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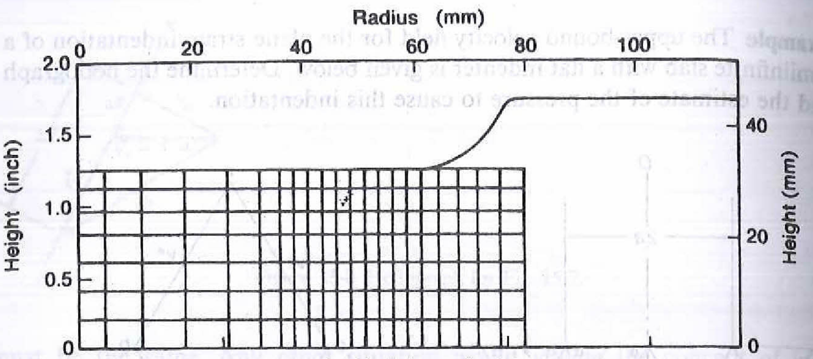
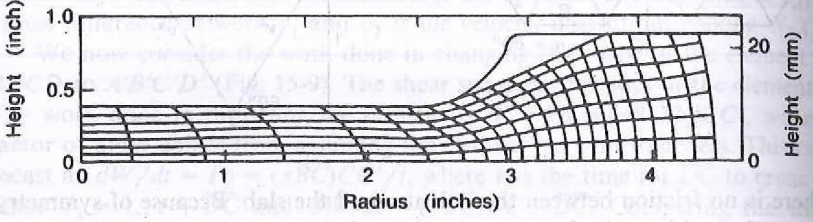
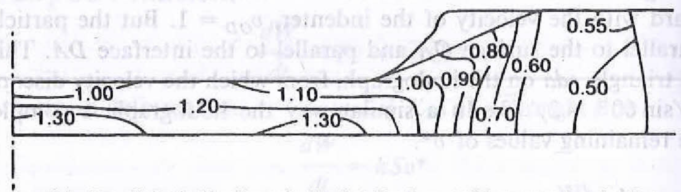


(a) Undeformed grid



(b) Grid distortion at 70 percent reduction



(c) Predicted effective strain distribution at 70 percent reduction

Figure 15-10 Distortion of FEM grid in forging of a compressor disk. Because of symmetry only one-quarter of the cross section need be considered. *(From T. Altan, S. I. Oh, and H. L. Gegel, "Metal Forming," p. 336, American Society for Metals, Metals Park, Ohio, 1983.)*

problems concentrated on elastic-plastic solutions. Because these problems require the use of very small increments of strain, with elastic calculations made at each increment, a very large amount of computer capacity is required.

A practical adaptation of the FEM to metalworking analysis was achieved by Kobayashi[1] in a technique called the *matrix method*. This method neglects elastic strains compared with the larger plastic strains and assumes rigid plastic behavior. Therefore, relatively large strain increments can be used and the computer

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[1] C. H. Lee and S. Kobayashi, *Trans. ASME Ser. B, J. Eng. Ind.*, vol. 93, pp. 445–454, 1971; S. Kobayashi and S. N. Shah, "Advances in Deformation Processing," J. J. Burke and V. Weiss (eds.), pp. 51–98, Plenum Press, New York, 1978.

requirements are reduced considerably. The mat
into a computer code called ALPID[1] (analysis of
tion). It assumes a rigid viscoplastic material in
of strain, strain rate, and temperature. ALPID
particle velocity, and temperature at any locat
Figure 15-10 shows the distortion calculated b
tion. Effective strain has been calculated at eac
of $\bar{\varepsilon}$ at the bottom of the figure. Because of
metalworking processes the initial FEM mesh
reliable information. When this happens it is ne
new mesh within the boundary of the defor
values of ε, $\dot{\varepsilon}$, v, and T to the new grid system

FEM analysis can be used to simulate d
combined with real time computer graphics ou
try, preform design, friction, and material prope
die fill and defect formation can be investigated
has been applied to two-dimensional metal de
be expanded to simulate three-dimensional def

15-3 FLOW-STRESS DETERMINATIO

The various expressions that will be developed
the forming stress, or pressure, in a particula
consist of three terms:

$$p = \bar{\sigma}_0 g(f) h($$

where $\bar{\sigma}_0$ = the flow resistance of the material f
uniaxial, plane strain, etc. It is a fu
strain rate.
$g(f)$ = an expression for the friction at the
$h(c)$ = a function of the geometry of the
deformation. This term may or ma
redundant deformation.

It is obvious from the above relationship t
predictions of forming loads and stresses,
resistance (flow stress). The experimental prob
under metalworking conditions are more severe
determined for structural or mechanical design
processes involve large plastic strains, it is desir

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[1] S. I. Oh, *Int. J. Mech. Sci.*, vol. 17, pp. 479–493, 1
Proc. NAMRC-X, 1982; T. Altan, H. L. Gegel, and S. I
Society for Metals, Metals Park, Ohio, 1983

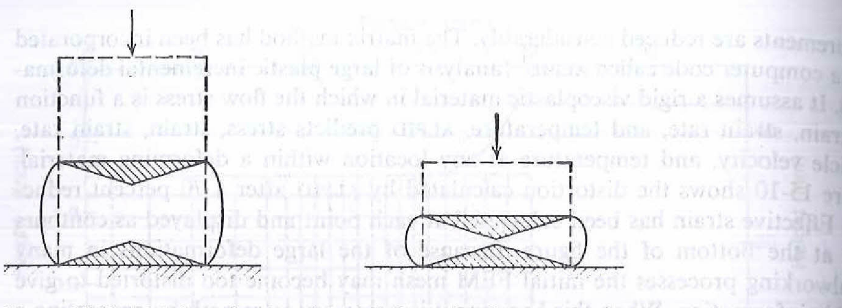

Figure 15-11 Undeformed regions (shaded) due to friction at ends of a compression specimen.

to a true strain of 2.0 to 4.0. In addition, many of these processes involve high strain rates ($\dot{\varepsilon} \approx 100\ \mathrm{s}^{-1}$), which may not be obtained easily with ordinary test facilities. Further, many metalworking processes are carried out at elevated temperatures where the flow stress is strongly strain-rate sensitive but nearly independent of strain. Thus, tests for determining flow stress must be carried out under controlled conditions of temperature and constant true-strain rate.[1]

The true-stress–true-strain curve determined from the *tension test* is of limited usefulness because necking limits uniform deformation to true strains less than 0.5 (see Sec. 8-3). This is particularly severe in hot-working, where the low rate of strain hardening allows necking to occur at $\varepsilon \approx 0.1$. The formation of a necked region in the tension specimen introduces a complex stress state and locally raises the strain rate.

The *compression* of a short cylinder between anvils is a much better test for measuring the flow stress in metalworking applications. There is no problem with necking and the test can be carried out to strains in excess of 2.0 if the material is ductile. However, the friction between the specimen and anvils can lead to difficulties unless it is controlled. In the *homogeneous upset test* a cylinder of diameter D_0 and initial height h_0 would be compressed in height to h and spread out in diameter to D according to the law of constancy of volume:

$$D_0^2 h_0 = D^2 h$$

During deformation, as the metal spreads over the compression anvils to increase its diameter, frictional forces will oppose the outward flow of metal. This frictional resistance occurs in that part of the specimen in contact with the anvils, while the metal at specimen midheight can flow outward undisturbed. This leads to a *barreled* specimen profile, and internally a region of undeformed metal is created near the anvil surfaces (Fig. 15-11). As these cone-shaped zones approach and overlap, they cause an increase in force for a given increment of deformation and the load-deformation curve bends upward (Fig. 15-12). For a fixed diameter,

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[1] H. J. McQueen and J. J. Jonas, Hot Workability Testing Techniques, in A. L. Hoffmanner (ed.), "Metal Forming: Interrelation Between Theory and Practice," Plenum Publishing Corporation, New York, 1971.

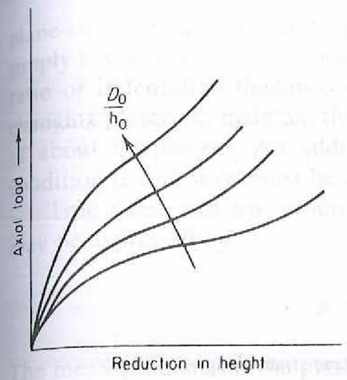

Figure 15-12 Load-
tests with different

a shorter specimen will require a greater axia
percentage reduction in height because of the rela
(Fig. 15-11). Thus, one way to minimize the barre
tion is to use a low value of D_0/h_0. However
$D_0/h_0 \approx 0.5$, for below this value the specimen b
true flow stress in compression without friction ca
versus D_0/h_0 for several values of reduction ar
$D_0/h_0 = 0$.

The friction at the specimen-platen interfac
smooth, hardened platens, grooving the ends of t
and carrying out the test in increments so that t
intervals.[3] Teflon sheet for cold deformation and
especially effective lubricants. With these techniqu
of about $\varepsilon = 1.0$ with only slight barreling. W
uniaxial compressive force required to produce yi

$$P = \sigma_0 A$$

The true compressive stress p produced by this f

$$p = \frac{4P}{\pi D^2}$$

and using the constancy-of-volume relationship

$$p = \frac{4Ph}{\pi D_0^2 h_0}$$

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[1] M. Cooke and E. C. Larke, *J. Inst. Met.*, vol. 71, pp. 3
[2] G. T. van Rooyen and W. A. Backofen, *Int. J. Mech. Sc*
and W. A. Backofen, *Trans. ASME, Ser. D: J. Basic Eng.*,
[3] Standard Methods of Compression Testing of Metallic
Standards, pt. 31, Designation E9-70; for elevated temperat

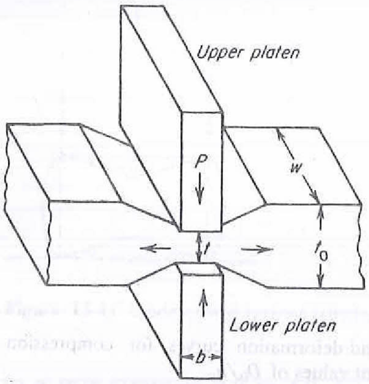

Figure 15-13 Plane-strain compression test.

where D_0 and h_0 are the initial diameter and height, and h is the height of the cylindrical sample at any instant during compression. The true *compressive* strain is given by

$$\varepsilon_c = \ln \frac{h_0}{h} \tag{15-24}$$

In a compression test at constant crosshead speed, the true-strain rate continuously increases with deformation [see Eq. (9-33)]. At strain rates up to 10 s^{-1} a servocontrolled testing machine can be modified to maintain a constant true-strain rate. For metalworking strain rates of 1 to 10^3 s^{-1} the only equipment capable of providing a constant true-strain rate is the cam plastometer.[1]

A compression test, such as that shown in Fig. 15-11, would be very difficult to conduct on a thin sheet, since it might be impossible to machine the specimens. A much more suitable test for sheet metal is the *plane-strain compression test*.[2] In this test a narrow band across the width of a strip is compressed by narrow platens which are wider than the strip (Fig. 15-13). The constraints of the undeformed shoulders of material on each side of the platens prevent extension of the sheet in the width dimension. There is deformation in the direction of platen motion and in the direction normal to the length of the platen, as occurs in the rolling process. In addition to its suitability with thin sheet, other advantages of this test are that it simulates the stress state in rolling, eliminates problems with barreling, and because the area under the platen is constant, the total deformation force does not rise as rapidly as in the compression of a cylinder. On the other hand, unless good lubrication is maintained, a dead metal zone will form in the specimen next to the face of the platens. Therefore, the test usually is carried out incrementally, measuring the sheet thickness after each increment and relubricating for the next higher load. Slip-line field theory has been used to analyze the

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[1] J. F. Alder and V. A. Phillips, *J. Inst. Met.*, vol. 83, pp. 80–86, 1954–1955; J. E. Hockett, *Am. Soc. Test. Mater. Proc.*, vol. 59, pp. 1309–1319, 1959.

[2] A. B. Watts and H. Ford, *Proc. Inst. Mech. Eng.*, vol. 169, pp. 1141–1156, 1955.

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plane-strain compression test. It has been foun
simply is the applied load divided by the contac
ratio of indentation thickness to platen width
changing platens to maintain this t/b range, it i
of about 90 percent. An additional requirem
condition is that w/b must be greater than 5.

True stress and true strain determined in
may be expressed by

$$p = \frac{P}{wb} \qquad \varepsilon_{pc} =$$

The mean pressure on the platens is 15.5 perce
corresponding uniaxial compression test (see F
strain curve in uniaxial compression (σ_0 versu
corresponding plane-strain compression curve
relations:

$$\sigma_0 = \frac{\sqrt{3}}{2} p = \frac{p}{1.155}$$

$$\varepsilon_c = \frac{2}{\sqrt{3}} \varepsilon_{pc} = 1.15$$

The *hot torsion test* (see Sec. 10-6) is capabl
of the order of 20. Since the dimensions of the sp
rate remains constant for a constant rpm.[1] Str
10^3 s^{-1} are readily achieved. The chief difficul
stress and strain vary with radial distance in the
values at the surface are reported, but this may l
if the surface strain-hardens more than the co
stress and strain is largely eliminated by usin
must be exercised to use a short specimen or buc
the excessive material reorientation that may occ
is not an accurate simulation of metalworking
the test for workability studies, but not for flow s
stress and strain are obtained from the torsional
by the following relations based on the von Mis

$$\sigma_0 = \sqrt{3}\,\tau \qquad \varepsilon =$$

The variation of flow stress with strain can b
(see Fig. 10-8) or for a highly cold-worked metal.
is present, the best approach to selecting a flow

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[1] J. A. Bailey and S. L. Haas, *J. Mater.*, vol. 7, pp. 8–13

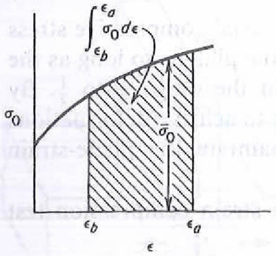

Figure 15-14 Definition of mean-flow stress.

calculations is to use the mean flow stress as given by

$$\bar{\sigma}_0 = \frac{1}{\varepsilon_a - \varepsilon_b} \int_{\varepsilon_b}^{\varepsilon_a} \sigma_0 \, d\varepsilon \tag{15-27}$$

Figure 15-14 shows the interpretation of this equation. This is considered a better choice than the flow stress based on $\varepsilon = (\varepsilon_a + \varepsilon_b)/2$. When analytical expressions for the flow curve are required, it is usually possible to fit the data to either Eq. (8-21) or Eq. (8-24). Extensive data for flow stress under metalworking conditions have been published.[1] However for large strains ($\varepsilon > 1$) it has been proposed[2] that the flow stress is best given by

$$\sigma_0 = A + B\varepsilon \tag{15-28}$$

where $A = K(1 - n)$
$B = Kn$

15-4 TEMPERATURE IN METALWORKING

Forming processes are commonly classified into *hot-working* and *cold-working* operations. Hot-working is defined as deformation under conditions of temperature and strain rate such that recovery processes take place simultaneously with the deformation. On the other hand, cold-working is deformation carried out under conditions where recovery processes are not effective. In hot-working the strain hardening and distorted grain structure produced by deformation are very rapidly eliminated by the formation of new strain-free grains as the result of recrystallization. Very large deformations are possible in hot-working because the recovery processes keep pace with the deformation. Hot-working occurs at an essentially constant flow stress, and because the flow stress decreases with increasing temperature, the energy required for deformation is generally much less for hot-working than for cold-working. Since strain hardening is not relieved in cold-working, the flow stress increases with deformation. Therefore, the total

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[1] T. Altan, S. I. Oh, and H. L. Gegel, "Metal Forming," pp. 56–72, American Society for Metals, Metals Park, Ohio, 1983.

[2] M. C. Shaw, *Int. J. Mach. Tool Des. Res.*, vol. 22, no. 3, pp. 215–226, 1982.

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deformation that is possible without causing frac
for hot-working, unless the effects of cold-work a
It is important to realize that the distinc
hot-working does not depend on any arbitrary t
most commercial alloys a hot-working operat
relatively high temperature in order that a ra
obtained. However, lead and tin recrystallize ra
large deformations, so that the working of the
constitutes hot-working. Similarly, working tungst
range for steel, constitutes cold-working becaus
recrystallization temperature above this working

The temperature of the workpiece in metalwo
temperature of the tools and the material, (2)
deformation, (3) heat generated by friction at th
heat transfer between the deforming material
environment. For a frictionless deformation pr
temperature is

$$T_d = \frac{U_p}{\rho c J} = \frac{\bar{\sigma}\bar{\varepsilon}\beta}{\rho c J}$$

where U_p = the work of plastic deformation per
ρ = the density of workpiece
c = the specific heat of the workpiece
J = the mechanical equivalent of heat, 77
β = fraction of deformation work convert
The remainder is stored in the mater
defect structure.

The temperature increase due to friction is given

$$T_f = \frac{\mu p v A \, \Delta t}{\rho c V J}$$

where μ = friction coefficient at material/tool int
p = stress normal to interface
v = velocity at the material/tool interface
A = surface area at the material/tool inter
Δt = time interval of consideration
V = volume subjected to the temperature r

Usually the temperature is highest at the
friction generates the heat and it falls off toward
into the die. For simplicity we can neglect th
consider the deforming material to be a thin plate

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[1] T. Altan, S. I. Oh, and H. L. Gegel, op. cit. p. 90.