Metal Forming Laboratory
Experiment No. 1 (a): DISC COMPRESSION TEST

- **Aim of the Experiment:** To demonstrate the effect of friction and height-to-diameter ratio in the axi-symmetric compression of a cylinder.

- **Apparatus Required:**

1. A compression testing machine (here Hydraulic type)
2. Cylindrical or cube shaped specimen of Aluminium
3. Vernier caliper

- **Theory:**

A compression test is used to determine the behaviour of a material under compressive load. The specimen is compressed and deformations at various loads are recorded. Compressive stress and strain are calculated and plotted as a stress-strain diagram(fig-1) , which is used to determine elastic limit, proportional limit, yield point, yield strength and, for some materials, compressive strength.

Several machine and structured components such as columns and struts are subjected to compressive load in applications. These components are made of high compressive strength materials. Not all the materials are strong in compression. Several materials which are good in tension are poor in compression. Contrary to this, many materials poor in tension but very strong in compression. Cast iron is one such example. That is why determining of ultimate compressive strength is essential before using a material. This strength is determined by conducting the compression test [1].

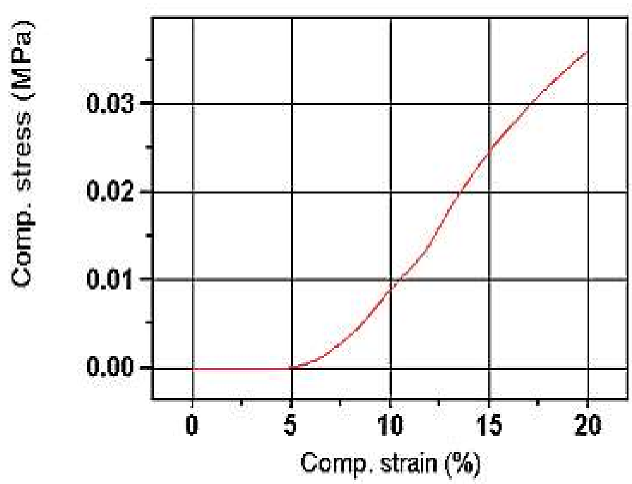


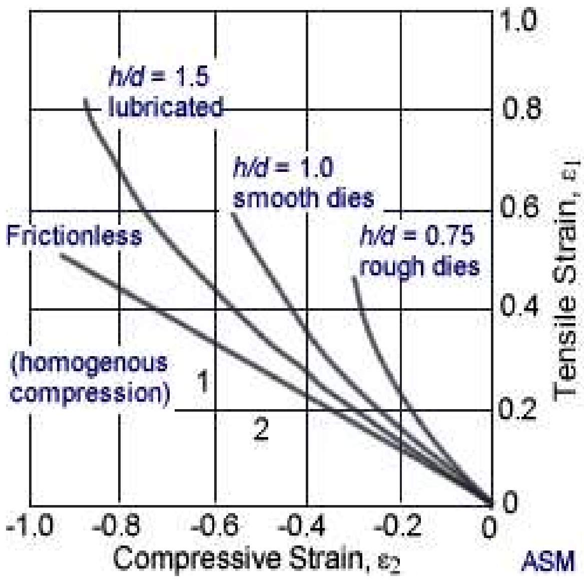
Fig-1: Compression test [Source: *www.instron.com*]

The following materials are typically subjected to a compression test.

- Concrete
- Metals
- Plastics
- Ceramics
- Composites
- Corrugated Cardboard

Compression test is just opposite in nature to tensile test. Nature of deformation and fracture are quite different from that in tensile test. Compressive load tends to squeeze the specimen with the gradual application of load. Brittle materials are generally weak in tension but strong in compression. Hence this test is normally performed on cast iron, concrete but ductile materials like aluminium, mild steel which are strong in tension are also tested in compression. Hence this test is **normally** performed on cast iron, concrete.

- ## Why Perform a Compression Test?



Axial compression testing is a useful procedure for measuring the plastic flow behaviour and ductile fracture limits of a material. Measuring the plastic flow behaviour requires frictionless (homogenous compression) test conditions, while measuring ductile fracture limits takes advantage of the barrel formation and controlled stress and strain conditions at the equator of the barrelled surface when compression is carried out with friction. Axial compression testing is also useful for measurement of elastic and compressive fracture properties of brittle materials or low-ductility materials. In any case, the use of specimens having large *L/D* ratios should be avoided to prevent buckling and shearing modes of deformation [1].

Fig-2: Variation of the strains during a compression test [Source: *www.instron.com*]

Figure-2 shows variation of the strains during a compression test without friction (homogenous compression) and with progressively higher levels of friction and decreasing aspect ratio L*/D* (shown as *h/d*).

- ## Modes of Deformation in Compression Testing:

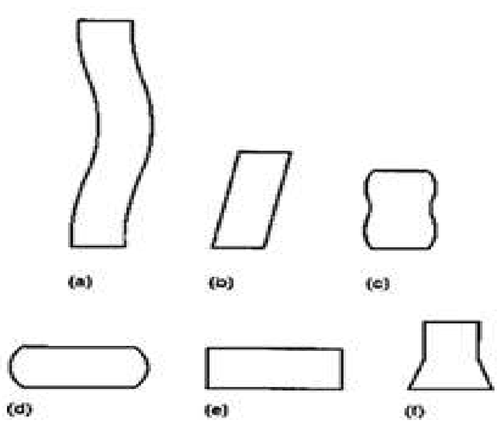


Figure-3 illustrates the modes of deformation in compression testing. (a) Buckling, when *L/D* > 5. (b) Shearing, when *L/D* > 2.5. (c) Double barrelling, when *L/D* > 2.0 and friction is present at the contact surfaces. (d) Barrelling, when *L/D* < 2.0 and friction is present at the contact surfaces. (e) Homogenous compression, when *L/D*< 2.0 and no friction is present at the contact surfaces. (f) Compressive instability due to work-softening material [1].

Fig-3: Modes of deformation in compression testing [Source: *www.instron.com*]

• Various idealisations of materials:

In order to obtain a solution to a problem, it is often necessary to idealize the stress-strain relation, which will simplify the solution. Thus the stress-strain curve can be idealized and we may describe in turn, these are shown in fig-4

(a) A rigid, perfectly plastic material.

(b) An elastic, perfectly plastic material.

(c) A rigid, linearly strain-hardening material.

(d) An elastic, linear strain-hardening material

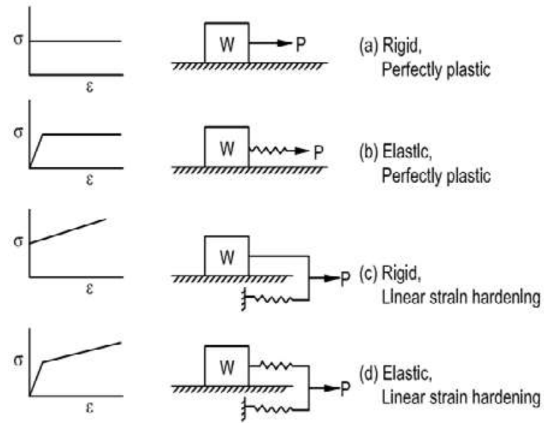


Fig-4 – Idealized stress-strain diagrams [Source: *Lal G.K, Gupta V and Reddy N.V, "Introduction to Machining Science", New Age International, 3rd edition, 2007, page no- 4*]

A simple mechanical analogy exist between the behaviour of these idealized materials and the motion of a spring-loaded block [2].

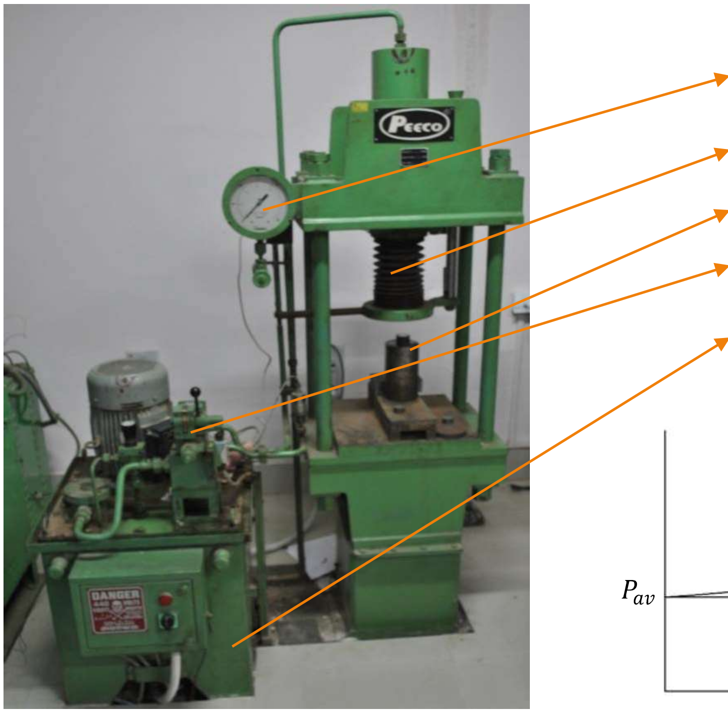
In fig 4(a), the block can move only when the applied force exceeds the friction force, thus representing a rigid, perfectly plastic material. Once the movement begins, it will continue to slide under a constant force. In fig 4(b), the deflection of the spring is proportional to the applied force and represents the elastic curve. Once the force exceeds a certain amount to overcome friction, the block will continue to slide under constant force. This model will represent the mechanical behaviour of an elastic, perfectly plastic material. A rigid, linear strain hardening material and an elastic, linear strain hardening material can similarly be represented by spring and block arrangements shown in fig 4(c) and 4(d).

• Test Set-up and Specification of Machine:

A compression testing machine shown in fig-5 below has two compression plates/heads. The upper head is movable while the lower head is stationary.

Under ideal conditions where there is no friction between the work piece and the dies, the billet deforms homogeneously (the cylindrical shape of the billet remains cylindrical throughout the process), the distribution of compressive stress on its flat face is uniform and is equal to the flow-stress in compression, σ_y. This also remains constant for all stages of compression (i.e. for all heights of the compressed cylinder) if the metal in question is perfectly plastic (Non-work hardening, e.g. lead).

But in practical conditions, the billet tends to barrel since there is some friction i.e. if the metal is of work hardening nature, the average stress required to compress the cylinder would increase with increasing the extent of compression i.e. at different heights of the cylinder (fig 6).



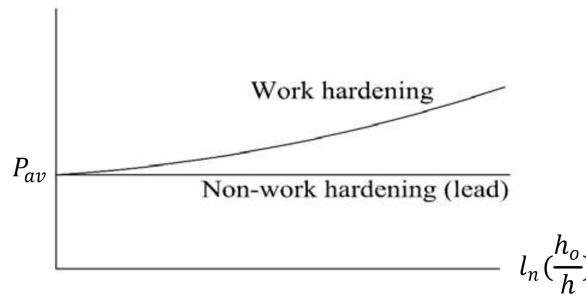


Fig-5-Hydraulic Compression testing machine

Fig-6 – Effect of work hardening on average normal stress

If a cylinder of non-work hardening metal is compressed between two rough (i.e. with a non-zero coefficient of friction) platens, the normal stress at any radius r, is given by [3]

$$P_z = \bar{\sigma}.e^{\frac{2\mu}{h}(r_f - r)} \qquad \text{(Ref: See Appendix-1)}$$

Here, $\bar{\sigma}$ = constant flow stress (yield stress of material)

μ = coefficient of friction for the platen-cylinder interfaces

d_0 = initial diameter of cylinder

r_f = current maximum radius of cylinder

r = any radius of cylinder

h, h_0 = current height and initial height of the cylinder

The distribution of stress on the flat surface of the cylinder is shown in fig-7 below

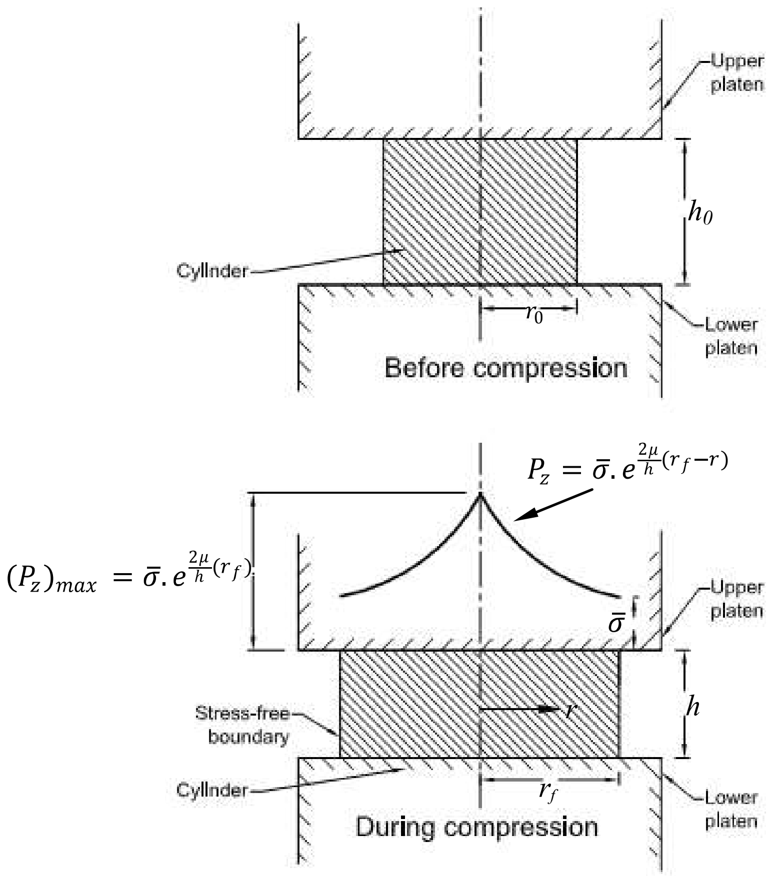


Fig-7 - Distribution of normal stress with rough platens

Figure 8 shows the effect of μ and $\frac{r_f}{h}$ ratio on the average normal stress on the flat surface of the cylinder .We see that the average stress continually increases.

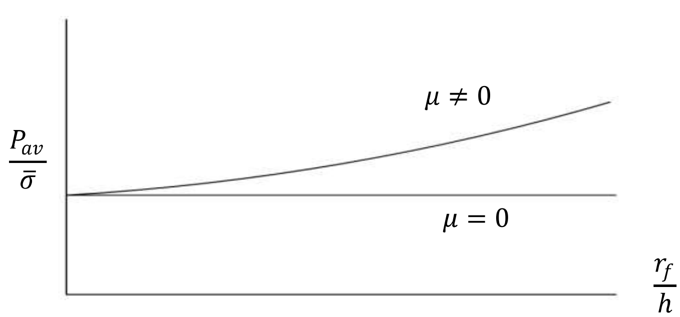


Fig-8 – Effect of friction and $\frac{r_f}{h}$ on average normal stress.

If we use a work hardening material, the increase of the average normal stress with increasing degree of compression would be more pronounced.

Ideal Homogeneous Upsetting of a Cylindrical Billet (without friction):

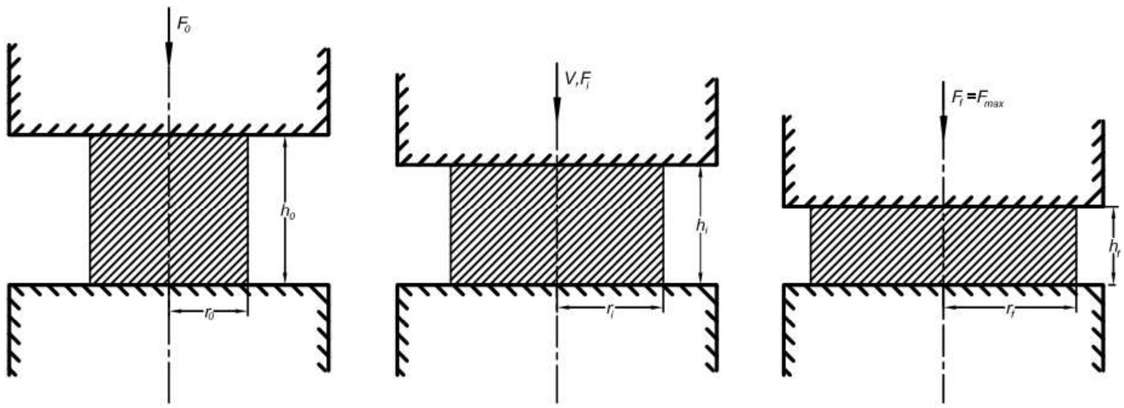


Fig -9: Homogeneous upsetting of cylindrical billet

Where V = Upper die Velocity
r_o, r_i, r_f = Average billet radius before, during and at the end of compression.
h_o, h_i, h_f are the corresponding heights.

- **Practical Upsetting of a Cylindrical Billet (with friction and barrelling):**

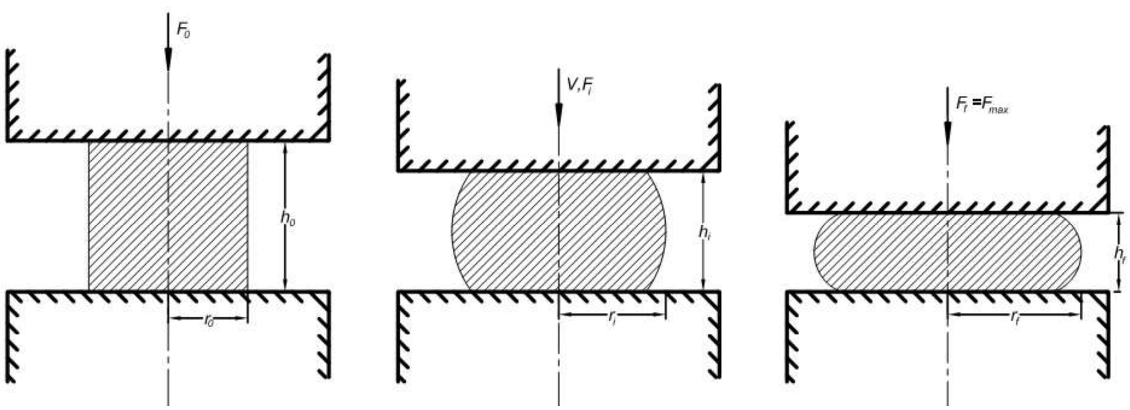


Fig-10: Practical upsetting of a cylindrical billet

Where h_0, h_i, h_f =billet height before, during and at the end of compression.

- **Procedure:**

Dimension of test piece is measured at three different places along its height and length to determine the average values. The specimen is placed centrally between the two compression plates such that the job axis is same as the axis of the plates. Load is applied on the specimen by moving the top platen. The load and corresponding contraction are measured at different intervals. The load interval is taken as 2 tonne i.e. each time note the load reached and measures the height and diameter of the specimen. Load is applied up to the maximum limit of the machine. Plot the variation of load vs *(r_f/h)*

- **Observation & Calculation:**

Sl. No.	Applied load (*P*) in Tonne	Diameter($2r_f$) in mm	Height(h) in mm	$\frac{r_f}{h}$

- Draw the variation of load vs (r_f/h)
- Determine young's modulus, Ultimate (maximum) compressive strength and percentage reduction in height of the specimen.

- **Questions for discussion:**

1. How do ductile and brittle materials behave in compression test?
2. Compression test are generally performed on brittle materials. Why?
3. Is it possible to plot true stress-train curve by compression test for a given material? Explain.
4. What is the limitation of tensile stress?
5. What is the difference between strain hardening and re-crystallisation? Is there any correlation between them?

- **Defects:**

Defects reduce the strength and life of a forging. Faults in the original metal, incorrect die-design, improper heating or improper heating operations are some of the reasons for forging defects. Defects can also occur due to machining-induced flaws which give rise to surface cracks when proper machining operation procedures are not observed [4]. Some of the important defects are

a) Hot tears and tears- The presence of segregation, seams or low melting or brittle second phases promotes hot tearing at the surface of a forging. These cracks or tears appear due to the faulty forging techniques.
b) Centre burst-This is a rupture in the centre of the billets and sometimes occurs when temperature of metal increases significantly as a result of large rapid reduction.
c) Cracks due to tangential velocity discontinuities and thermal cracks- cracks due to tangential velocity discontinuities may arise in material which is insufficiently ductile.
Cracks caused by stresses resulting from non-uniform temperature within a metal are called "thermal cracks"..
d) Orange peel- forging billets containing coarse grains whether as cast or wrought, will develop wrinkles are commonly known as orange peel.

- **References:**

1) *www.instron.com*
2) *Lal G.K, Gupta V and Reddy N.V, "Introduction to Machining Science", New Age International, 3rd edition, 2007, page no- 4.*
3) *Ghosh and Mallik, "Manufacturing Science", East-West Press Private Limited, 2nd Edition, 2010, pages 119-122.*
4) *Mousawi M.M.Al, Daragheh A.M and Ghosh S.K, "A database for some physical defects in metal forming processes" volume 43, 1995, pages 387-400.*

Appendix-1

Figure (11) shows a typical open die forging of a circular disc at the end of the operation (i.e. when F is maximum) when the disc has a thickness h and a radius r_f.

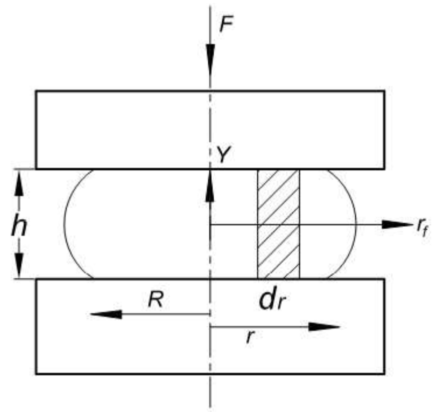


Fig-11(a): Forging of disc

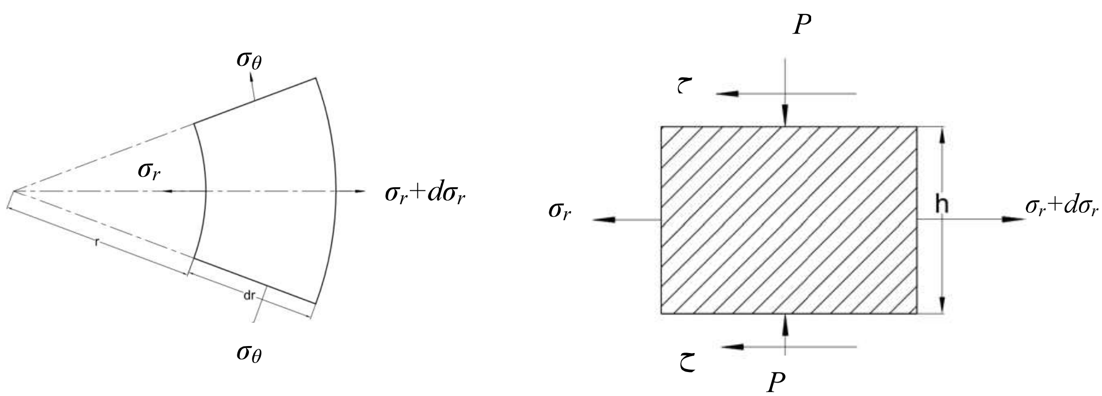


Fig-11(b): Stresses on element during disc forging

[Source: *Ghosh and Mallik, "Manufacturing Science", East-West Press Private Limited, 2nd Edition, 2010, pages 119-122*]

The origin of the cylindrical coordinate system r, θ, y is taken at the centre of the disc. An element of the disc, subtending an angle $d\theta$ at the centre, between the radii r and $r+dr$ is shown in fig (b) along with the stresses acting on it.
To simplify the analysis, the following assumptions are taken:-

(i) The forging force F attains its maximum value at the end of the operation.

(ii) The coefficient of friction μ between the work piece and the platens is constant.

(iii) The thickness of the work piece is small as compared with its other dimensions and the variation of the stress field along the y-direction is negligible.

Considering the cylindrical symmetry, it can be shown that $\sigma_\theta = \sigma_r$ and both σ_θ and σ_r are independent of θ.

Considering the radial equilibrium of the element, we have

$$(\sigma_r+d\sigma_r)h(r+dr)d\theta - \sigma_r hrd\theta - 2\sigma_\Theta hdr\, sin(\frac{d\theta}{2}) - 2\tau rd\theta.dr = 0 \quad (1)$$

Neglecting the higher order terms and using $\sigma_\Theta = \sigma_r$, the equation becomes

$$hd\sigma_r - 2\tau dr = 0 \quad (2)$$

Again to simplify the analysis, we take σ_r, σ_θ and $-P$ as the principal stresses. Using Von-mises yield criteria with $\sigma_1=\sigma_r$, $\sigma_r=\sigma_\theta$ $(=\sigma r)$ and $\sigma_3=-P$,we obtain

$$\sigma_r + P = \sqrt{3}K \quad (3a)$$

$$\Rightarrow d\sigma_r = -dP \quad (3b)$$

Since the shear yield stress K is constant. Substituting $d\sigma_r$ in equation (2) from equation (3b), we obtain

$$hdp + 2\tau dr = 0 \quad (4)$$

In this case, sliding takes place at the interface to allow the radial expansion of the work piece.

Hence $\tau = \mu p$ (5)

Thus, in these two zones, equation (5) takes the forms

$$\frac{dp}{p} + \frac{2\mu}{h} dr = 0 \quad (4)$$

Integrating the equation, we get

$$P = c_1 e^{-2\mu r/h} \quad (5)$$

As the periphery of the disc is free,at $r=r_f$, $\sigma_r = 0$ .So, from equation(3a),

$$P = \sqrt{3}K \quad (6)$$

Using equation (5) in equation (6) we obtain

$$C_1 = \sqrt{3}Ke^{\frac{2\mu r_f}{h}}$$

Final the expression for the pressure becomes

$$P = c_1\, e^{-2\mu r/h}$$

$$\Rightarrow \quad P = \sqrt{3}K\, e^{2\mu r_f/h} * e^{-2\mu r/h}$$

$$\Rightarrow \quad P = \sqrt{3}K\, e^{2\mu(r_f - r)/h}$$

$$\Rightarrow \quad \boxed{P = \overline{\sigma}\, exp[\frac{2\mu}{h}(r_f - r)]}$$

Therefore, the total forging force is $F = 2\pi \int_0^{r_f} Prdr$

Metal Forming Laboratory
Experiment No. 1(b): RING COMPRESSION

- **Aim of the Experiment:** To determine the coefficient of interfacial friction during plastic deformation of metals by means of compression of a ring between two compression platens.

- **Theory:**

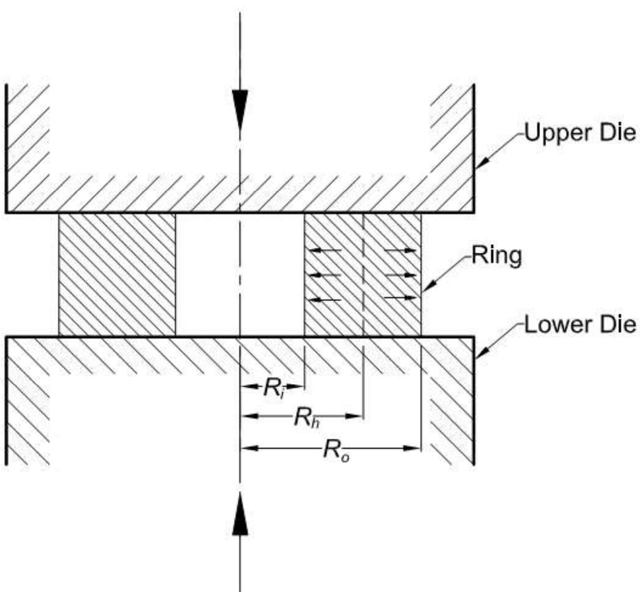
The friction at the interface of die/work piece plays an important role in the overall integrity of metal forming processes. Friction affects the deformation load, product surface quality, internal structure of the product, as well as dies' wear characteristics. Understanding of the friction phenomenon is, therefore, signficant for understanding what actually happens at the die/work piece interface during deformation. So, several methods have been developed for quantitative evaluation of friction in metal forming processes. The most accepted one for quantitative characterization of friction is to define a coefficient of friction, μ, at the die/work piece interface is the Coulomb law of friction [1].

Coulomb law of friction: $\tau = \mu P$,

where, τ = frictional shear stress , μ is the coefficient of friction and

P is the normal stress.

The ring compression test is one of the best techniques to determine the frictional condition at the interfaces. This technique utilizes the dimensional changes of a test specimen to arrive at the magnitude of the friction coefficient.



Fig–1: Ring compression

When a flat ring specimen is plastically compressed between two flat platens, increasing friction results in an inward flow of the material, while decreasing friction results in an outward flow of the material [1], as schematically shown in fig-1.

If there were no friction between the dies and work piece, both the inner and outer diameters of the ring would expand. However, for large friction at material/ die interface, the internal diameter of the ring is reduced with increasing deformation (fig-2).

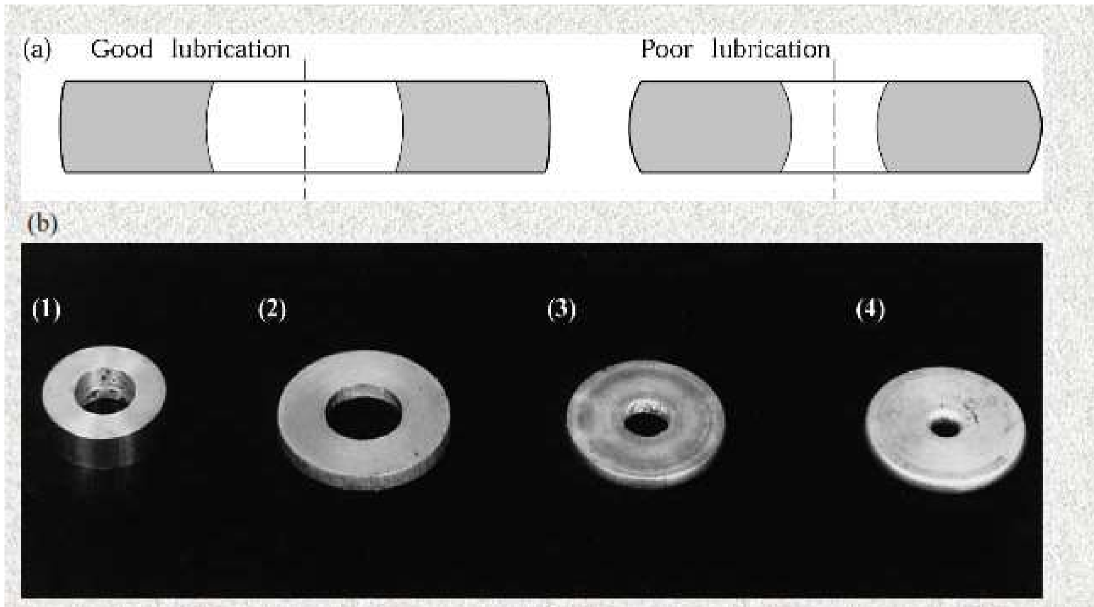


Fig- 2: Ring compression test between flat dies. (a) Effect of lubrication on type of ring specimen barrelling. (b) Test results: (1) original specimen and (2) - (4) increasing friction. [Source: *Kalpakjian S, Schmid S R, "Manufacturing Engineering and Technology", Prentice Hall, 6th Edition, 2009, fig.32.2*]

For a given percentage of height reduction during compression tests, the corresponding measurement of the internal diameter of the test specimen provides a quantitative knowledge of the magnitude of the prevailing coefficient of friction at the die/work piece interface. For lower friction, specimen's internal diameter increases during deformation but for higher friction internal diameter decreases during the deformation. Using this relationship, specific curves, later called friction calibration curves, were generated by Male and Cockcroft [2] relating the percentage reduction in the internal diameter of the test specimen to its reduction in height for varying degrees of the co-efficient of friction (fig-2)

The chart (fig-3) gives the calibration curves for a specific ring geometry (OD: ID: Height = 6:3:2) and for different coefficients of friction, μ.

In this chart, the variation of the % change in internal diameter is given for % reduction in height of the compressed ring.

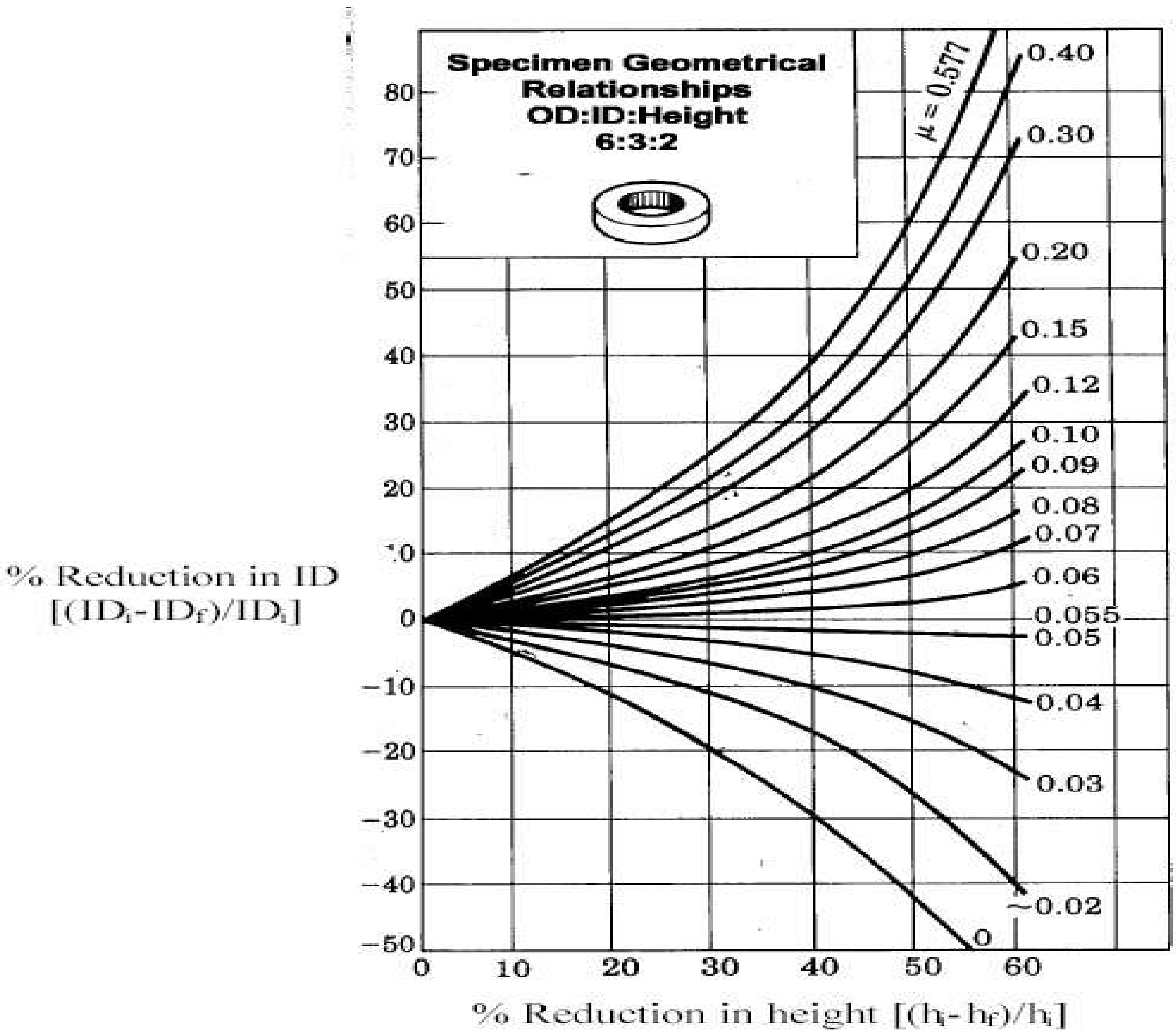


Fig-3: Standard calibration chart

[Source: *Kalpakjian S, Schmid S R, "Manufacturing Engineering and Technology", Prentice Hall, 6th Edition, 2009, fig.32.3*]

- **Procedure:**

Measure and record the initial dimensions of the ring type cylindrical specimen (I.D, O.D and Height) ID= inner diameter, OD= outer diameter using vernier caliper.

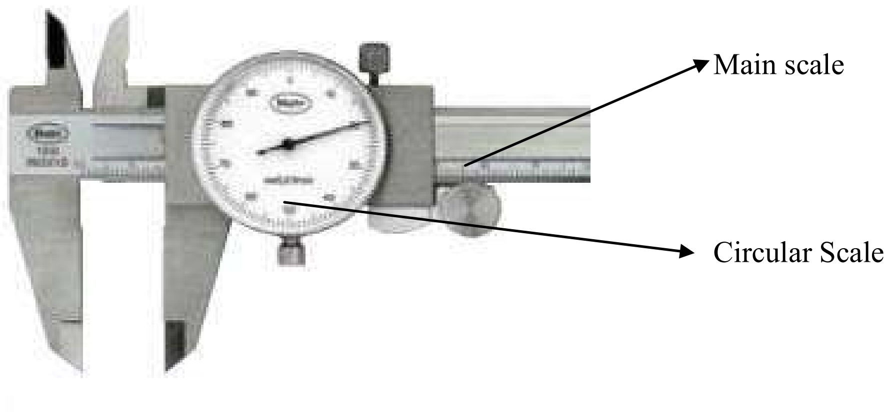


Fig-4: Vernier Caliper

The smallest value that can be measured by the measuring instrument is called its least count.

Here L.C= 0.05 mm

Actual reading= main scale reading + circular scale reading$_*$ L.C

The specimen is compressed and measured at different load interval as done in case of disc compression. Once the ring compression test is completed, the ID and height of the upset ring is measured for each loading condition and the % reduction is found out. By superimposing the measured data on the fig-3From the location of the experimental point on the chart, μ can be estimate (Ref-fig-3).

- **Questions for Discussion:**

(1) What is the limitation of ring compression test?

- **References:**

(1) *Sofuoglu H, Rasty J, "On the Measurement of Friction Coefficient by Utilizing the Ring Compression Test", Tribol. Int., 1999, volume 32(6), pages 327–335.*

(2) *Male AT, Cockcroft MG, "A method for the determination of the coefficient of friction of metals under condition of bulk plastic deformation". J Inst Metals 1964–1965, volume 93, pages 38–46.*

(3) *Kalpakjian S, Schmid S R, "Manufacturing Engineering and Technology", Prentice Hall, 6th Edition, 2009, pages 676-685.*