary to Newtonian constant shear viscosity fluids, metal filled polymeric flow shows a rapid exponential decay of viscosity versus increase of shear rate. In case of pure polymeric flows this behaviour is known as shear thinning or *Pseudoplasticity* (Aoki 1987), (Aoki 1986), and (Yamaguchi 1952). This characteristic, shown in Figures 4.2, is particularly important in that the required force needed to provide enough pressure to push the material through the FDM nozzle can be supplied using the existing step motors with minimal change of torque.

Currently there are a few mathematical models, which explicitly explain this type of behaviour, namely, Cross, Hershel Bulkley, Ostwald de Waele, and Carreau Yasuda as given by equations 5-8 (ANSYS 2008).

$$\textit{Cross: } \mu = \frac{\mu_0}{1+(\lambda\dot{\gamma})^n} \tag{4.7}$$

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$$\textit{Hershel Bulkley: } \mu = \frac{\tau_y}{(\lambda\dot{\gamma})} + K(\lambda\dot{\gamma})^{n-1} \quad (4.8)$$

$$\textit{Ostwald de Waele: } \mu = K(\lambda\dot{\gamma})^{n-1} \quad (4.9)$$

$$\textit{CarreauYasuda: } \mu = \mu_\infty + \frac{(\mu_0 - \mu_\infty)}{(1+(\lambda\dot{\gamma})^a)^{\frac{1-n}{a}}} \quad (4.10)$$

where τ_y, μ, μ_0, and μ_∞ denote yield stress, viscosity, low shear viscosity, and high shear viscosity, and K, n, a denote consistency index, power law and Yasuda exponent.

In search for the best existing theoretical model to predict the flow behaviour of the newly developed polymeric composite, 2-D and 3-D finite element analysis of the melt flow behaviour has been carried by setting up the FEM model in FLOTRAN and CFX, which are embedded modules in the latest release of the ANSYS Workbench. Detailed procedures of the finite element analysis have been discussed in the next chapter. Existing non Newtonian fluid models was incorporated in these commercial codes and material property constants as well as flow indexes were extracted from foregoing experimental data. A MATLAB code was used to best fit a correlation of data representing those mathematical models.

Curve fitting of rheological experimental data using a MATLAB code revealed that mathematically, the flow behaviours of filled polymeric composite were closely represented by Cross and Oswald de Waele viscosity models with certainty of 99% and 97% respectively. The Hershel Bulkley and Carreau Yasuda expressions were found not to be a good model for such composites with error certainty of 70%.

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Table 4-1: Conformity of Fe/ABS/Ca.St for existing viscosity models

Model	R-Square
Hershel Bulkley:	70%
Oswald de Waele:	97%
Cross:	99%
Carreau Yasuda:	70%

4.8. Summary

Comprehensive rheological study of iron powder filled acrylonitrile butadiene styrene composites proves to be an indispensible tool to understand the flow behaviours and processablity of such composites through fused deposition modelling. Viscosity of such composites greatly increases as a result of incorporation of iron powder particulates, and therefore poses the most challenging obstacle to rapid prototyping them through FDM machines. This challenge can be overcome when compounded with appropriate type and amount of surfactants and therefore without modifying the current available hardware on FDM machines. As shown in Figure 4.37, there is a direct proportionality between volume fraction of metallic filler and flow-improving effect of calcium stearate in the sense that the higher loading of iron powder filler requires more concentrated presence of calcium stearate so that it can provide a processable viscosity for deposition through current Fused Deposition Modelling technology.

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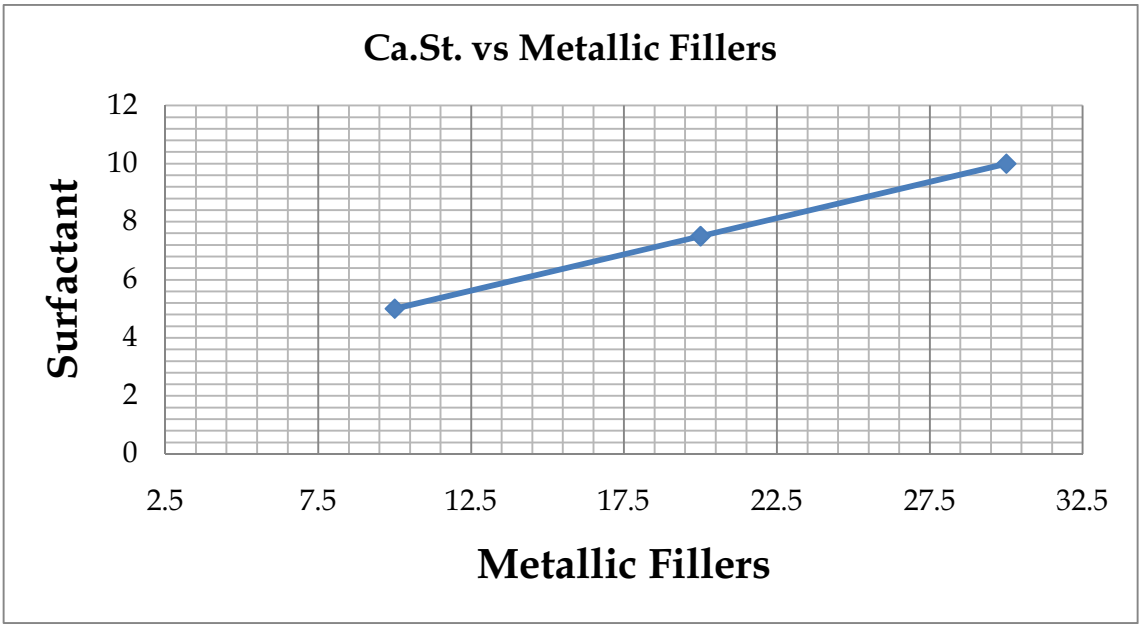

Figure 4-37: Relative viscosity of compounds of ABS and varying volume fractions of Ca.St.

From the plots of the relative viscosity of composites versus volume fraction of iron particulate fillers, Tables 4.2 & 4.3 are drawn suggesting the optimum formulation of Fe/ABS/Ca.St composites for processing in Fused Deposition Modelling.

Table 4-2: Optimum Fe/ABS/Ca.St composition for Fused Deposition Processing under low shear & high shear rates

	Fe (Coarse)	ABS	Ca.St.
Low Shear(1)	(1-15) vol%	(80-94) vol %	5 vol %
Low Shear(2)	(14-23) vol %	(71-80) vol %	7.5 vol %
High Shear(1)	(1-12) vol%	(83-94) vol %	5 vol %
High Shear(2)	(15-20) vol %	(73-78) vol %	7.5 vol %

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Table 4-3: Optimum Fe/ABS/Ca.St composition for Fused Deposition Processing under low & high shear rates

	Fe (Fine)	ABS	Ca.St.
Low Shear	(14-21) vol%	(74-81) vol%	5 vol%
High Shear	(1-14) vol%	(81-94) vol%	5 vol%

General flow behaviour of Fe/ABS/Ca.St composites has been found to be non-Newtonian. Despite the addition of high percentage of iron powder, the shear thinning behaviour is retained within the shear rates range suitable for fused deposition processing. The effect is pronounced under higher shear rates and higher concentration of filler. Such a characteristic is particularly found to be important in that the required force needed to provide enough pressure to push the material through the FDM nozzle can be supplied using the existing step motors with minimal change of torque. There is an obvious effect of variation of temperature on the viscosity of composites expressed by Arrhenius equation. Increase of temperature reduces the viscosity but the effect is not as dominant as of the shear rate within the working temperature range of FDM processing. Due to poor distribution of smaller size filler particles, and possible agglomerations, addition of calcium stearate does not seem to be effective as the viscosity of composites monotonously increases with increase of finer iron powders. Through parallel rheometry, it is shown that addition of filler can reduce the effective normal stresses in the compounds of ABS/Ca.St under shear, and subsequently decrease the amount of die swell in the extrudate helping to improve the uniformity of final strands exiting from FDM nozzle.

Curve fitting of rheological data revealed that Cross mathematical model is the best existing viscosity model to represent the non-Newtonian behaviour of Fe/ABS/Ca.St composites by taking into account the volume fraction of fillers

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and surfactants. Such a model can very well be used to predict and modify the processing conditions of metal-polymer composites for rapid prototyping and manufacturing applications.

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Chapter 5 Mechanical & Electro thermal Properties of Metal/Polymer Composites

5.1. Introduction

Mechanical, thermal and electrical properties of parts and tools made using the fused deposition modelling technology would inevitably depend on the static and dynamic response, heat capacity, thermal conductivity as well as intrinsic resistivity of their initial building material, respectively. In particular, the knowledge of static and dynamic behaviour of Fe/ABS composite materials will be necessary in designing the applications for prototypes, and tools developed based on such materials on the FDM rapid manufacturing/tooling platform. Therefore, this chapter deals with the experimental determination of quasi static mechanical properties such as load-deformation behaviour, tensile strength and modulus of elasticity as well as their dynamic response under frequency based load variable conditions representing viscoelastic properties of metal-polymer composites namely, storage modulus and loss modulus. In addition, heat capacity and thermal conductivity of Fe/ABS composites are studied to get an insight into thermal stability of parts made of such composites for use as either in-die-material or tooling inserts. Finally, imparting electrical conductivity to the ABS polymer matrix by addition of metal particulate fillers has also been studied. Among others, one useful application of such electrically conductive particle-reinforced plastic can be found in many electronic devices, which require shielding against electromagnetic interference and improving their signal stabilities and performance.

In addition to the study of Fe/ABS composites, a limited investigation has also been presented on the development and properties of Copper/ABS composites, as such composites would also be useful for certain applications in FDM. Specifically dynamic mechanical properties of Cu/ABS composites of varying

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copper content and particle size are included and compared with those of Fe/ABS composites in this chapter.

5.2. Micro/nano metal-polymer composites

Characteristics of the heterogeneous polymeric composites containing micro/nano particulate fillers are influenced primarily by their individual component properties, composition, structure and interfacial bonding (Móczó & Pukánszky 2008). For example, only with the alteration of the morphological and interface properties, a great variety of functionalities can be achieved for the final performance of the composite system. The strength of interfacial bond can greatly affect mechanical behaviour (Martinatti & Ricco 1994). Changes in the mechanical properties of polymers due to the addition of filler particles, in many cases, can be predicted from the basic principles, however, in the cases, where there is not sufficient knowledge of polymer-filler interactions to work out the effect of filler concentration on the properties of composites, experimental measurement must be conducted to understand such properties (Bigg 1987b).

The effects of foregoing parameters have been of great interest to researchers and therefore a large body of literature has been produced (Bloor et al. 2005; Brassell & Wischmann 1974; Bruschi, Nannini & Massara 1991; Cho, Joshi & Sun 2006; Chow 1978a, 1982, 1993, 1994; Devaprakasam et al. 2008; Farshidfar, Haddadi-Asl & Nazokdast 2006; Gungor 2006, 2007; Herbold et al. 2008; Hussain et al. 2006; Lewis & Nielsen 1970; Liang 2009; Liu et al. 2007; Luyt, Molefi & Krump 2006; Martinatti & Ricco 1994; Móczó & Pukánszky 2008; Molefi, Luyt & Krupa 2010; Montazeri et al. 2010; Nurazreena et al. 2006; Rusu, Sofian & Rusu 2001; Rusu et al. 2001; Sideridis & Konstantellos 1996; Taşdemir & Gülsoy 2008; Unal 2004). Modulus as a bulk property, which primarily depends on the geometry, modulus, particle size distribution, and concentration of the filler, is the easiest property of filled polymer to be

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measured whereas, due to difficulty in predicting local polymer-filler interaction, tensile properties of the filled polymer composites are more difficult to estimate (Bigg 1987b; Chacko, Farris & Karasz 1983; Nielsen 1974a; Schrager 1978). Interfacial bonding between the filler particle and the matrix is driven by mechanisms of adhesion, which promotes the strength of the bond. These mechanisms have been explained by three types of chemical bonding arising from functional groups existing on the filler particle and matrix, mechanical interlocking and friction resulting from surface morphology, and physical-chemical interactions between the filler and the matrix (Iskandarani 1996). Some predictive models have also been developed to explain the strength of interfacial bonding and subsequent stress-strain behaviour of particulate-filled composites by taking into account the formation of weak structures in such composites (Bigg 1987c; Ghosh & Maiti 1996; Rusu, Sofian & Rusu 2001).

In addition to the adhesive bond between the filler particles and the matrix, other factors influencing the mechanical properties of metal-polymer composites include particle size, shape, aspect ratio, distribution, dispersion and agglomeration of particles. Isolating influence of these factors is often difficult (Basaran et al. 2008). But generally it is assumed that the increase of volume fraction of particles proportionally decrease the ductility of the polymeric matrix. Curves shown in Figure 5.1, classify two general trends for tensile strength response of particulate filled polymers (Bigg 1979; Bigg 1987b).

Rusu et. al (Rusu, Sofian & Rusu 2001) have investigated the effect of zinc powder on the tensile strength of high density polyethylene (HDPE). It has been shown (see Figure 5.2), that loading of zinc powder in HDPE matrix has decreased the ultimate strength, and resulted in a brittle response of HDPE/zinc against various stresses.

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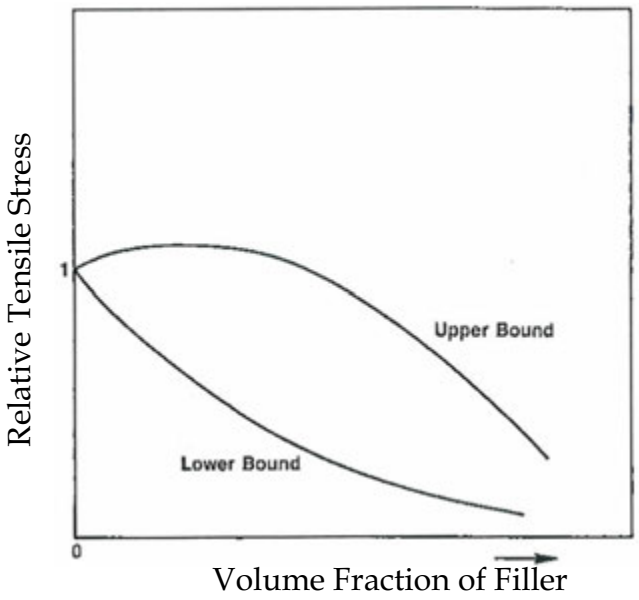

Figure 5-1: Typical tensile stress vs. concentration curves for filled polymers showing upper bound and lower bound responses (Bigg 1987b)

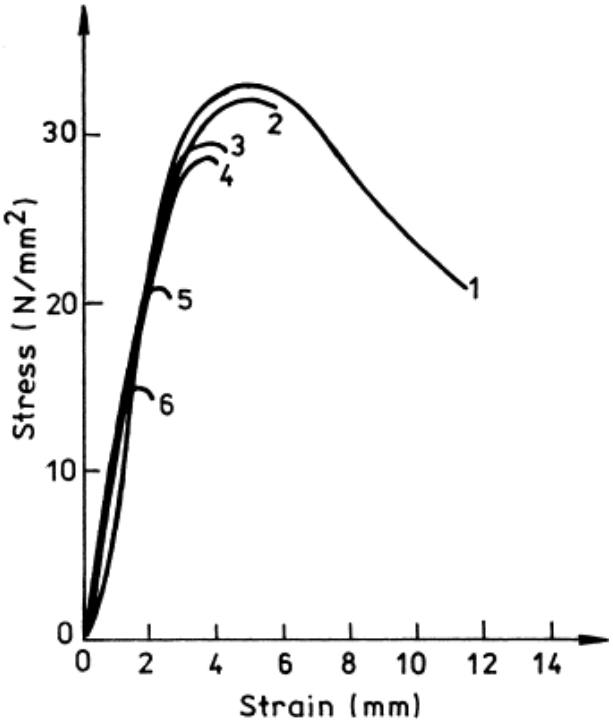

Figure 5-2: Stress–strain curves for HDPE/zinc composites with different concentrations of zinc powder: 0% vol (1); 4% vol (2); 8% vol (3); 12% vol (4); 16% vol (5); 20% vol (6) (Sofian & Rusu 2001)

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As discussed in the previous chapter, due to viscoelastic nature of the polymeric matrix, the composites would exhibit mechanical behaviour characteristic of either an elastic solid or a viscous liquid. But under actual circumstances their mechanical response will depend upon the temperature, in relation to the glass transition temperature (T_g), and the scale of deformation (Fried 2003). Dynamic mechanical analysis (DMA) is employed to measure the response of a polymeric matrix as a function of temperature and time. In this technique, the stress is measured as a function of strain which is a periodic function of time, usually a sine wave. Contrary to fatigue testing, a very small rate of strain is applied during the testing to avoid any permanent deformation.

Effect of metallic micro and nano particles on the dynamic mechanical properties of polyethylene has been investigated by Molefi et al (Molefi, Luyt & Krupa 2010). They have reported that, in solid state, both storage modulus and loss modulus as the representative dynamic mechanical properties of polyethylene matrix, have increased as a result of addition of micro copper particles. Three grades of polyethylene namely, low density polyethylene (LDPE) and linear low density polyethylene (LLDPE), and high density polyethylene (HDPE) have been used with varying content of copper powder. The increase of storage modulus in all samples, as shown in Figure 5.3, has been attributed to the stiffening of the matrix due to increase of copper (Cu) content. They have also concluded that higher loss modulus of micro copper reinforced LDPE,LLDPE, and HDPE, as demonstrated in Figure 5.4, implied lower elastic recovery as the result of higher polymer rigidity. However, both storage modulus and loss modulus were decreased with increase of temperature along with a change in the slope of the line around the glass transition temperature due to increased mobility in the polyethylene chain (Molefi, Luyt & Krupa 2010).

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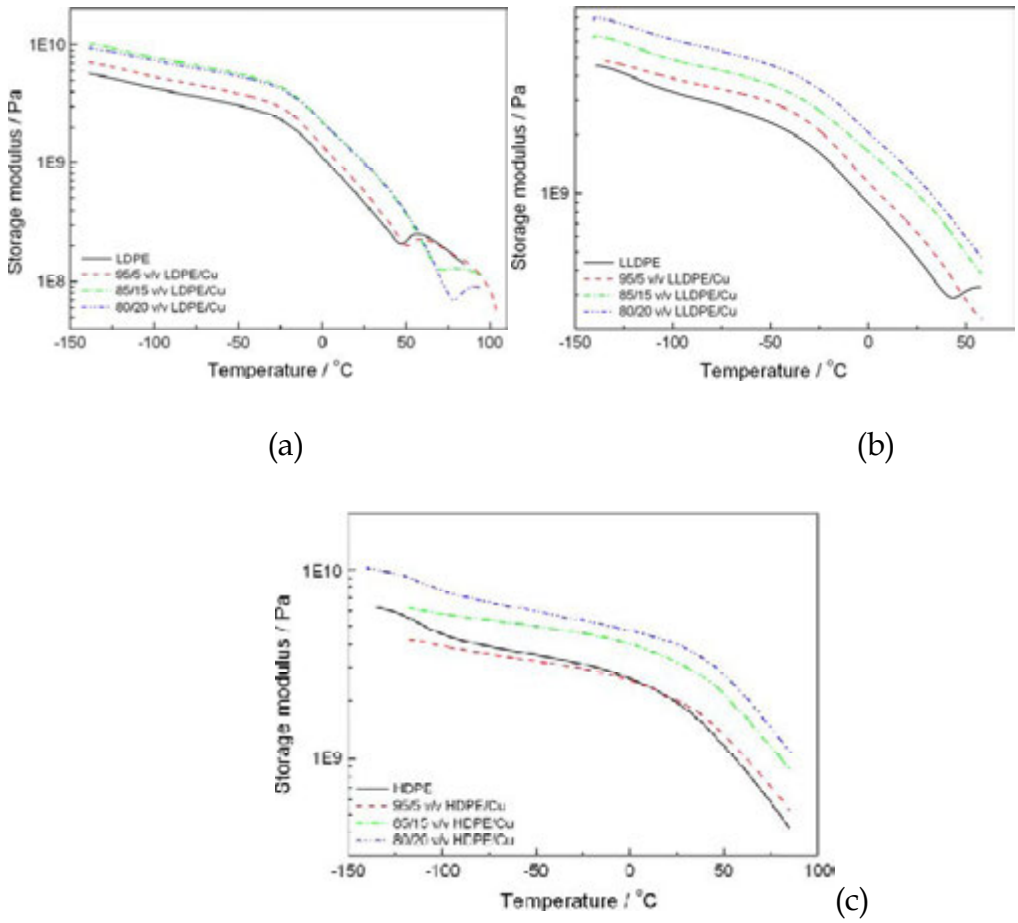
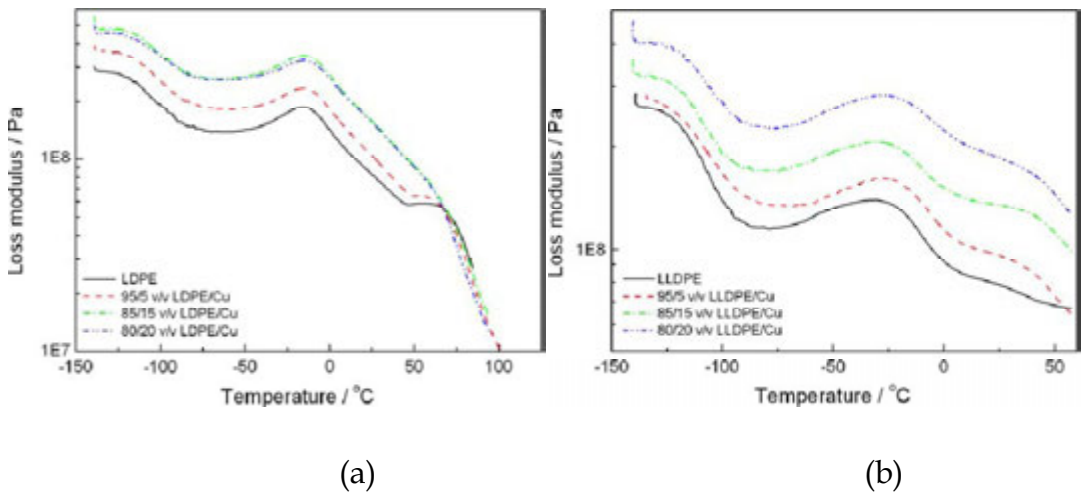


Figure 5-3: Storage Modulus of copper reinforced (a) LDPE, (b) LLDPE, (c)HDPE (Molefi, Luyt & Krupa 2010)



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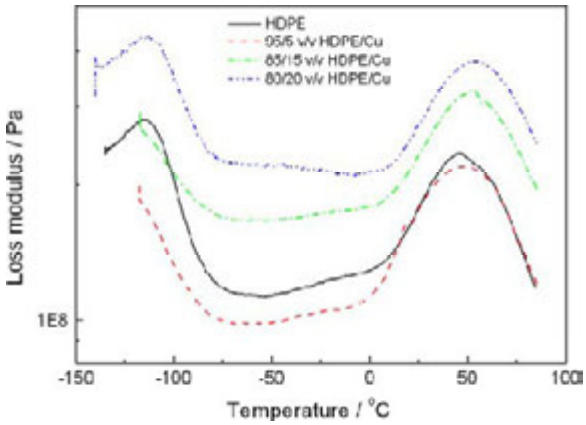

(c)

Figure 5-4: Loss Modulus of copper reinforced (a) LDPE, (b) LLDPE, (c)HDPE(Molefi, Luyt & Krupa 2010)

Alongside the improvement of viscoelastic properties of polymer composites, enhancing thermal properties due to introduction of metallic fillers has also been of great interest. In particular, the thermal conductivity of the metal-polymer composite is one of the very important properties of the material which is usually determined for different volumetric percentage of metal and polymer material. This property is especially useful for proper functioning of injection moulding dies and inserts made by fused deposition modeling process. The life of injection moulding dies depends greatly on the value of thermal conductivity of the die material and hence on the thermal conductivity of the feedstock FDM material of the composites.

Some efforts have been made, pioneered by Nielson (Nielsen 1974b), to theoretically model the thermal conductivity of filled polymeric composites but they have been hampered due to lack of good experimental data (Chow 1978b). However, there have been numerous reports of measuring heat flow, heat capacity, and thermal diffusivity, which can indirectly be used to evaluate the thermal conductivity of polymeric composites. Differential Scanning Calorimeter (DSC) and Thermo- gravimetric analysis (TGA) are among the

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common techniques used to measure the foregoing thermal properties (Boudenne et al. 2005; Luyt, Molefi & Krump 2006; Molefi, Luyt & Krupa 2010; Rusu, Sofian & Rusu 2001). Direct measurement of thermal conductivity value can provide valuable data for developing theoretical models to be used for prediction of thermal properties of metal particle filled composites on Fused Disposition Modelling.

Enhancing electrical properties is another primary reason that conductive particulate fillers are added to the polymeric matrix. The desirable characteristics of polymers such as low cost, light weight, corrosion resistance, attractive aesthetics, and ease of forming complex shapes make them ideal matrix materials for development of conductive metal-polymer composites, such as by addition of highly conductive, and readily available metallic fillers. Once developed, such composites can be particularly used in fabrication of housings for electronic devices to provide electromagnetic shielding (Bigg 1979; Boudenne et al. 2005) .

Numerous works have been reported on enhancement of electrical conductivity of polymeric matrices due to addition of conductive fillers (Boudenne et al. 2005; Farshidfar, Haddadi-Asl & Nazokdast 2006; Fortelný et al. 2001; King et al. 2006; Luyt, Molefi & Krump 2006; Xu et al. 2009). However, it is not well understood if the mechanisms of electrical conduction in such materials is of *electronic nature;* where an electric current results from motion of electrically charged particles under an externally applied field or *ionic conduction* whereby a current is produced through motion of charged ions (Callister 1940 & c2007). While most of the published literature on electrical conductivity of metal-polymer composites employed a DC method for measurement of conductivity, it has also been shown that AC methods such as Electrochemical Impedance Spectroscopy (EIS) can appropriately be used to measure the intrinsic electrical properties such as conductance, dielectric constant and the properties of the

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interfaces in a given system. This technique works based on analysis of impedance, which results from the application of an alternating potential with measurement of current as a function of frequency (Shekibi et al. 2007).

5.3. Experimental

5.3.1. Stress-Strain behaviour of Iron/ABS composites

To measure the maximum load and elongation at break point, and subsequently calculating stress-strain curves, standard tensile test according to ASTM D 638 test procedure with different sample sizes was conducted on a Zwick/Z010 Instrument at a speed of 50 mm/min. At least three samples were prepared for each test and the average values have been considered. In order to observe the effect of processing techniques on the final structural properties of Iron/ABS composites, two sets of samples with various compositions were tested. For ease of referencing, samples prepared via centrifugal mixing are designated as C1, C2, C3, C4, and those made by melt compounding are designated as C'1, C'2, and C'3. Detailed procedures for both of centrifugal mixing and melt compounding techniques have been outlined earlier in chapter 3. A complete list of various composites prepared for experimental characterisation including tensile testing, dynamic mechanical analysis as well as thermal and electrical conductivity measurements is shown in Table 5.1.

Figure 5.5 shows the tensile test results of various Iron/ABS composites made out of feedstock prepared by centrifugal mixing. It can be observed that an increase of iron powder content reduces the elastic deformation of samples under increasing load. Samples C1, containing only 5% by volume of iron powder presents the minimum deviation from the strength of original ABS matrix, while further increase of filler content dramatically drops the extent of elongation as in samples C2-C4 once pulled along their axis.

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Table 5-1: Metal/Polymer Composites Constituents and their designation

Composite	Matrix	Metal Filler	Filler Size	Filler	Prepared by
C1	ABS	Fe	10	5%	Centrifugal Mixing
C2	ABS	Fe	10	10%	Centrifugal Mixing
C3	ABS	Fe	10	20%	Centrifugal Mixing
C4	ABS	Fe	10	30%	Centrifugal Mixing
C5	ABS	Fe	10	40%	Centrifugal Mixing
C′1	ABS	Fe	10	10%	Melt Compounding
C′2	ABS	Fe	10	20%	Melt Compounding
C′3	ABS	Fe	10	30%	Melt Compounding
C″1	ABS	Fe	45	5%	Melt Compounding
C″2	ABS	Fe	45	10%	Melt Compounding
C″3	ABS	Fe	45	20%	Melt Compounding
C″4	ABS	Fe	45	30%	Melt Compounding
C″5	ABS	Fe	45	40%	Melt Compounding
A1	ABS	Cu	10	5%	Melt Compounding
A2	ABS	Cu	10	10%	Melt Compounding
A3	ABS	Cu	10	20%	Melt Compounding
A4	ABS	Cu	10	30%	Melt Compounding
A5	ABS	Cu	10	40%	Melt Compounding
B1	ABS	Cu	45	5%	Melt Compounding
B2	ABS	Cu	45	10%	Melt Compounding
B3	ABS	Cu	45	20%	Melt Compounding
B4	ABS	Cu	45	30%	Melt Compounding
B5	ABS	Cu	45	40%	Melt Compounding

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This behaviour is confirmed by other researches (Bigg 1987b; Rusu et al. 2001) arguing that addition of untreated short fibre fillers induces weaker interfacial bonding, at the interface of the filler-matrix, than shear strength of the matrix. As it can be seen, as shown by C1 to C4 curves, the behaviour of iron filled ABS is of characteristics of a brittle and hard material with much lower elongation.

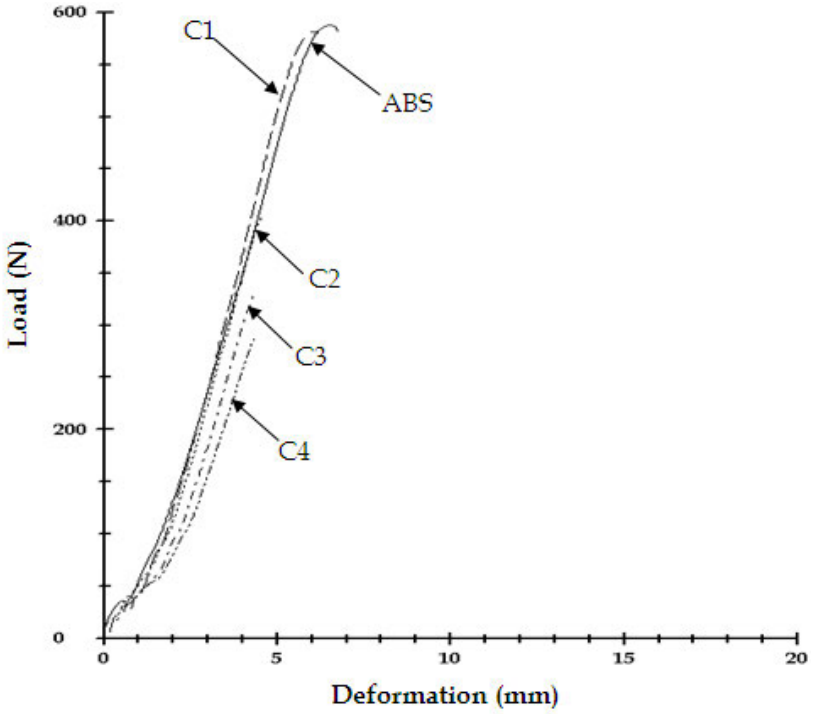

Figure 5-5: Load vs deformation behaviour of Iron/ABS composites prepared by centrifugal mixing with various volume fractions of Iron powder

Figure 5.6 shows the stress-strain behaviour of as-received virgin ABS from Stratasys, and a 10wt% filled ABS with iron particles. It is seen that virgin ABS demonstrates much higher yield stress and % elongation than iron filled ABS; suggesting that mere addition of filler particle to the polymeric matrix detrimentally affects its tensile strength. However, a different trend is observed in Figure 5.7., where tensile test results of samples prepared by both techniques are overlaid for comparison. It is observed that, contrary to the behaviour of those samples prepared by centrifugal mixing namely, C1-C4, there is a

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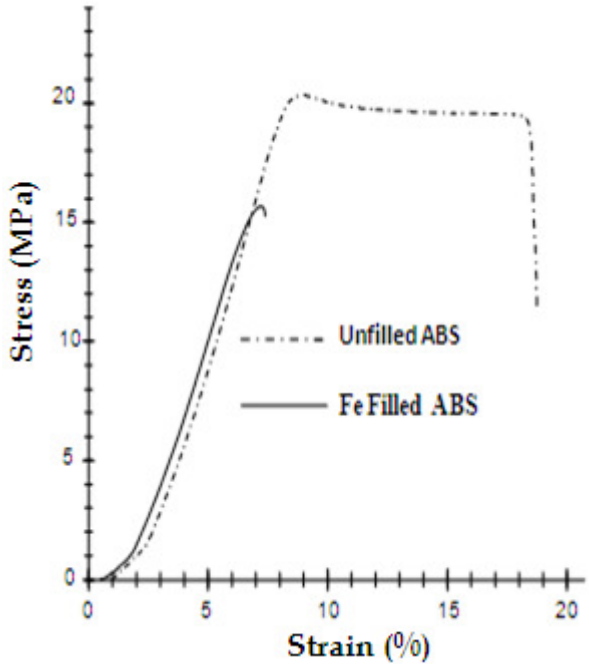

Figure 5-6: Stress-strain behaviour of 10wt% Iron filled ABS and virgin ABS used in FDM

compelling strengthening mechanism appearing on C'1 to C'3, which are prepared by twin screw mixing and coated by a small fraction of surfactant. The reinforcement is evident as the content of filler increases from 10 vol% to 20, and 30 vol% depicted by curves C'1 to C'3. In addition, slope of the plot lines from C'1 to C'3 significantly increases implying the increase of modulus of elasticity which represents much higher strength.

According to a work reported by Bigg (1987b), there are factors that are responsible for integrity and long-term durability of metal-polymer bonds. These factors include morphology of the surface oxide on the metal and environmental stability of the same oxide films.

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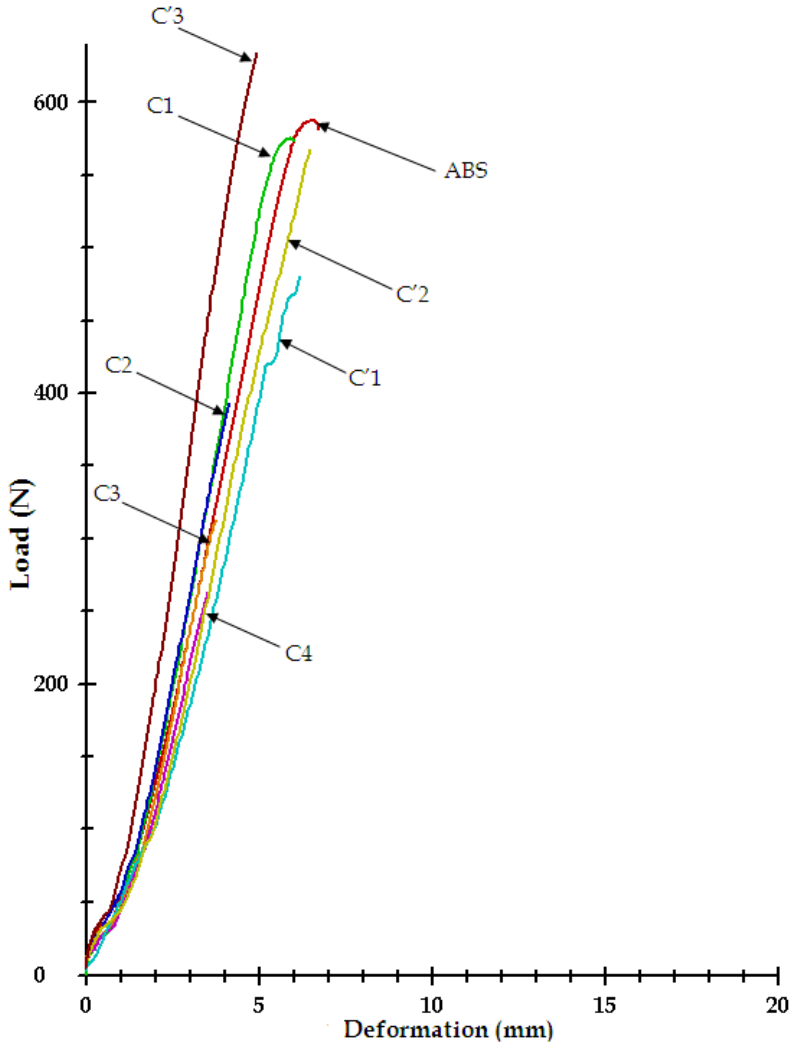

Figure 5-7: Load vs deformation behaviour of ABS-Iron Composites prepared by melt compounding on a twin screw extruder for various volume fraction of Iron powder

5.3.2. Morphological properties of ABS-Iron Interface

In order to study the possible effects of initial processing techniques on the morphology and interfacial bonding strength and subsequently structural stability of Iron/ABS composites, Scanning Electron Microscopy (SEM) was conducted. Fractured surfaces, as shown in Figure 5.8, of tensile test specimen were gold-coated for investigation of morphological properties of filler-matrix interface in Iron/ABS composites with varying filler loading. A SUPRA 40VP-25-38 scanning electron microscope was used at an acceleration voltage of 15kV.

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Microstructural images of various composites as well as ABS obtained by SEM microscopy are shown in Figures 5.9 to 5.15.

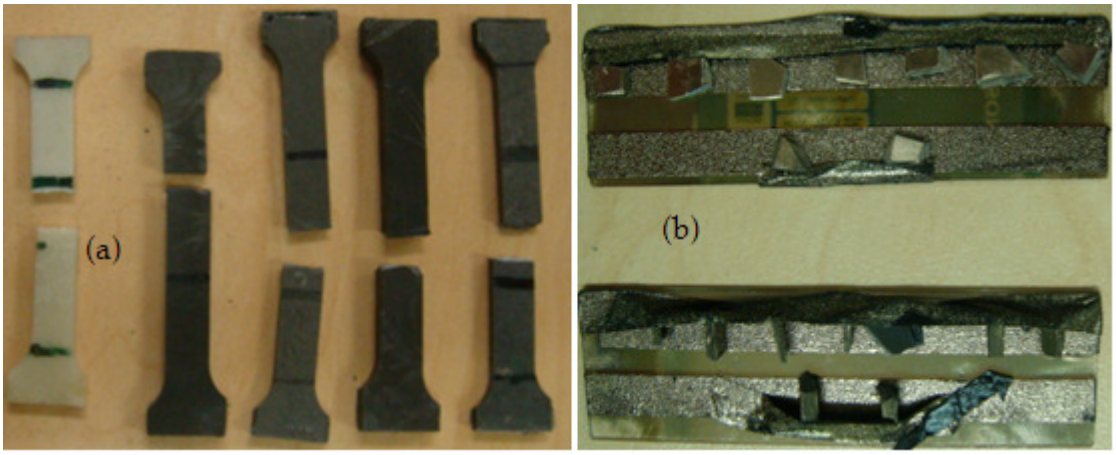

Figure 5-8: (a) Fractured tensile specimen (b) Samples prepared for SEM

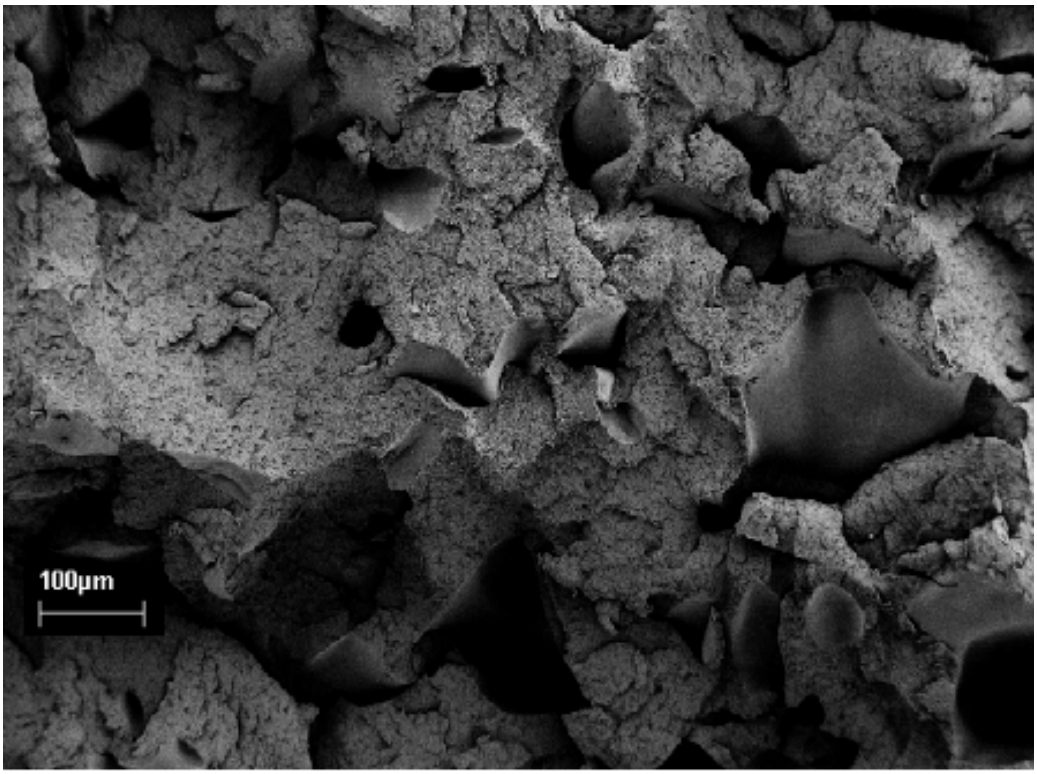

Figure 5-9: Fracture surface of re-processed FDM ABS P400

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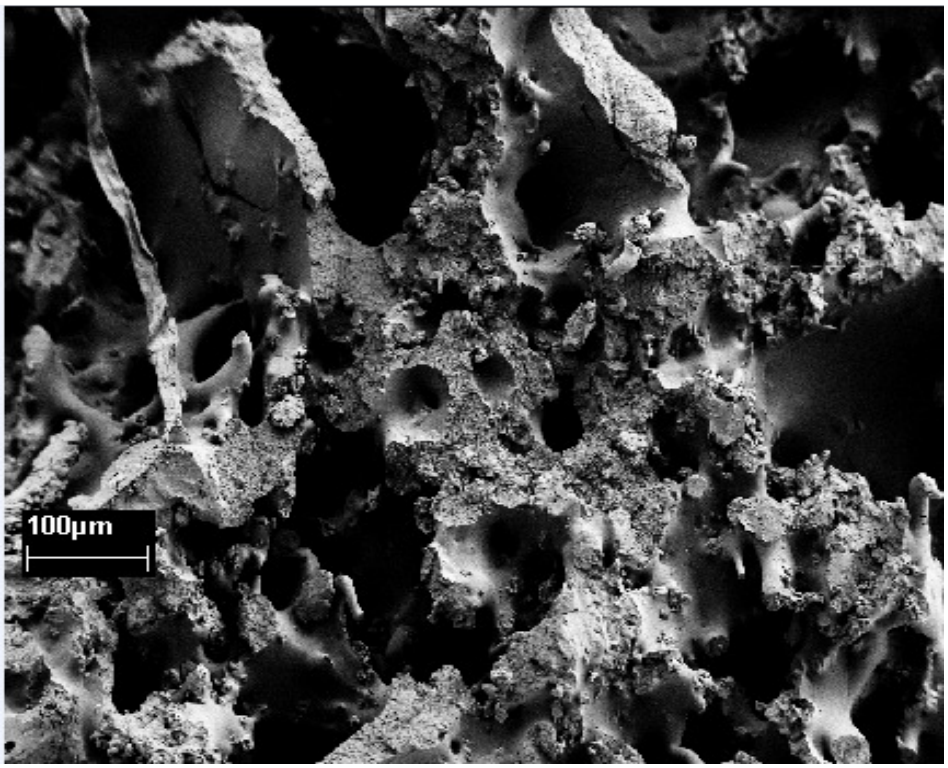

Figure 5-10: SEM image of fracture surface ABS-Fe(10 vol%)prepared via centrifugal mixing

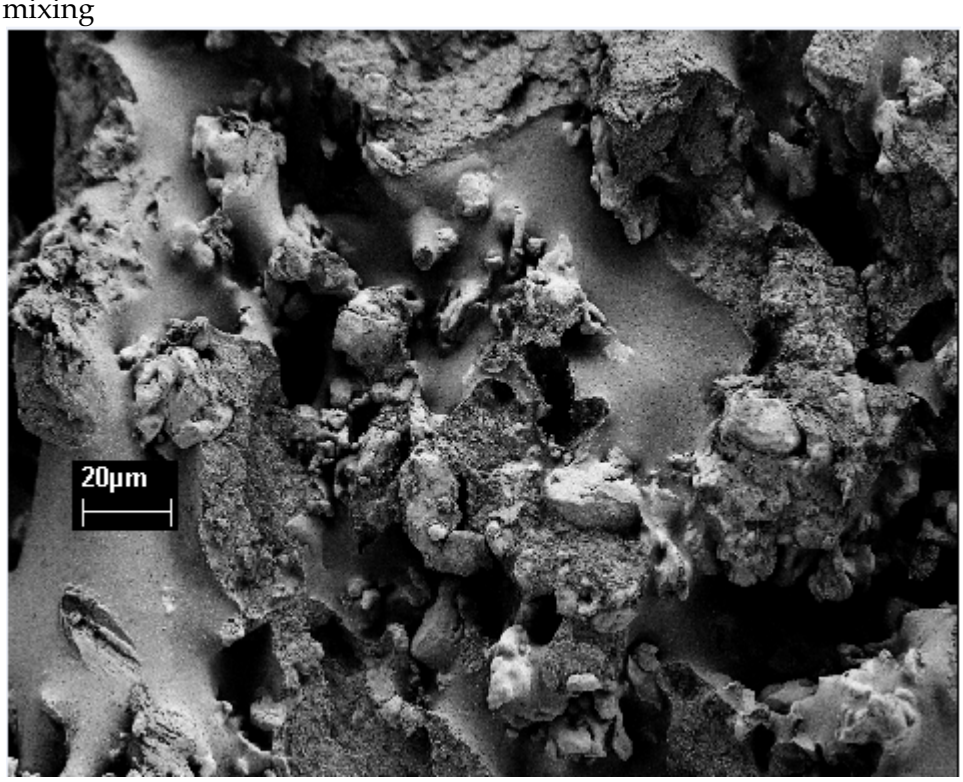

Figure 5-11: SEM image of fracture surface ABS-Fe(20 vol%) prepared via centrifugal mixing

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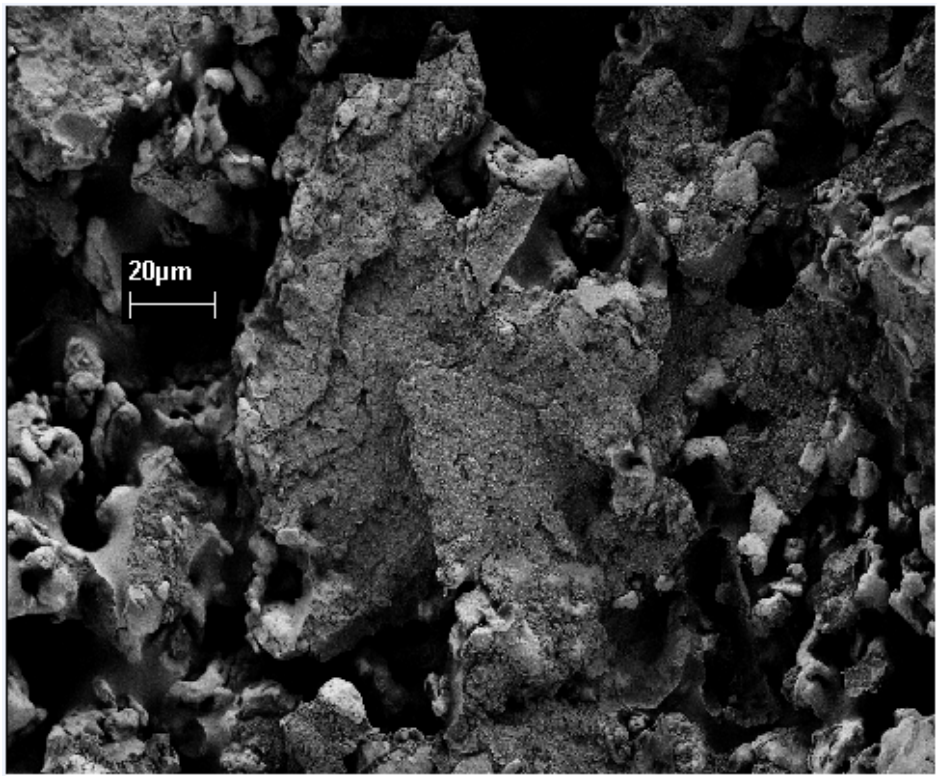

Figure 5-12: SEM image of fracture surface ABS-Fe(30 vol%) prepared via centrifugal mixing

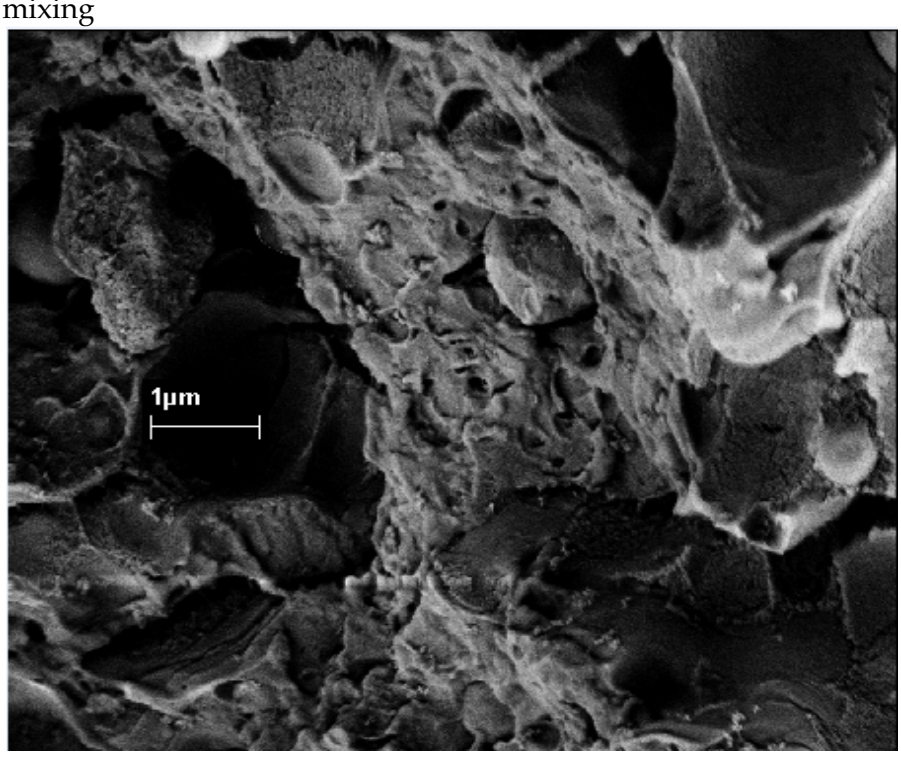

Figure 5-13: SEM image of fracture surface ABS-Fe(10 vol%) prepared by melt compounding

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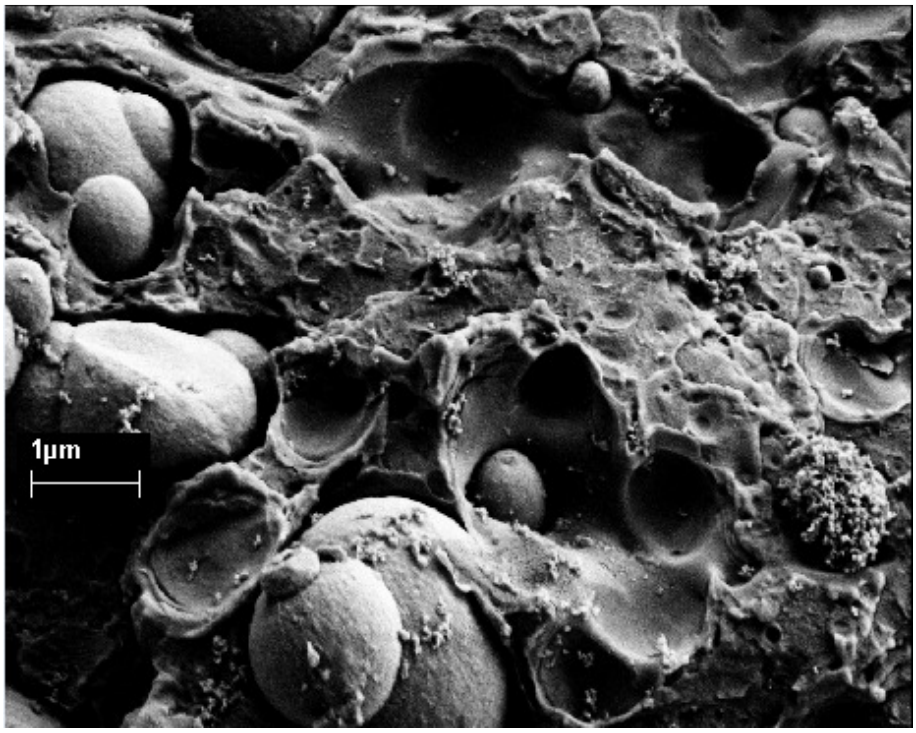

Figure 5-14: SEM image of fracture surface ABS-Fe(20 vol%) prepared by melt compounding

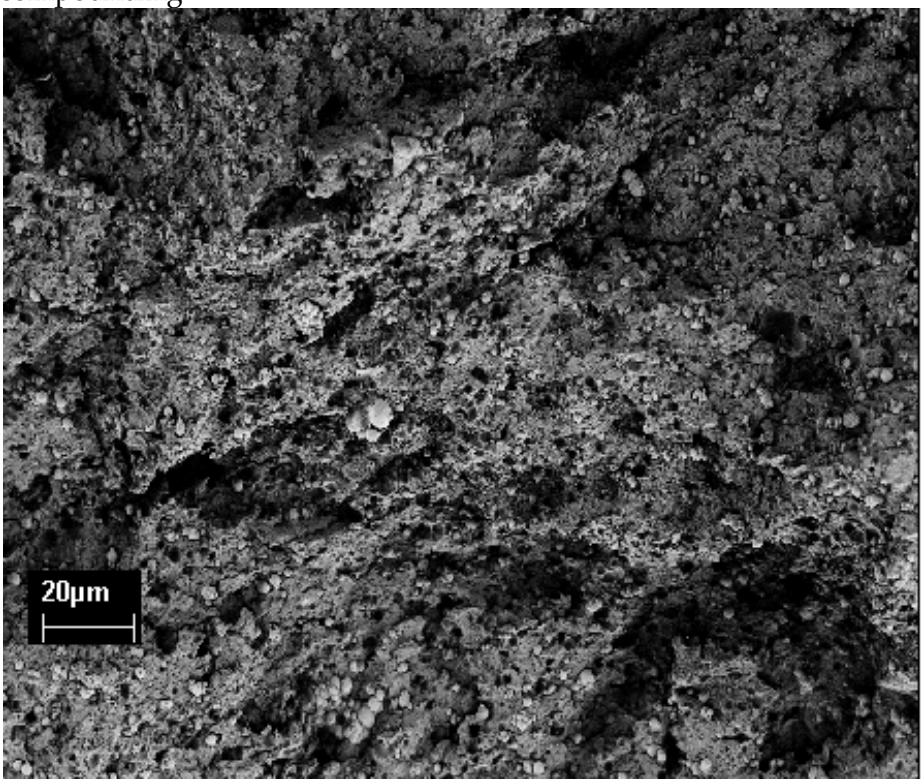

Figure 5-15: SEM image of fracture surface ABS-Fe(30 vol%) prepared by melt compounding

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As revealed by Figures 5.10 & 5.12, fracture surfaces are much poorer than the native surfaces of ABS in Figure 5.9. Seemingly, centrifugal mixing does not provide a strong bonding as concentration of iron powder is increased. The trend gets worse from low filled composites to highly filled ones. However, quite different trend is seen in Figures5.13 to 5.15 whereby post-fracture surfaces of Iron/ABS composites prepared by melt compounding are shown. Two distinctions can be made at this point. First, much smoother fracture surfaces are seen compared to the Figures 5.10 to 5.12, which is believed to be due to improved contribution of filler in bearing the load applied on the cross section of composites during tensile test. The trend gets better as filler concentration increases. Secondly, distributions of filler are much wider and more homogenous throughout the matrix, which results in reduced agglomeration of particles; usually considered to be one of the primary weakening mechanisms in particulate filled composites. It should be noted that both improved distribution of particles and better bonding are also attributed to addition of a small of fraction of surfactant in case of composites C'1 to C'3. It is believed that coating of particles by surfactant plays an important role in reducing the free surface energy of metallic particles, and facilitates better mixing of these fillers with grounded particles of ABS matrix during the initial mixing process. Lastly, another possible factor which is speculated to promote a better interfacial boding in composite C'3 (with highest yield point in Figure 5.7) is formation of an oxide layer during melt compounding as can be seen in Figure 5.15. As reported by Venables(Venables 1984), morphologically, metal oxide layers are attributed with porosity and microscopic roughness, which promote mechanical interlocking of filler particles in the matrix, and therefore forming a much stronger interfacial bonds.

Table 5.2 shows the comparison of actual values of maximum elongation (dL) at maximum load and at break point along with the values of maximum load(F_{max}) and load at break (F_{break}) for the unfilled ABS and the iron filled ABS.

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Additionally, amount of work or energy required to overcome the yield stress, and complete fracture are measured. In the Table 5.2, F_{max}, F_{Break} dL , W denote maximum load material undergoes before yielding, load at break, amount of deformation, and work done before yielding or break, respectively. Also a_0, b_0, S_0 refer to the thickness, width and cross sectional area of the tensile test sample as shown in Figure 5.16.

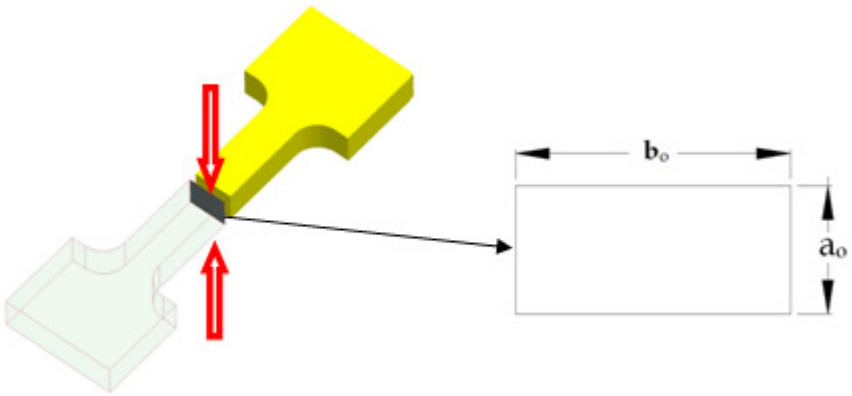

Figure 5-16: Specifications of Tensile Test Sample

Although there is only slight difference on elongation at maximum load, it becomes significant at break point. Tensile strength drops significantly as a result of addition of varying weight percent (wt%) of iron powder for untreated samples of C1, C2, C3 & C4. Decrease of value of work (or equally amount of energy spent before composite fracture) in the 'W to F_{Break}' column is indicative of ductile-to-brittle behaviour from virgin ABS to filled ABS which is developed by further addition of metal filler.

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Table 5-2: Tensile test results comparing load and deflection response of various ABS-Iron composites at yield and break points

No.	F_{max}	dL at F_{max}	F_{Break}	dL at break	W to F_{max}	W to F_{Break}	a_0	b_0	S_0
	N	mm	N	mm	Nmm	Nmm	mm	mm	mm^2
ABS	588	2.6	581	2.7	740.22	798.94	3	8	24
C1	575	2.6	574	2.6	693.67	731.86	3	8	24
C2	393	1.6	393	1.6	272.00	272.00	3	8	24
C3	313	1.5	313	1.5	199.40	199.40	3	8	24
C4	263	1.5	263	1.5	167.29	167.29	3	8	24
C'1	480	2.1	480	2.1	449.80	449.80	3	8	24
C'2	567	2.3	567	2.3	580.73	580.73	3	8	24
C'3	634	1.9	634	1.9	562.78	562.78	3	8	24

In unfilled ABS, predominant failure mechanism is '*crazing*' where regions of much localized plastic deformation, and small interconnected discontinuities, as shown in Figure 5.9, leads to disintegration of thermoplastic polymer structure. In presence of untreated filler particles, micro voids are easily developed at filler-matrix interface, and under sufficient tensile load they are bridged together and cracks are initiated as shown in Figures 5.10 to 5.12. Surface treatment of filler particles promotes better bonding at filler-matrix interface, as shown Figures 5.13 to 5.15, and therefore prohibits initiation of voids leading to improvement of the fracture strength. Another implication of surface treatment of fillers, as noted before, is homogenous spread of fillers in the matrix, even at highly loaded systems such as the one in Figure 5.15, and preventing agglomeration of particles. It is assumed that agglomerated particles proportionally result in formation of crazes through inter particle voids promoting weaker bonds and reduction of fracture energy of composite structure.

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5.3.3. Dynamic Mechanical Analysis

Dynamic mechanical analysis was conducted on a Multi-Frequency-Dual Cantilever DMA Instrument, which is an ideal experiment for rapidly screening and comparing the viscoelastic properties of the polymer based materials such as Storage Modulus and Loss Modulus as well as glass transition temperature. In this method, the material is heated at a constant rate and deformed (oscillated) at a constant amplitude (strain) and frequency. The test mode applied was single frequency one with amplitude of 15 μm with a temperature ramp of 5 ^{o}C/min upto 150 ^{o}C. Data sampling interval was 2 sec/pt. To investigate the effect of filler size and type of filer, various composites of Iron/ABS, and Copper/ABS were formulated and tested. Composites containing iron powders are designated with letter C, those containing coarse(45μm) and fine(10μm) copper particles are designated with letter B, and A respectively (see also Table 5.1).

Dynamic storage modulus of polymer composites represents the elastic contribution of polymeric matrix to an external excitation, and defines the ability of composite to store energy when deformed. Dynamic loss modulus, for a viscoelastic material, indicates its ability to dissipate energy in the form of heat and is representative of viscous behaviour. These viscoelastic properties can be related using the following equation (Fried 2003):

$$E^* = E' + E'' \tag{5.1}$$

where E', E'', and E^* are storage modulus, loss modulus, and complex modulus respectively.

Another important characterising parameter for viscoelastic polymer composite is the ratio of loss modulus and storage modulus. This ratio, known also as tan delta, is used to evaluate the damping or energy dissipation in such materials. The peak value in a tan delta graph indicates glass transition temperature; the

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temperature at which a viscoelastic material changes from elastic phase to viscous phase. Below glass transition temperature, polymers behave as hard and rigid glasses, whereas above glass transition, they exhibit a soft and flexible structure.

Figure 5.17 shows the variation of solid state dynamic mechanical response of various copper/ABS composites with copper particle size of 10 μm under wide temperature range. Below glass transition temperature, while in a solid state, there is a dramatic increase in storage modulus of composites as the volume fraction of filler increases. A maximum value of approximately 3.5-4 GPa at room temperature is achieved for storage modulus of Copper/ABS composite with fine copper particles containing 30 vol% of copper (sample A4). This demonstrates a strong interlocking of copper particle into ABS matrix which increases the stiffness of the composite. However, the trend reverses for filler content of more than 30 vol%. At very high loading of copper (40 vol%), due to significant agglomeration of filler particles (sample A5), and accumulation of inter-particular voids results in the weakening of the matrix rather reinforcing it.

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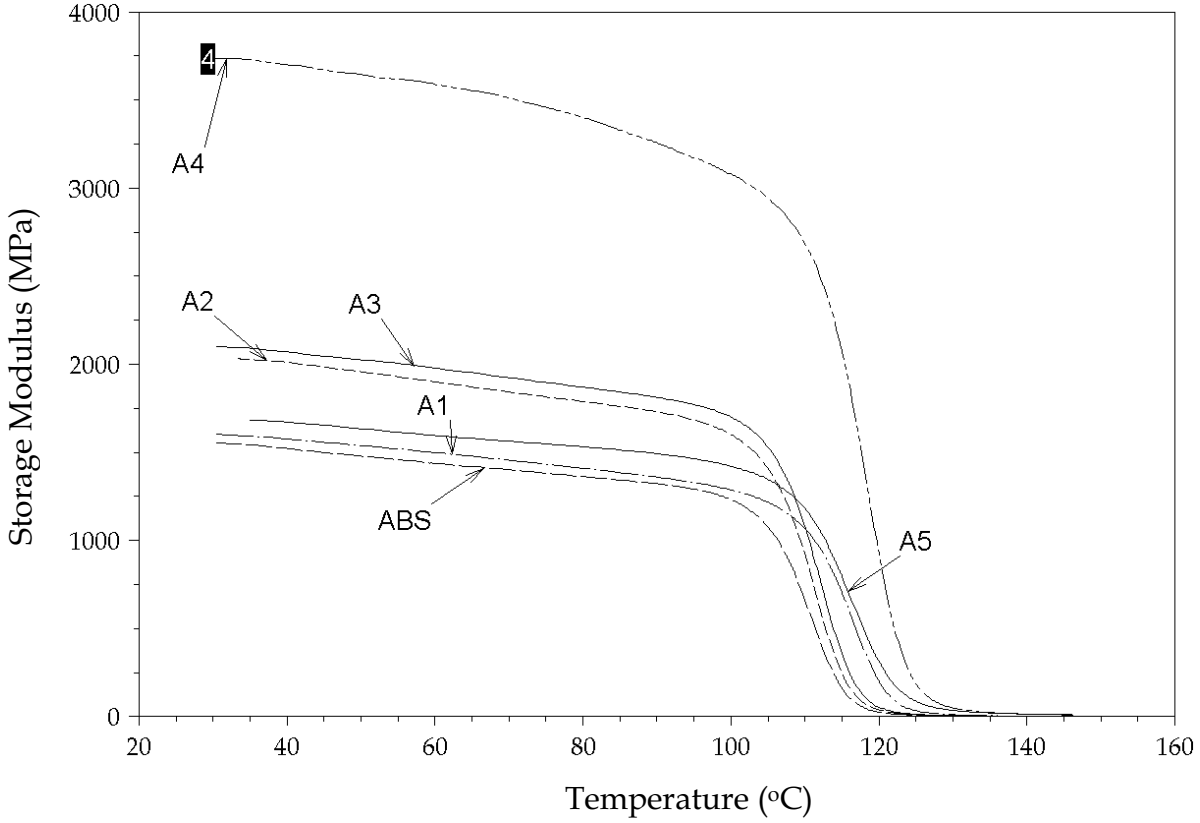

Figure 5-17: Storage Modulus of Various Copper/ABS Composites with copper particle size of 10 μm at Temperature Scan

In Figure 5.18, effect of temperature on viscous behaviour of ABS reinforced with fine copper particles is shown. As can be seen, for various composition of Copper/ABS, the loss modulus is increased by increasing temperature up to the glass transition temperature. A peak max is recorded at glass transition temperature, and the effect fades away while the composite approaches the melting temperature. Higher loss moduli indicate higher heat dissipation at the vicinity of glass transition temperature. No specific trend can be extracted as for relation of increasing filler content on the loss moduli of the composites. However, evidently, initial increase of filler concentration increases energy dissipation, which is maximized at 30vol %(sample A4) concentration of copper powder. This may partially be due to added inter particle friction or filler matrix interaction.

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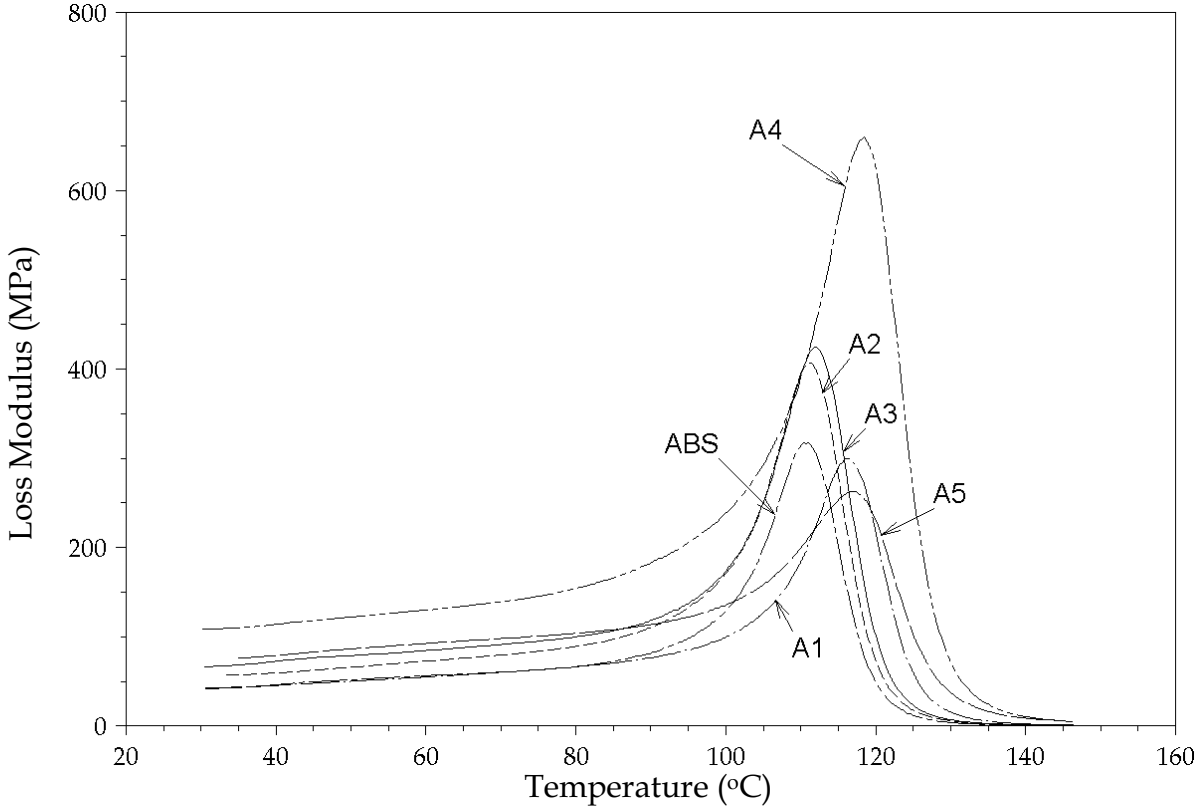

Figure 5-18: Loss Modulus of Various Copper/ABS Composites with copper particle size of 10 μm at Temperature Scan

The trend at which tan delta varies with temperature scan, as shown in Figure 5.19, is identical to that of loss modulus in the sense that with initial increase of temperature it increases up to glass transition temperature indicating a rise of damping coefficient in the structure of the composites. Once past the glass transition temperature, tan delta (damping coefficient) reduces sharply and flats out as the temperature sweep approaches melting point of the material. The trend is completely repeatable for all concentration of fillers (Samples A1-A5). But one remarkable phenomenon is the drop of peak max of the tan delta graphs as the concentration of filler increases while a rightward shift in the curves are observed. This shift indicates that glass transition temperature for filled systems is higher than of virgin polymer. Also at high filler loading (samples A & A5), in the vicinity of glass transition temperature, softened composite still exhibits a bit of glassy solid behaviour, which results in decrease

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of damping coefficient. This phenomenon may be explained by mechanisms of particle-particle friction where particles touch one another in weak agglomerates, particle-polymer friction with no interfacial adhesion, and excess friction in the polymer near the interface due to induced thermal stress or changes in polymer conformation or morphology(Bilyey, Brostow & Menard 2001; Lawton & Murayama 1976).

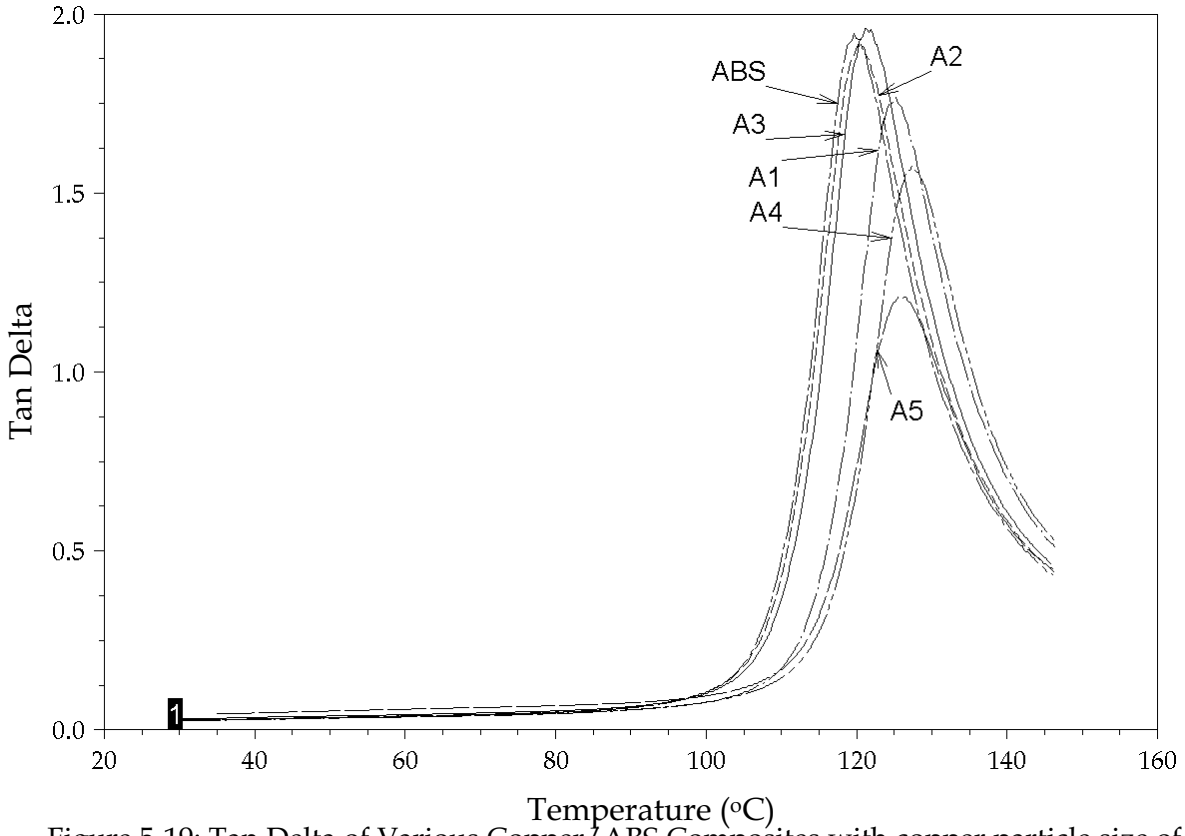

Figure 5-19: Tan Delta of Various Copper/ABS Composites with copper particle size of 10 μm at Temperature Scan

Figure 5.20, shows the dynamic mechanical responsse of copper/ABS composites containing large copper particles (45 μm) under temperature variation. It is observed that the storage modulus of the composite increases with the increase of copper content up to 10 vol%, but significantly drops by further increase of filler. The trend presents less reinforcefortment in composites containing large particles which could be due to weaker

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interlocking, and poor distribution of the fillers in the matrix. It is worth noting that during preparation of these composites, there have been no coupling agent involved. It is usually recommended that a coupling agent be used to provide better bonding between the metallic fillers and the polymeric matrix. The maximum storage modulus of approxmimately 2 GPa could be achived in case of using large copper particles. It should be noted that composites containing higher volume content (30% and 40%) of large copper particles could not be tested due to adverse bonding between the particles and the polymer matrix.

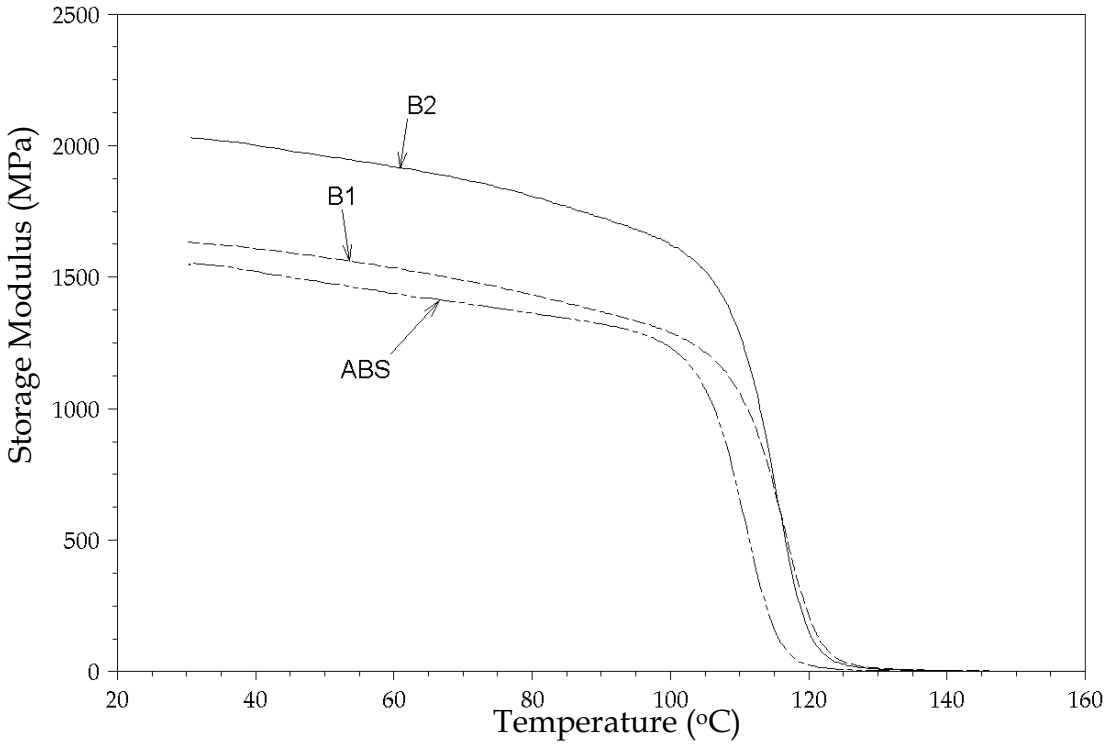

Figure 5-20: Storage Modulus of Various Copper/ABS Composites with copper particle size of 45 μm at Temperature Scan

Variation of loss modulus of Copper/ABS composites contaning coarse particle size of 45 μm is shown in Figure 5.21. Samples tested contained only 5 vol% and 10vol% copper particles spread homogenouelsy in ABS matrix. In a similar trend to the behavior of composites reienforced with fine copper particles, maximum loss modulus occurs in the vicinity of glass transition tempearture

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where structurally material is highly viscous and heat dissipation reaches a peak max. Interestingly, phenomenon of "glass transition shift" to the right of the graph is also observed.

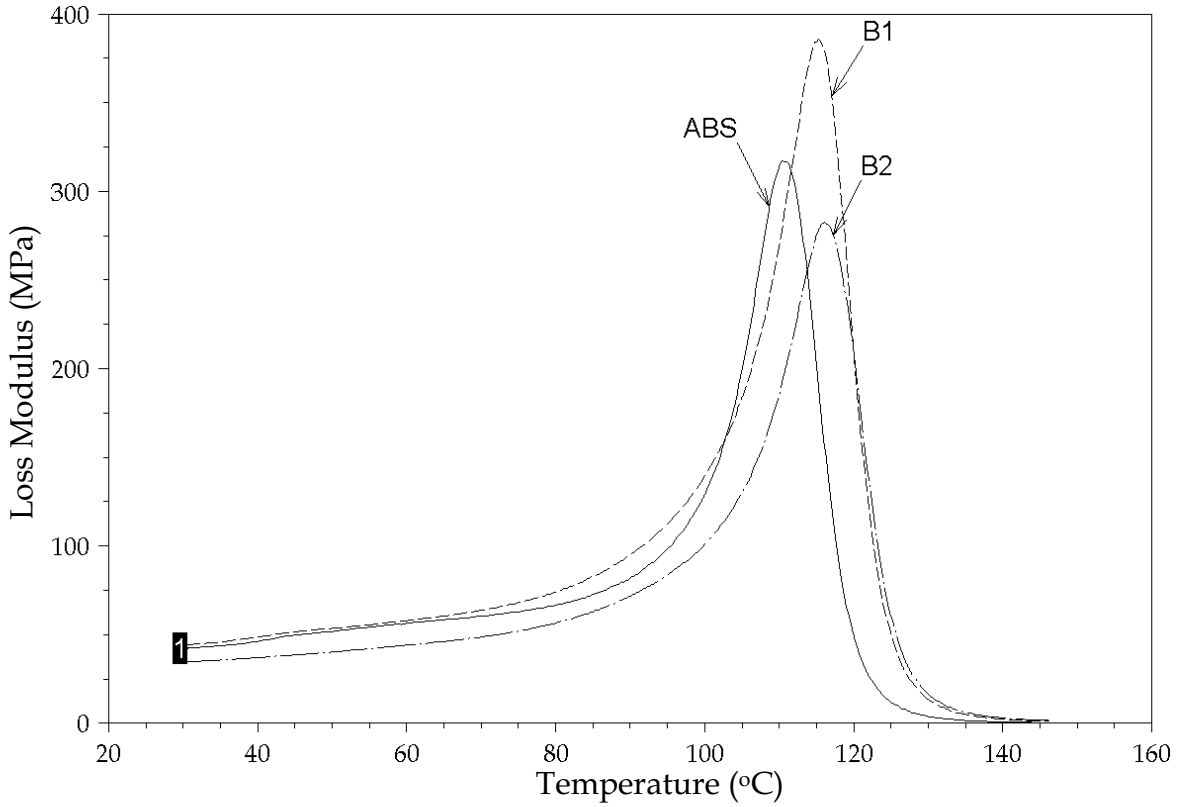

Figure 5-21: Loss Modulus of Various Copper/ABS Composites with copper particle size of 45μm at Temperature Scan

Figure 5.22. shows the variation of storage modulus of Iron/ABS composites for varying temperature. Similar to the graphs in Figure 5.17, for Copper/ABS composites, reinforcement effect of addition of iron filler particle is evident up to 30 vol% by which storage modulus (stiffness) of Iron/ABS composite reaches a range of 2.5-3 GPa at room temperature, and subsequently drops back to the storage modulus of the ABS matrix. Compared to the Copper/ABS composites of the same particle size, the stiffness values are much higher for Iron/ABS composites with 10 to 20% volume fraction of iron.

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Stiffness of all three types of composites dramaticlly drops as the temperature approaches the glass transition temperature, where matrix polymer transforms from solid state into semi-liquid or rubbery state, and therefore due to larger free volume available, it suppresses any potential for interlocking of polymer and filler particles.

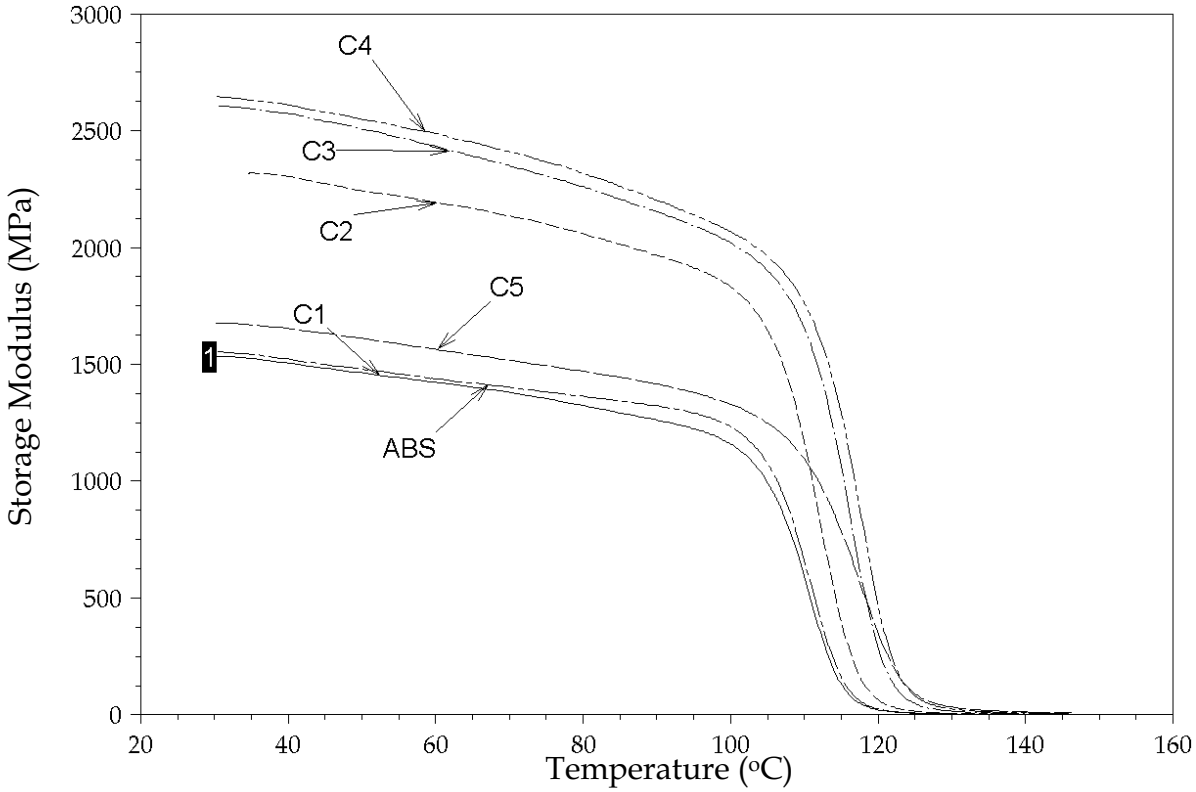

Figure 5-22: Storage Modulus of various Iron/ABS Composites with iron particle size of 45 μm at Temperature Scan

Figures 5.23 and 5.24 show the effect of iron particle concentration on loss modulus and tan delta of ABS-Iron composites, respectively. While loss modulus is increased by the increase of filler concentration due to pronounced heat dissipation driven by presence of metallic particle, tan delta peak is monotonically reduced. The rise of loss modulus is observed for filler concentration up to 30 vol% (sample C4 in Figure 5.23) after which a counter-effect is seen at filler concentration of 40 vol%. This may be explained by the speculation that at very high concentrations, dynamic mechanical behaviour of

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ABS-Iron is dominated by inter-particle interaction and weak agglomerates where less friction is involved and heat dissipation is less significant than the cases where the interfacial filler-matrix friction is dominating energy loss mechanism.

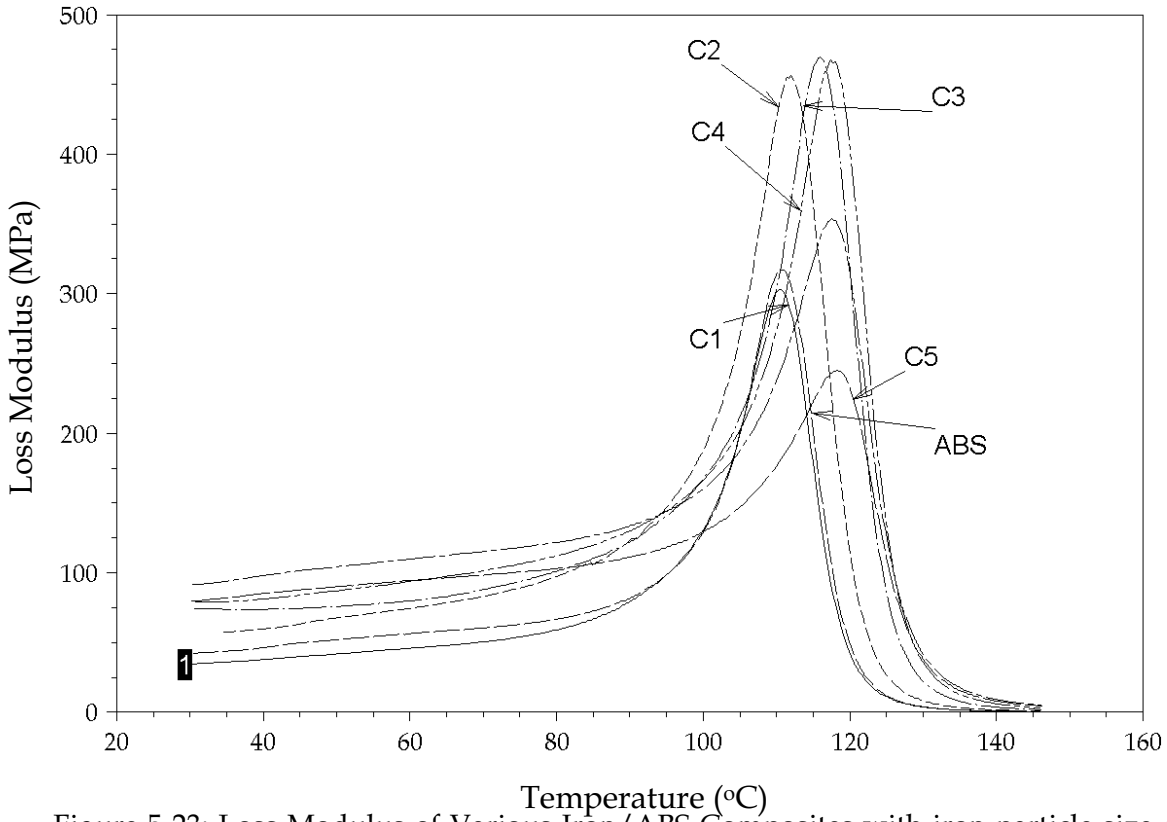

Figure 5-23: Loss Modulus of Various Iron/ABS Composites with iron particle size of 45 μm at Temperature Scan

Monotonic reduction in tan delta peak, as shown in Figure 5.24, indicates lower damping coefficient for ABS-Iron composites as the concentration of filler increases. This is expected due to very low damping coefficient of metallic filler. However, this effect is only significant in the vicinity of glass transition temperature, and insignificant in room temperature. Therefore, in application of such composites maximum temperature usage limit is of extreme importance to provide appropriate functionally for parts and tools made out of such materials.

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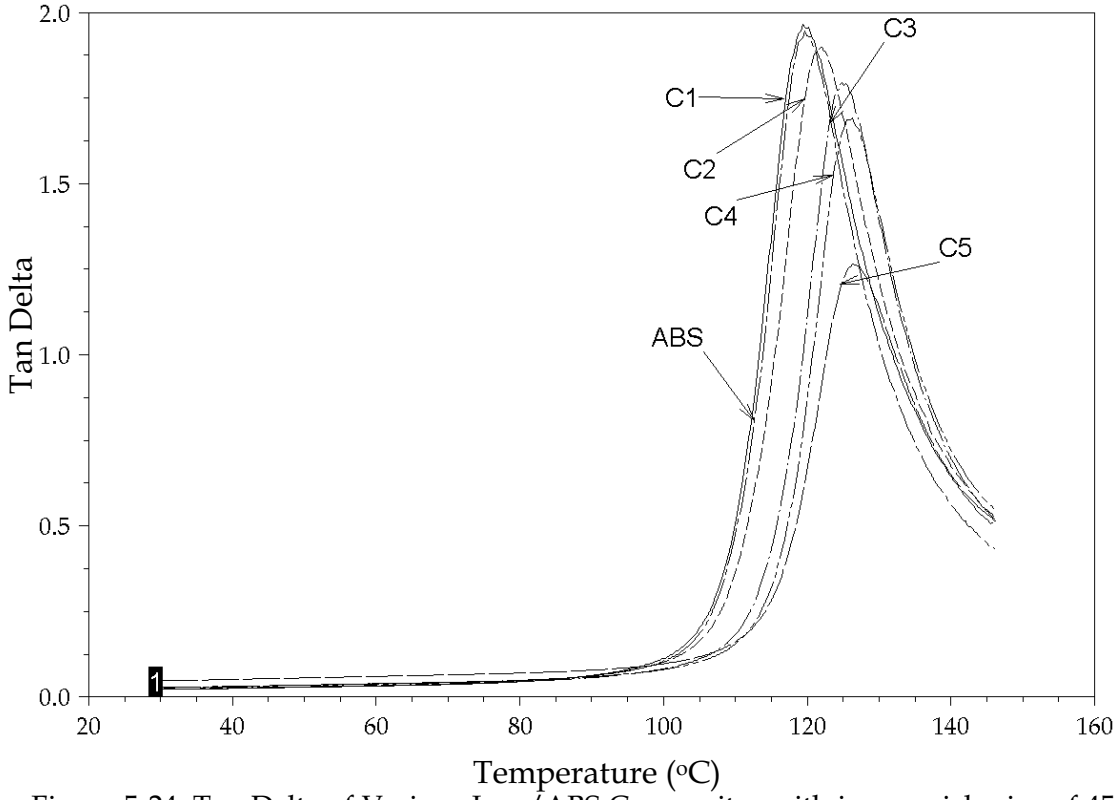

Figure 5-24: Tan Delta of Various Iron/ABS Composites with iron paricle size of 45 µm at Temperature Scan

In order to see the effect of particle loading on glass transition temperature, Figure 5.25 shows the comparison of dynamic mechanical properties of 30 vol% iron-powder filled ABS composite (shown by solid line) and virgin ABS (shown by dotted line). As it can be seen from the graphs, the glass transition temperature represented on Tan Delta curve has shifted by 7 degrees Celsius for the composite material. By further increase of glass transition temperature, softening point of the new composite material will be higher, which gives the promise of using the new material as die or insert material for injection moulding of polymers and plastics with lower softening point.

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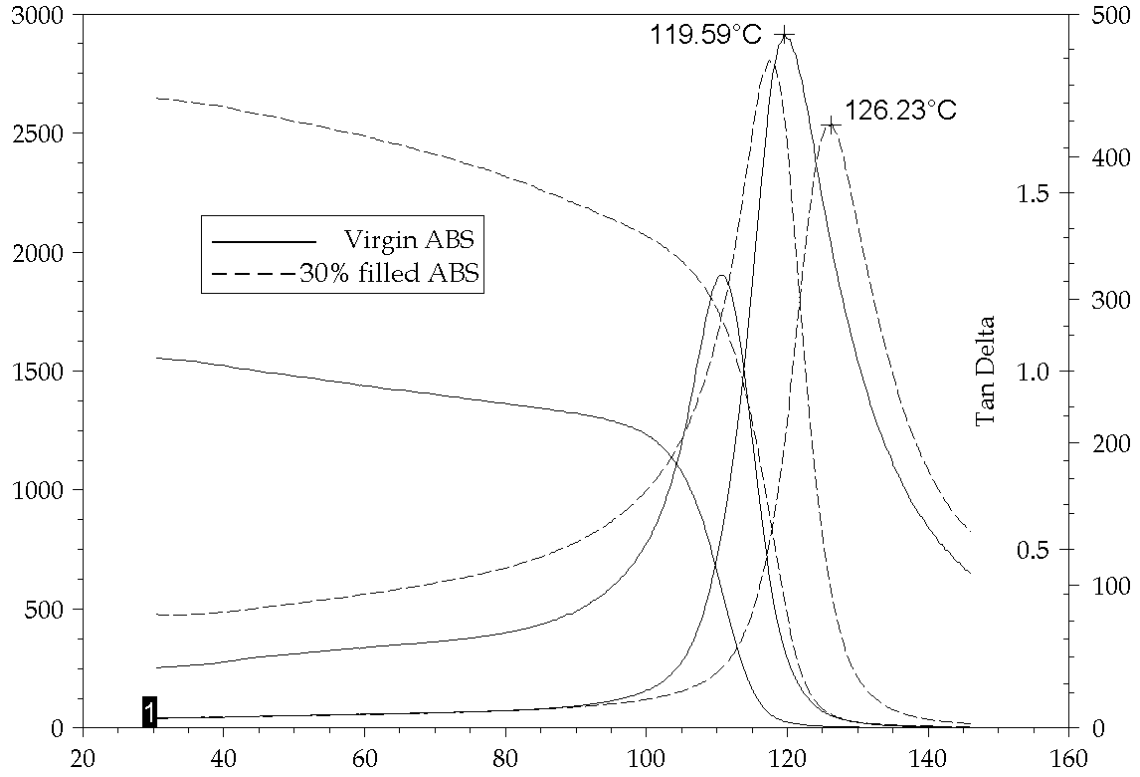

Figure 5-25: Comparison of dynamic mechanical properties of virgin ABS and 30 % iron-powder filled ABS

5.3.4. Thermal Properties of ABS-Iron composites

5.3.4.1. Thermal Conductivity

Thermal conductivity tests for the composites were conducted in Autodesk Moldflow Plastic Labs, Melbourne using ASTM D5930 test method. Thermal conductivity was measured using a transient line-source heating method as shown in the schematic diagram of Figure 5.26, where a probe was inserted into the centre of a molten composite sample, held at its processing temperature.

A line-source heater ran through the length of the probe and a temperature sensor was placed in the middle of the probe. A known amount of heat (**Q**) was supplied to the line-source heater. Once the thermal equilibrium was

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achieved, the temperature rise in the sensor was recorded over a period of time. The thermal conductivity (**k)** was calculated from the following equation:

$$k = \frac{QC1n(t_2/t_1)}{4\pi(T_2 - T_1)} \tag{5.2}$$

where T_1 and T_2 are temperatures of the samples at times t_1 and t_2 respectively, and **C** is the probe constant. Cooling scans were produced automatically by programming a range of temperatures. For each type of composite sample, thermal conductivity was calculated at different temperatures.

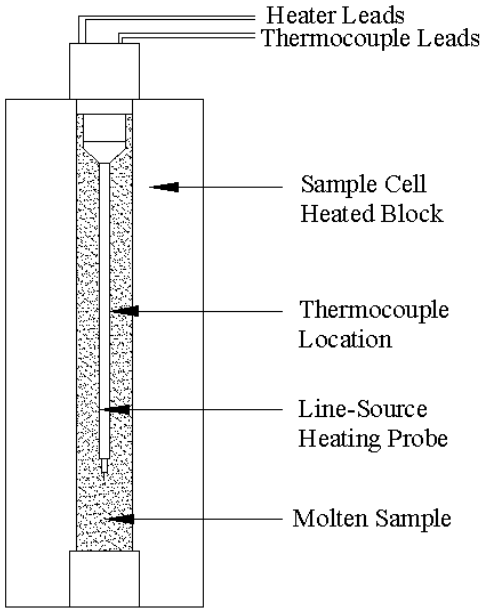

Figure 5-26: Schematic of Thermal Conductivity Apparatus

Figure 5.26 shows the variation of thermal conductivity of copper-filled ABS composites of various metal content of larger particle sizes at different temperatures. It is seen that for lower concentraion of fillers, increase of temperature has a negligible effect whereas in high concentration of copper particles (30 vol%- sample B4) above glass tranision temperature of the matrix, there is a significant increase in the thermal conductivity of copper-ABS composite. This is believed to be the result of increase in the mobility of

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particles in a semi-molten matrix at temperatures beyond its glass transition temperature.

Moreover, it is observed that addition of even up to 10 vol% of copper particles(samples B1 & B2) cannot break the thermal resistane of the ABS matrix, and it is only at about 20vol% concentration of particles that conductive chains begin to form and therefore heat conductivity is improved by an order of magnitude. This effect is significant for copper contents of 30 vol% where particle chains are compleletly formed and their mobilization is facilitated due to phase change in the ABS matrix from solid state to liquid state above its glass transition temperature.

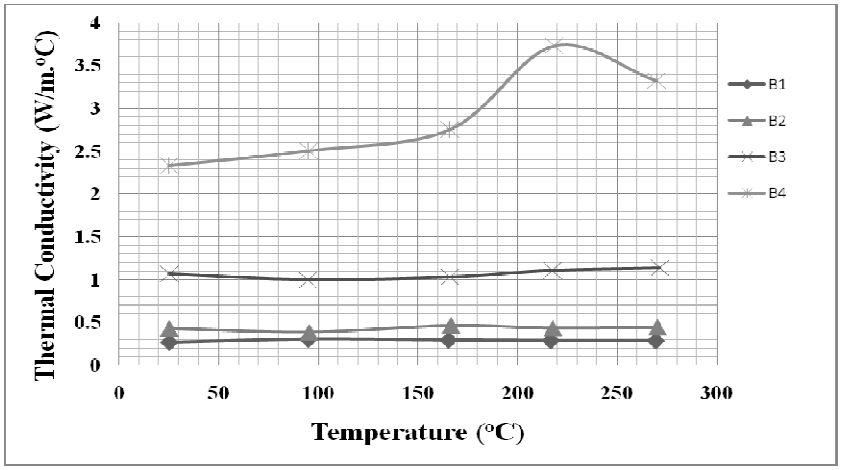

Figure 5-27: Thermal Conductivity of copper filled ABS composites at various temperatures

Figure 5.28 shows the thermal conductivity of iron-filled ABS composites of varying metal contents of larger particle sizes at different temperatures. As can be seen in comparison to Figure 5.27, the influence of iron particles on the thermal conductivity of ABS is lower than that of copper particles. This follows the rule of mixture as thermal conductivity of iron is less than that of copper. Thermal resistance of the ABS matrix is only overcome considerably when iron particle concentration reaches 30 vol% (sample C4). At concentrations above 30

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vol%, the chain formation of metal particles begin to appear in the matrix, and therefore the thermal conductivity of the iron-ABS composite is improved noticebly.

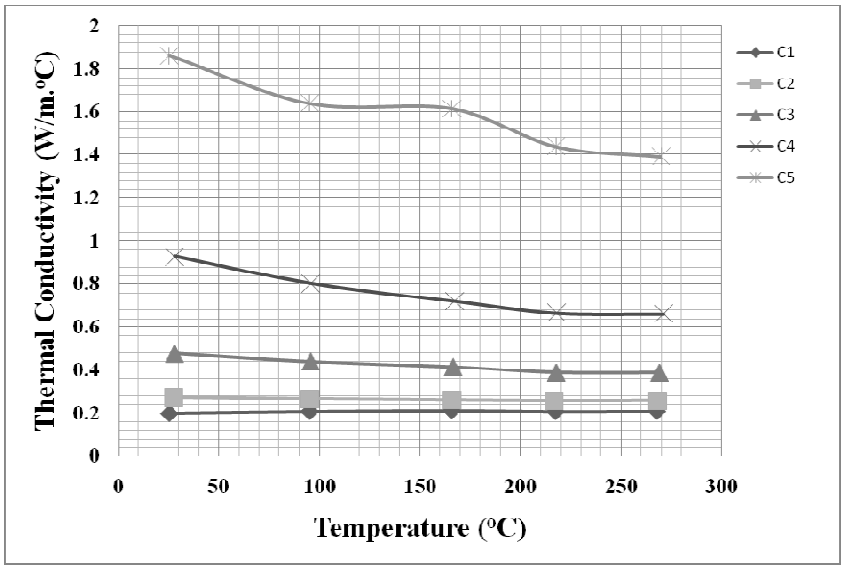

Figure 5-28: Thermal Conductivity of iron filled ABS composite for various temperatures

It should be noted that the thermal conductivity is achieved through the molecular vibrations and free electron movement. Moreover, since the thermal conductivity of iron is only about 380 times that of ABS polymer, heat flows not only through conductive iron chains but also substantially through the polymer matrix itself. With further increase of the volume fraction of iron, the space between filler particles becomes very small. It has a high probability of making 'effective' contact with neighbouring particles to form the contacting chains. The free electrons are hopping across the gap between points of close contact. The rate of hopping increases as the distance to be spanned decreases. As more particles are loaded, the more easily the particles get gathered to form conductive chains called a touching system. The thermal conductivity of particles thus contributes to change the thermal conductivity of the composite. If volume fraction of filler particles approaches the maximum packing fraction,

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it may lead to the particle becoming very difficult to achieve a well-dispersed homogeneous mixture. The existence of agglomerates at high volume loading may introduce voids into the composite, which reduces the thermal conductivity of the material [16].

5.3.4.2. Heat Capacity

Heat capacity and heat flow were measured using standard Differential Scanning Calorimetry modulated at +/- 5 ^{o}C at every 40 seconds with temperature ramp of 3 ^{o}C/min up to 150 ^{o}C. Figure 5.29 demonstrate the graphs of heat capacity (Rev C_p) variation with temperature for virgin ABS and composite materials with 10% iron and 20% iron powder. It shows that 10% Fe decreases heat capacity of the unfilled ABS. Further addition of iron powder confirms the same trend of reduction in heat capacity which on the other hand means the thermal conductivity increases by approximately the same percentage. Increase of thermal conductivity is another advantage of the new material by which much more thermally stable prototypes can be produced on FDM machine making them dimensionally more accurate and reliable for reducing the cooling cycle time when employed as material for injection moulding tools.

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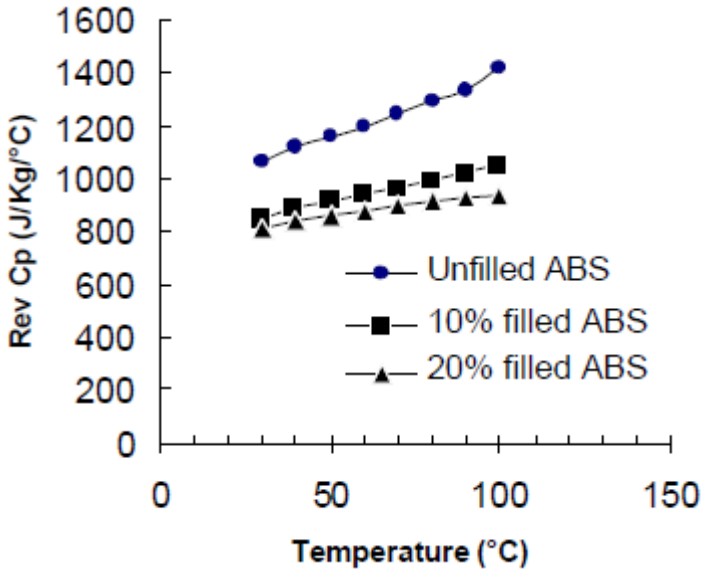

Figure 5-29: Rev Cp of the iron filled ABS composites

5.3.5. Electrical Conductivity of Iron/ABS composites

In order to measure the electrical conductivity of Iron/ABS composites, two methods of DC, and AC electrical conductivity were used to test both bulk "*electronic*" and "*ionic*" conductivities, respectively. In DC method a voltage scan up to 500 V was used to measure the resistance of varying volume fraction filled ABS-Iron composites. An interface program produced with Lab View® in Monash University was used to record the variation of current passing through the bulk of disk-shape samples.

For ionic conductivity measurement at low filled Iron/ABS composites, the AC Electrochemical Impedance Spectroscopy (EIS) was used, which is capable of measuring the electrical conductivity far more accurately than the other traditional methods. In other word, this technique is measuring the true electrical conductivity of the material.

Test samples were punched out from compression-moulded Iron/ABS composite films with approximately 13 mm in diameter, and 0.8 mm thickness (Figure 5.30). To avoid sample displacement during the measurement, they

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were fitted inside a Teflon washer, and then placed between the cell chamber and spring-loaded electrode head. Additionally, test samples were sandwiched between two aluminium disks to ensure a uniform distribution of voltage onto the sample surfaces, where electrodes were attached.

EIS measurement of samples in solid state was performed by placing the disk or pellet sample between two parallel electrodes. In CSIRO Energy Technology laboratories, a special cell setup is used, as shown in Figure 5.31, where the sample can be loaded into the cell inside the dry box and can be isolated from ambient atmosphere to avoid moisture absorption.

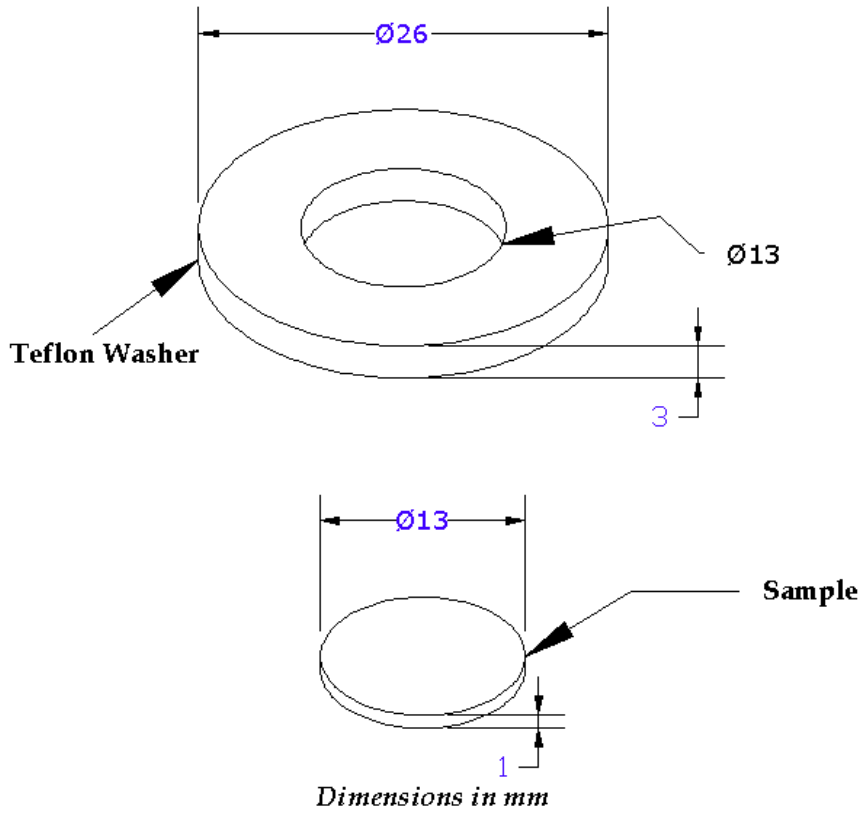

Figure 5-30: Specifications of test sample for Impedance Spectroscopy

To measure the true ionic conductivity of the sample, it is necessary to exclude the electronic conductivity arising from the motion of electrons during the measurement. Electronic conductivity is determined by placing sample between

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ion-blocking metallic electrode such as gold, steel or aluminium, and measuring the DC resistance.

The output of EIS measurement, as impedance behaviour of material, is usually demonstrated by a Nyquist plot in a complex coordinate system by setting the imaginary component on the vertical axis, and the real component on horizontal axis (Shekibi et al. 2007). For a conducting material, the Nyquist plot is produced similar to the one shown in Figure 5.32 which is ideally interpreted by a capacitor and resistor in parallel with one another.

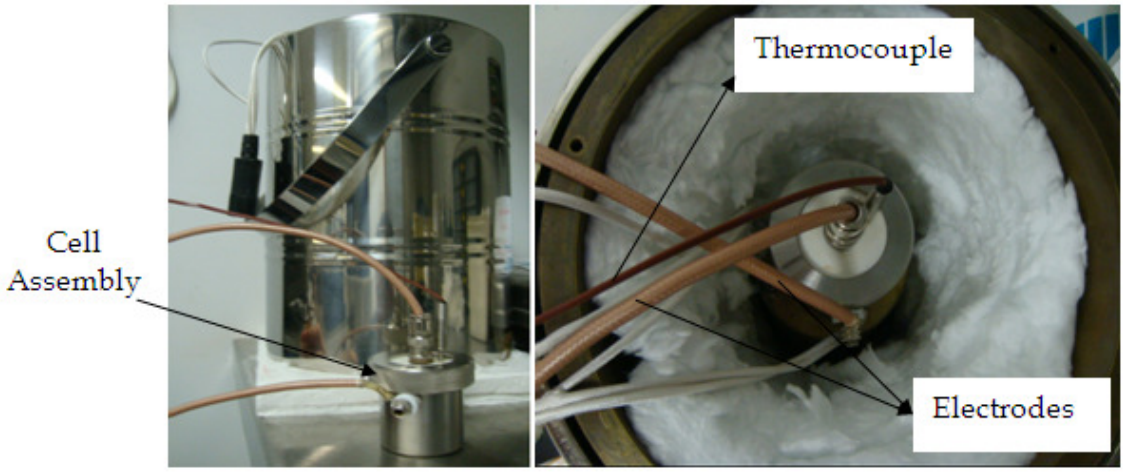

Figure 5-31: The cell setup used for Impedance spectroscopy in CSIRO

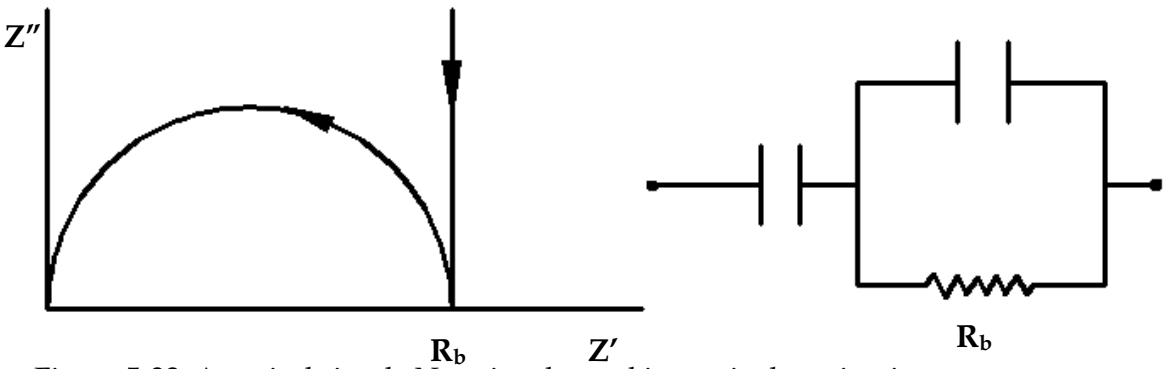

Figure 5-32: A typical simple Nyquist plot and its equivalent circuit

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With a reasonable approximation, the intercept value on the real axis of Nyquist semicircle plot was taken as equal to the DC resistance of the sample. A typical Nyquist semicircle for a low filled Iron/ABS composite at its glass transition temperature is shown in Figure 5.33. The conductivity of samples, for disk-shape geometry in this case, depends on the area (A) of electrodes and the distance between the electrodes (d), and is calculated as follows:

$$\sigma = \frac{C}{R} \tag{5.3}$$

where σ is the conductivity, R as resistance, and C denotes the cell constant which is the ratio of distance between the electrodes and their area(d/A). Electrical conductivity (σ) is expressed in $(\frac{1}{\Omega.cm})$ or $(S.cm^{-1})$.

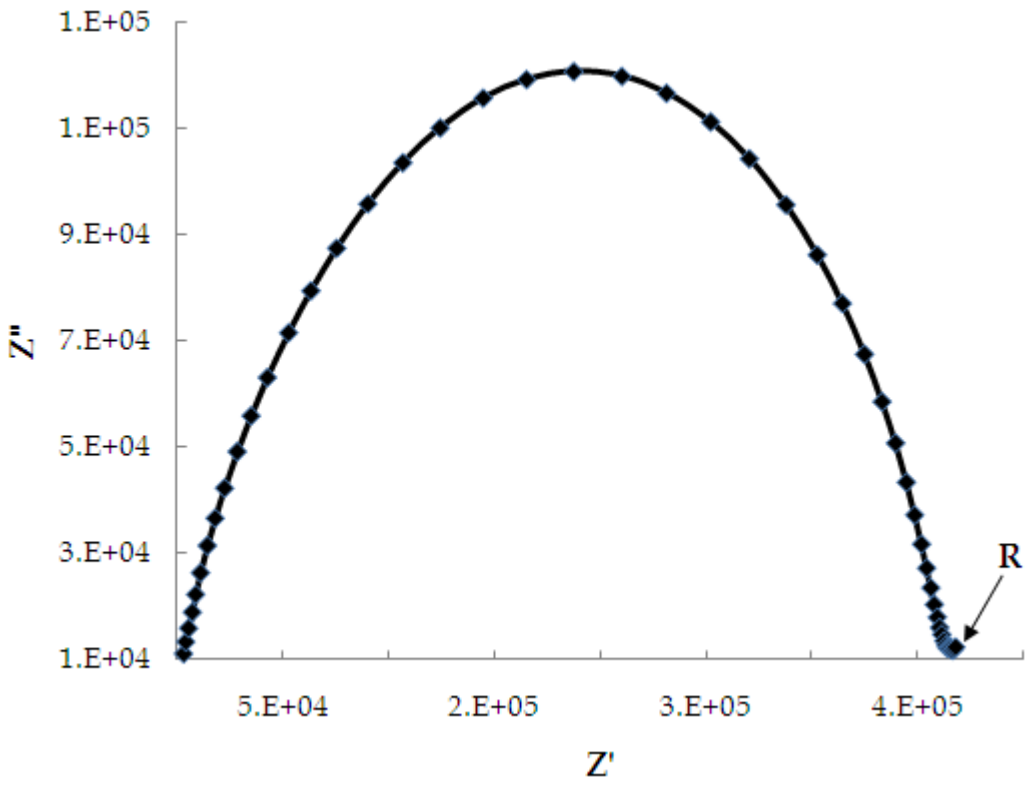

Figure 5-33: Nyquist plot of a Low-filled ABS Composite below Glass Transition Temperature

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The cell constant (*d/A*) was worked out by measuring *d* and *A* in units of centimetre (cm) and square centimetre (cm^2) respectively. The conductivity value was calculated as *[(d/A)/R]* where R was the touch-down value measured by the software for a frequency sweep of 1 to 10 GHz as shown in Figure 5.33. For disk-shaped samples with diameter of 1.365 cm and thickness of 0.06 cm, cell constant is calculated as: [(0.06cm/(π*(1.365)^2)/4)] = (.08/1.3273)= 0.04 cm^{-1}.

In order to observe the effect of temperature on the conductivity of ABS-Iron composites, temperature sweep range of (25, 50, 75, 90, 115, 130, and 150)^0 *C* were used.

Figure 5.34 shows the effect of temperature on the ionic conductivity of a low filled Iron/ABS composite. It is clear that ionic conductivity is increasing by the rise of temperature maxing out around glass transition temperature of the composite (~130 ^0C). The graph then becomes asymptotic as temperature further increases. From room temperature to just above glass transition temperature, the conductivity is increased by 10 times.

At lower concentration of filler, the electrical conductivity of metal-filled polymer is believed to be dominated by hopping of electrons across the insulator gap, where the conductive particles are in "close proximity" with each other (Bigg 1977). Addition of a small fraction of iron powder size of 45 μm showed a doping effect on the ionic conductivity of ABS, considered as an insulator material, and significantly decreased its resistivity. However, by further increase of filler content, ionic conductivity was proved to be immeasurable and this was thought to be the result of dominant *electronic conductivity* at higher filler concentration, due to strong presence of free electrons in valence layers of particulate fillers.

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Thus a more rigorous DC resistivity tests with single frequency was conducted to measure the electronic conductivity in the matrix by establishing varying voltage fields up to 500V.

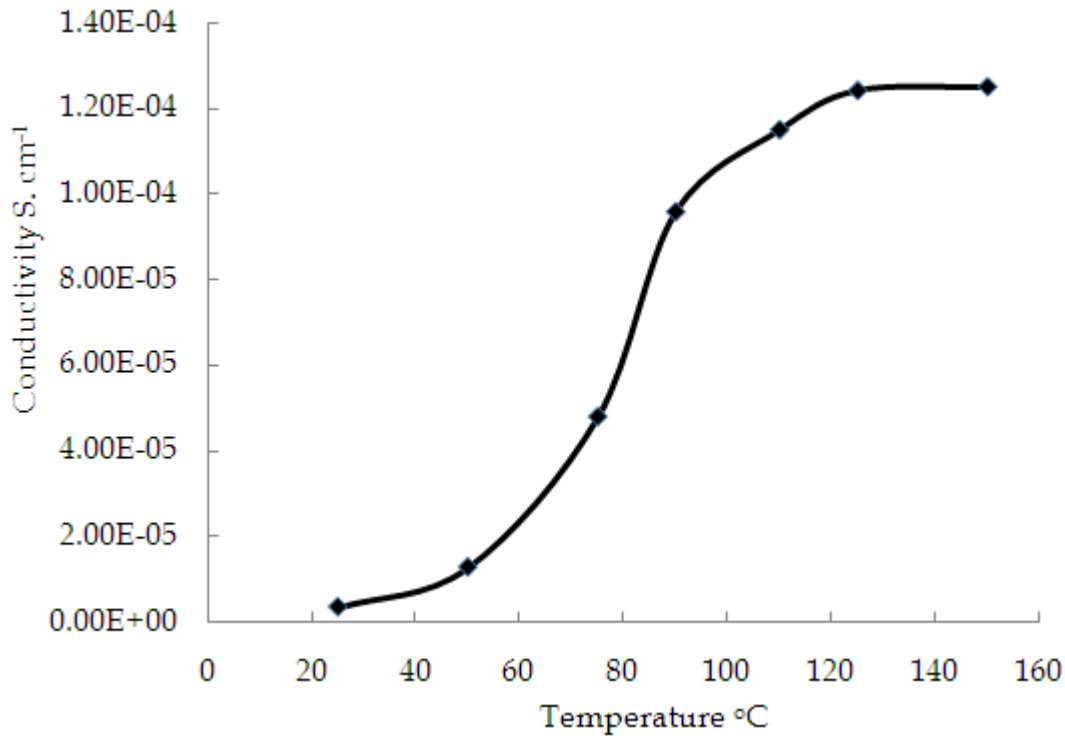

Figure 5-34: Effect of temperature on ionic conductivity of Iron/ABS composites with low iron content

Figure 5.35 shows DC resistivity of Iron/ABS composites containing various volume fractions of iron powder with the size of 45 μm. It is seen that at lower concentration of filler (less than 5 vol %) the resistivity of composite is slightly lower than that of virgin polymer, which is about 1.3 X 10^{16} ohm-cm whereas for the same concentration, the ionic resistivity was by orders of magnitude lower (see Figure 5.34). However, contrary to ionic conductivity, DC conductivity was constantly improved by increase of filler content, up to 30 vol% at which percolation was observed indicating a full formation of conducting network of filler particles.

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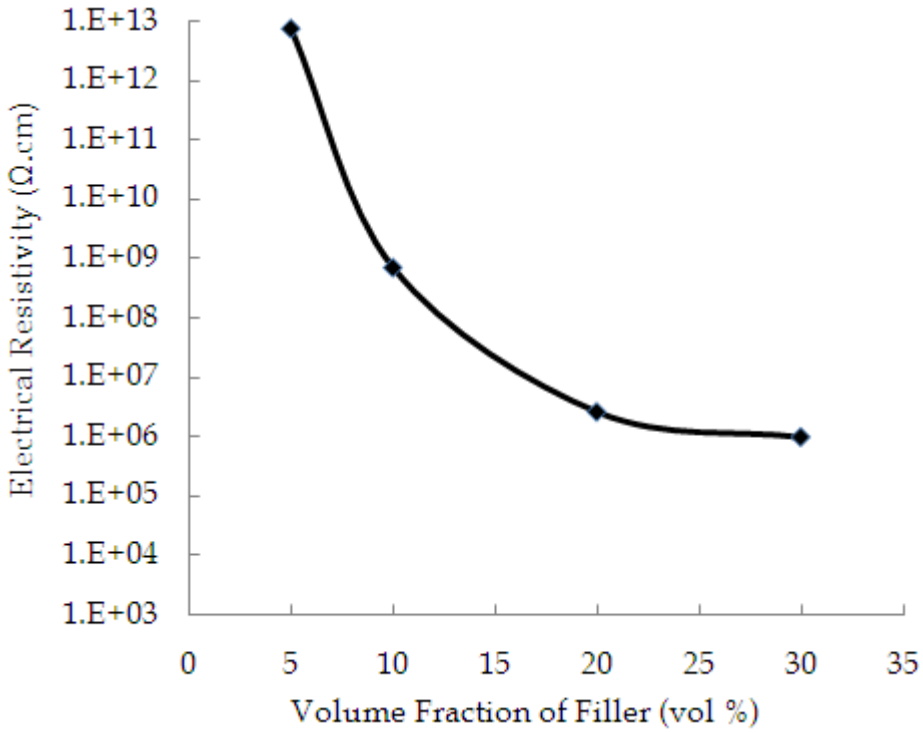

Figure 5-35: DC resistivity of Iron/ABS composites for filler concentration up to 30vol%

Figure 5.36 shows the relative conductivity of Iron/ABS composites versus varying volume fraction of 45 micron iron particles. Relative conductivity of composite is sharply rising by changing the fraction of filler to above 5 vol%, and it follows on exponentially by increasing filler content up to 30 vol%. Such exponential increase of conductivity has been related to the ability of an electron to jump the inter-particle insulating gap under a given voltage field (Bigg 1977; Scarisbrick 1973).

Below 5 vol% of particles, SEM images [Appendix A] revealed no inter-particle contacts, but at higher filler concentration, conductive particles get to a closer proximity, and therefore electrons can jump the insulation gap between the particles and flow is created, and conductivity increases exponentially. Increase of filler contents beyond this point, further reduces the gap between the

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particles and at about 30 vol% some physical particle-particle contacts are made, which results in steady current flow.

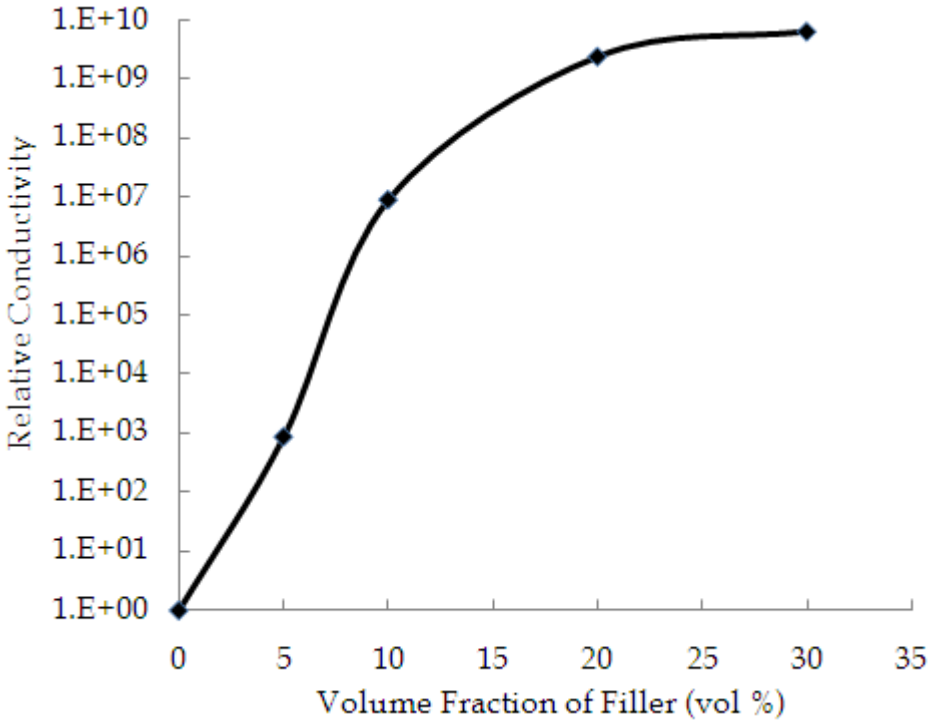

Figure 5-36: Relative DC conductivity of Iron/ABS composites for filler concentration up to 30 vol%

It is clearly seen that metallic fillers, as excellent conductors, can induce electrical conductivity in polymeric matrices at even low concentration, and therefore conductive metal/polymer composites are made, which are suitable for various application in electrical and electronics industry. For example, it has been demonstrated (Al-Saleh & Sundararaj 2008) that polymer composites filled with conductive filler can be effective materials for shielding electromagnetic interference (EMI).

5.4. Summary

Extensive experiments were carried out to fully characterise new composites materials processed and developed during this research. It has been shown that

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the new metal/polymer composite material developed in this research work, involving use of iron particles and copper particles in a polymer matrix of ABS material, offers much improved thermal, electrical and mechanical properties enabling current Fused Deposition Modelling technique to produce rapid functional parts and tooling. Higher thermal conductivity of the new metal/polymer composite material coupled with implementation of conformal cooling channels enabled by layer-by layer fabrication technology of the Fused Deposition Modelling will result in tremendously improved injection cycles times, and thereby reducing the cost and lead time of injection moulding tooling.

Due to highly metal-particulate filled matrix of the new composite material, injection tools and inserts made using this material on Fused Deposition Modelling will demonstrate a higher stiffness comparing to those made out of pure polymeric material resulting in withstanding higher injection moulding pressures. Moreover, metallic filler content of the new composite allows processing of functional parts with electrical conductivity and in case of using ferromagnetic fillers, namely as fine iron powders, it introduces magnetic properties, which will make FDM-built components suitable for electronic applications specifically whereby shielding electromagnetic interference is of high interest.

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Chapter 6 A Melt Flow Analysis of Iron/ABS Composites in FDM Process

6.1. Introduction

This chapter presents a numerical study of melt flow behaviour of ABS-Iron composite through the melt flow tube of the liquefier head of the Fused Deposition Modelling (FDM) rapid prototyping process using the finite element analysis.

As discussed in earlier chapters, Fused Deposition Modelling (FDM) is a filament based rapid prototyping system, which offers the possibility of introducing new composite material for the FDM process as long as the new material can be made in feedstock filament form. It involves flow of molten thermoplastic filament through a long bent melt flow channel, and extruded through a nozzle to build a part by layer by layer deposition directly under computer control. In this process, the plastic filament is delivered on a spool and supplied into a liquefier where it is heated to semi molten state with the help of the external heater placed on the FDM head. This semi liquid material is then extruded through a nozzle in the form of ultra-thin semi-liquid thermoplastic filament, while the arriving filament in the head, still in solid phase, acts as a piston. The nozzle attached to the FDM head can be moved in the xy plane according to the geometry created in CAD model, depositing a thin bead of extruded plastic, known as ''roads'' on a table, which can be moved in the vertical plane.

In the FDM head, the melt flow channel's shape and length are designed for ABS and other thermoplastic material, and it would be indispensible to know what happens in the melt flow channel when other types of material passes through the heated FDM extrusion head. It is therefore important to investigate first the flow behaviour of new composite material in the melt flow channel as it

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is affected by the pressure drop, velocity and the geometrical dimension at the exit. The pressure drop along the melt flow significantly affects the force required to push the filament. This directly affects the quality of the product as the road width of the product varies. Hence it is crucial to know the force required to push the filament in the melt flow channel. But the force applied in the FDM machine is constant as the current machine does not have pressure feedback system. The other parameter for the investigation of melt flow behaviour of the ABS-Iron composites is the length of the melt flow channel and the temperature distribution along the melt flow channel as the material from the solid filament converts into semi molten state in the melt flow channel. In past, the mathematical models using finite element methods were only used to investigate the flow behaviour of polymer with viscous heat dissipation (Bellini, Shor & Guceri 2005; Masood, Nikzad & Patel 2009; Ramanath et al. 2008).

In order to predict the behaviour of new ABS based composite materials in the course of FDM process, it is necessary to investigate the flow of the composite material in liquefier head. No such study is available considering the geometry of the liquefier head. In this chapter, main flow parameters including temperature, velocity and pressure drop have been investigated. Liquefier head of FDM machine has been modelled parametrically and the effects of physical modifications including nozzle angle variation on the melt flow parameters have been investigated accordingly. Results provided an insight on flow behaviour of new ABS based composites for processing in the FDM system to fabricate new products as detailed in next chapter.

Finite element method (FEM) is a powerful numerical technique that has been applied for the solution of fluid mechanics problems and, in particular, to slow viscous flows that are usually encountered in the processing of polymer melts. In such application, the domain is divided into sub domains (finite elements) and the problem solution is sought in each sub-domain, thus having a

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"piecewise" approximation to the governing equations. Such discretization of the domain requires a different approach for solving the differential equations (Mitsoulis & Vlachopoulos 1984).

Few published works are available on finite element analysis of the melt flow within the liquefier head of the commercially available FDM machines developed by Stratasys. Bellini and Bertoldi (Bellini, Shor & Guceri 2005) have investigated flow behaviour within straight liquefier head of the FDM process in order to process ceramic prototypes through fused deposition modelling. Zhang and Chou (Zhang & Chou 2008) have developed a finite element analysis model using element activation method to simulate the mechanical and thermal behaviour of parts built on FDM. They have also studied the model for residual stress, part distortion simulation and tool-path effects on the FDM process. Ramanath et al. (Ramanath et al. 2007; Ramanath et al. 2008) carried out their research on modelling of extrusion behaviour of biopolymer in fused deposition modelling. They developed finite element analysis model of the melt flow channel of FDM using the ANSYS software. Then they had studied the thermal and flow behaviour of biopolymer by varying input conditions and analysing the velocity, and pressure drop profiles at various zones of extrusion liquefier. Zdanski et al. (Zdanski, Vaz Jr & Inácio 2008) have applied the finite volume approach to simulate non-Newtonian flows in channels. Shih et al. (Shih, Huang & Tsay 1995) investigated the entrance laminar heat transfer of power law polymer fluids in circular tubes with wall slip by Leveque series, which uses a linear velocity profile. Flores et al. (Flores et al. 1991) surveyed the heat transfer to power-law flow in tubes and flat ducts with viscous heat generation by superposition procedures.

In this work, an investigation of melt flow behaviour of Acrylonitrile Butadiene Styrene (ABS) terpolymer reinforced with micro/nano sized carbonyl iron

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powder as a representative metal-polymer composite in the FDM liquefier head is described.

Figure 6.1 (a) shows the liquefier head of the FDM3000 machine, in which the feedstock material is fed in the form of a flexible plastic filament. The filament is delivered on a spool and supplied into a 90-degree bent liquefier, where it is heated to semi molten state with the help of the external heater placed on the FDM head. This semi liquid material is then extruded through a nozzle in the form of very thin semi-liquid thermoplastic filament while the incoming filament, still in solid phase, acting as a ''plunger''. Figure 6.1 (b) shows the geometry of the FDM nozzle tip. The head and nozzle is mounted to a mechanical stage, which can be moved in the XY plane. As the nozzle is moved over the table according to the geometry created in CAD software, it deposits a thin bead of extruded plastic, referred to as ''roads'', which solidify quickly upon contact with substrate and/or roads deposited earlier(Bellini, GÃ¼Ã§eri & Bertoldi 2004).

This chapter presents the results of the investigation of melt flow behaviour of Acrylonitrile Butadiene Styrene (ABS) plastic containing 10 % volume fraction of iron as well as a small fraction of surfactant. 2D and 3D finite element models of the melt flow channel have been generated using ANSYS-FLOTRAN and CFX Module of the ANSYS Workbench software. Experiments, outlined in the previous chapters, have been carried out to measure the thermo-rheological properties of the developed composite. Values of the properties from the experiments were used in ANSYS software to investigate the melt flow behaviour. Results of pressure drop, velocity and temperature profile of the flow along the melt flow channel are obtained by solving complex equations derived from principles of conservation of mass, momentum, and law of conservation of energy, respectively. Numerical results have also been verified using power law model suitable for Non-Newtonian flows.

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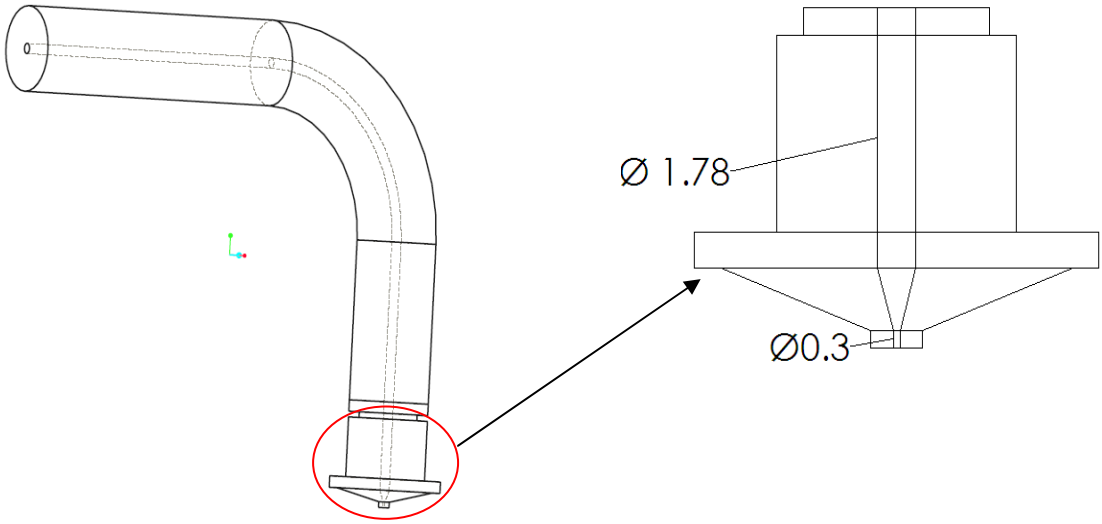

Figure 6-1: (a). Schematic of FDM Liquefier, (b). FDM Tip Nozzle Configuration

6.2. Material Characterisation for Boundary Condition Setup

To develop the new metal-polymer composite, mixtures of iron powder and ABS powder, as representative metal-polymer elements, were chosen with varying volume fractions of iron (10%, 20%, and 30% Fe) with the aim of producing appropriate feed stock filament for FDM processing. The main reasons for selection of iron powder as short fibre fillers were its reasonably good mechanical and thermal properties as well as its capabilities of mixing and surface bonding with polymers. Iron powder was purchased from Sigma-Aldrich in Australia. The purity of powder was 99.7% with average particle size of $45\,\mu m$. The specific gravity of iron powder was $7.88\,gr/cm^3$ and the shape of the iron particles was spherical.

The polymer used was P400-grade acrylonitrile butadiene styrene (ABS) supplied by the Stratasys Inc. This ABS is the FDM-grade polymer recommended by the Stratasys for use in fabrication of prototypes on their FDM3000 machine. The specific gravity of ABS was $1.05\,gr/cm^3$.

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The filament used in FDM process needs to be of a specific size, strength and properties. A single screw extruder was used to fabricate the filaments from the composite mixture. Due to die swell phenomenon during the extrusion process of polymeric materials, there was slight difference between dimensions of the extrusion die and those of the extrudate. To minimize this difference and achieve a consistent diameter on the extrudate in such a way that the produced filament could be fed into the FDM machine smoothly, different variables including screw speed, pressure and temperature were examined and selected until an optimum dimension (diameters of 1.75-1.80 mm) for the filament was achieved (Nikzad et al. 2007). Figure 6.2 shows the final filament produced by this process.

Figure 6-2: FDM filament produced from Iron/ABS composite material

Dynamic thermal and mechanical analysis was used to characterize the new composite material. Dynamic mechanical analysis was conducted on a Multi-Frequency-Dual Cantilever DMA Instrument in order to determine the Storage Modulus and Loss Modulus as well as glass transition temperature. Figure 6.3 shows the variation of Storage Modulus and Loss Modulus for the pure ABS and the composite material with 10% iron. The glass transition of the composite was found to be 126 ^{o}C, which is above that of the ABS matrix.

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Heat capacity and heat flow were measured using standard Differential Scanning Calorimetry modulated at +/- 5 ^{o}C at every 40 seconds with temperature ramp of 3 ^{o}C/min up to 150 ^{o}C. Figure 6.4 shows the variation of heat capacity with temperature for pure ABS and composites of ABS with 10% and 20% filled iron. Using the values of heat capacity, the thermal conductivity(λ) was calculated under the quasi-isothermal conditions within the temperature range of 0 to 90 ^{o}C using the following equation of thermal conductivity(Marcus & Blaine 1994):

$$\lambda = \frac{[\lambda_0 - 2D + (\lambda_0^2 - 4D\lambda_0)^{1/2}]}{2} \tag{6.1}$$

where:

$\lambda_0 = (8LC^2)/(C_p m d^2 P)$ as observed thermal conductivity in (*W/(K.m)*)

$D = (\lambda_0 \lambda_r)^{1/2} - \lambda_r$ as thermal conductivity calibration constant in (*W/(m.K)*)

λ_r = reference thermal conductivity (*W/(m.K)*)

L = specimen length (*mm*)

C= apparent heat capacity (*mJ/K*)

C_p= specific heat capacity (*J/(g.K)*)

m= specimen mass (*mg*)

d= specimen diameter (*mm*) and *P* = period(s).

Using the above equation (6.1), the thermal conductivity of 10% iron filled composite was found to be 0.258 *W/(m.K)*.

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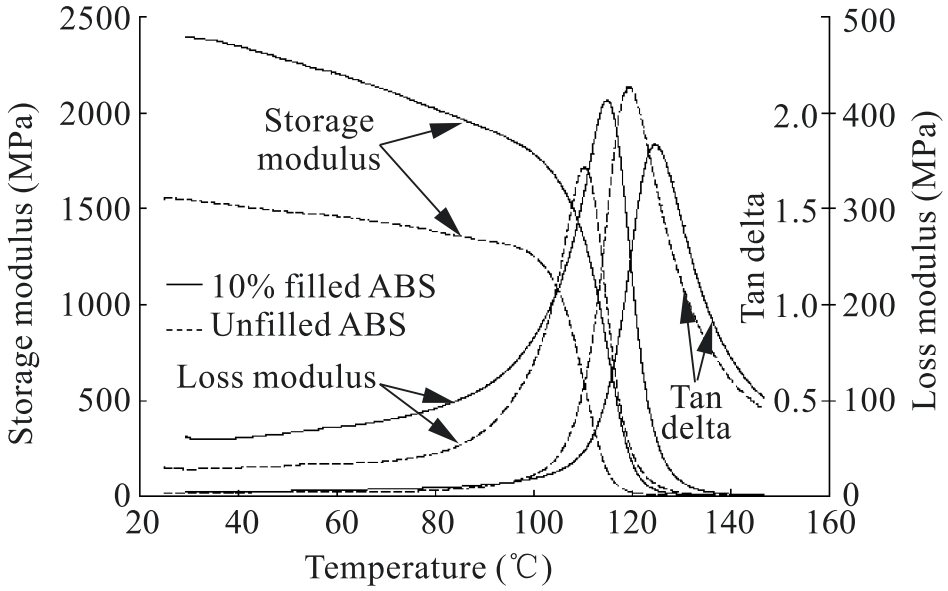

Figure 6-3: Glass transition temperature of 10% Iron filled ABS

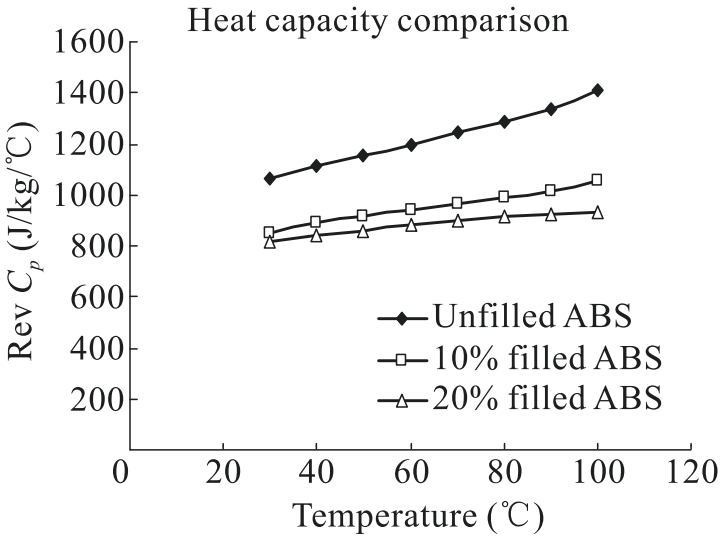

Figure 6-4: Rev Cp of the filled ABS used for thermal conductivity calculation

Using the TA Rheometer, the proportionality of viscosity and shear rate was investigated at 270 °C, which was the processing temperature for the new composite. Disc shaped test samples were prepared by the compression moulding technique. Despite the addition of up to 30% volume fraction of coarse iron particle (45 μm in size) as well as up to 15% volume fraction of

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surfactant, the experimental data showed decrease of viscosity with increase of shear rate.

The initial rheological results for the conducted tests are shown in Figures 6.5 and 6.6 (apparent viscosity vs apparent shear rate and corrected viscosity vs shear rate, respectively):

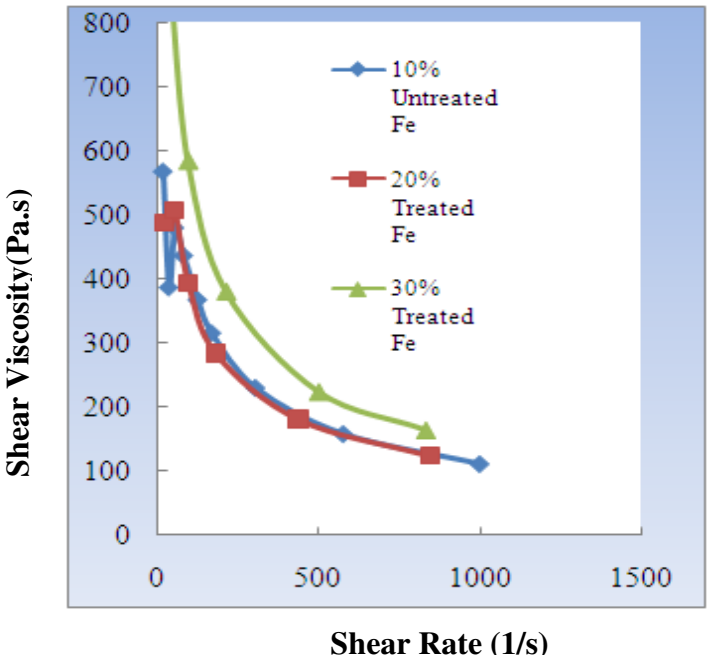

Figure 6-5: Apparent viscosity vs apparent shear rate

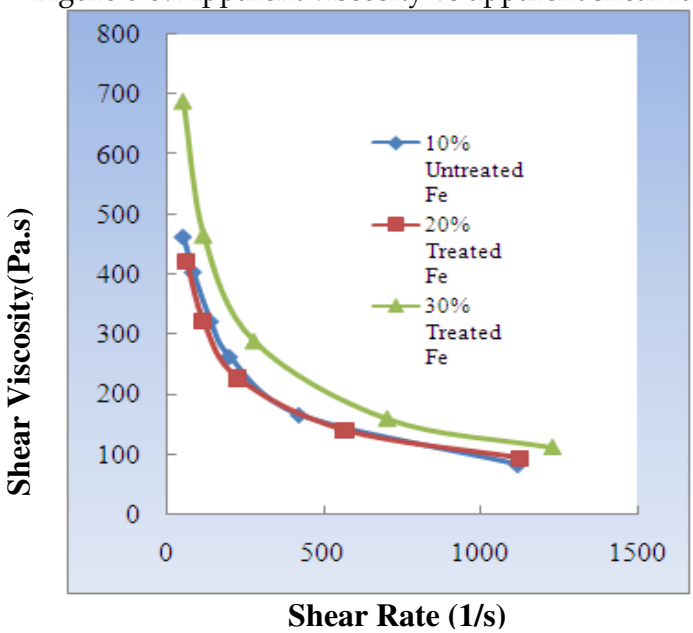

Figure 6-6: Corrected viscosity vs shear rate

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6.2.1. General Flow Behaviour

As it can be seen clearly, contrary to Newtonian constant shear viscosity fluids, metal filled polymeric flow shows a rapid exponential decay of viscosity versus increase of shear rate. In case of pure polymeric flows this behaviour is known as shear thinning or *Pseudoplasticity* (Aoki 1986, 1987; Yamaguchi 1952). This characteristic, shown in Figures 6.7(a) & 6.7(b), is particularly important in that the required force needed to provide enough pressure to push the material through the FDM nozzle can be supplied using the existing step motors with minimal change of torque.

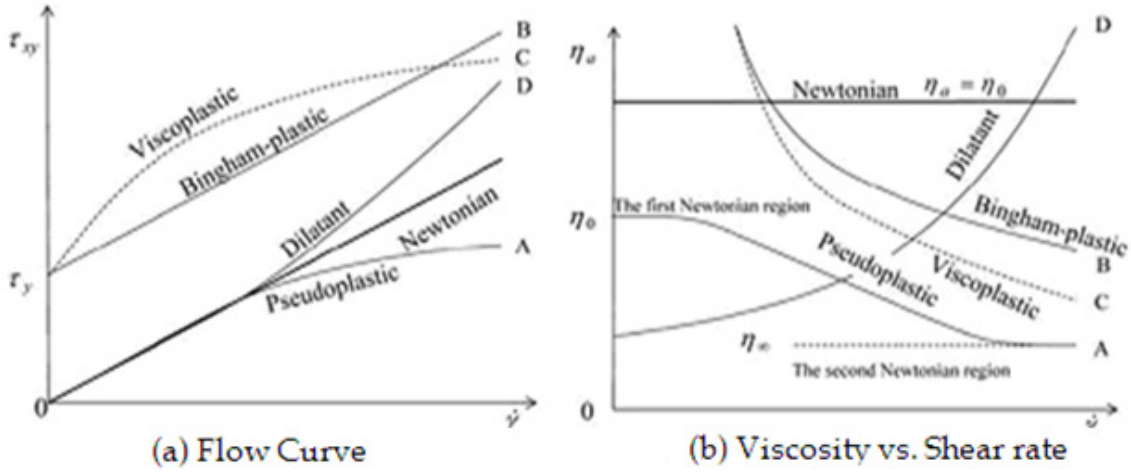

Figure 6-7: (a) Characteristics flow curves, and (b) viscosity vs shear rate for non-Newtonian fluids (Yamaguchi)

Currentl there are a few mathematical models which explicitly explains this type of behaviour, namely Cross, Hershel Bulkley, Ostwald de Waele, and Carreau Yasuda (equations 5-8) (ANSYS 2008), as given below:

$$\textit{Cross: } \mu = \frac{\mu_0}{1+(\lambda\dot{\gamma})^n} \tag{6.2}$$

$$\textit{Hershel Bulkley: } \mu = \frac{\tau_y}{(\lambda\dot{\gamma})} + K(\lambda\dot{\gamma})^{n-1} \tag{6.3}$$

$$\textit{Ostwald de Waele: } \mu = K(\lambda\dot{\gamma})^{n-1} \tag{6.4}$$

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$$\textit{Carreau Yasuda: } \mu = \mu_\infty + \frac{(\mu_0 - \mu_\infty)}{(1+(\lambda\dot{\gamma})^a)^{\frac{1-n}{a}}} \quad (6.5)$$

where τ_y, μ, μ_0, and μ_∞ denote yield stress, viscosity, low shear viscosity, and high shear viscosity, and K, n, a denote consistency index, power law and Yasuda exponent.

To predict the flow behaviour of the newly developed polymeric composite, 2-D and 3-D finite element analysis of the melt flow behaviour has been carried by setting up the FEM model in FLOTRAN and CFX, which are embedded modules in the latest release of the ANSYS Workbench. Detailed procedures of the finite element analysis have been discussed in the following section. Existing and modified non-Newtonian fluid models were used in these commercial codes and material property constants as well as flow indexes were extracted from logarithmic plot of viscosity versus shear rate data (Figure 6.8). A MATLAB code was used to best fit a correlation of data representing those mathematical models.

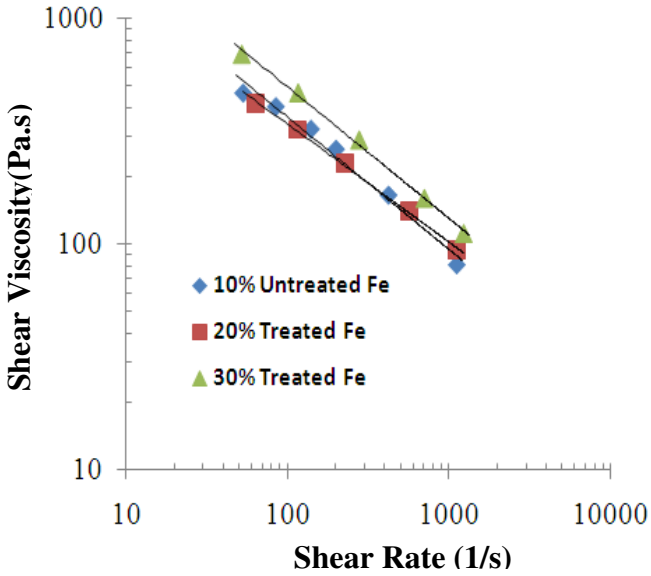

Figure 6-8: Characteristics flow curves plotted to determine flow indices

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6.3. Finite Element Analysis

2D and 3D finite element analysis of the melt flow behaviour was carried by setting up the FEA model in FLOTRAN and CFX, which are embedded modules in the latest release of the ANSYS Workbench. Due to the nature of FDM process [4, 5], the following assumptions were considered:

- The flow is considered as a steady state as there is no significant change over time
- There is no change in flow profile with the time implying a laminar flow
- Temperature in the liquefier stays constant as the working chamber is isolated
- Velocity components at the wall of the channel are zero as the melt is assumed to be adhering to it.

The following main steps were undertaken to accomplish the Finite Element Analysis on ANSYS:

6.3.1. Geometry development

The geometrical dimensions of the liquefier head were determined by the X-ray imaging technique. Using the collected data, the 2D model of the liquefier tube was created using the ANSYS modelling commands. However, due to the complex geometry involved, the 3D model was created on Pro/Engineer CAD software and then it was exported into ANSYS workbench. Figure 6.9 shows the liquefier model created in Pro/Engineer and Figure 6.10 shows the geometry as imported in ANSYS environment.

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6.3.2. Problem domain and flow regime definition

Based on the experimental observation, the thermodynamic state chosen has to be liquid, although due to the high viscosity of the composite melt, it seems that even after exposure to temperatures well above the glass transition temperature, the flow keeps its solid shape. The flow regime is normally a function of the fluid properties, geometry and the approximate magnitude of the velocity field. Fluid flow domain that FLOTRAN could solve includes the gas and the liquids. But in CFX (ANSYS 2008) it is also possible to define a solid thermodynamic state. As the fluid density, viscosity and thermal conductivity depends on the temperature, the density change was also taken into account. Because of the non Newtonian nature of the flow, as shown in Figure 6.5, the viscosity was defined as a function of power law. The values of density, thermal conductivity and specific heat are taken as obtained from the experiment tests described earlier.

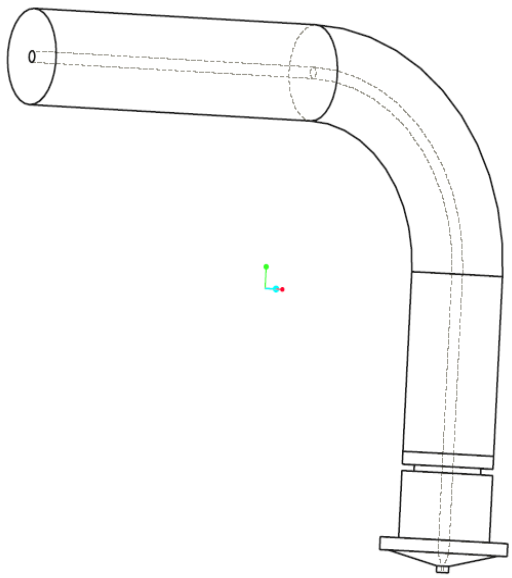

Figure 6-9: Liquefier model used in FDM3000

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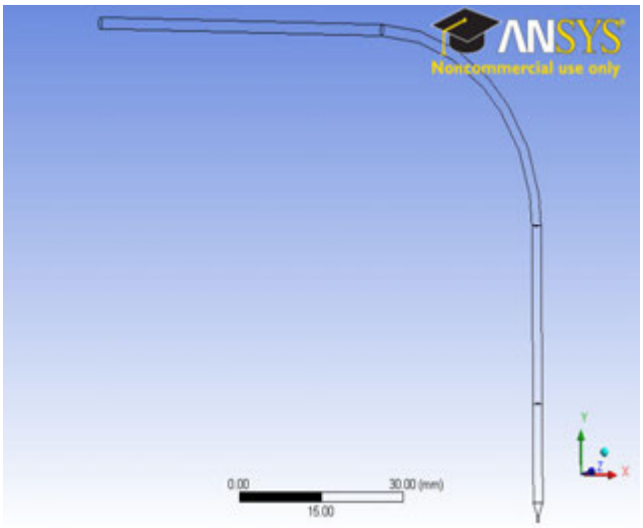

Figure 6-10: Internal feathers of liquefier used in FDM3000

6.3.3. Meshing

Figure6.11 shows the meshing details of the melt channel and Figure 6.12(a) and Figure6.12 (b) show the meshing details of the nozzle tip for the 2D finite element analysis. Figure6.13 and Figure6.14 show the meshing details of the melt channel and nozzle tip respectively used for the 3D finite element analyses. For the 2D analysis, both the mapped and free meshing techniques were used to ensure the results are independent of mesh characteristics of the problem. For 3D analysis, the CFX mesh is used, in which a combination of tetrahedral, pyramid and prism shaped elements were employed to achieve the optimum result [10]. The total number of elements for the finest mesh applied was 371139 for the entire flow domain i.e. tube and the nozzle.

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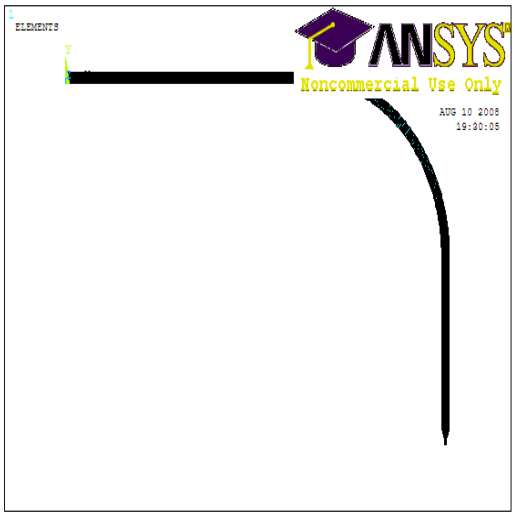

Figure 6-11: 2D meshing of melt channel used in FLOTRAN

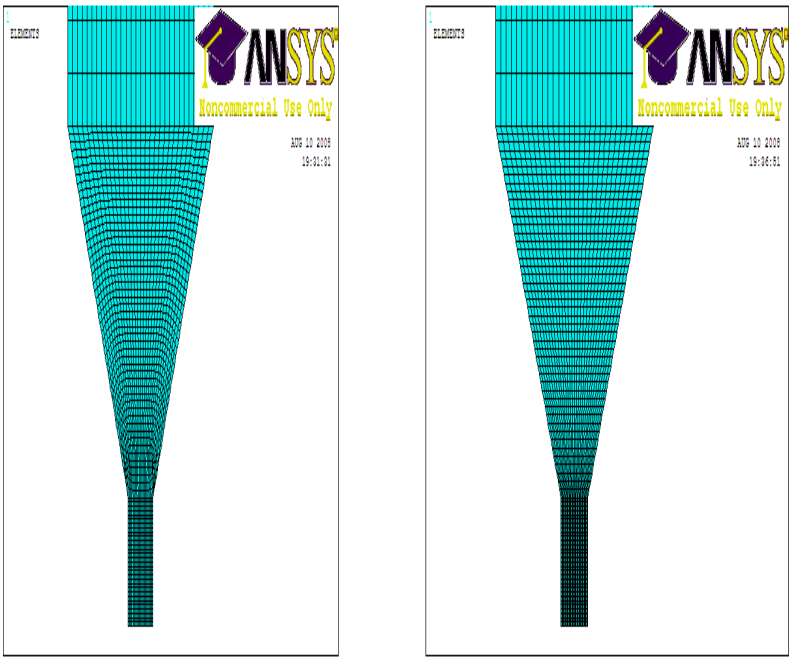

Figure 6-12: (a) Free meshing of nozzle tip (b).Mapped meshing of nozzle tip

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6.3.4. Boundary conditions

Three boundary sets namely temperature, velocity and pressure were used to solve for thermo-fluid analysis. At the inlet of the channel, load value of normal velocity was set. The pressure boundary condition was set at the exit of the nozzle. The load value of the temperature at the inlet of the channel and at the wall of the channel was specified. To calculate the mass flow rate, a similar experiment as described by Ramanath et al [4] was conducted. Figure6.15 shows the boundary conditions used for the melt flow channel.

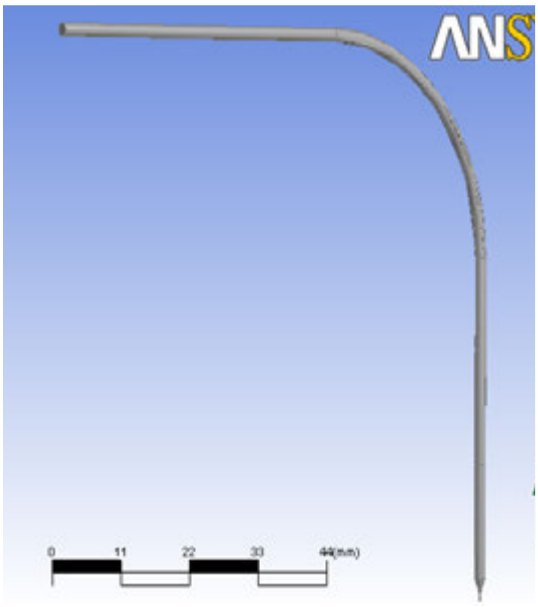

Figure 6-13: 3D mesh of the melt channel

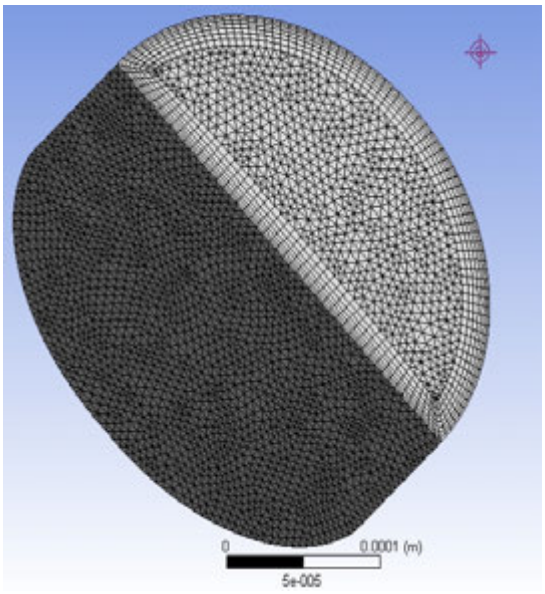

Figure 6-14: Close-up of 3D mesh at Nozzle Tip

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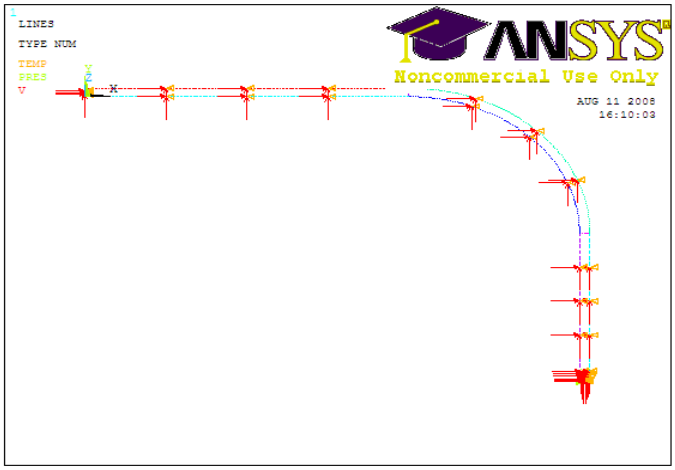

Figure 6-15: Boundary conditions set for thermo-fluid analysis of the FDM3000 melt flow channel

6.4. Results and Discussion

Figures 6.16-6.21 show the 2D numerical analysis results by ANSYS FLOTRAN. Fig 6.22 to 6.27 demonstrates results of the 3D numerical analysis by ANSYS CFX.

Temperature distribution along the melt flow channel and at inlet is shown in Figures 6.16 & 17 for 2D analysis and in Figures 6.22&6.23 for 3D analysis by using the two software modules of ANSYS. Solid filament with envelope temperature of 333 ^{0}K enters the liquefier and during a short residence time, due to good thermal conductivity of aluminium wall with temperature of 543 ^{0}K, composite filament is heated well above its glass transition temperature ensuring the advancement of fully molten flow. Both analyses by FLOTRAN and CFX confirm that filament will be in molten state well before reaching the nozzle tip thus ensuring a smooth flow during the deposition.

Results of 2D and 3D analyses of pressure drop in the channel and the nozzle during the deposition of ABS-Iron composite are presented in Figures 6.18 and 6.19 for 2D analysis and in Figures6.24 and 6.25 for 3D analysis. It is shown that the initial high pressure of the filament flow, applied by a stepper-motor drive

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embedded on FDM machine, is well maintained during the flow until it reaches the tip nozzle. At this stage, due to rapid changes of the cross sectional area (diameter changing from 1.80 mm to 0.3 mm), there is a considerable pressure drop. While FLOTRAN calculates higher pressure drops, CFX analysis reveals smaller values, which are interpreted as the difference in dimensionality of the analysis. As the initial plunging force applied by the solid filament at the entry to the molten filament during the channel is constant, and also due to lack of force feedback system in the current FDM3000 machine, this pressure drop cannot be accurately compensated. Experiments were conducted by feeding the filament both automatically and manually. In automatic mode, where machine applied initial force by the small stepper motor embedded for this purpose, the flow turned out to be intermittent. While feeding manually, by applying extra force, the pressure drop at the nozzle tip could be compensated and there was a smooth flow observed.

Figure6.20 shows the velocity gradient in melt channel and Figure6.21 shows the maximum velocity at the nozzle exit obtained by 2D analysis using FLOTRAN. Figure6.26 shows the maximum velocity vector at nozzle exit and Figure6.27 shows the velocity distribution of nozzle cross section using 3D analysis by CFX. It is observed that an entrance velocity of filament at a rate of 0.001 m/s is maintained along the tube until it gets to the nozzle tip, where again, as a result of decrease in the channel diameter to as low as 0.3 mm, maximum velocity vectors (field) are developed reaching a maximum rate of 0.081 m/s as shown in Figure 6.26 and Figure 6.27 shows the velocity distribution across the nozzle tip cross section. Melt flow speed in the centre is the highest while it drops to the lowest at the wall due to no-slip condition set as a boundary condition.

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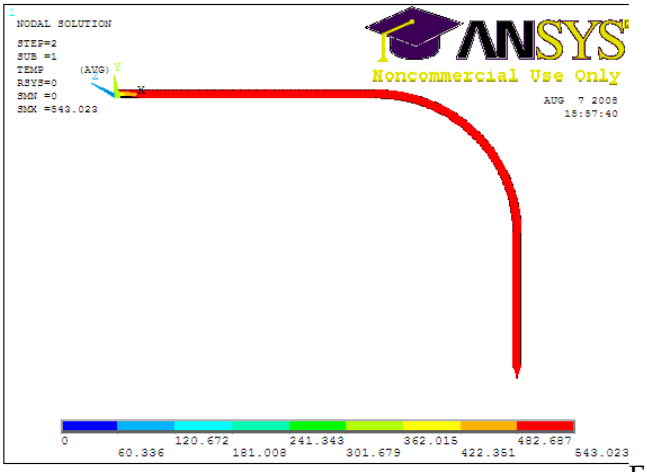

Figure 6-16: Temperature gradient over the melt channel within liquefier

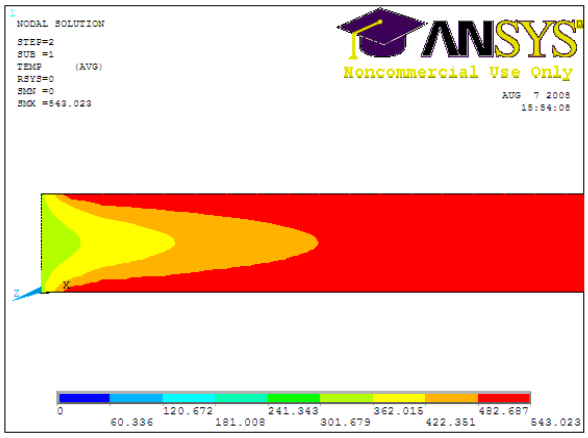

Figure 6-17: Temperature profile of melt at the channel inlet

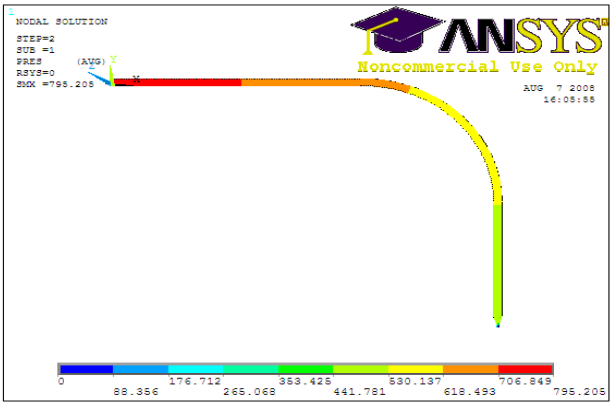

Figure 6-18: pressure drop calculated using Flotran

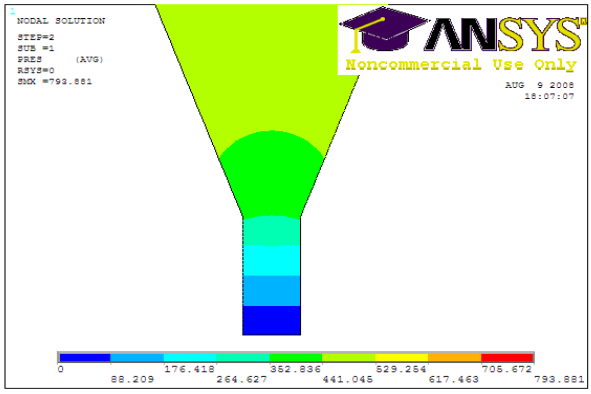

Figure 6-19: pressure drop at nozzle tip

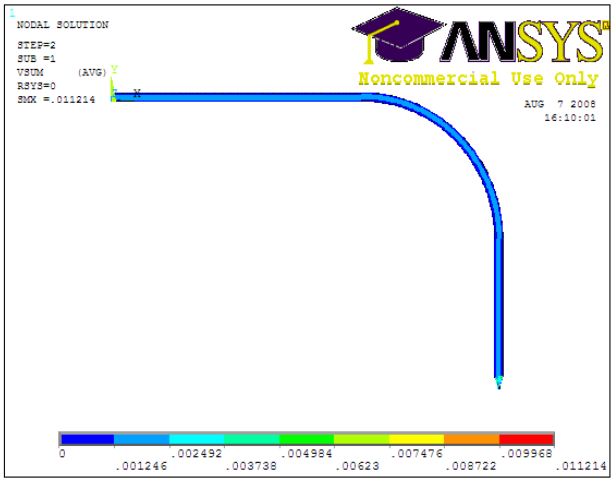

Figure 6-20: 20Velocity gradient along melt channel in liquefier head

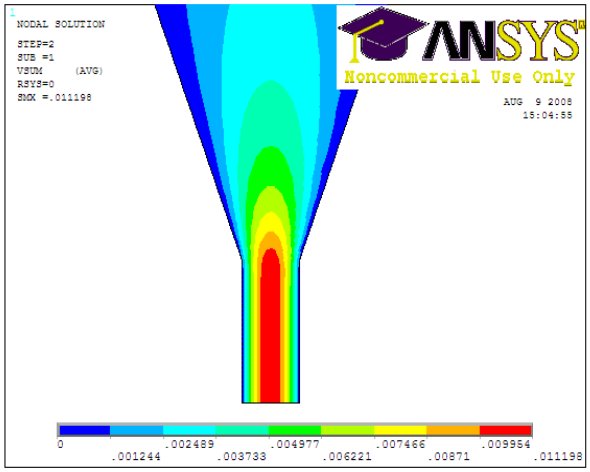

Figure 6-21: Maximum velocity at the nozzle exit

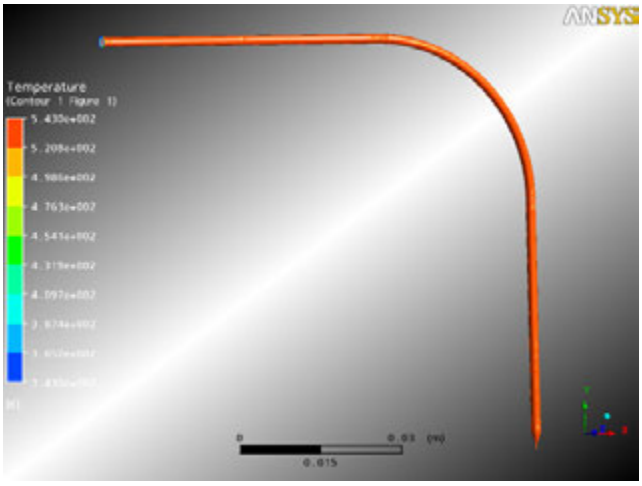

Figure 6-22: 3D Temperature profile along the melt channel in the liquefier head using CFX

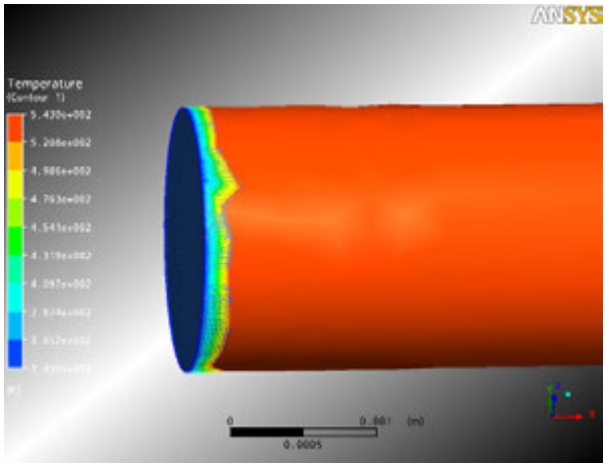

Figure 6-23: 3D Temperature evolution at the inlet using CFX

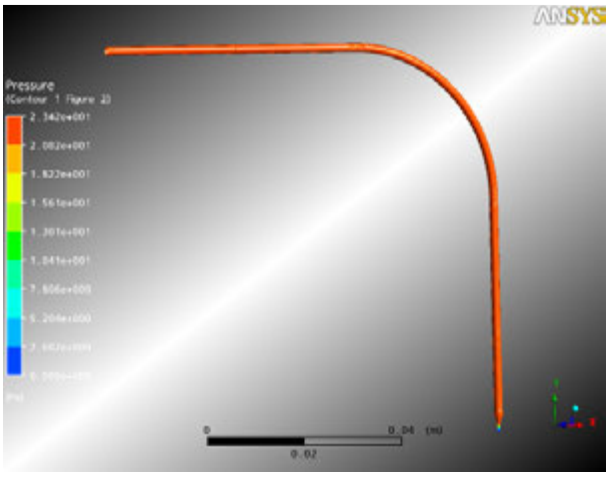

Figure 6-24: Pressure drop along the melt channel in the liquefier head calculated using CFX

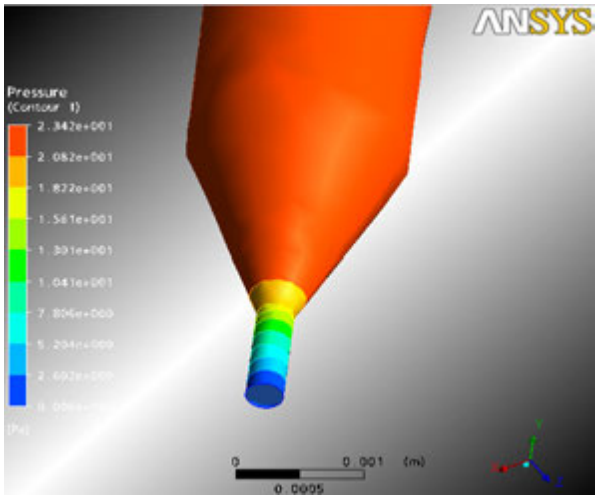

Figure 6-25: Maximum pressure drop at nozzle exit

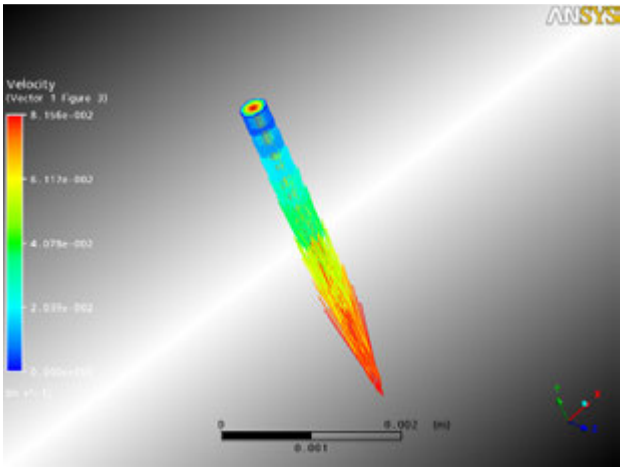

Figure 6-26: Max. Velocity vector at nozzle exit obtained by CFX

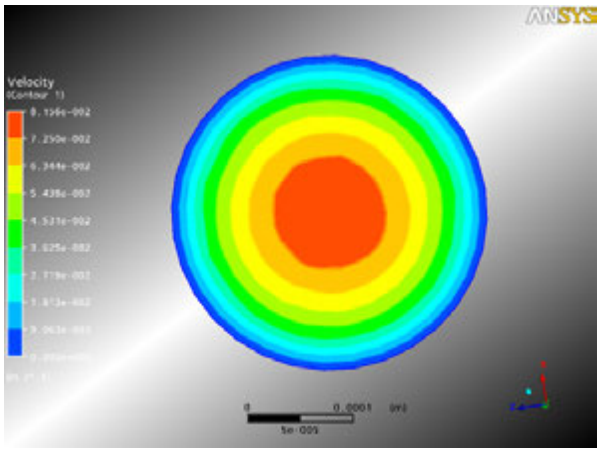

Figure 6-27: Velocity distribution at centre cross section of the tip nozzle tip

From above results, the behaviour of a representative ABS/Iron composite containing 10%vol iron powder in the melt flow channel of the FDM system can be examined by the behaviour of heat, pressure drop and speed profile. The main parameters essential for the simulation study are the parameters of the FDM system and the physical properties of the ABS/Iron composite material. The value of the physical properties like thermal conductivity, specific heat and viscosity was taken from the experiments. The value of pressure drop obtained can be used to calculate the force necessary to feed the ABS/Iron filament, as it

directly influences the amount of material extruded. The mathematics and simulation results showed that the nozzle diameter and angle change has a direct influence on the pressure drop along the chain of fluidity and the results showed that the pressure drop lines in the simulation and mathematical model follow the similar pattern.

The numerical simulation results showed that the ABS/Iron composite reaches to a semi molten state at half part of the melt flow channel. It indicates that the ABS/Iron composite remains in the glass transition temperature up to the exit tip of the nozzle. So we can say that the material fully flows up to the nozzle tip to build the product. Since the viscosity and the melting temperature are high for the ABS/Iron composite material therefore the length of the melt flow channel is longer.

The velocity profiles showed that the smooth flow occurs at the centre of the melt flow channel while the flow remain stationary at the walls, as we have assumed that the melt is adhering to the melt flow channel. The results obtained in this investigation are meaningful and they can be used to optimize the FDM machine parameter settings to create the better quality product.

Investigation of the effect of back pressure is particularly important in relation to extruding high viscous ABS/Iron composites through the nozzle of FDM. The effect of applying low turbulence model, due to a number of vortices and severe back flow; in the case that the diameter of exit is too small or the angle of nozzle tip is too large, is indispensible in having converged results of numerical simulation. There is an optimum value where a relationship between the exit angle and diameter of tip nozzle is dictating the design of such nozzles and practical success of extruding such composites through the FDM head. From the analysis point of view, demonstrating the vortex vectors in the flow would be of great interest and discussion worth.

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6.5. Summary

The results obtained by both the analyses have been compared and show a very good correlation in predicting the flow behaviour. The flexible filaments of the new material have been successfully produced and processed in the existing FDM3000 machine to produce sample parts.

The relationship between the pressure drop and the force necessary to boost the filament has been developed in this study. The current FDM machine used in this study does not have any pressure feedback system. Therefore it was not possible to determine the force necessary to push the filament. Also the force applied at the entrance of the FDM head is kept constant. So it is necessary to investigate the melt flow behaviour in FEA software which can provide the information on pressure drop at various zones and hence the force required to feed a new material.

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Chapter 7 Experimental Trials of Iron/ABS in Fused Deposition Modelling

7.1. Introduction

As discussed in the literature review (Chapter 2) there are various fields where application of RT/RM can offer invaluable benefits. The shift from mass production towards "*mass customization*" concepts projected by the pioneers in the RP/RM fields (Eyers & Dotchev 2010), shows that due to rapid socio-economical changes predicted in society, such techniques will be the only viable methods of producing constantly-changing and highly customized concepts and designs. Injection moulding industry, as one of the most widely used plastic manufacturing process, is considered one such field wherein demands for versatility in the type of products and changing their design makes it too costly to meet the requirements and simultaneously keeping a competitive edge using traditional mould making processes. For any new plastic product, alongside the initial conceptualization stage, process of mould cavity design as well as other considerations such as design of cooling channels, runners and gates together with their location makes it all a time consuming and costly process using traditional methods of injection mould manufacturing. As discussed in Chapter 2, emerging Rapid Manufacturing processes can offer effective and viable solutions to most of these challenges faced by tooling industries today.

Owing to their "layer-by-layer" manufacturing fashion, emerging RM techniques can be used to build mould cavities of literally any complexity. A good example, specific to injection moulding process, is incorporating conformal cooling channel around the mould cavity, which provides a more uniform cooling system and faster cooling cycle times, and also helps reduce warpage, uneven shrinkage and cracking in the final injected parts. This also

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leads to reducing total production time. Such considerations are not possible within the scope of traditional subtractive production methods.

This chapter presents a new platform whereby the newly developed metal/polymer composite material with unique properties can be used directly in Fused Disposition Modelling system to provide a short term and viable solution to some of the foregoing issues in tool making. The emphasis is given to the possibility of producing functional metal/polymer composites prototypes, which can also be used as tooling insert in industrial injection moulding machines. A fast response to the changes in cavity insert shape is shown to be inexpensive compared to the traditional manufacturing processes.

7.2. Fused Deposition Modelling of Metal/Polymer Composites

After successful production of strong, flexible, and spoolable filaments of ABS/Iron composites, as described in detail in chapter 3, they were kept under vacuum oven overnight at around 80 ^{0}C in order to make sure the material would be free of moisture during the fused deposition modelling process. As also discussed in chapter 3, for a successful processing of prototypes, it is crucial that the filament exhibits enough strength and suitable viscosity especially at the entrance of melt channel. Any presence of moisture in the feedstock material can detrimentally affect foregoing processing parameters, and thus may result in failure of fabrication process.

In this research, Stratasys FDM 3000 is used as the RP platform to fabricate parts and tools from the Iron/ABS composites. Figure7.1 shows winding of composite filament onto a spool before loading on the FDM3000 machine for processing.

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Dried Iron/ABS filaments were removed from the oven and placed into a sealed container at the back of FDM 3000 machine for a couple of days. In the meantime CAD models of various parts and tooling inserts were designed in Pro/Engineer® software for STL file preparation.

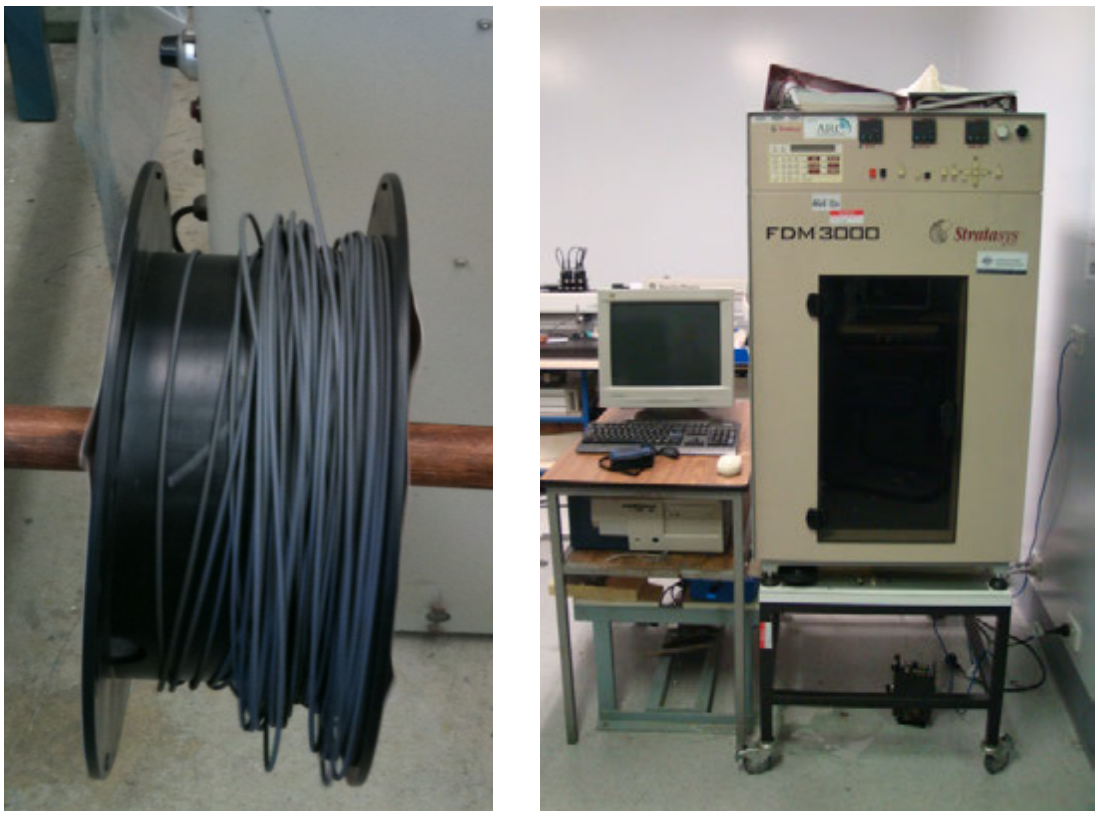

Figure 7-1: (a) Spool of Iron/ABS composite filament and (b) Stratasys FDM 3000

In principle, Fused Deposition Modelling like most of other RP/RM technologies, works by layer-by-layer deposition of Iron/ABS composites material on a substrate by tracking tool paths created from STL file of CAD model of final product. The actual fabrication process begins with unwinding the feedstock filament from a spool and feeding it through the liquefier head located inside the system working envelop, as shown in Figure 7.2, where it

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gets gradually heated by temperature gradient provided by a number of coils wrapped helically about the axis of the liquefier .

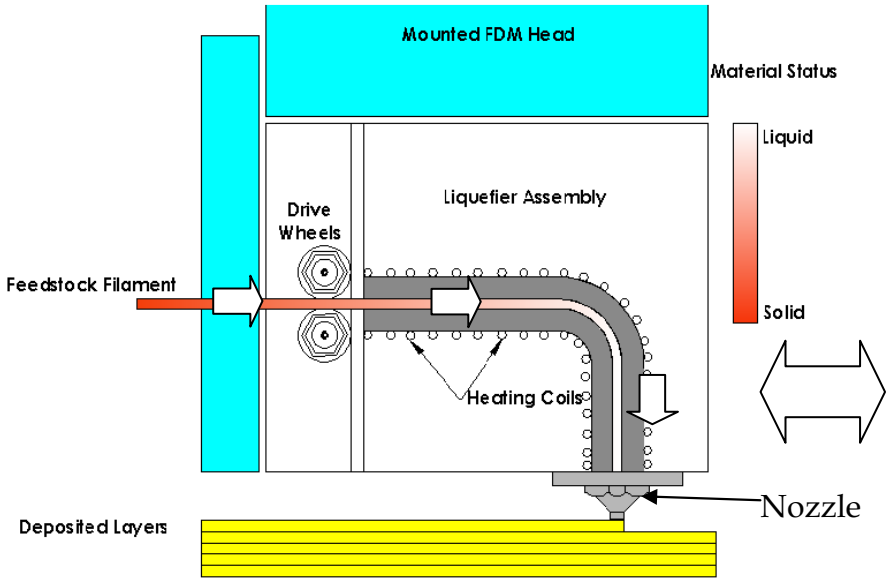

Figure 7-2: Fused Deposition Modelling process in FDM3000

The heated liquefier melts the filament and deposits the melt through a nozzle attached at the exit, as shown in Figure7.3, controlling the diameter of final extrudate. Two step-motors at the entrance of liquefier make sure that a continuous supply of material during the model build-up. The nozzle and liquefier assembly is mounted onto a mechanical stage numerically controlled in X-Y plane. Upon receipt of precise tool paths prepared by the Insight software, the nozzle moves over the foam substrate depositing a thin bead of the composite material along with any necessary support structure. Deposition of fine extruded filaments onto the substrate produces a layer corresponding to a slice of the CAD model of the object. Once a layer is built, the platform moves down in z direction in order to prepare the stage for the deposition of next layer. The deposited filaments cool down immediately below the glass transition temperature of the material and get hardened. The entire build system is contained within a temperature-controlled environment with

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temperatures just below the glass-transition temperature of the polymer to provide an efficient intra-layer bonding.

Where applicable, support structures are deposited along with the model material for overhanging geometries and are later removed by breaking them away from the model. A water-soluble support material is also available which can be washed away in a water-based sodium hydroxide solution contained within a mechanically agitated tank.

Figure 7-3: Fused Deposition Modelling of ABS/Iron Composites in FDM3000

Figure 7.4 shows the initial CAD model of a tooling insert designed in Pro/Engineer software. After designing the model, it was converted into STL

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file format, which can be read and interpreted by FDM Insight® software. It is important to note that the degree of triangulation directly affects the surface texture of the parts produced by layered manufacturing technologies. Usually two geometrical parameters of "Chord Height" and "Angle Control" are available in commercial CAD software by which deviation of triangles are controlled to make sure they best fit within the CAD model domain and result in smoother transition on the edges of the finished parts. To this, smaller chord height and finer angle were used during conversion of CAD model into STL format as shown in the Figure 7.5.

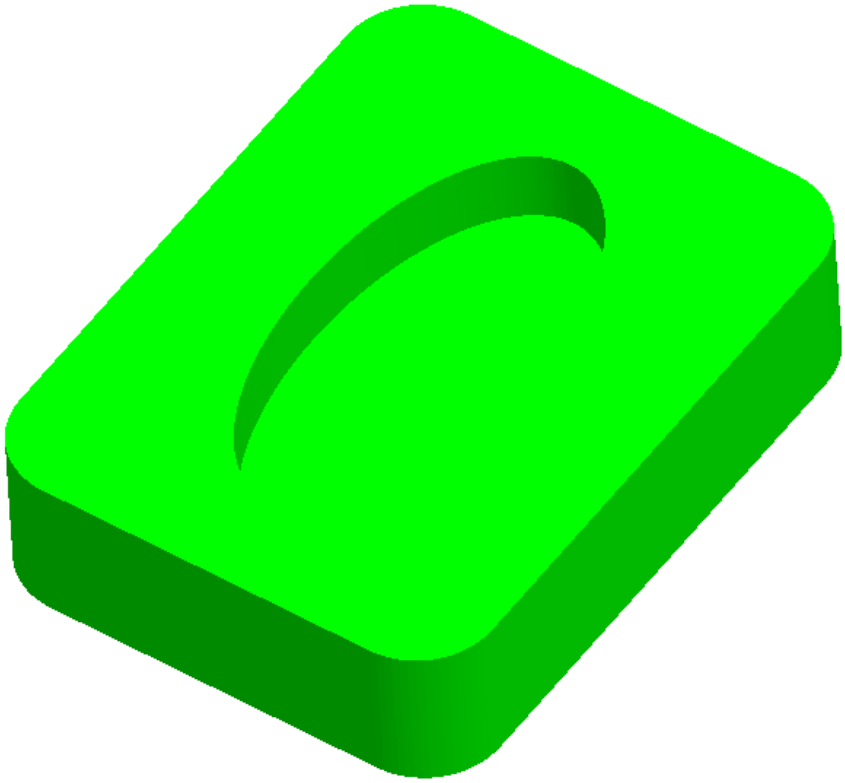

Figure 7-4: CAD model of tooling insert produced in Pro/Engineer®

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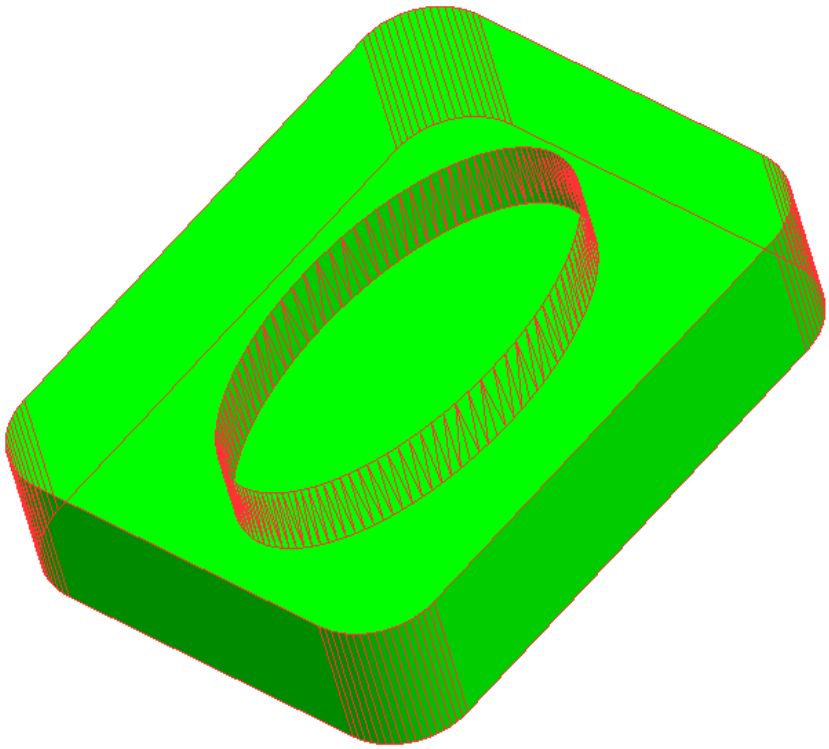

Figure 7-5: Triangulated image of CAD model for input into Insight® software

Effect of larger chord height and angles on the quality of final part edges are shown in Figure 7.6. A conformal cooling channel design has also been demonstrated which is built around the cavity by fused deposition process in order to promote the uniform cooling of final injected moulded part into the insert. Researchers have shown that by means of incorporating conformal cooling channels, cycle time of the injection process as well as part quality can be improved tremendously (Park, Yang & Lee 2009; Safullah, Sbarski & Masood 2009; Saifullah, Masood & Sbarski 2010). However, there have been challenges of manufacturing such conforming geometries due to limitation of traditional methods, and cost of production in case of applying a hybrid method whereby a combination of CNC machining is coupled with laser based layered manufacturing process. In contrast, Fused Deposition Modelling of the newly developed metal/polymer composites offers much cheaper, faster and

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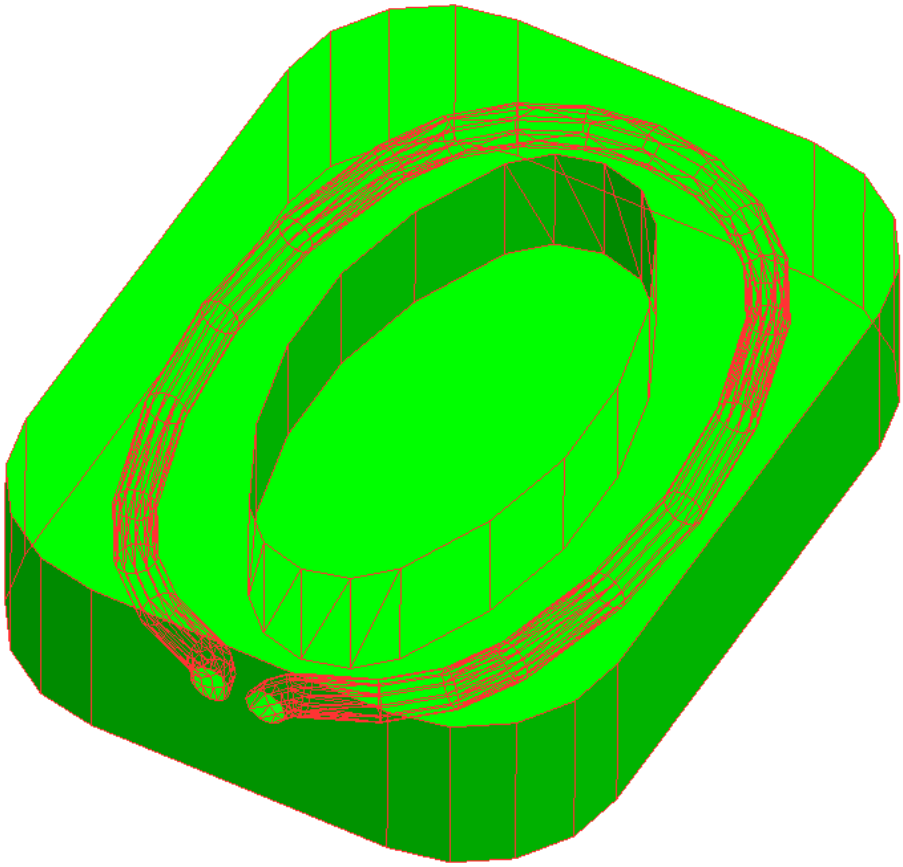

Figure 7-6: Tessellated CAD model of tool insert with conformal cooling channel design

viable solutions for manufacturing of such complex features especially for short-term tooling purposes. This is motivated further with emerging shift towards mass customization where the focus is given to more rapid and flexible mould developments for short term tooling providing a faster and inexpensive realisation of final parts.

After creating STL file, it was exported into FDM Insight software to slice and produce tool paths. Given the geometry of the part, only a small number of support slices are produced in order to make sure layers of model Iron/ABS composite material sufficiently bond to substrate, and subsequent movement of

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nozzle head across the different layers would not pull out the part during the build process. Figures 7.7 to 7.9 show screen shots of sliced layers, tool paths of bottom and top layers of the part, respectively using Stratasys Insight software.

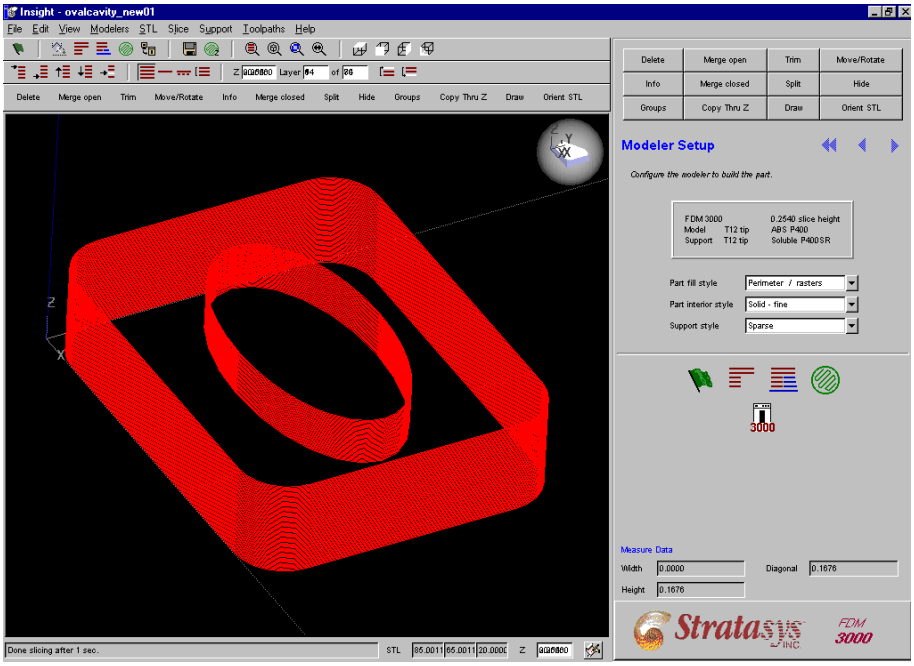

Figure 7-7: Sliced model of the tooling insert for creation of tool paths

A criss-cross raster orientation was used for deposition of successive layers of the composite material on top of one another. Volume of CAD model was computed through the insight software to make sure sufficient amount of ABS/Iron filament material would be available to build the full model. Table 7.1, summarizes the parameters used for the successful processing of ABS/Iron composites using Fused Deposition Modelling.

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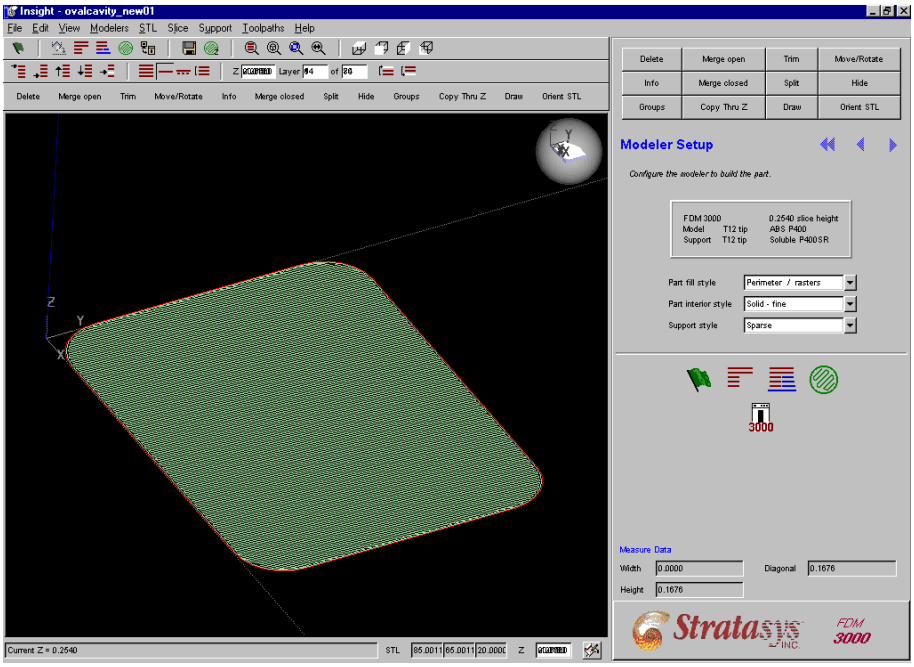

Figure 7-8: A criss-cross fill pattern for the bottom layer of the model

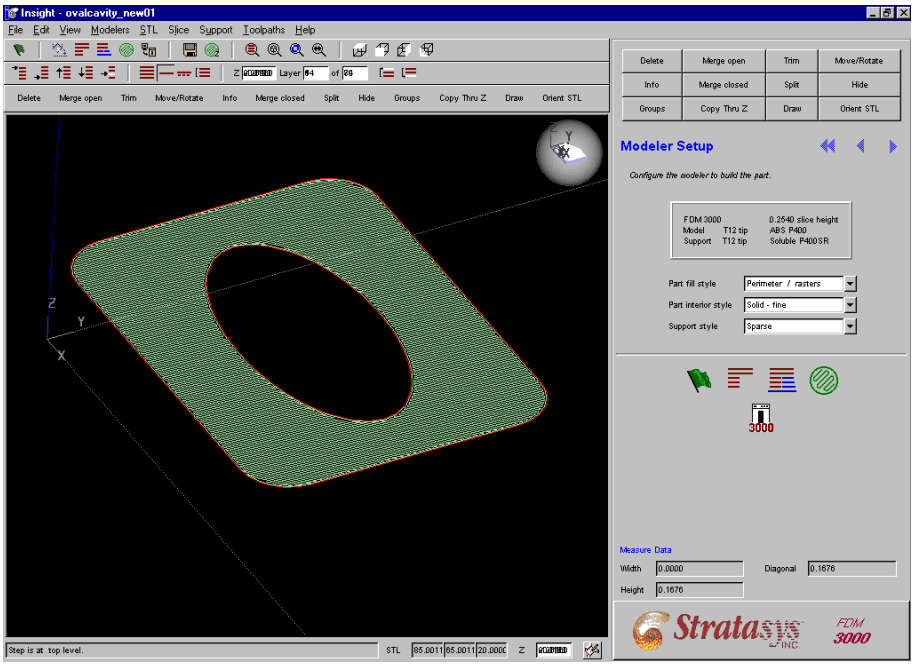

Figure 7-9: Generated tool path shown for the top layer of model

Table7.1. Processing parameters of Fused Deposition Modelling of ABS/Iron composites using Stratasys FDM 3000

Composite Filament Material	25% Vol Fe+ 65%Vol ABS + 10 %Vol Additives
Flow Rate	100-120%
Raster Width	0.5 mm
Model Nozzle Temperature	270 ^{0}C
Support Nozzle Temperature	235 ^{0}C
Envelope Temperature	75 ^{0}C
Raster Orientation	Criss-Cross [+45/-45]
Filament Diameter	1.55 mm
Nozzle Tip Diameter	0.4 mm

Figure7.10 shows a number of metal/polymer composite parts and tool inserts with various shape complexity successfully processed on the fused deposition modelling (FDM3000) platform.

Figure 7-10: Fused Deposition Modelling of ABS/Iron Composites in FDM3000

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It is worth noting that during the initial try-out of rapid manufacturing of ABS/Iron composites, a huge amount of back pressure coupled with the increased viscosity of melt, due to presence of metal powders, hampered the process and resulted in a reverse flow and stoppage of the deposition process. However, through numerical study, a new mozzle with optimum tip-angle was designed and fit into the liquefier of the existing FDM 3000 machine after which a normal flow was observed, and fabrication of the various prototypes was accomplished with no interruption.

7.3. Industrial Implementation

In order to demonstrate direct rapid tooling solution offered by the combination of the newly developed ABS/Iron composites and Fused Deposition Modelling technology, a couple of tooling inserts with rectangular and oval shape cavity were fabricated on the FDM. The inserts were then assembled into injection moulding blades which was also designed taking into account the dimension of the inserts and assembly constraints of the injection moulding machine available at IRIS, Swinburne. Appropriate locator pins, ejector pin and holes were designed and manufactured. A detailed drawing of the injection blades are given in Figure7.11. The assembled tooling insert is shown in Figure7.12 used as cavity to produce some parts from thermoplastic materials.

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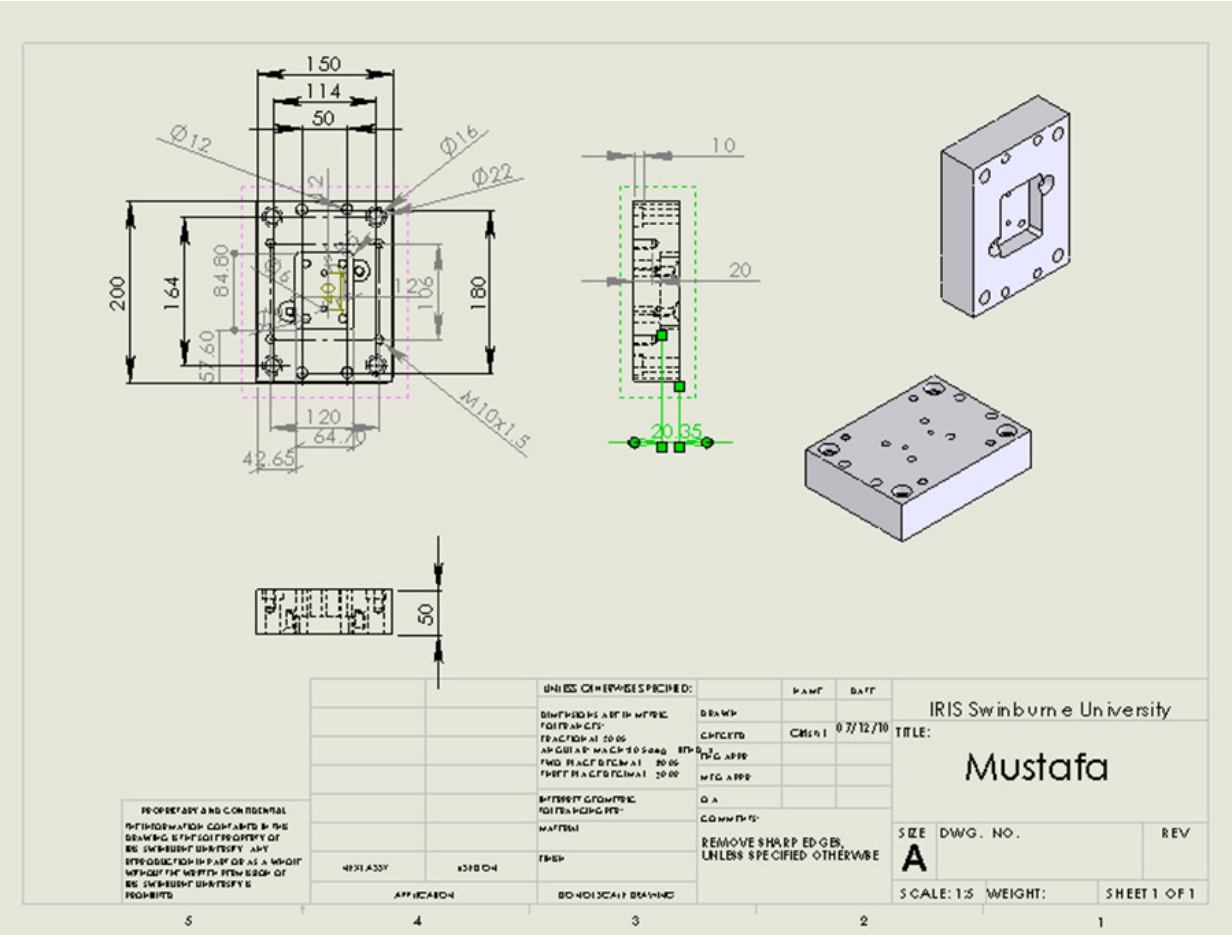

Figure 7-11: Drawing detail of injection blade as the backing for tooling insert

Polypropylene (PP) and high density polyethylene (HDPE) were chosen as the two candidate material for injecting thermoplastic parts.

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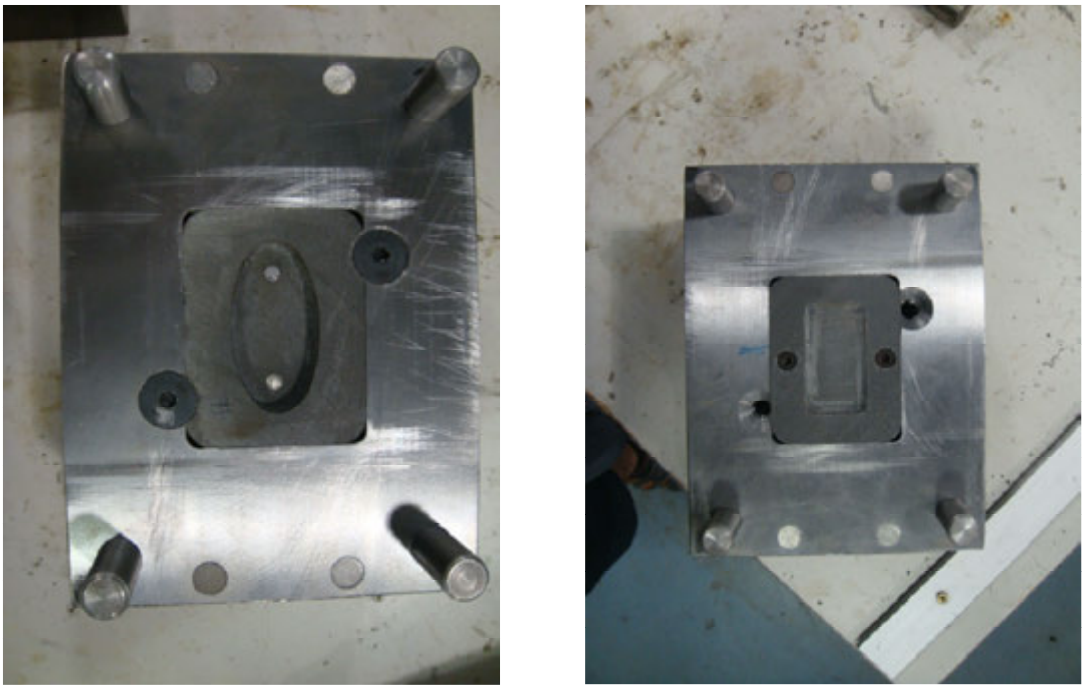

Figure 7-12: Oval and rectangular tooling inserts assembled into an injection moulding blade

Direct rapid tooling process was implemented in two stages: Initially, for a trial run, a small scale cavity was made from the new composite material on FDM. The cavity was fixed inside an aluminium backing plate for ease of assembling it into a larger steel frame as shown in Figure7.13. Then a mini injection moulding machine, as shown in Figure 7.14 was used to inject a polypropylene thermoplastic into the mini-cavity and the filling process was observed.

Mini injection moulding was accomplished successfully, and a small part was produced in the first shot (Figure7.15). However, during ejection of injected part a strong adhesion between the part boundary and the cavity wall was experienced, which required application of extra force to take the injected part out. This slightly damaged the part edge. In order to resolve this, two types of mould release agent were tested, and it was understood that spraying a certain

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amount of such release materials would facilitate the ejection of plastic parts at the end of injection cycle.

Figure 7-13: Mini tool insert fabricated on FDM fitted into steel blade for injection moulding

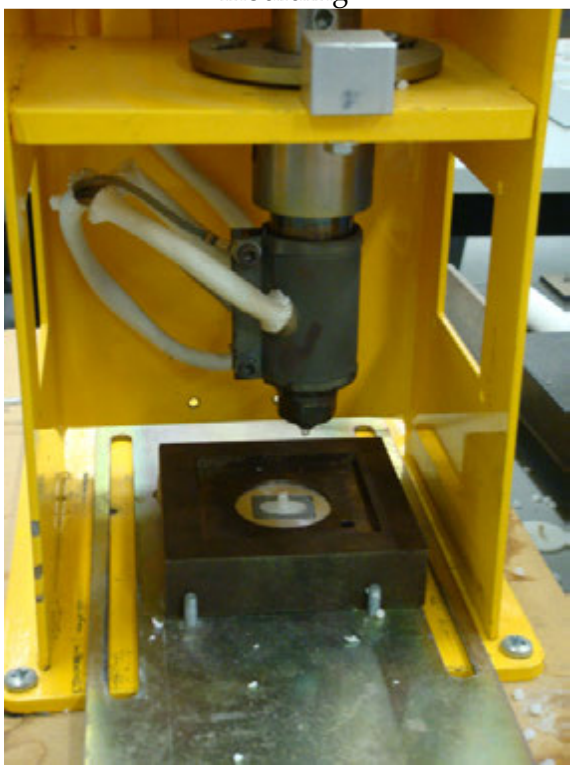

Figure 7-14: Mini injection moulding of polypropylene into metal/polymer tool inserts

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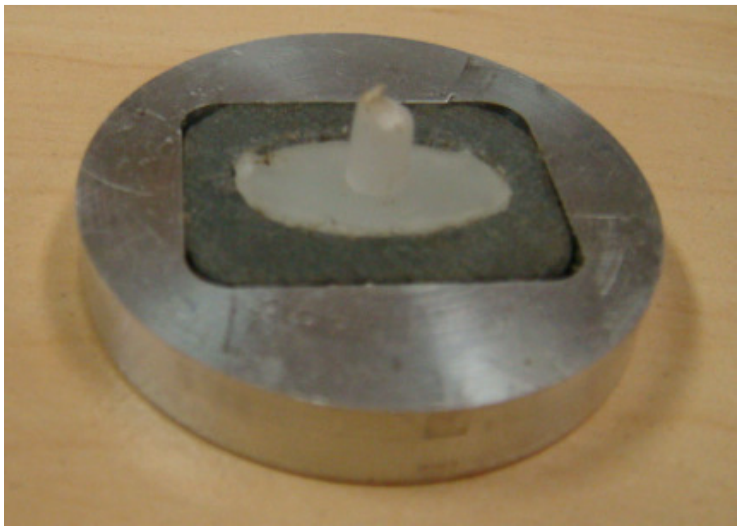

Figure 7-15: Polypropylene part made in mini injection moulding process on an ABS/Iron tool inserts

Figure7.16 shows a full scale Iron/ABS insert made by FDM process fitted into a Battenfeld injection moulding machine (Figure7.17) for injection moulding of polypropylene(PP). Barrel temperature used were 204 ^{0}C, 218 ^{0}C, 232 ^{0}C,232 ^{0}C for rear, centre, front and nozzle part of the heating barrel, respectively. Mould temperature of 50 ^{0}C , and melt temperature of 240 ^{0}C was used, and injection hold pressure was applied at 50% of the maximum machine pressure of 14 MPa in order to avoid flashing. A medium-to-fast fill rate was used for cavity filling.

Barrel temperature setting for HDPE was 232 ^{0}C, 243 ^{0}C, and 246 ^{0}C, 246 ^{0}C for rear, centre, front and nozzle, respectively. The rest of processing parameters were similar to those of PP. A cycle time of 10 seconds was used for injection moulding of both thermoplastic materials into Iron/ABS composite inserts. This cycle time was sufficient for filling of the entire cavity, and at the same time it kept the residence time of molten thermoplastic to a minimum within the metal/polymer cavity, during which composite material did not exceed its glass transition temperature. It was crucial that the die material did not get exposed to temperatures beyond its glass transition, and therefore it could

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withstand high injection moulding pressure with its full capacity of storage modulus.

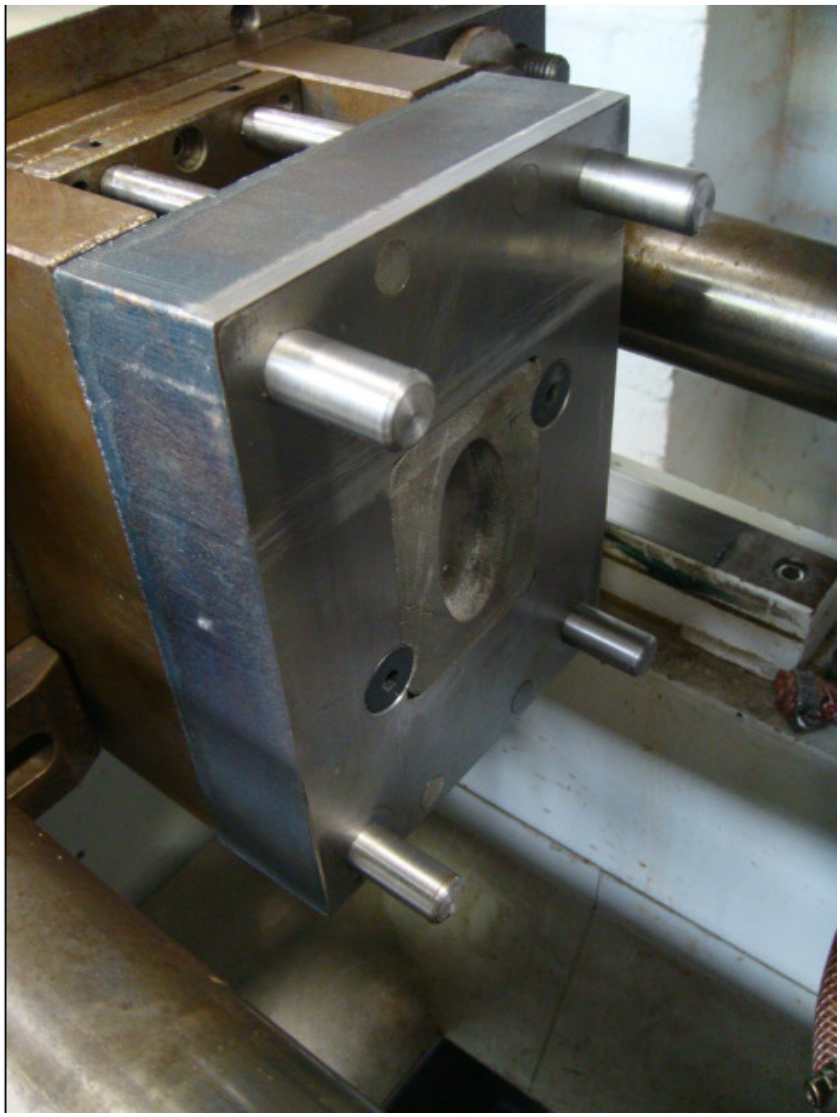

Figure 7-16: Injection moulding cavity insert of ABS/Iron composite fitted into the injection mould base

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Figure 7-17: Battenfeld Injection Moulding machine was fitted with metal/polymer tool inserts

Finally, oval and rectangular shaped parts, as shown in Figure 7.18, and Figure 7.19, were successfully injected from polypropylene and high density polyethylene material into the Iron/ABS composite cavity processed by Fused Deposition Modelling Process.

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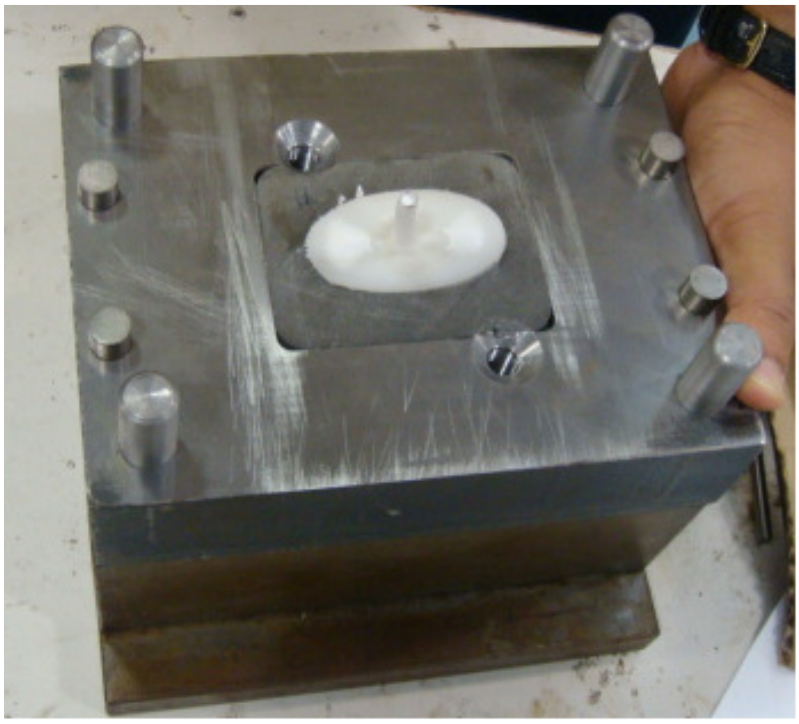

Figure 7-18: PP part produced by injection moulding into Iron/ABS tool insert made on FDM platform.

Figure 7-19: HDPE part produced by injection moulding into Iron/ABS tool insert made on FDM platform

Experimental trials of direct rapid tooling of our new metal/polymer composites have shown that the material can be used in making tooling inserts

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and dies for injection moulding. More refinement of the process is required to convert it to a commercially viable process.

It should also be noted that there are several rapid manufacturing systems, such as selective laser melting and electron beam melting, available, which can be used for direct fabrication of tooling. But such systems are extremely expensive powder based and have not been accepted by tooling industries due to high costs of equipment and powder metals. Our FDM-based direct rapid tooling process with our new metal/polymer will provide a much more cost-effective option for tooling industry for applications in short to medium run production and mass customisation.

7.4. Summary

Tooling inserts and parts with simple to complex geometries were successfully produced using the newly developed metal/polymer composites on Fused Deposition Modelling platform. A direct rapid tooling has been tested using such composites to develop injection moulding dies and tooling inserts. By employing these metal/polymer composite tools, functional parts of different shapes from two different thermoplastic materials namely, polypropylene (PP) and high density polyethylene (HDPE) were produced successfully both in laboratory type and production scale injection moulding machines.

Application of the new metal/polymer composite material in fused deposition platform offer a unique highly customized, and inexpensive solutions of direct rapid tooling for short term production run in injection moulding application. Improved thermo-mechanical properties of such materials coupled with layered manufacturing capability of FDM technology, injection moulding dies and inserts can be produced with conformal cooling channels leading to tremendous improvement of production time through cycle time reduction and increase of quality of injection moulded parts. Moreover, the new material itself

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can be used for direct fabrication of functional parts for various engineering applications.

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Chapter 8 Conclusions and Recommendations

8.1. Introduction

The principal objective of this research was to develop new metal/polymer composite materials for direct use in the current Fused Deposition Modelling rapid prototyping platform with long term aim of developing direct rapid tooling on the FDM system. Using such composites, the direct rapid tooling will allow fabrication of injection moulding dies and inserts with desired thermal and mechanical properties suitable for using directly in injection moulding machines for short term or long term production runs. The new metal/polymer composite material developed in this research work involves use of mainly iron particles in a polymer matrix of ABS material, which offers much improved thermal, electrical and mechanical properties enabling current Fused Deposition Modelling technique to produce rapid functional parts and tooling.

8.2. Major Findings & Original Contributions

Initially, some new and unique sets of metal/ABS composite have been processed with the aim of providing complimentary feedstock materials for use in Fused Deposition Modelling rapid prototyping process. As outlined in Chapter 2, development of new materials is indispensible to the process of shifting current FDM *prototyping* process towards a viable rapid *manufacturing* process. Such materials fill the outstanding gap in properties and functionalities, which cannot be offered by the existing feedstock materials. For this purpose, various compositions of metal/ABS composites containing Iron and Copper particles as metallic fillers, as well as appropriate amounts of surfactants and plasticiser were processed delivering desired properties.

In order to be able to use these new composites as feedstock material in current FDM3000 prototyping platform, without any hardware modification, development of durable and flexible filaments of the new material with

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required properties was the second major contribution of this research work, details of which have been outlined in Chapter 3.

The most challenging step in accomplishment of developing new composites for FDM has been the application of correct proportions of various elements and constituents for the composites, which has been overcome by rigorous rheological study of such composites containing varying volume fractions of filler, surfactants, and under varying temperature. Through extensive rheological studies, as detailed in Chapter 4, optimum combinations, and ranges of filler/additives/polymer have been found for the successful processing of metal/polymer filaments. In addition, the best viscosity model representing metal/polymer melts has been identified for use in numerical analysis of developing such composites for wider use and applications in extrusion based RM processes.

Extensive experiments were carried out to fully characterise new composites materials processed and developed during this research. Mechanical, thermal and electrical properties of parts and tools made using the fused deposition modelling technology would inevitably depend on the static and dynamic response, heat capacity, thermal conductivity as well as intrinsic resistivity of their initial building material, respectively. In particular, the knowledge of static and dynamic behaviour of Fe/ABS composite materials will be necessary in designing the applications for prototypes, and tools developed based on such materials on the FDM rapid manufacturing/tooling platform.

It has been shown that the new metal/polymer composite material developed in this research work, involving use of iron particles and copper particles in a polymer matrix of ABS material, offers much improved thermal, electrical and dynamic mechanical properties enabling current Fused Deposition Modelling technique to produce rapid functional parts and tooling. Higher thermal conductivity of the new metal/polymer composite material coupled with

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implementation of conformal cooling channels enabled by layer-by layer fabrication technology of the Fused Deposition Modelling will result in tremendously improved injection cycles times, and thereby reducing the cost and lead time of injection moulding tooling.

Due to highly metal-particulate filled matrix of the new composite material, injection tools and inserts made using this material on Fused Deposition Modelling, will demonstrate a higher stiffness comparing to those made out of pure polymeric material resulting in withstanding higher injection moulding pressures. Moreover, metallic filler content of the new composite allows processing of functional parts with electrical conductivity and in case of using ferromagnetic fillers, namely as fine iron powders, it introduces magnetic properties which will make FDM-built components suitable for electronic applications specifically whereby shielding electromagnetic interference is of high interest.

Through Melt-Flow analysis of the new material for FDM processing, using finite element and finite volume based commercial codes, it was found that the effect of back pressure is particularly important in relation to extruding high viscous Iron/ABS composites through the nozzle of FDM. The effect of applying low turbulence model, due to a number of vortices and severe back flow in the case that the diameter of exit nozzle is too small or the angle of nozzle tip is too large, was identified as the indispensible parameter in having converged results of numerical simulation. This can therefore reliably predict the melt flow behaviour including velocity and pressure fields as well as temperature gradient from computer based numerical analyses. It was found that there is an optimum value, where a relationship between the exit angle and diameter of tip nozzle is dictating the design of such nozzles and practical success of extruding such composites through the FDM head.

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Finally, tooling inserts and parts with simple to complex geometries were successfully produced using the newly developed metal/polymer composites on Fused Deposition Modelling platform. A direct rapid tooling has been tested using such composites to develop injection moulding dies and tooling inserts. By employing these metal/polymer composite tools, functional parts of different shapes from two different thermoplastic materials namely, polypropylene (PP) and high density polyethylene (HDPE) were produced successfully both in laboratory type and production scale injection moulding machines.

Application of the new metal/polymer composite material in fused deposition platform offers a unique highly customized, and inexpensive solution of direct rapid tooling for short term production run in injection moulding application. Improved thermo-mechanical properties of such materials coupled with layered manufacturing capability of FDM technology, injection moulding dies and inserts can be produced with conformal cooling channels leading to tremendous improvement of production time and increase of quality of injection moulded parts. Moreover, the new material itself can be used for direct fabrication of functional parts for various engineering applications.

8.3. Recommendation for Future Work

As emphasized throughout this thesis, introduction of new materials is and will continue to be the most outstanding requirement, which upon fulfilment will drive the shift from existing rapid prototyping processes towards viable future rapid manufacturing processes. Composites are particularly attractive materials for use with FDM, as its unique technology allows producing tools and parts with unique properties based on synergism of multiple components in such materials, in a way much simpler and faster than the conventional manufacturing processes.

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With emerging technologies enabling production of inexpensive and affordable nano fibres and nano particles, development of nano-compsoites can offer new generation of materials suitable for fused deposition modelling technology. However, certain challenges will continue to hamper development of such materials, and therefore more rigorous research will need to be conducted accordingly. The choices of nano carbon fibres and nano carbon tubes combined with engineering plastics such as polyether ether ketone (PEEK) are exemplary candidates of elements for developing nanocompsoites for FDM as rapid manufacturing process.

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Appendix A

Morphology of Metal/Polymer Composites

The morphology of both Iron and ABS composites, and Copper and ABS composites, as one of the most important parameters influencing the interfacial bonding of the filler-matrix (Bigg 1983) was studied using Scanning Electron Microscopy (SEM). The following images show the elemental investigation of the new composites and their surface morphology using Energy Dispersive X-ray Spectroscopy (EDS) and SEM respectively. They indicate the homogenous mixing of the composites.

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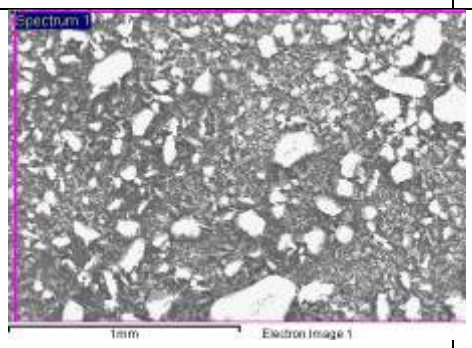
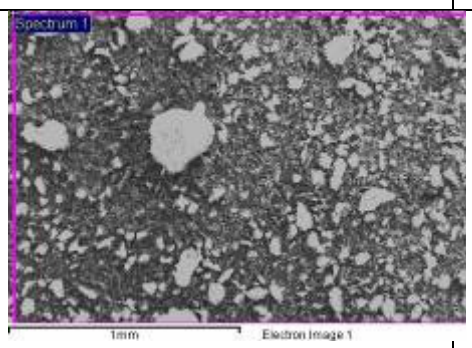
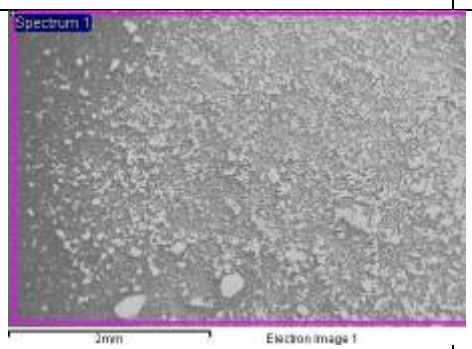
A.1: EDS Result of ABS and Iron (6-9 µm) Composites

IRON - Carbonyl-Iron (6-9µm) & ABS Composite				
No	% Vol		Image	Component Composition
	Metal	Polymer		
1	5	95		Element / Weight% / Atomic% C K / 86.15 / 94.26 O K / 4.23 / 3.47 Fe K / 9.62 / 2.26 Totals / 100.00
2	10	90		Element / Weight% / Atomic% C K / 78.84 / 93.10 O K / 2.42 / 2.14 Fe K / 18.74 / 4.76 Totals / 100.00
3	20	80		Element / Weight% / Atomic% C K / 58.40 / 86.72 Fe K / 41.60 / 13.28 Totals / 100.00

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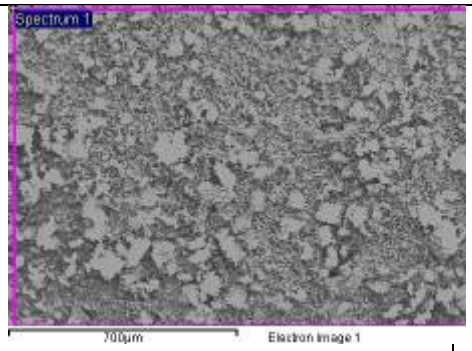
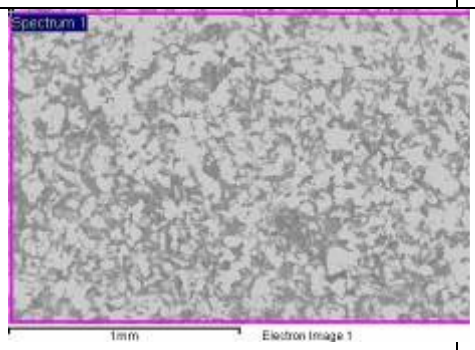
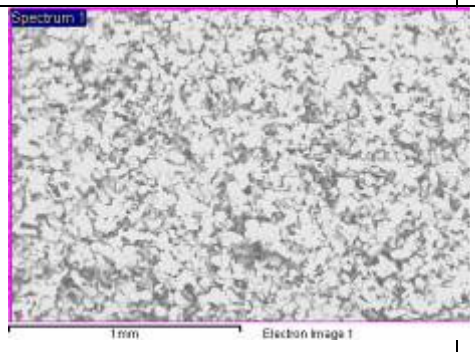
4	30	70		

Element	Weight%	Atomic%
C K	45.42	79.46
Fe K	54.58	20.54
Totals	100.00	

A.2: EDS Result of ABS and Copper (45 µm) Composites

COPPER (+45µm) and ABS Composite				
No	% Vol		Image	Component Composition
	Metal	Polymer		
5	5	95		
6	10	90		

Element	Weight%	Atomic%
C K	73.34	92.62
O K	1.44	1.36
Cu L	25.22	6.02
Totals	100.00	

Element	Weight%	Atomic%
C K	58.63	86.78
O K	1.98	2.20
Cu L	39.40	11.02
Totals	100.00	

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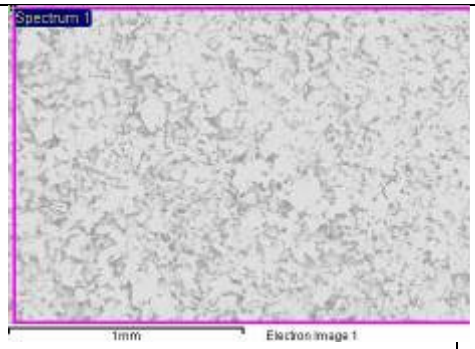
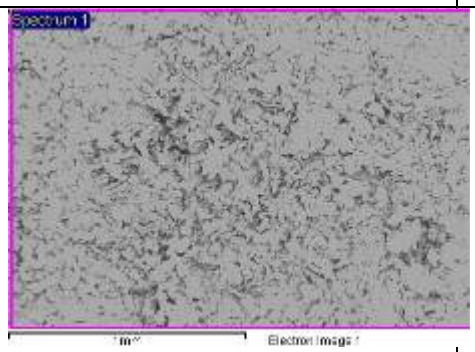
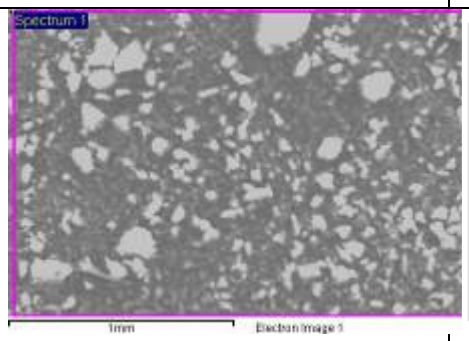
7	20	80		Element / Weight% / Atomic% C K / 42.74 / 78.11 O K / 2.06 / 2.82 Cu L / 55.20 / 19.07 Totals / 100.00
8	30	70		Element / Weight% / Atomic% C K / 27.29 / 64.45 O K / 2.34 / 4.14 Cu L / 70.37 / 31.41 Totals / 100.00

A.3: EDS Result of ABS and Copper (10 µm) Composites

COPPER (<10µm) and ABS Composite				
No	% Vol		Image	Component Composition
	Metal	Polymer		
9	5	95		Element / Weight% / Atomic% C K / 90.59 / 96.75 O K / 2.26 / 1.81 Cu L / 7.15 / 1.44 Totals / 100.00

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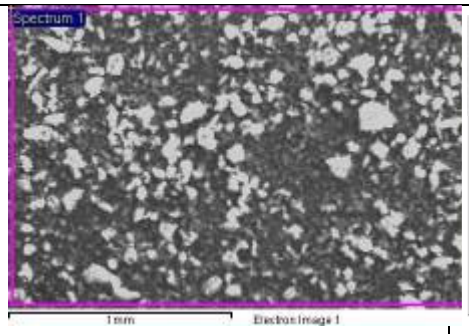
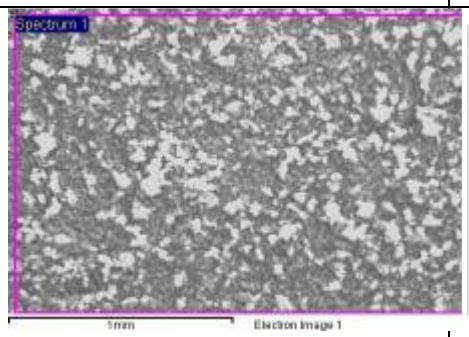
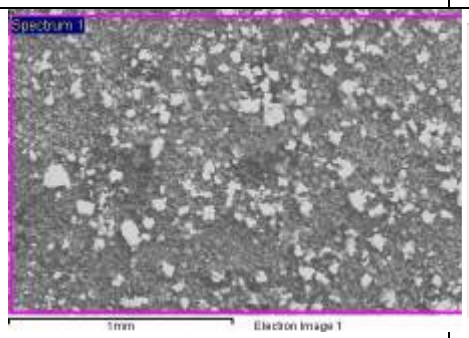
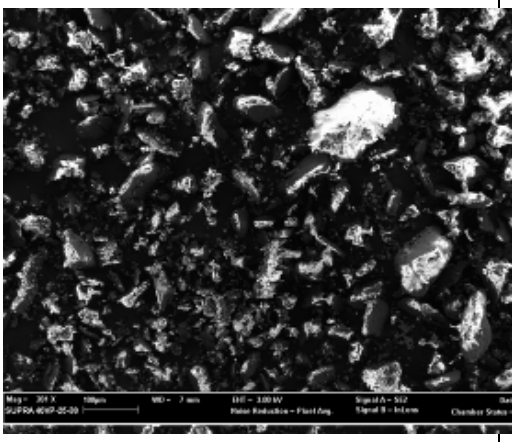
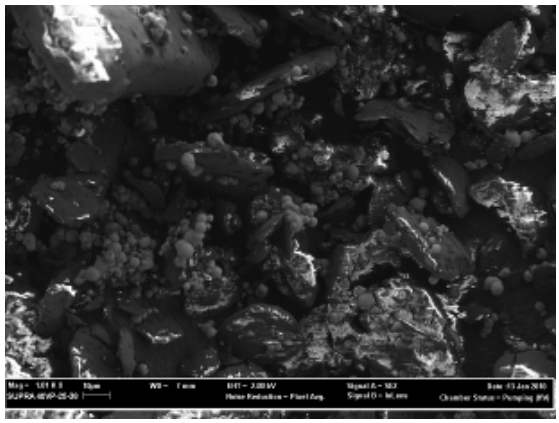
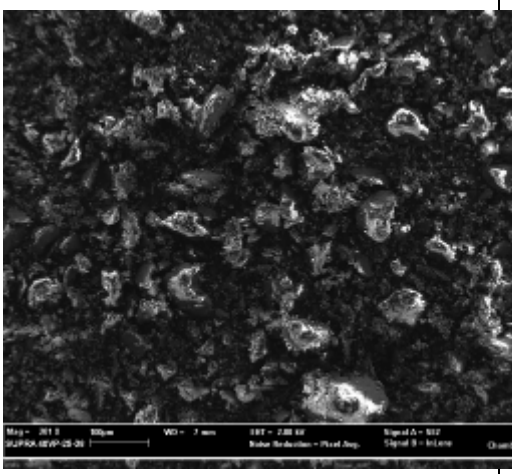
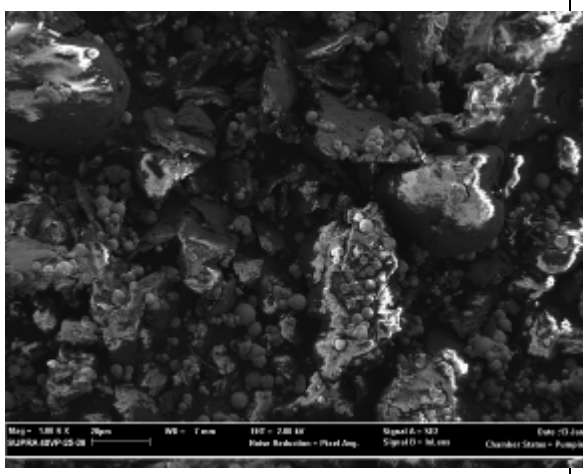
10	10	90		Element / Weight% / Atomic% C K / 86.52 / 96.08 O K / 1.74 / 1.45 Cu L / 11.73 / 2.46 Totals / 100.00
11	20	80		Element / Weight% / Atomic% C K / 73.09 / 92.33 O K / 1.75 / 1.66 Cu L / 25.16 / 6.01 Totals / 100.00
12	30	70		Element / Weight% / Atomic% C K / 63.08 / 88.86 O K / 1.65 / 1.74 Cu L / 35.27 / 9.39 Totals / 100.00

A.4: SEM Images of ABS and Iron (6-9 μm) Composites

IRON - Carbonyl-Iron (6-9μm) & ABS Composite			
% Vol.		200 x	1.00k x
Metal	Polymer		
5	95		
10	90		

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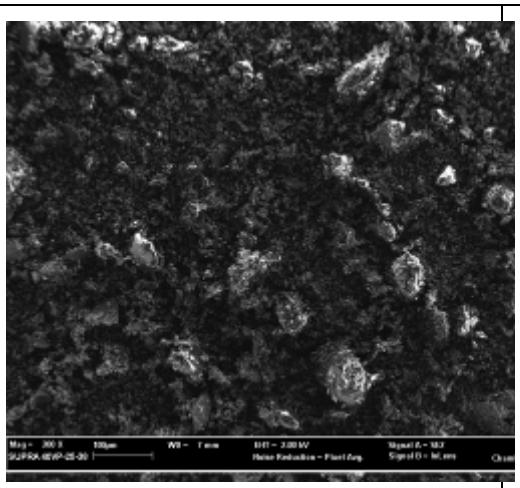
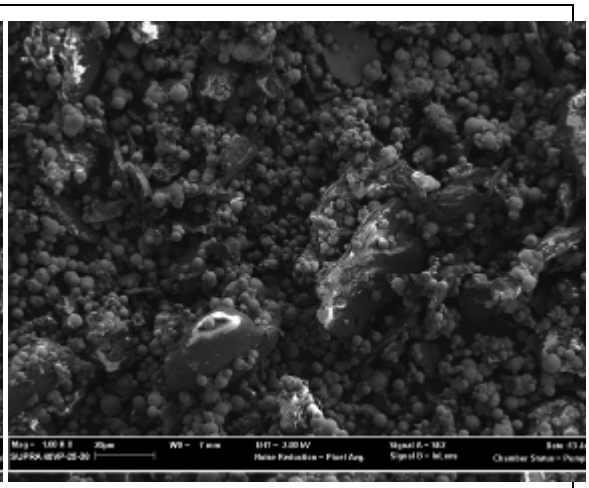
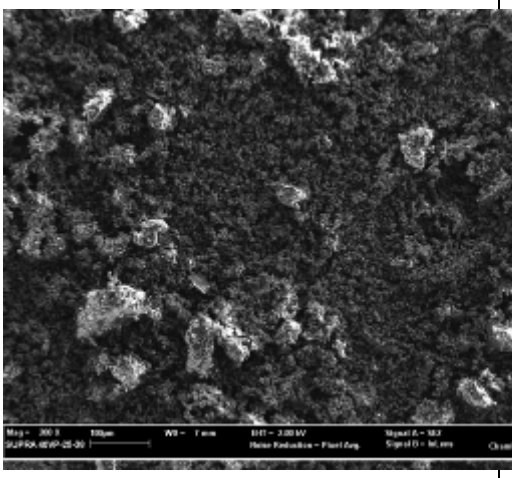
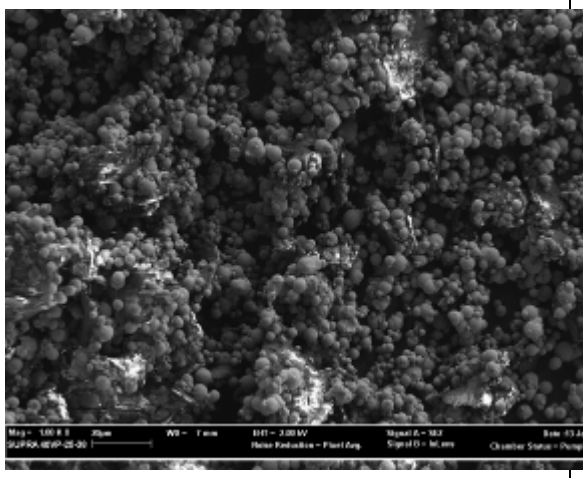
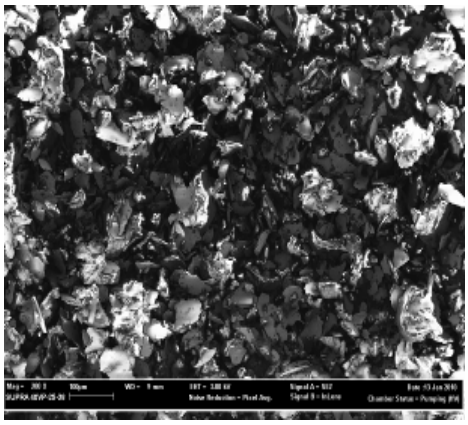
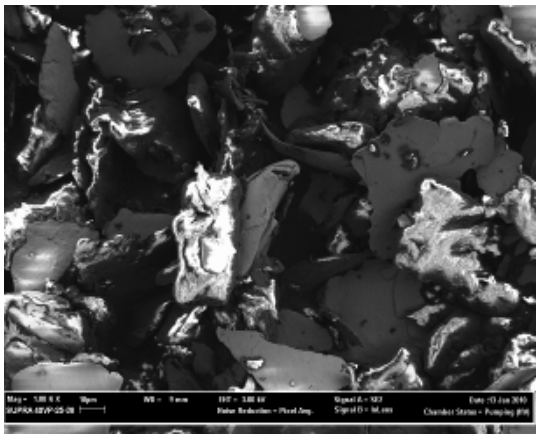
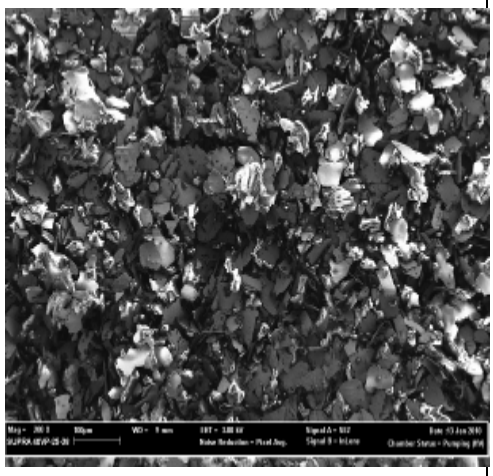
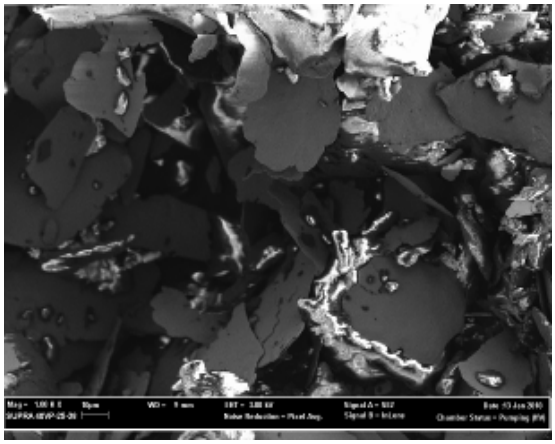
20	80		
30	70		

A.5: SEM Images of ABS and Copper (45 μm) Composites

COPPER (+45μm) and ABS Composite			
% Vol.		200 x	1.00k x
Metal	Polymer		
5	95		
10	90		

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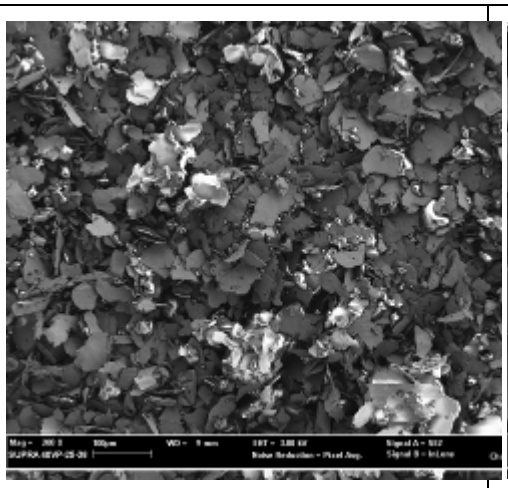
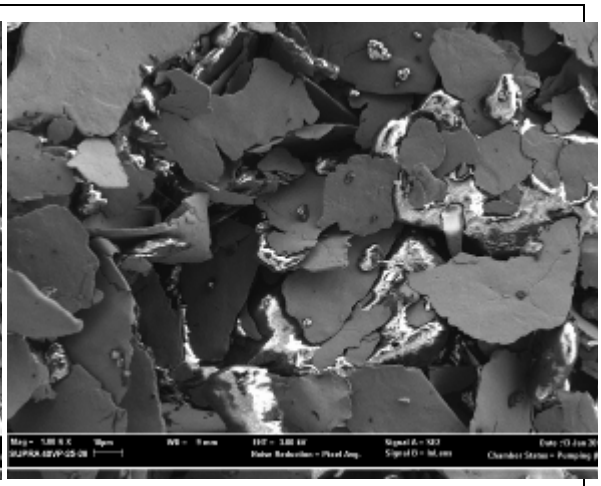
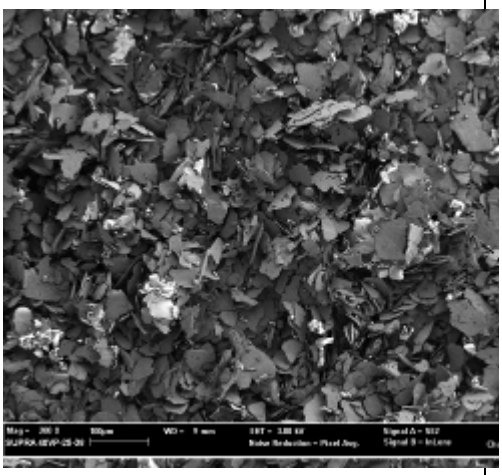
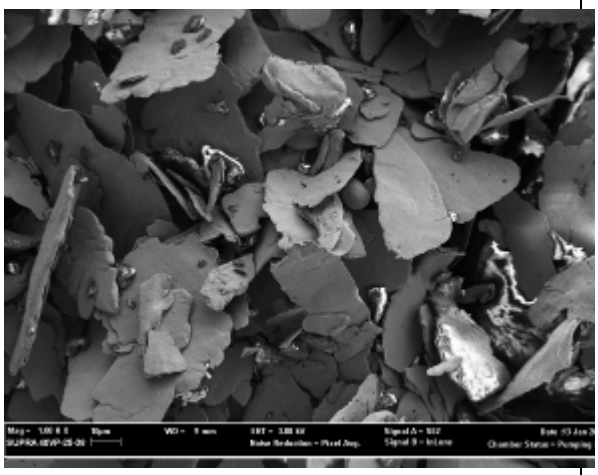
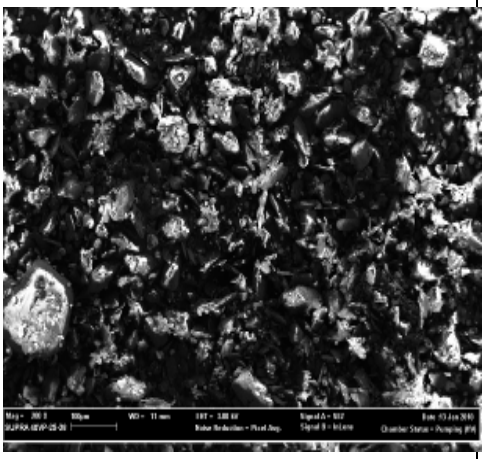
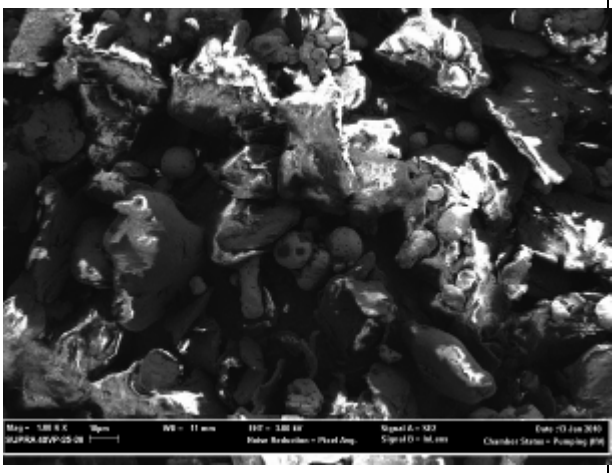
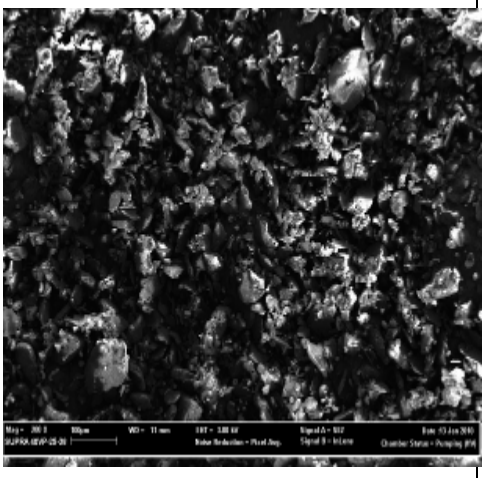
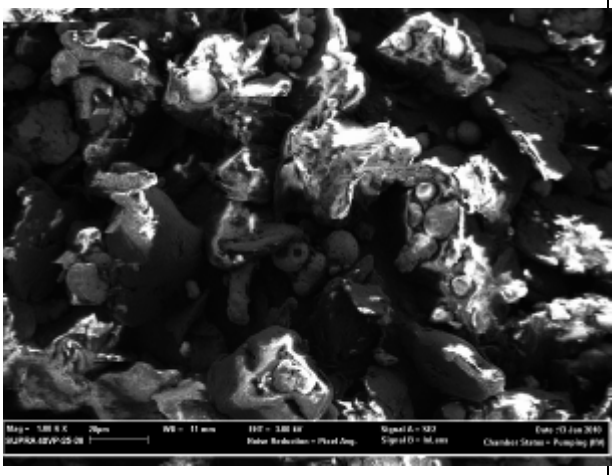
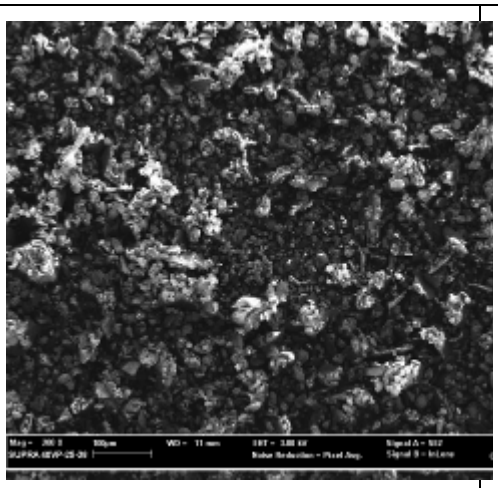
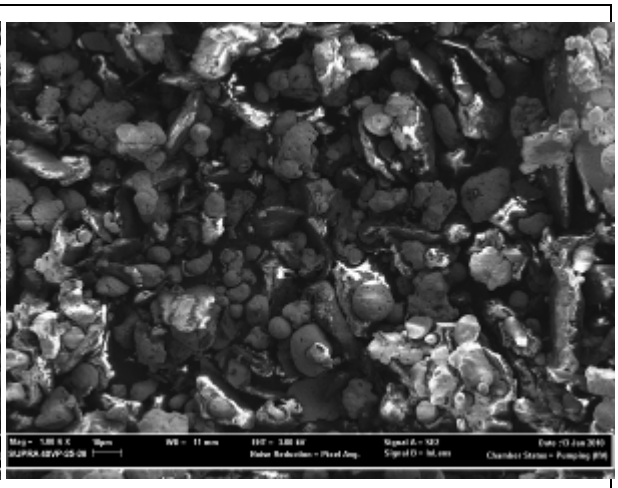
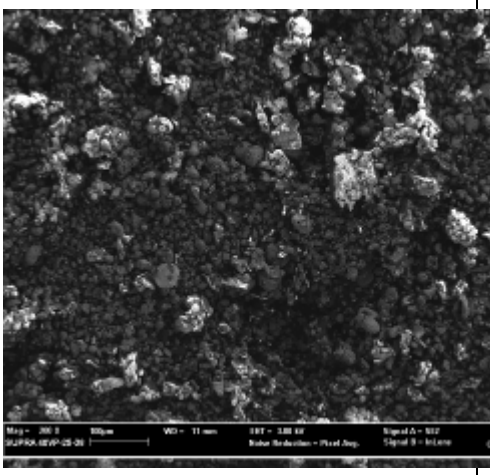
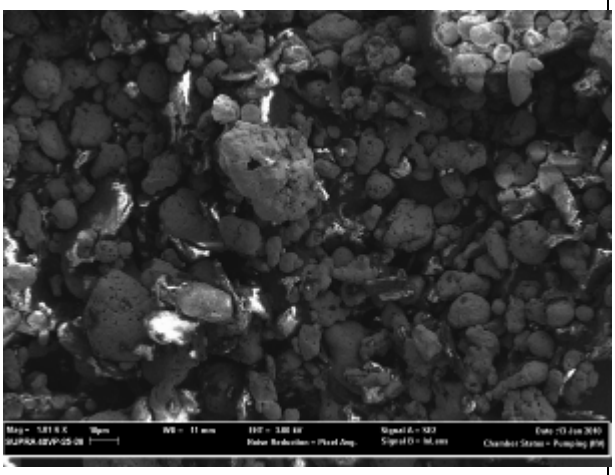
20	80		
30	70		

A.6: SEM Images of ABS and Copper (10 μm) Composites

COPPER (<10μm) and ABS Composite			
% Vol.		200 x	1.00k x
Metal	Polymer		
5	95		
10	90		

20	80		
30	70		

Appendix B

Publications from This Research

B1: Refereed Journal Papers

1). Mostafa Nikzad, S. H. Masood, I.Sbarski, "Thermo-mechanical Properties of a Highly Filled Polymeric Composite for Fused Deposition Modelling", Materials & Design, Vol.32, Issue 6(2011), pp. 3448-3456.

2). Mostafa Nikzad, S. H. Masood, I.Sbarski, A.Groth, "Rheological Properties of a Particulate-filled Polymeric Composite through Fused Deposition Process", Materials Science Forum, Vol.654-656 (2010), Trans Tech Pub, pp. 2471-2474.

3). Mostafa Nikzad, S. H. Masood, I.Sbarski, A.Groth, "A Study of Melt Flow Analysis of an ABS-Iron composite in Fused Deposition Modelling Process", Tsinghua Science and Technology Journal, Elsevier, Vol 14, No S1, June 2009, pp 29-37.

B2: Refereed Conference Papers

4). Mostafa Nikzad, S. H. Masood, I.Sbarski, A.Groth, "Thermo-mechanical properties of a metal-filled polymer composite for fused deposition modelling applications", Proceedings of 5th Australasian Congress on Applied Mechanics, (ACAM 2007), December 10-12, 2007, Brisbane, Australia, pp.319-324.

5). S.H. Masood, M. Nikzad, V.Patel, "Melt flow analysis of ABS in Fused Deposition Modelling Process", Proceedings Annual Technical Conference 2009 *(ANTEC)*, Society of Plastics Engineers, Chicago, USA, June 2009, pp.1355-1359.

Markforged Ex. 1009
Markforged v. Continuous Composites, IPR2022-01218

(12) UK Patent Application (19) GB (11) 2 213 793 (13) A

(43) Date of A publication 23.08.1989

(21) Application No 8826325.6

(22) Date of filing 10.11.1988

(30) Priority data
(31) 3743485 (32) 22.12.1987 (33) DE

(51) INT CL⁴
B65H 81/00

(52) UK CL (Edition J)
B8G G1D G4

(56) Documents cited
GB 1160021 A GB 1114657 A EP 0265915 A2
US 4170505 A

(58) Field of search
UK CL (Edition J) B8G
INT CL⁴ B65H

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(54) Winding airfoil

(57) In the manufacture of a three-dimensionally twisted airfoil of a rotor blade, a fibre strand 9 is continuously impregnated with resin material, pressed by roller 11 on to an airfoil surface 1 and immediately precured at 15. The method permits the fast, simple and fully automatic manufacture of airfoils. The precuring device 15 may be an infrared radiator. The strand may be looped around nipples on a blade root. The winding device may be a six-axis robot. The precured airfoil is cured in a mould.

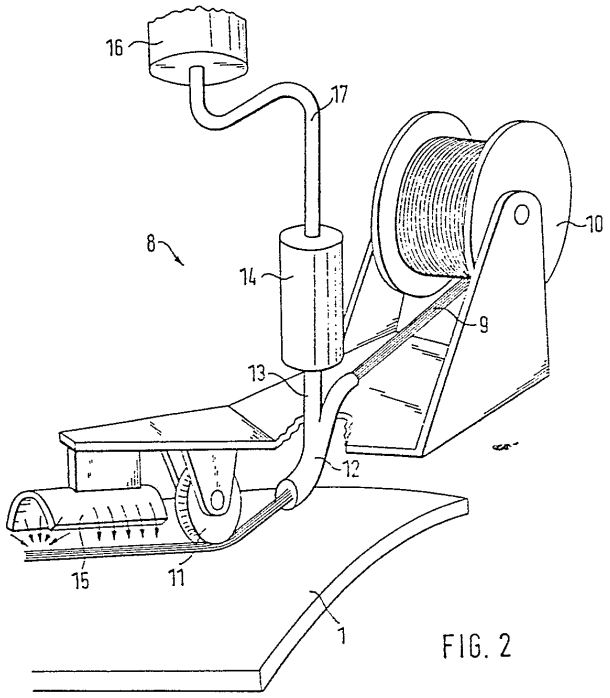

FIG. 2

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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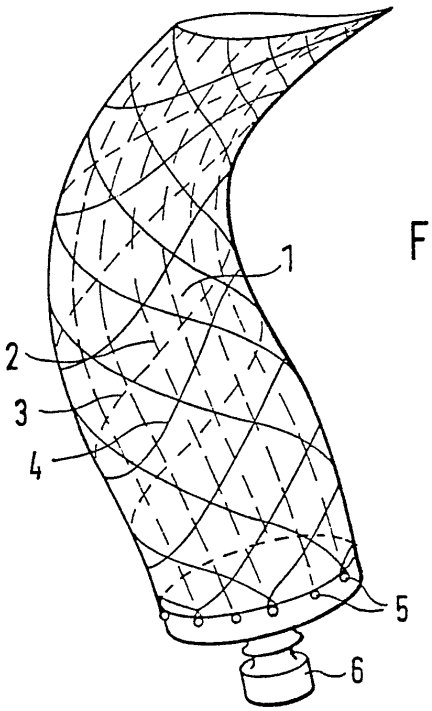

FIG.1

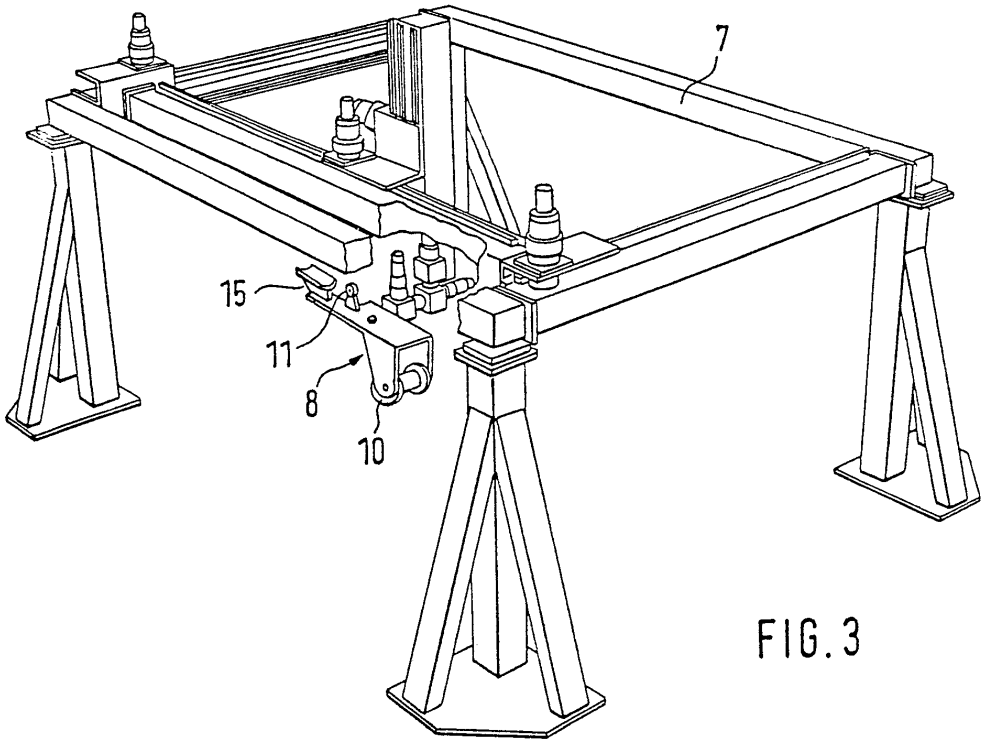

FIG.3

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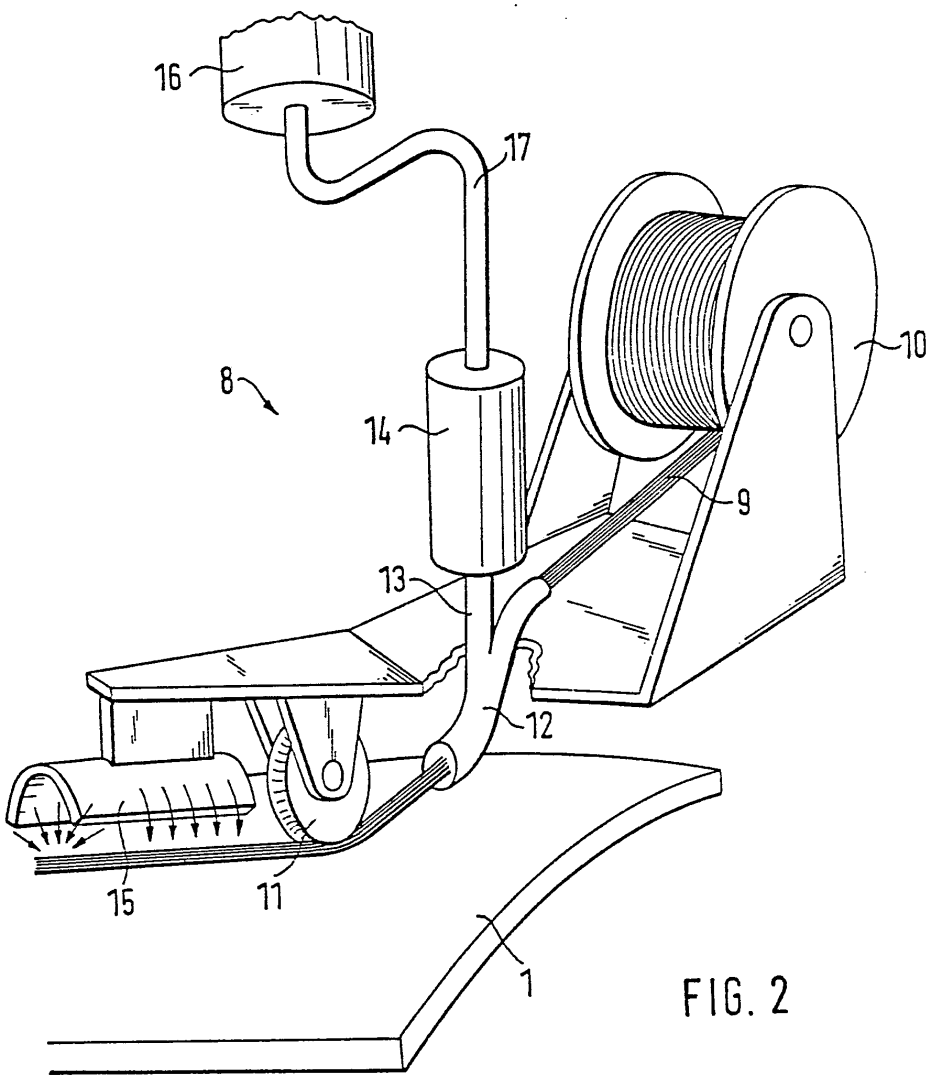

FIG. 2

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METHOD FOR MANUFACTURING A THREE-DIMENSIONALLY TWISTED ROTOR BLADE AIRFOIL

This invention relates to a method for the manufacture of a fibre reinforced component, particularly a three-dimensionally twisted rotor blade airfoil, by wrapping a core with a resin-impregnated fibre material.

Fibre components are rapidly gaining technical significance on account of their excellent properties. Their low density, high tensile strength and relative ease of shaping invites their use in areas that had formerly been the sole domain of metallic materials. Fibre-reinforced materials, e.g. are also finding use in aircraft applications, as for dynamically highly stressed rotor blades and propellors or for propfan airfoils.

Another outstanding property of fibre-reinforced materials is the option of influencing component properties by laying the fibres in preferred orientation to obtain different material data in different directions for, e.g. the modulus of elasticity or damping constants.

Technical problems are encountered, however, in the manufacture of fibre-reinforced components of complex shapes with three-dimensionally twisted surfaces, especially if these take a partially concave form and if the requirements are for different strength and vibration properties in different directions. This applies particularly to modern turbine engine fan or propan blades, where the attachment of the airfoil to the root or rotor poses another specific problem.

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Conventional manufacture of these components is associated with considerable effort involving high manufacturing costs. It employs so-called prepegs, which are fibre panels impregnated with a matrix material and inserted in a hollow mould to be cured under pressure and heat. One disadvantage of this method is the extremely high cost involved when trying to deliberately influence component properties with it, which basically is a feasible proposition.

One object of this invention is to enable the manufacture of a fibre-reinforced component, particularly a three-dimensionally twisted rotor blade airfoil by a simple and rapid method that permits selective manipulation of component properties by selective routing of the fibres and more particularly so as to permit ready application of fibres also to concave surfaces.

According to this invention we propose a method for the manufacture of a fibre-reinforced component such as an airfoil, particularly a three-dimensionally twisted rotor blade airfoil by wrapping a core with a resin impregnated fibre material, wherein fibre strands wetted with a resin matrix are pressed against the core for example, by means of a nip roller, and the resin matrix precured immediately thereafter, preferably by a precuring facility such as an infrared radiator coupled to the nip roller.

Fibres can be applied in a simple manner, in each and every direction and on any shape of airfoil surface and

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so that they will then adhere and not subsequently become dislodged. After the fibres have precured they will adhere also to concave surfaces, so they can be laid rapidly and accurately in position. Depending on requirements several plies of fibre can be deposited one over the other in different or identical orientations.

Precuring the matrix material causes it to gel to a point where the fibre is cemented in place before the fibre matrix mixture still is fully cured. Thereafter the wrapped component is pressed to final size in a mould and cured in a furnace.

The time needed to manufacture a twisted fibre component is substantially shorter than that expended in conventional manufacture. An essential consideration also is that concave blades can simply and accurately be covered with layers of fibre, which with the conventional methods of fibre application cannot be achieved with full satisfaction.

This much simplifies the wrapping process and so makes it susceptible of fully automated computer and robot controlled implementation.

The fibre strands can advantageously be laid along preferred tracks. This permits a selective anisotropic component structure to be achieved in arrangements benefiting stability and strength. This helps eliminate especially vibration problems.

In a preferred embodiment, the fibre strands are looped around a number of attaching nipples on the blade root to

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attach the airfoil to the root. This permits a particularly favourable transfer of the centrifugal forces acting on the root in operation.

Embodiments of the present invention will now be described by way of example with reference to the accompanying drawings, in which

Figure 1 is a perspective view illustrating a fan blade;

Figure 2 is a perspective view illustrating a fibre laying device; and

Figure 3 is a perspective view illustrating a six-axis portal robot.

With reference now to Figure 1 the airfoil 1 of a rotor blade is shown. Depicted also are the preferred directions of the fibres to be deposited: the main tensile direction 2 and the diagonal layers 3 and 4. The fibres are preferably looped around attaching nipples 5 on a blade root 6, so as to ensure a satisfactory union between the two components and for good transfer to the blade root 6 of the tensile force arising in operation.

The fibre laying device 8 shown in Figure 2 essentially comprises a fibre drum 10, a fibre feed duct 12 leading to a fibre nip roll 11, and a precuring facility 15. The fibre strand 9 unwound from the fibre drum 10 is pulled by the nip roll 11 through the fibre feed duct 12 into which matrix material is fed in defined quantities from a matrix metering unit 14 through a feed duct 13. The matrix material is supplied from a storage container 16 to the matrix metering unit 14 through a

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flexible feed line 17. The volume of matrix fed per unit length of fibre can be adjusted, preferably to suit the fibre throughput. Having been wetted in this manner the fibres are accurately laid on to the component in the desired track under the fibre nip roll 11 and are precured (gelled) by means of the precuring device 15, causing the surface to dry and stick. In this manner, the fibre is fixed to a point where it can be laid on to radiused tracks. Thereafter, further fibre layers can be deposited in any desired orientation over the precured fibres.

As it will become apparent from Figure 3, the fibre laying device 8 here shown in schematic arrangement is connected to the "wrist" of a six-axis portal robot 7 and can thus - under computer control - deposit the fibre strand 9 on the component core fully automatically along precalculated tracks. This makes for very accurate reproducibility (< 0.2 mm) of the fibre laying process.

The rough item having been manufactured in this manner, is then placed in a mould and conventionally finish cured under pressure and heat.

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CLAIMS

1. A method for the manufacture of a fibre-reinforcedx component by wrapping a core with a resin-impregnated fibre material, wherein fibre strands wetted with a resin matrix are pressed against the core and the resin matrix precured immediately thereafter.

2. A method according to claim 1 wherein the wetted fibre strands are pressed against the core by a nip roller having coupled thereto a resin matrix precuring facility.

3. A method according to claim 1 wherein the component is an airfoil and the fibre strands are looped around a number of attaching nipples on a blade root to secure the airfoil to the blade root (6).

4. A method according to claim 2, wherein the precuring facility comprises an infrared radiator.

5. A method according to claim 2 wherein the fibre strands are drawn through a fibre feed duct into which matrix material is introduced to wet fibre strands.

6. A method for the manufacture of fibre reinforced component, particularly a three-dimensionally twisted airfoil, substantially as hereinbefore described with reference to the accompanying drawings.

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