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The potential of knitting for engineering composites—a review

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Abstract

Current literature on knitted composites tends to address the aspects of manufacture and characterisation separately. This paper aims to bring together these two sets of literature to provide the reader with a comprehensive understanding of the subject of knitted composites. Consequently, this paper contains a detailed outline of the current state of knitting technology for manufacturing advanced composite reinforcements. Selected mechanical properties of knitted composites, and some of the predictive models available for determining them are also reviewed. To conclude, a number of current and potential applications of knitting for engineering composites are highlighted. With a comprehensive review of the subject, it is believed that textile engineers would be able to better understand the requirements of advanced composites for knitting, and, by the same token, composites engineers can have a better appreciation of the capability and limitations of knitting for composite reinforcement. This should lead to more efficient usage and expanded application of knitted composites.

Keywords: Knitted fabrics; B. Mechanical properties

1. Introduction

The textile industry has developed the ability to produce net-shape/near-net-shape fabrics using highly automated techniques such as stitching, weaving, braiding and knitting. In view of the potential for cost savings and enhanced mechanical performance, some of these traditional textile technologies have been adopted for manufacturing fabric reinforcement for advanced polymer composites. Knitting is particularly well suited to the rapid manufacture of components with complex shapes due to the low resistance to deformation of knitted fabrics [1]. Furthermore, existing knitting machines have been successfully adapted to use various types of high-performance fibres, including glass, carbon, aramid and even ceramics, to produce both flat and net-shape/near-net-shape fabrics. The fabric preform is then shaped, as required, and consolidated into composite components using an appropriate liquid moulding technique, e.g. resin transfer moulding (RTM) or resin film infusion (RFI).

The use of net-shape/near-net-shape preforms is obviously advantageous for minimum material wastage and reduced production time (see, for example, Nurmi and Epstein [2]). However, the development of a fully fashioned knitted preform can prove time consuming and expensive so that this option could still be economically inefficient overall. In such instances, flat knitted fabrics with a high amount of formability/drapability should be used to form over a shaped tool for subsequent consolidation to produce the required composite component (see, for example, Höhfeld et al. [3]).

Notwithstanding the exceptional formability, there are serious concerns over the generally poorer in-plane mechanical performance of knitted composites compared with more conventional composites and materials [4–8]. This relative inferiority in properties of knitted composites results predominantly from the limited utilisation of fibre stiffness and strength of the severely bent fibres in the knit structure that afford the fabric to be highly deformable. In addition, damage inflicted on the fibres during the knitting process could also degrade mechanical properties [6].

This paper aims to provide to the reader a general appreciation of the knitting process and the many opportunities it provides for producing efficient fibre reinforcement for advanced composites. Within this objective, the paper first outlines some of the more common types of knitting techniques and machines, and discusses some of the recent innovations to facilitate the manufacture of knitted composites with improved mechanical performance. In this context, the

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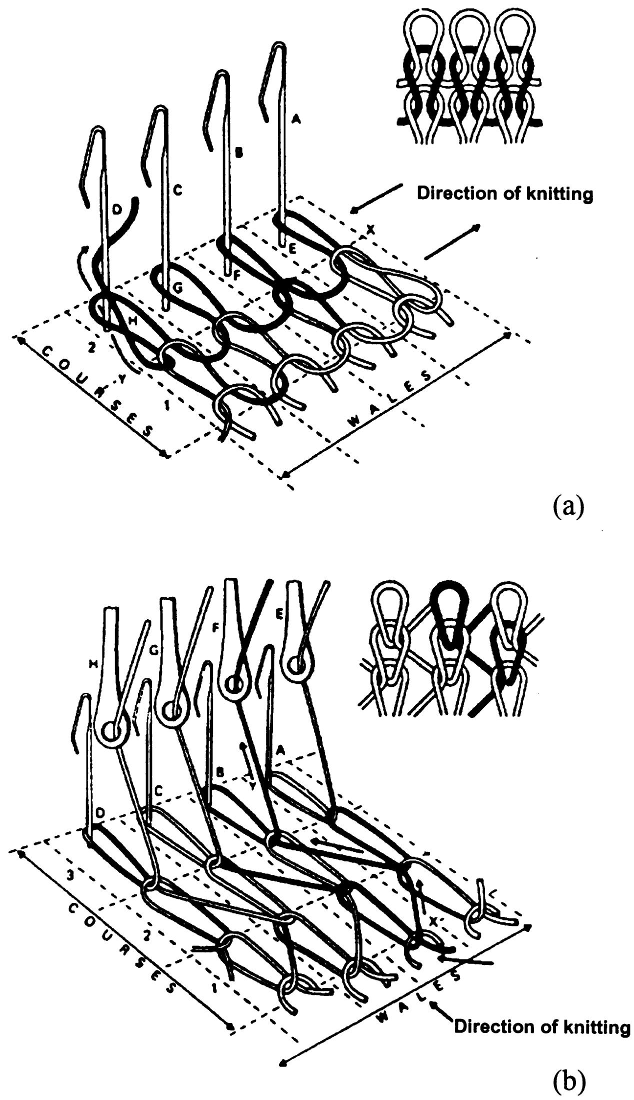


Fig. 1. Schematic diagrams showing the wale and course components of a knitted fabric, and the principles of (a) weft and (b) warp knitting.

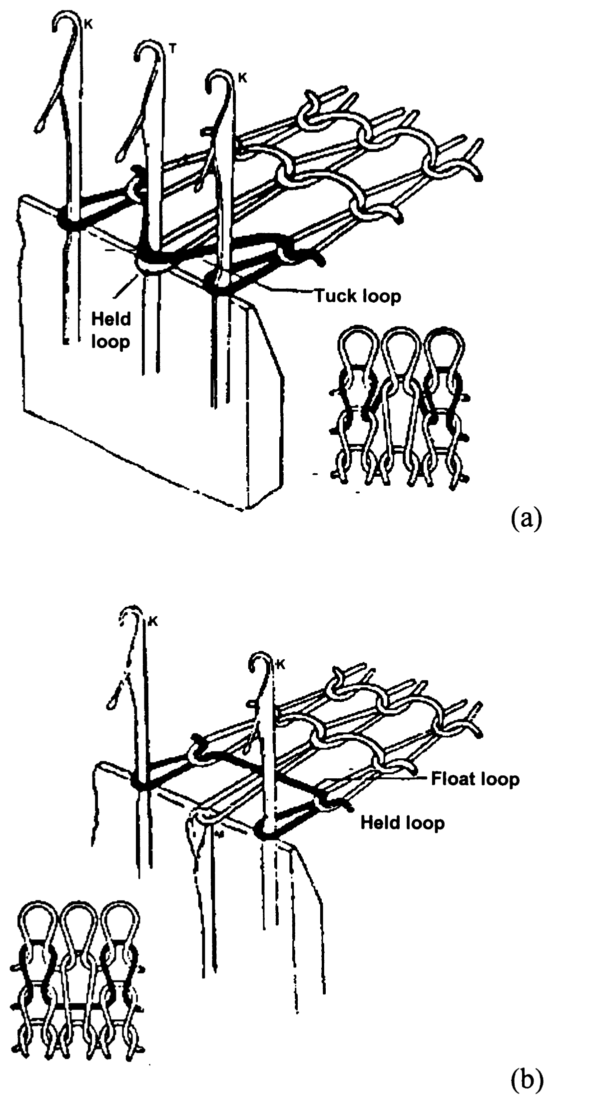


Fig. 2. Schematic diagrams showing the (a) tuck and (b) float stitches.

performance of advanced knitted composites with respect to mechanical properties such as tension, compression, energy absorption, impact and bearing are reviewed. Analytical and numerical models currently available for predicting stiffness and strength of knitted composites are also presented. Finally, some current and potential applications of knitting for engineering composites are highlighted.

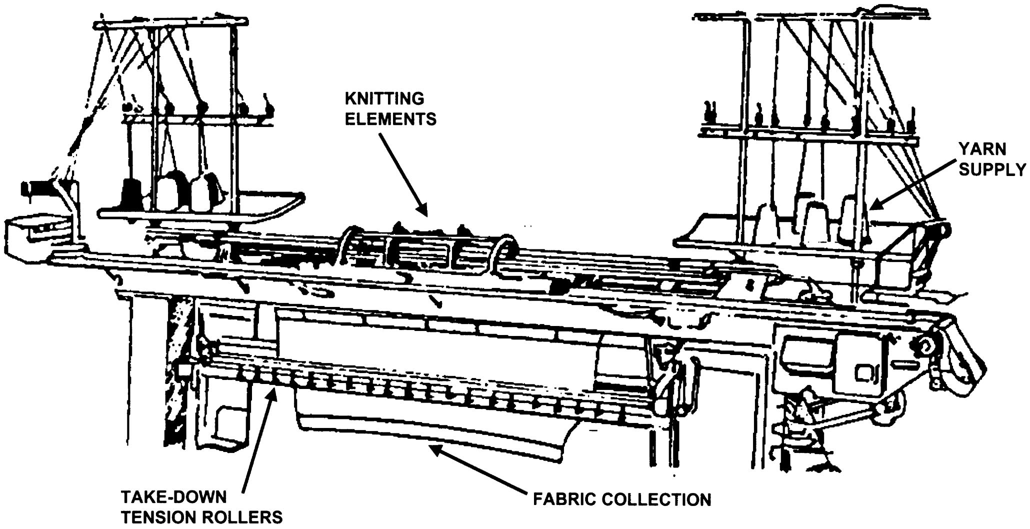
2. The knitting process

Literature on the basics of knitting is widely available, including one by Gohl and Vilensky [9], upon which most of this section of the paper is based.

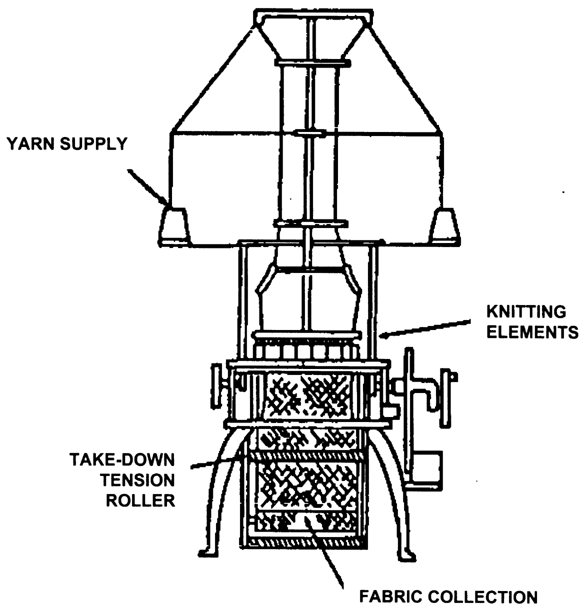
Knitting refers to a technique for producing textile fabrics by intermeshing loops of yarns using knitting needles. A continuous series of knitting stitches or intermeshed loops is formed by the needle catching the yarn and drawing it through a previously formed loop to form a new loop. In a knit structure, rows, known in the textile industry as *courses*, run across the width of the fabric, and columns, known as *wales*, run along the length of the fabric. The loops in the courses and wales are supported by, and interconnected with, each other to form the final fabric (Fig. 1).

A wale of loops is produced by a single knitting needle during consecutive knitting cycles of the machine. The number of wales per unit width of fabric is dependent on inter alia the size and density of the needles[1] used as well as the knit structure, yarn size, yarn type, and the applied yarn tension. A course of loops, on the other hand, is produced by a set of needles during one knitting cycle of the machine. The number of courses per unit length of fabric is controlled

[1] The density of needles is more commonly represented by the term ‘gauge’, which is a measure of needles per unit length in inches.



(a)



(b)

Fig. 3. Illustrations of (a) flat-bed and (b) circular weft knitting machines.

by manipulating the needle (knockover) motion and yarn feed. Standardised tests for measuring and quantifying the number of wales and courses in a unit length of knitted fabric are well documented in the literature [10].

Depending on the direction in which the loops are formed, knitting can be broadly categorised into one of two types—*weft knitting* and *warp knitting* (Fig. 1). Weft knitting is characterised by loops forming through the feeding of the weft yarn at right angles to the direction in which the fabric is produced (Fig. 1(a)). Warp knitting, on the other hand, is characterised by loops forming through the feeding of the warp yarns, usually from warp beams, parallel to the direction in which the fabric is produced (Fig. 1(b)). More precisely, warp knitting is effected by interlooping each yarn into adjacent columns of wales as knitting progresses. Fig. 1 shows the basic structure of the weft (i.e. plain knit) and warp (i.e. single tricot) knitted fabrics. Generally, weft-knit structures are less stable and, hence, stretch and distort more easily than warp-knit structures so that they are also more formable. It is noteworthy that an obvious advantage of

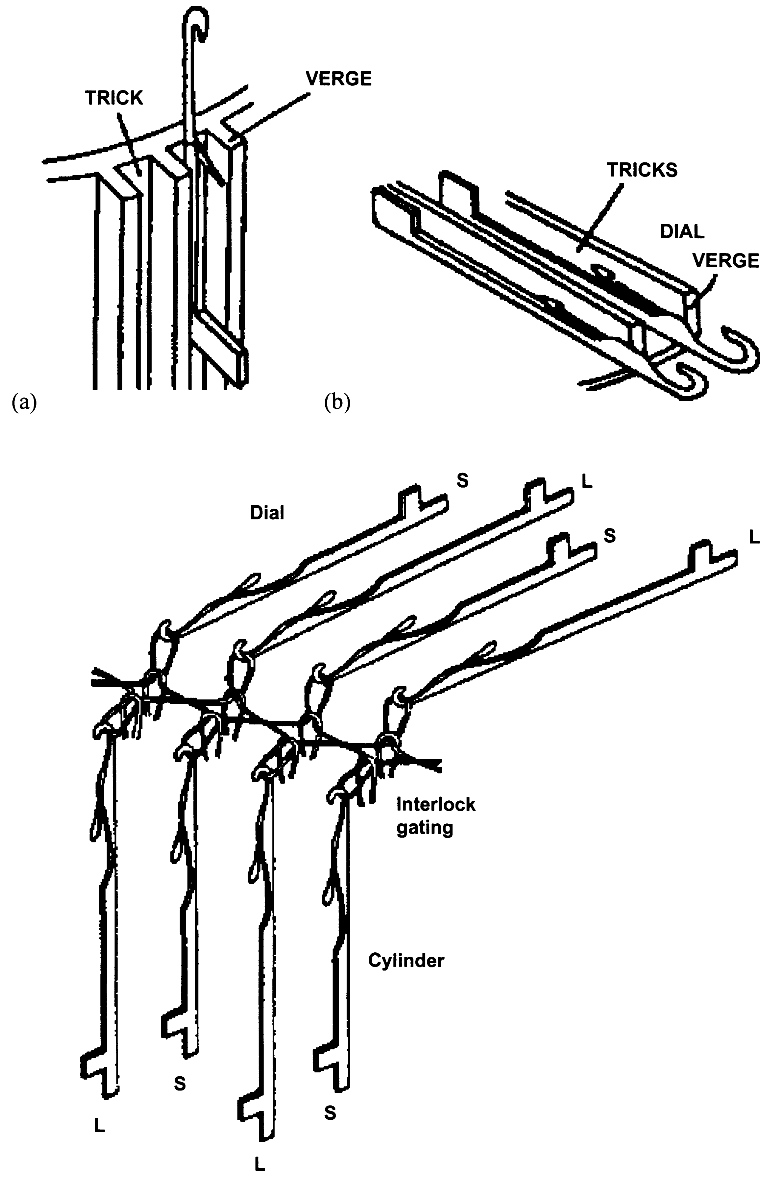


Fig. 4. Schematic diagrams of the (a) cylinder, and (b) dial, needles of a circular knitting machine, and (c) the manner in which they interact to effect the knitting process.

warp over weft knitting is that the former tends to have a significantly higher production rate since many yarns are knitted at any one time. The ease with which weft-knitted fabrics unravel and the cost associated with warping beams are also important considerations in choosing between weft and warp knitting. Clearly, weft knitting is preferred for developmental work whereas warp knitting would be more favourable in large-scale production.

In knitting, *float* and *tuck* stitches/loops (Fig. 2) represent the main routes for modifying knit structures to achieve specific macroscopic properties in the fabric. In general a tuck stitch makes a knitted fabric wider, thicker and slightly less extensible. A float stitch, on the other hand, creates the opposite effect, as well as increases the proportion of straight yarns in the structure, which is an important consideration for many composites applications.

3. Knitting machines

According to Gohl and Vilensky [9], weft knitting machines may be broadly classified into two types, namely flat-bed and circular, whilst the two most common warp knitting machines are the Tricot and the Raschel.

3.1. Weft knitting

3.1.1. Flat-bed machines

Flat-bed, or flat-bar, machines are characterised by the

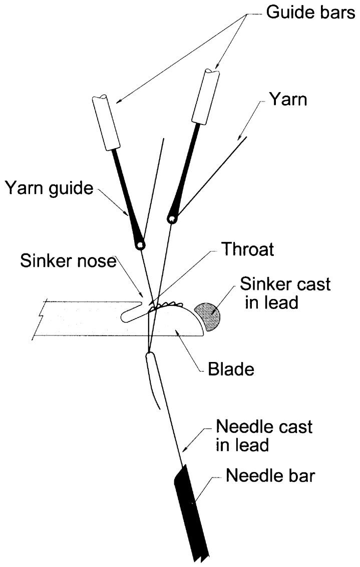


Fig. 5. Schematic diagram showing the relative positions of the guide bars to the knitting needle in warp knitting machines.

arrangement of their needles on a horizontal or flat needle bed (i.e. linear needle arrangement) (Fig. 3(a)). Most flat-bed machines have two needle beds which are located opposite to each other. The motion of the needles during knitting is controlled by cams in the yarn carrier which act upon the butt of the needles as they travel back and forth along the needle bed. This action causes each of the needles to rise and fall in turn to facilitate loop formation of the yarn along the length of the needle bed. It is from this action that the term 'weft knitting' is derived. It is noteworthy that flat-bed knitting machines have low production rates since the yarn is knitted back and forth across the needle bed. This results in slight time delays with each direction change that would become significant over an extended period. Flat-bed machines have gauges ranging from 3 to 15 and therefore their fabrics are normally of large loops with low stitch densities.

3.1.2. Circular machines

Circular weft knitting machines may be single- or double-bed and their needles, as the name suggests, are arranged in a circular needle bed (i.e. circular needle arrangement) (Fig. 3(b)).

Single-bed machines have their needles arranged vertically along the perimeter of the circular knitting bed. This set of needles are called *cylinder needles* (Fig. 4(a)). Double-bed machines have an additional set of needles, called *dial needles*, mounted horizontally along the circumference of a dial which in turn sits above and perpendicular to the cylinder needle bed (Fig. 4(b)). The relative positions of the dial needles are so that they are sandwiched between a pair of cylinder needles, and vice versa. In both types of machines, the needles are normally rotated past stationary yarn feeders to effect knitting. As with the flat-bed machines, the motion of the needles are controlled by cams.

Since with a circular machine the yarn is knitted in a continuous fashion, significantly higher production rates are achieved compared with flat-bed machines. This continuous knitting also means that fabrics produced on circular machines are tubular and contain no seams. Circular machines have gauges ranging from 5 to 40, and therefore their fabrics normally consist of small loops with relatively high-stitch densities.

3.2. Warp knitting

3.2.1. Tricot machines

Tricot machines have only a single needle bar and up to four yarn guide bars to a needle (Fig. 5). The needle bed is straight and occupies the width of the machine. The guide bars essentially move relative to the needles to facilitate interlooping of yarns with adjacent loops as the fabric is knitted. Being typically fine gauge machines, the tolerance between the needles and yarn guides is very fine and therefore Tricot machines are commonly used with multifilament yarns. With the smoothness and regularity in fibre diameter, speedier and relatively problem-free knitting is achieved with these machines. It is noteworthy that the non-stretch characteristics of Tricot knits and thus their relative stability of structure often render them substitutes for woven fabrics.

3.2.2. Raschel machines

Raschel knitting machines may have one or two straight needle beds that occupy the width of the machine. Depending on the knit structure more than 20 guide bars can be used, although the usual number is between four and 10. Due to the greater number of guide bars that a Raschel machine can accept, it is possible to knit an immense variety of structures on these machines. Nevertheless, the basic stitch formation of Raschel knits is the same as for Tricot knits.

Since Raschel machines usually have more guides fitted to them than Tricot machines, they are coarser gauge machines too. The coarser tolerance between the needle and yarn guides means that spun yarns can be knitted. It is noteworthy that Raschel has become the generic name for describing fabrics knitted on a warp knitting machine with two needle bars. Further, Raschel fabrics generally tend to be characterised by their open mesh, net or lace-like structure, that are usually knitted from spun, rather than multifilament, yarns.

The myriad of knit architectures that are possible with either weft or warp knitting are highlighted by Ramakrishna [11].

4. Fibre damage during knitting

During knitting, fibres are required to bend over sharp radii and manoeuvre sharp corners in order to form the

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