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].

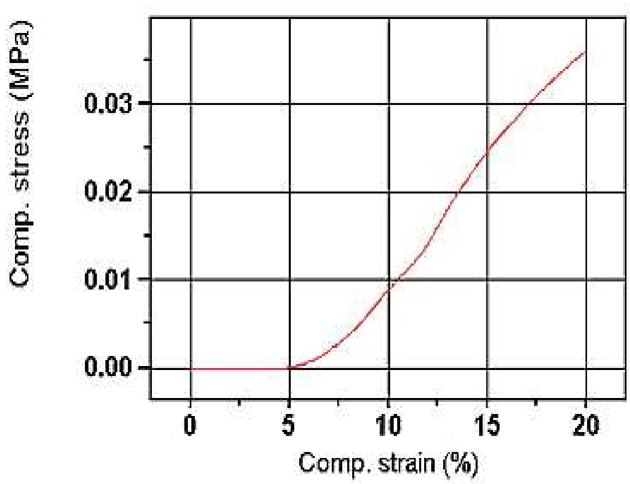


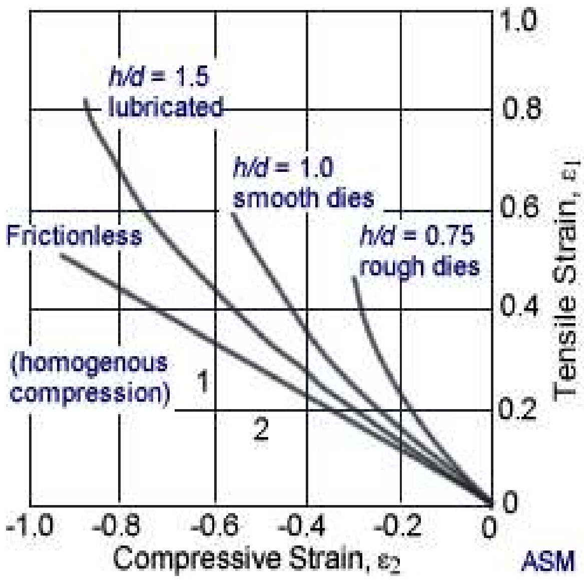
Fig-1: Compression test [Source: *www.instron.com*]

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:**

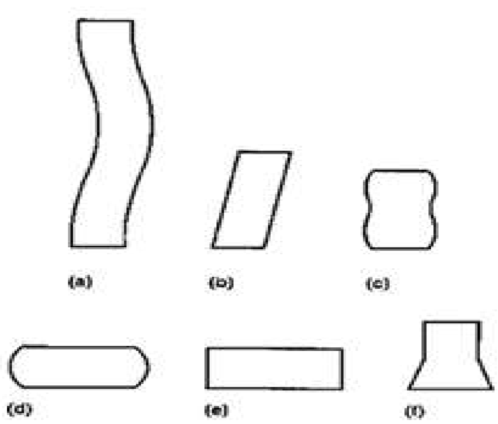


Figure-3 illustrates the modes of deformation in compression testing. (a) Buckling, when *L/D* > 5. (b) Shearing, when *L/D* > 2.5. (c) Double barrelling, when *L/D* > 2.0 and friction is present at the contact surfaces. (d) Barrelling, when *L/D* < 2.0 and friction is present at the contact surfaces. (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

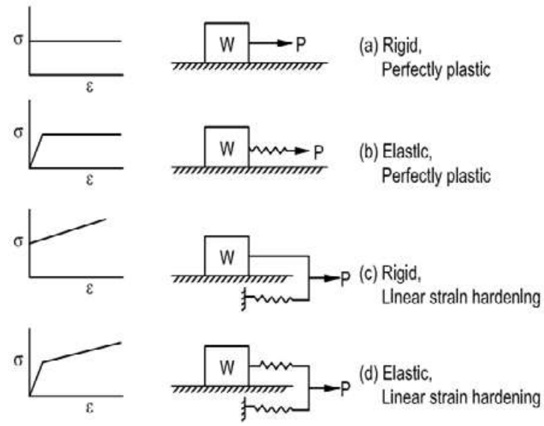


Fig-4 – Idealized stress-strain diagrams [Source: *Lal G.K, Gupta V and Reddy N.V, "Introduction to Machining Science", New Age International, 3rd edition, 2007, page no- 4*]

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).

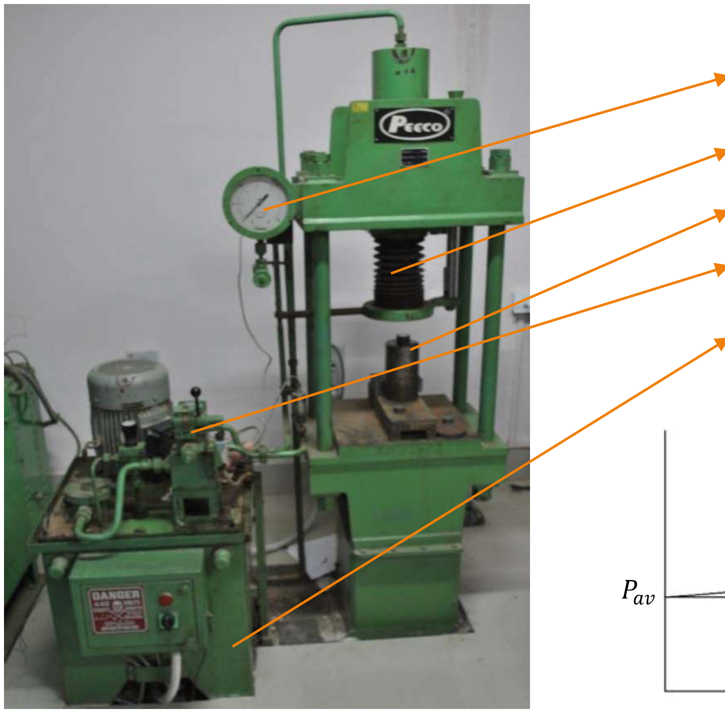


Fig-5-Hydraulic Compression testing machine

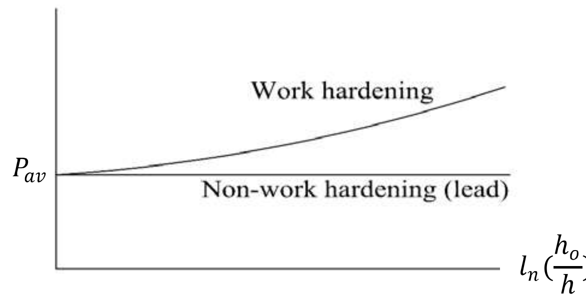


Fig-6 – Effect of work hardening on average normal stress

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

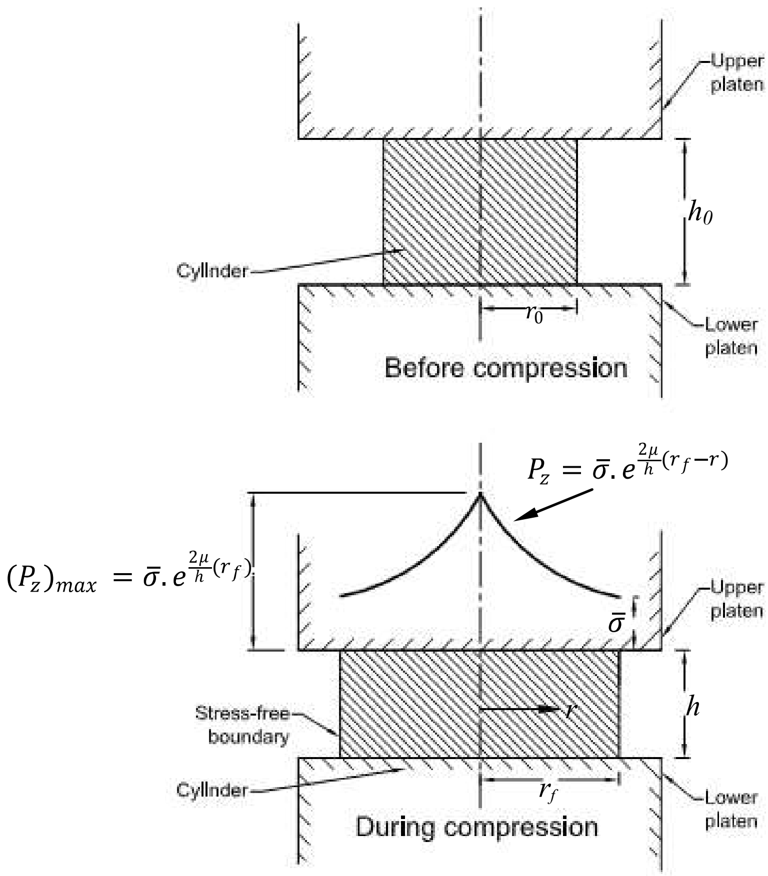


Fig-7 - Distribution of normal stress with rough platens

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.

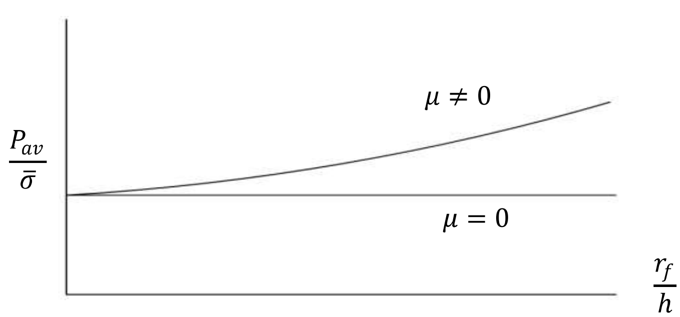


Fig-8 – Effect of friction and $\frac{r_f}{h}$ on average normal stress.

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):

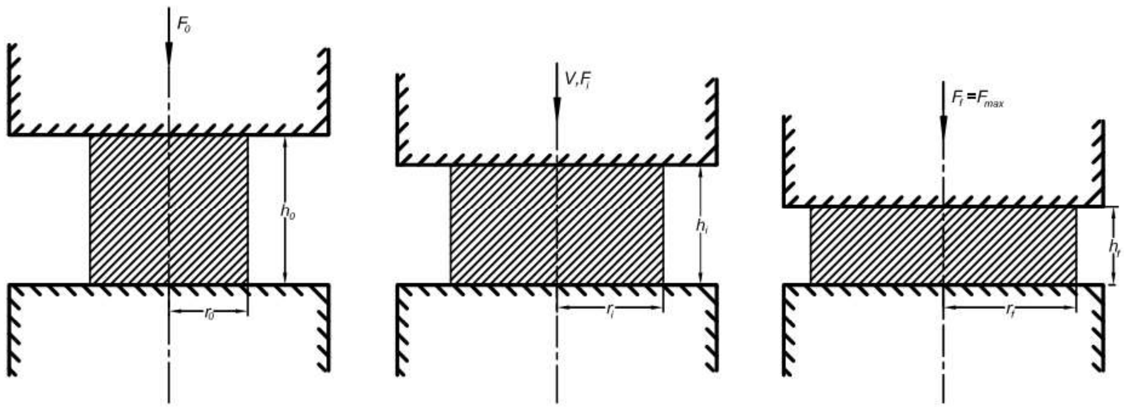


Fig -9: Homogeneous upsetting of cylindrical billet

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):**

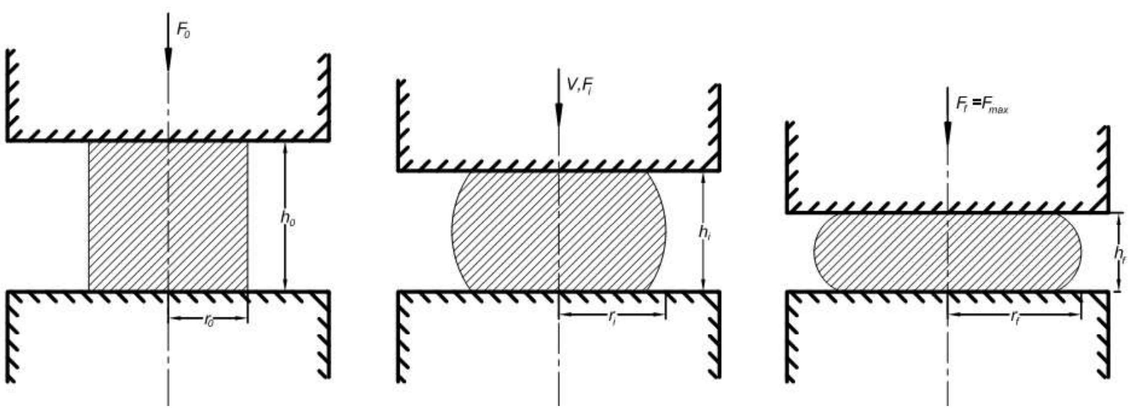


Fig-10: Practical upsetting of a cylindrical billet

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.

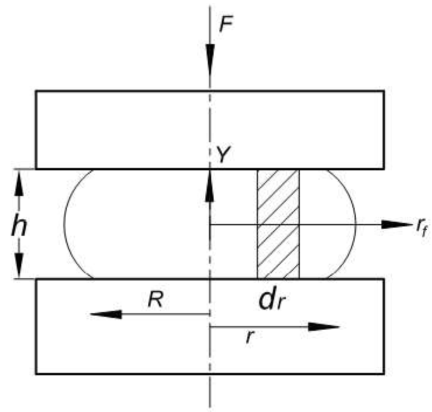


Fig-11(a): Forging of disc

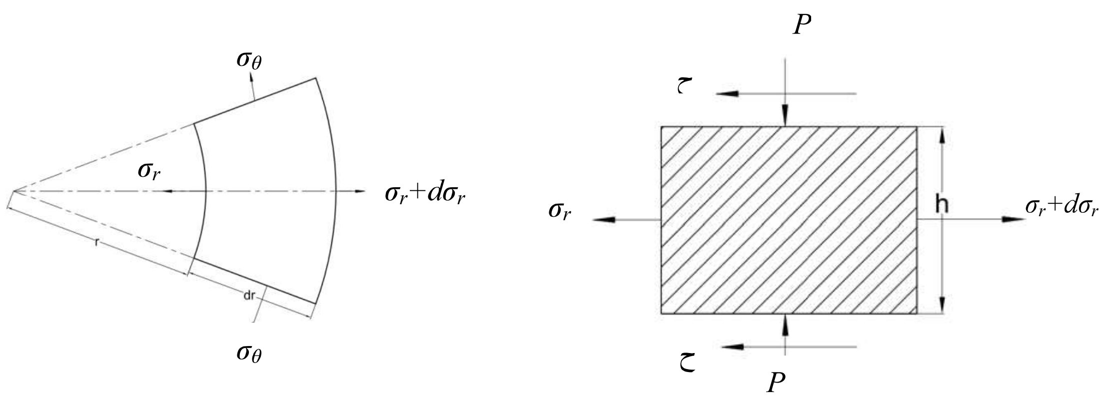


Fig-11(b): Stresses on element during disc forging

[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:**

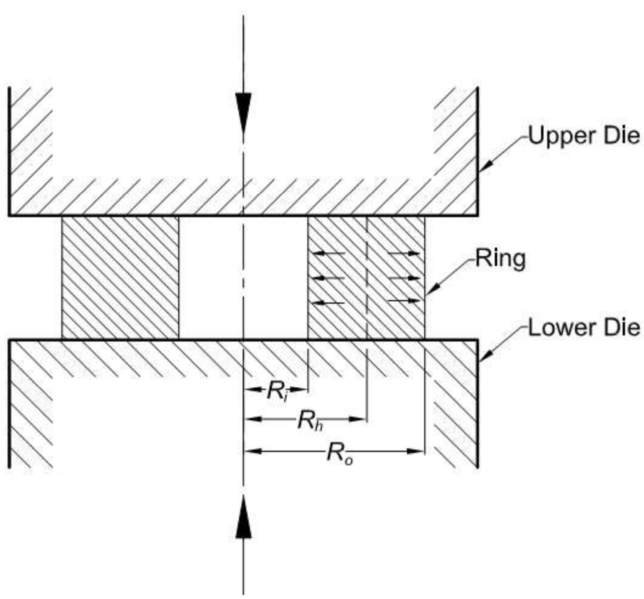
The friction at the interface of die/work piece plays an important role in the overall integrity of metal forming processes. Friction affects the deformation load, product surface quality, internal structure of the product, as well as dies' wear characteristics. Understanding of the friction phenomenon 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).

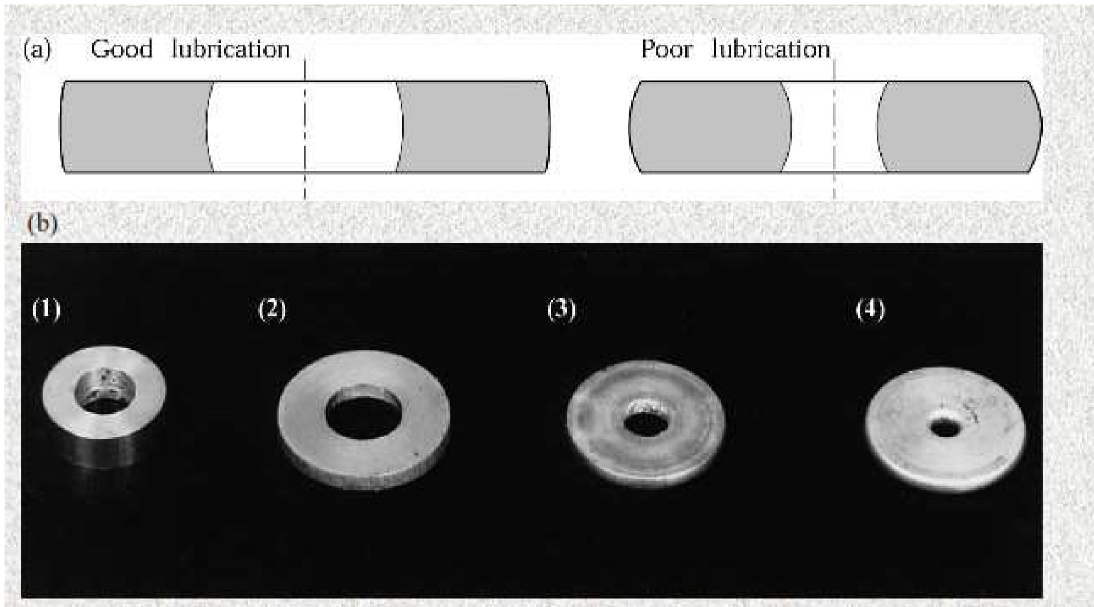


Fig- 2: Ring compression test between flat dies. (a) Effect of lubrication on type of ring specimen barrelling. (b) Test results: (1) original specimen and (2) - (4) increasing friction. [Source: *Kalpakjian S, Schmid S R, "Manufacturing Engineering and Technology", Prentice Hall, 6th Edition, 2009,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

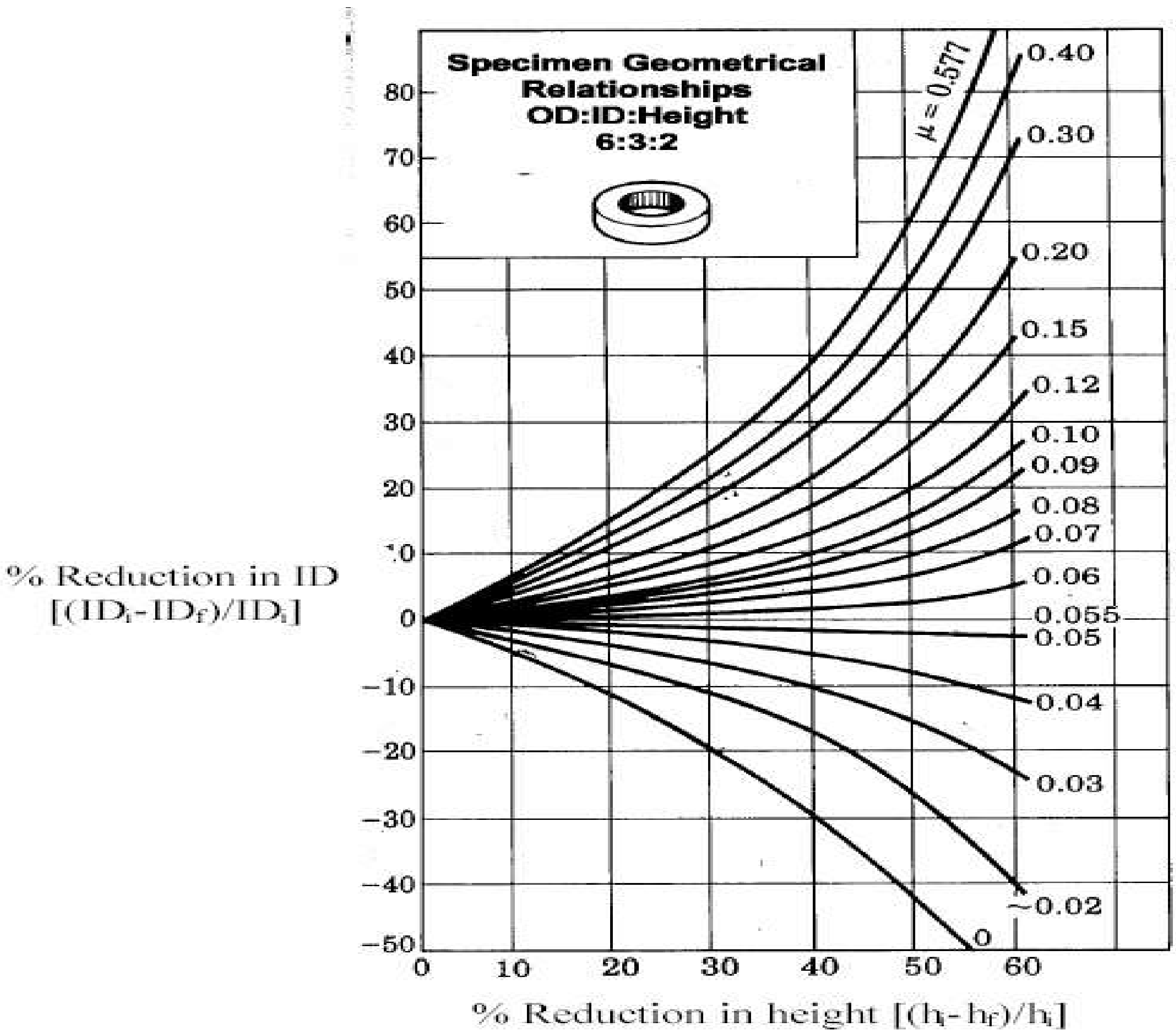


Fig-3: Standard calibration chart

[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.

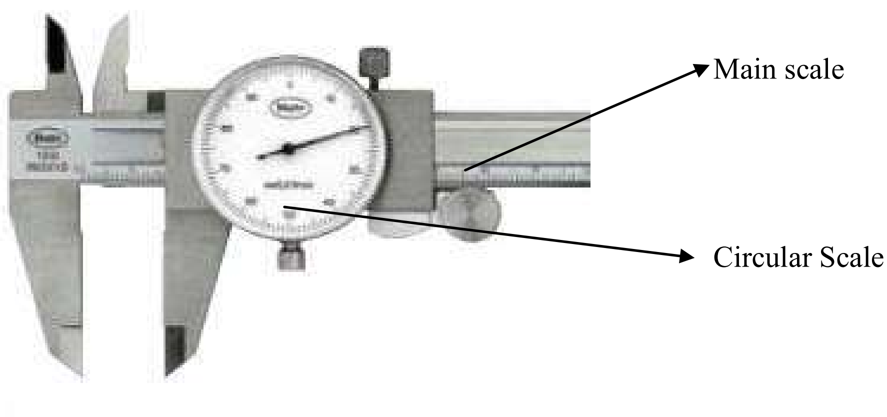


Fig-4: Vernier Caliper

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.*

Metal Forming Laboratory
Experiment No. 2: Deep Drawing

- ## Aim of the Experiment:

To learn the forming characteristics of sheet metal specimens with Deep Drawing operation.

- ## Objective:

i. To do the deep drawing experiment of brass (or any metallic) specimen with the help of a Compression Testing Machine
ii. To correlate the initial and final dimensions of the job
iii. To determine the deep drawing ratio of the material (given sample)
iv. To determine the deep drawing load (i.e. drawing initiation load and fracture load)
v. To measure the thickness variation in the critically deep cup
vi. To study the nature of load-displacement curve

- ## Equipment Used:

Deep drawing die, constant clearance Blank holder, Punch, Compression Testing machine, blank (metallic sample), LVDT (Linear Variable Differential Transducer), Load cell (Pressure transducer), Torque range, screw gauge, vernier calipers, divider, screw driver, etc.

- ## Theory:

Deep drawing is a sheet metal forming process in which a sheet metal blank is radially drawn into a forming die by the mechanical action of a punch. It is thus a shape transformation process with material retention. The process is considered "deep" drawing when the depth of the drawn part exceeds its diameter. This is achieved by redrawing the part through a series of dies. The operation is carried out on a pass with punch and dies as shown in Fig.1. The material initially flat flanges of the blank flows to form the walls of the cup. Due to shrinkage of the outer periphery, circumferential compressive stress develops which might thicken the sheet or cause local buckling (wrinkling). The flange region (sheet metal in the die shoulder area) experiences a radial drawing stress and a tangential compressive stress due to the material retention property. These compressive stresses (hoop stresses) result in flange wrinkles (wrinkles of the first order). Wrinkles can be prevented by using a blank holder, the function of which is to facilitate controlled material flow into the die radius [1].

For all forming operations, some important solid material's properties are involved here.

Ductility is the ability of material to deform under tensile stress; this is often characterized by the material's ability to be stretched into a wire.

Malleability is the ability of material to deform under compressive stress; this is often characterized by the material's ability to form a thin sheet by hammering or rolling

Formability is the ability of material to undergo plastic deformation without being damaged. The mechanical properties are aspects of plasticity, the extent to which a solid material can be plastically deformed without fracture [1].

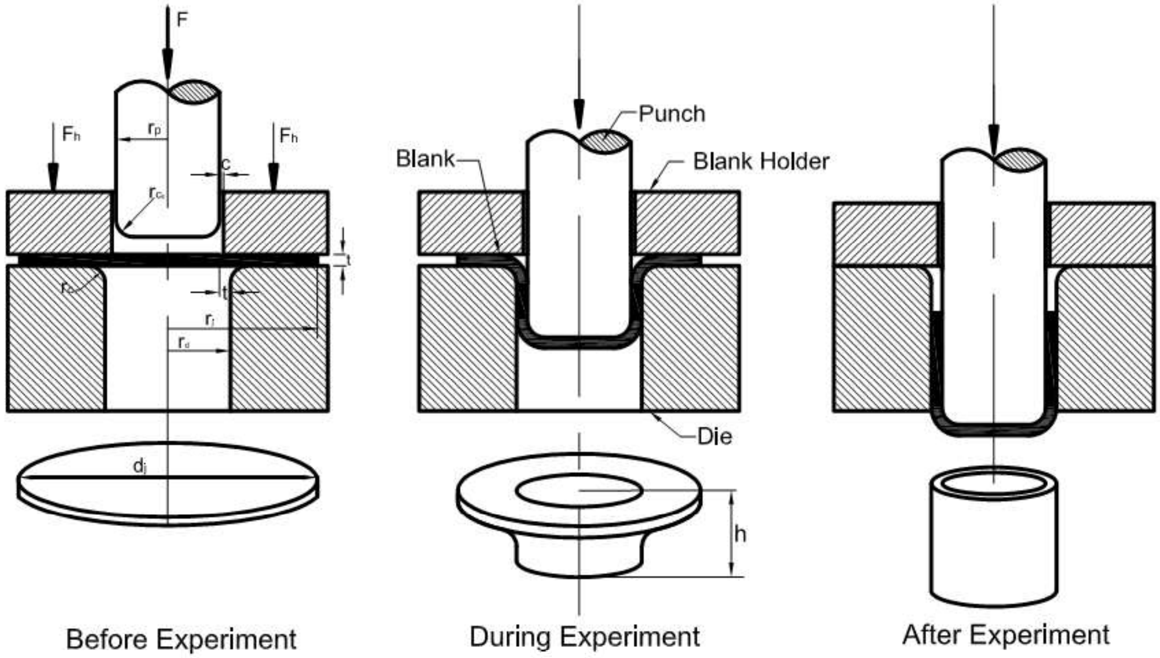


Fig.1. Schematics of deep drawing: **(a)** Die-Punch combination and position of Blank before drawing, **(b)** Drawn cup with flange, and **(c)** Drawn cup without flange

Blank size

The size of the blank required for deep drawing operation can be easily calculated as the thickness of the blank does not change much and can be assumed to remain constant before and after drawing for all practical purposes. The maximum diameter of the blank that can be successfully drawn into a cup is a material property [2].

The maximum drawable diameter can be empirically calculated as

$$D_{max} = \sqrt{\left(d_o - 2r_{c_p}\right)^2 + 4d_o\left(h - r_{c_p}\right) + 2\pi r_{c_p}\left(d_o - 0.7r_{c_p}\right)} \quad when \quad d_o < 10r_{c_p} \quad (1)$$

Where, $\boldsymbol{r_{c_d}}$ = die corner radius, $\boldsymbol{r_{c_p}}$ = Punch corner radius, $\boldsymbol{F}$ = drawing force, $\boldsymbol{F_h}$ = blank holding force, $\boldsymbol{c}$ = Clearance, $\boldsymbol{h}$ = height of cup (or shell), $\boldsymbol{d_i}$ = inner diameter of the cup, $\boldsymbol{d_o}$ = outer diameter of the cup, $\boldsymbol{D_F}$ = flange outer diameter. The radii of the punch, the job (blank), and die are $\boldsymbol{r_p}$, $\boldsymbol{r_j}$ and $\boldsymbol{r_d}$, respectively and corresponding diameters are $\boldsymbol{d_p}$, $\boldsymbol{d_j}$ and $\boldsymbol{d_d}$ respectively. The clearance between the die and the punch $\left(\boldsymbol{r_d - r_p}\right)$ is equal to the job thickness $\boldsymbol{t}$ and $\boldsymbol{\sigma_z}$ is the maximum allowable stress of the material.

Drawing ratio

Fracture occurs in the wall of the cup when the forces necessary to draw the material from under the blank holder is more than what can be sustained by the wall of the cup, as the force has to be transmitted from the punch to the unreformed blank through the cup walls [2].

The limiting drawing ratio (LDR) i.e. β_o is defined as the ratio of the maximum blank diameter (D_{max}) that can be safely drawn into a cup without flange to the punch diameter (d_p). The ratio of blank diameter (d_j) and the punch diameter (d_p) is called drawing ratio (β).

$$\boldsymbol{\beta_o = \frac{D_{max}}{d_p}}\ , \qquad \boldsymbol{\beta = \frac{d_j}{d_p}} \quad \text{and} \quad \text{Subsequent Deep Drawing ratio,}\ \boldsymbol{\beta_F = \frac{D_F}{d_i}}$$

Radius of curvature of punch (corner radius)

Though there is no set rule for the provision of corner radius on the punch, it is customary to provide a radius of four to ten times the blank thickness. Too small a corner radius makes for the excessive thinning and tearing of the bottom of the cup. Ideally, the punch radius should be the same as the corner radius of the required cup, because it takes its forms [2].

Radius of curvature of die (corner radius)

Since the draw radius on die does not contribute to the cup shape, it can be made as larger as possible. Higher the radius, higher would be the freedom for the metal to flow. Too high a radius causes the metal to be released early by the blank holder and thus lead to edge wrinkling. Too small a radius causes the thining and tearing of side wall of cups [2].

Drawing force

The force on the punch required to produce a cup is the summation of the ideal force of deformation, the frictional forces, and the force required to produce ironing (if present). If the clearance between the punch and the die is less than the thickness, the material in this region will be squeezed, or *ironed*, between the punch and die to produce a uniform wall thickness. In commercial deep drawing clearances about 10 to 20 percent greater than the metal thickness are common. Ironing operations in which applicable uniform reductions are made in the wall thickness use much smaller clearances [3].

The drawing force depends upon the material property, its dimension (desired shape and size). The drawing force can be calculated using the following equation for cylindrical shell (or cup shape) [4]. See in Appendix 2, equation (11).

$$\boxed{\boldsymbol{F = \sigma_z 2\pi r_p t}}$$

- ## Experimental Procedure:

1. Measure the thickness of three blanks (specimens).
2. Place a blank at the centre position of the die, put blank holder over it.
3. Tighten the blank holder with three bolts, with the help of torque range with 5 N-m torques.
4. Place the punch at its position.
5. Now, put the total setup at exact location in the compression-testing machine.
6. Rest the load cell on the upper surfaces of the punch.
7. Place the LVDT in its holder and tighten with screwdriver. Set both Load cell and LVDT display as zero.
8. Close the hydraulic release valve and oil flow valve, after that put on s/w of oil pump; then slowly open the oil flow valve.
9. Start taking reading of applied load with equal increment of linear displacement value.

- ## Experimental Details:

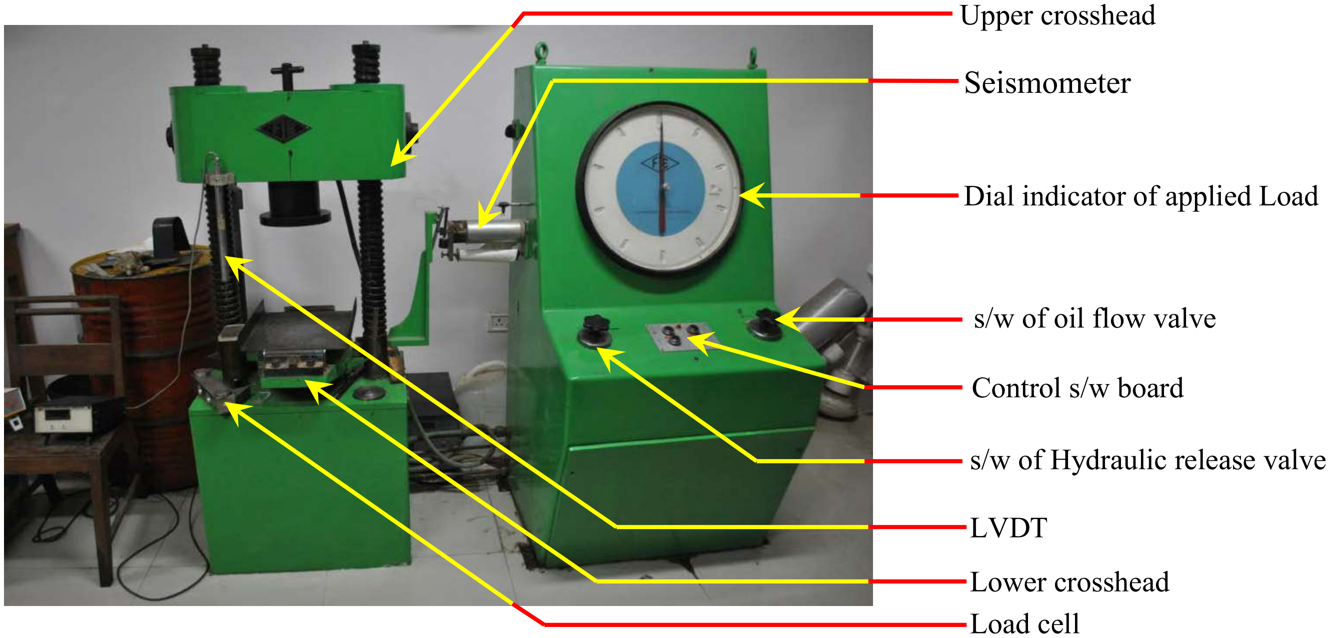


Fig.2. Compression Testing Machine

Fig.3. Critically draw cups ***Sample-1, 2*** and ***3***

Table-1: Sample thickness

Take *five* thickness readings of blanks at five different points with the help of screw gauge for three samples, and make its average.

Sample No.	thickness					Average thickness, ***t*** *(in mm)*
1						$t_1 =$
2						$t_2 =$
3						$t_3 =$

- ## Observations

Table-2: Load and displacement

Sample-1	
Cup height, $\boldsymbol{h}$ *(in mm)*	Applied Load, $\boldsymbol{P}$ *(in kgf)*
00.0	
00.2	
00.4	
00.6	
. .	

← *Fracture load*

Take the load value in each 0.2 mm interval of cup height (i.e. displacement of die), and identify the *drawing initiation load* & *fracture load* for three samples with arrow mark.

Similarly for ***Sample-2*** and ***Sample-3***

Table-3: Inner and outer diameter of the cup

Sample No.	Shell-inner diameter (*in mm*)											Shell-outer diameter (*in mm*)										
	Root diameter					Bottom diameter					Average (d_i)	Root diameter					Bottom diameter					Average (d_o)
1											d_{i-1} =											d_{o-1} =
2											d_{i-2} =											d_{o-2} =
3											d_{i-3} =											d_{o-3} =

Die corner radius, $\boldsymbol{r_{c_d}}$ = **5.25** *mm*, Punch corner radius, $\boldsymbol{r_{c_p}}$ = **4.25** *mm* and Punch diameter, $\boldsymbol{d_p}$ **= 36.75** *mm*, [measured with CMM, in Metrology Lab.]. Given (sample) blank diameter, $\boldsymbol{d_j}$ **= 80** ***mm.***

Take *five* readings of flange diameter **(**$\boldsymbol{D_F}$**)** for each sample, with the help of vernier caliper and make their average.

Table-4: Flange diameter

Sample No.	Five reading of $\boldsymbol{D_F}$ (*mm*)					Average of Flange Outer diameter, $\boldsymbol{D_F}$	Depth of cup $\boldsymbol{h}$ *(mm)*
1						D_{F1} =	
2						D_{F2} =	
3						D_{F3} =	

- ## Calculation:

Now, calculate D_{max} for ***Sample-1, 2*** and ***3*** with the help of r_{c_p} , h and $d_{o\text{-}1}$, $d_{o\text{-}2}$, $d_{o\text{-}3}$ values.

LDR, $\beta_o = \frac{D_{max}}{d_p} =$

Subsequent drawing ratio, $\beta_F = \frac{D_F}{d_i} =$

Compute both drawing ratio for ***Sample-1, 2*** and ***3***.
Calculate the drawing force F from equation (11)[4]for three samples.
The maximum allowable stress for *70:30 annealed brass* is 275 MPa

- ## Results:

Samples	***Sample-1***	***Sample-2***	***Sample-3***
LDR, β_o			
Subsequent Drawing ratio, β_F			
Calculated Drawing force, F			
Experimental fracture Load, P_{max}			
Variations, $F \sim P_{max}$			

- ## Discussion:

I. How will depth of cup with its diameter ratio >1can be drawn?
II. Would lubricant improve the deep drawing ratio?
III. How annealing can influence on deep drawing operation?
IV. Plot the displacement vs applied Load graphs and discuss the nature of the curves.
V. What is the function of blank holder?

- ## References:

[1] Deep drawing - Wikipedia, the free encyclopedia.
[2] Manufacturing Technology, by P N Rao, *Second Edition.309-316.*
[3] Mechanical Metallurgy, by George E. Dieter, *Third Edition.666 -670.*
[4] Manufacturing Science, by A.Ghosh and A. K. Mallik, *1999, 133-135.*
[5] Technology of Metal Forming Processes, by Surender Kumar, *2008, 120-127.*

- ## Compression Testing Machine:

The Compression testing machine is a universal type m/c, in which Deep drawing, Extrusion, Bending, Blanking, Piercing, and some special type of forming operations are carried out. The m/c has two sub units; one is main control unit (driver part) and other is press unit (driven part). The control unit consists of hydraulic oil chamber, motor, pump, control valves and control switches. On the other hand, the press unit consists of upper and lower crosshead, high-pressure chamber, electric motor, ram, and base. In dial meter, the black needle displays the load reading instantaneously, and red needle shows fracture (ultimate) load reading.

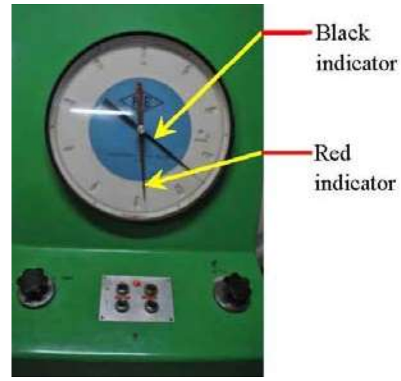
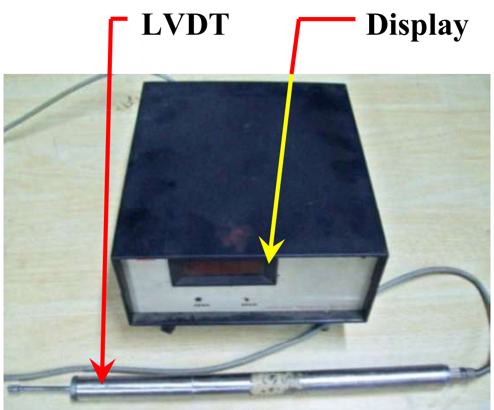


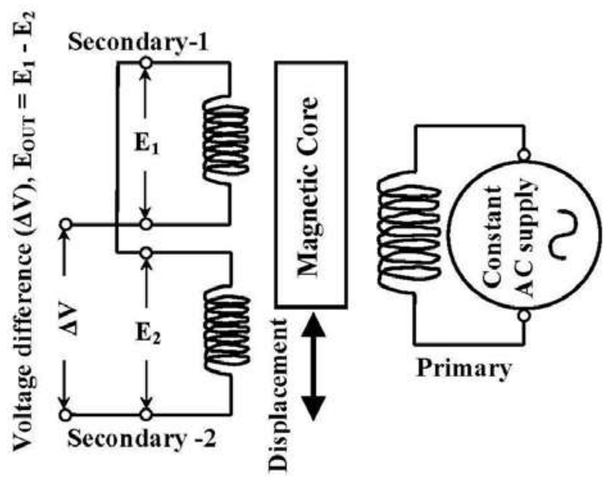
Fig.4. Main control unit of Compression Testing Machine

- ## LVDT:

The LVDT is abbreviation of linear variable differential transformer, that is basically an electromechanical transducer, which can able to convert the rectilinear motion of an object into a corresponding electrical signal.



(a)



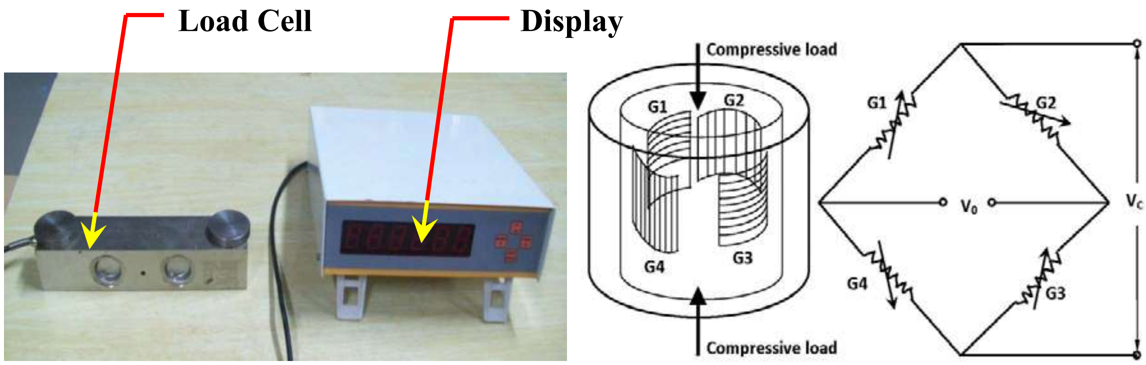
(b)

Fig.5. Arrangement of Linear Variable Differential Transformer: **(a)** The LVDT and its display, **(b)** The circuit diagram of LVDT

The main structure consists of a magnetic core; one primary winding covers the centre position of the core and a pair of secondary windings covers the two ends. The coils are encircle on a one-piece hollow, thermally stable glass reinforced polymer, encapsulated with magnetic and electrical insulator, and finally placed into a hollow stainless steel cylindrical tube. The secondary windings are mirror identical i.e. numbers of windings are same but directions are opposite. A constant alternating current flows through the primary coils and combination of two secondary coils produce the ultimate voltage difference in the high accurate level of few millivolts, when the magnetic core displaced from its initial position. The capability as linear position sensors can measure the movement of the object followed by the magnetic core, in the order of a few thousandths of a millimeter, and display shows the reading, which has been calibrated previously. In our laboratory, the LVDT can identify the linear difference of one tenth of an mm division.

• Load Cell:

The load cell is another type of transducer, which is applied to measure the load value. The common load cells, which are used in industry, are strain gauge load cell, hydraulic load cell, piezoelectric load cell, capacitive load cell etc. The most applicable and packed compressive load transducer is strain gauge type, which converts the applied force into the voltage difference. The load transducer utilizes four strain gauges, which are attached on the outer peripheral wall of a cylindrical small chamber. The gauges are connected into Whetstone Bridge circuit in such a manner as to make use of Poisson's ratio, i.e. the ratio between the relative compression in the direction of force applied and the relative expansion perpendicular to the force. The applied force alters the resistance of deformed strain gauge, which controls the ultimate change of electric signal as mechanical arrangement in the cylindrical chamber. The electrical output signal is actually as small as a few millivolts range; and the display shows load readings exactly, that already calibrated in its manufacturing time.



(a) (b)

Fig.6. Compressive force transducer: **(a)** The load cell and its display, **(b)** The frame and circuit diagram of strain gauges in Whetstone Bridge, applied in load cell.

• Torque Wrench:

A torque wrench is a special type of wrench, which has specific application to fastener a nut or bolt with precise torque in such a manner with the correct amount of force, so that it will break neither the tightened object nor makes loosens. The most important part of wrench is its internal mechanism and sockets; accompanying, the other parts are adjustable screw, lever and the grip. There are many types of torque wrenches available such as Slipper type, Beam type, Deflecting beam type, Click type, "No-hub" wrench, Electronic torque wrenches, Programmable electronic torque / angle wrenches etc. In deep drawing experiment, the adjustable torque wrench is Click type, and it is used to fasten the bolts of blank holder with five N-m torques.

Fig.7. Adjustable torque wrench

Appendix 2: Drawing force derivation

To start with, let us consider the portion of the job between the blank holder and the die. Fig.8. shows the stress acting on an element in the region [4].

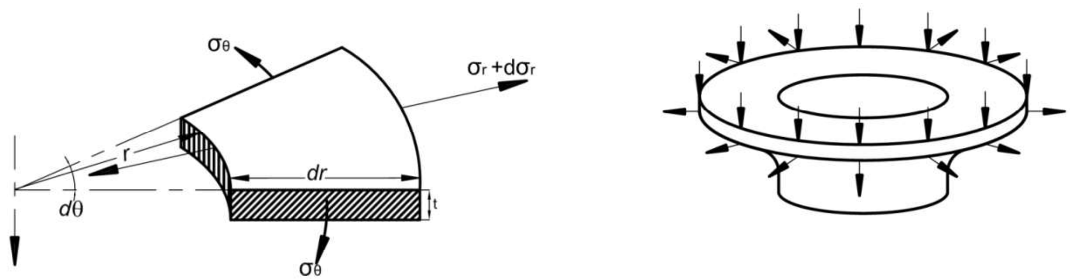


Fig.8. Analysis of deep drawing operation:
(a) Stress acting on element during drawing, and **(b)** Radial stress due to blank holding pressure

It should be noted that the maximum thickening (due to the decreasing circumference of the job using a compressive hoop stress) takes place at the outer periphery, generating a line contact between the holder and the job. As a result, the entire blank holder force F_h is assumed to act along the circumference in Fig.8.(b). Thus, the radial stress due to friction can also be represented by equivalent radial stress $\frac{2\mu F_h}{2\pi r_j t}$ at the outer periphery [4].

Now, considering the radial equilibrium of the element shown in Fig.8.(a), we get

$$\boldsymbol{r d\sigma_r + \sigma_r dr - \sigma_\theta dr = 0} \qquad (2)$$

As $\boldsymbol{\sigma_r}$ and $\boldsymbol{\sigma_\theta}$ are the principal stresses, the equation we obtain by using *Tresca's yield criterion* is

$$\boldsymbol{(\sigma_r - \sigma_\theta) + 2K} \qquad (3)$$

Substituting σ_θ from the equation (3) in equation (2), we get

$$\boldsymbol{\frac{dr}{r} + \frac{d\sigma_r}{2K} = 0} \qquad (4)$$

Integrating, we obtain

$$\boldsymbol{\frac{\sigma_r}{2K} = C - \ln r.} \qquad (5)$$

Now, at $\boldsymbol{r = r_j}$, $\boldsymbol{\sigma_r = \frac{\mu F_h}{\pi r_j t}}$ as mentioned.

Hence,

$$\boldsymbol{C = \frac{\mu F_h}{2\pi K r_j t} + \ln r_j} \qquad (6)$$

Using this in the expression for σ_r , we have

$$\frac{\sigma_r}{2K} = \frac{\mu F_h}{2\pi K r_j t} + \ln\frac{r_j}{r} \qquad (7)$$

So, the radial stress at the beginning of the die corner (i.e., at $r = r_d = r_p + t$) is giving by

$$\left.\frac{\sigma_r}{2K}\right]_{r=r_d} = \frac{\mu F_h}{2\pi K r_j t} + \ln\left(\frac{r_j}{r_d}\right) \qquad (8)$$

As the job sides along the die corner, the radial stress, given by the above equation, increase to σ_z due to the frictional forces, as shown in Fig.9.

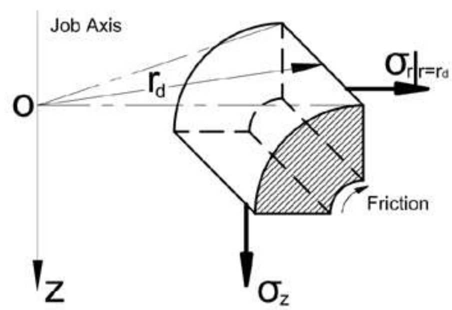


Fig.9. Effect of friction at corners.

This increment can be roughly estimated by using a belt-pulley analogy.

Thus,

$$\frac{\sigma_z}{\sigma_r]_{r=r_d}} = e^{\mu\frac{\pi}{2}} \qquad (9)$$

Where μ is the coefficient of friction between the workpiece and the die.

There is a further increase in the stress level around the punch corner due to bending. As a result, the drawn up normally tears around this region. However, to avoid this, an estimate of the maximum permissible value of $\left(\frac{r_j}{r_d}\right)$ can be obtained by using equations (9) and (8) with σ_z equal to the maximum allowable stress of the material. Science, d_O is the final outside diameter of the product, it is easy to arrive at such an estimate. This estimate is based on the consideration of fracture of the material. However, to avoid buckling (due to the hoop stress in the flange region), $(r_j - r_p)$ should not, for most materials, exceed $4t$.

Normally, the blank holder force is given as

$$F_h = \xi\, \pi {r_j}^2 K \qquad (10)$$

Where, ξ is between 0.02 to 0.08. An estimate of the drawing force F (neglecting the friction between the job and the die wall) can easily be obtained from the above equation, as

$$F \approx \sigma_z 2\pi r_p t \qquad (11)$$

This is the calculated value of drawing force [4].

Metal Forming Laboratory
Experiment No. 03: Extrusion

- ## Aim of the Experiment:

  - To extrude a cylindrical cup by backward extrusion.
  - To determine the load variation with the thickness of the bottom of the cup.

- ## Equipment & Specimen Required:

  - Extruding punch and dies
  - Compression testing machine
  - LVDT
  - Load cell
  - Vernier caliper
  - Lead specimen

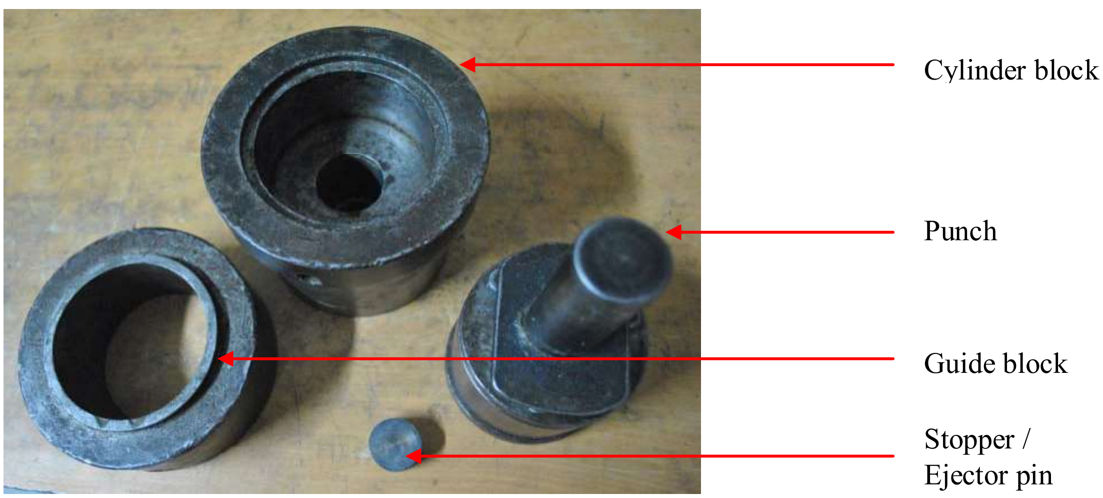


Fig. 1 Extruding punch and dies

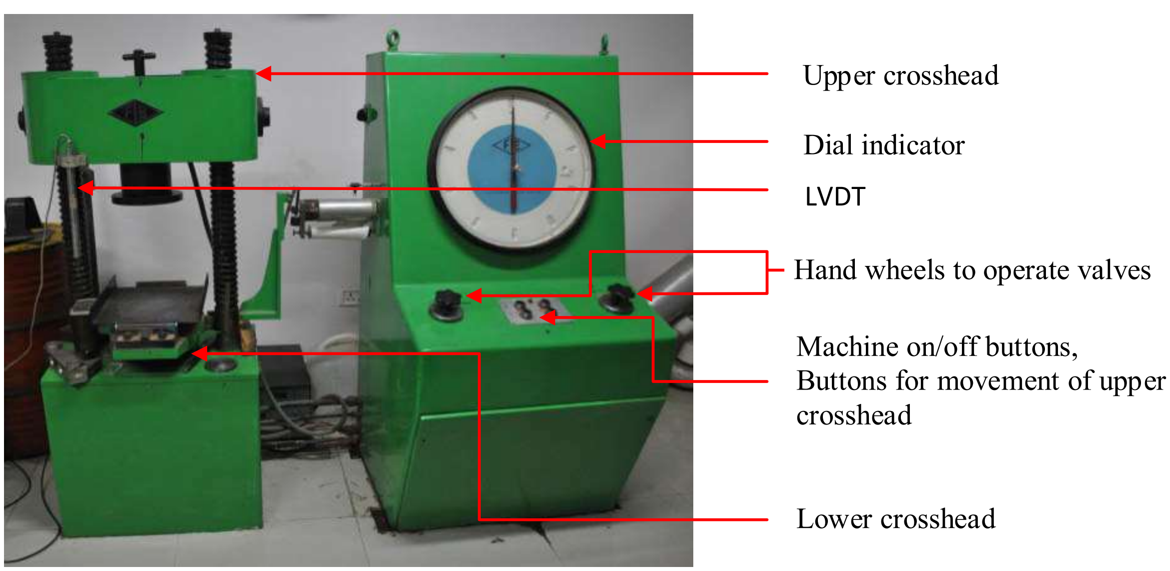


Fig. 2 Compression testing machine

- **Theory:**

Extrusion is a plastic deformation process in which a block of metal (billet) is forced to flow by compressing through the die opening of a smaller cross-sectional area than that of the original billet. The different types of extrusion processes are:

In **direct** or **forward extrusion,** metal flows in the same direction as that of the ram. Because of the relative motion between the heated billet and the chamber walls, friction is severe and is reduced by using lubricant. (See Fig. 3)

In **indirect** or **backward extrusion,** metal flows in the opposite direction as that of the ram. It is more efficient since it reduces friction losses considerably. The process, however, is not used extensively because it restricts the length of the extruded component. (See Fig. 4)

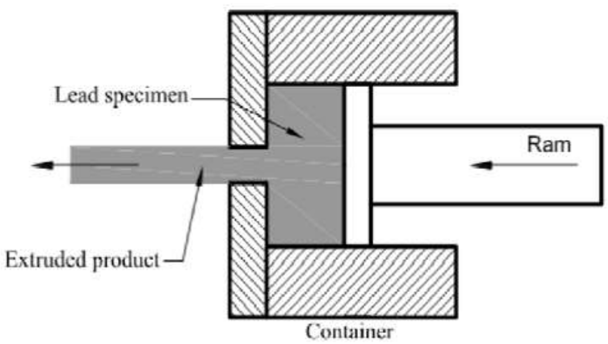


Fig. 3 Direct extrusion

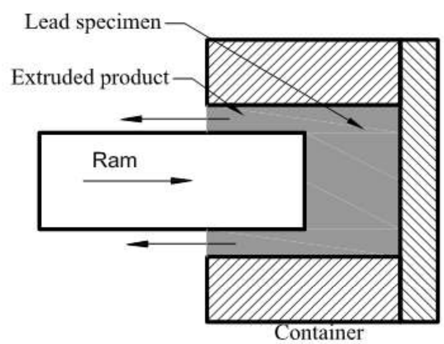


Fig. 4 Indirect extrusion

Extrusion may be hot extrusion or cold extrusion depending on the recrystallization temperature of the material to be extruded. If the extrusion is carried out above the recrystallization temp of the material, it is called **hot extrusion;** and if it is carried out below the recrystallization temperature of the material, it is called **cold extrusion**.

The force required for extrusion can be calculated approximately by equating specific internal strain energy to the external work per unit volume of the material extruded under the assumption of no losses. For details see Appendix I.

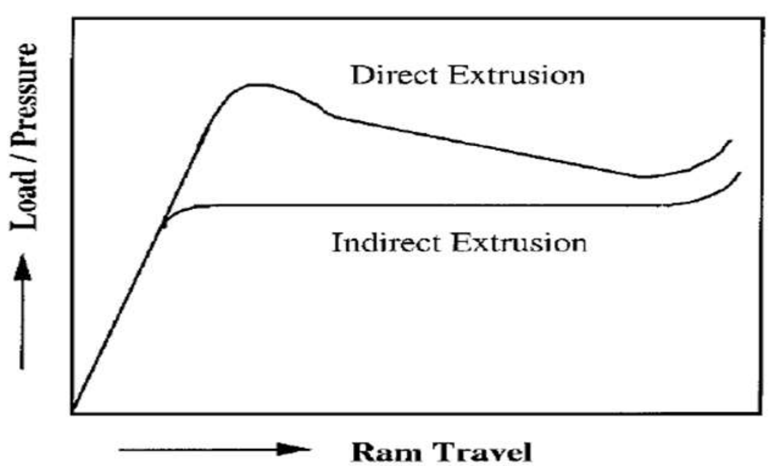


Fig. 5 Variation of force with ram displacement
(Source: www.wikipedia.org)

- **Compression Testing Machine:**

The Extrusion operation is carried out on Compression testing machine. The machine is divided into two sub assemblies. One assembly consists of hydraulic oil container, few valves to operate the machine, a motor which sucks oil from oil container & deliver it with high pressure to high pressure oil chamber (at another assembly) & circular scale which gives load readings. Another assembly consist of upper & lower crosshead, high pressure oil chamber, oil pipe lines & base. The upper crosshead can be moved by electric motor, just operating valves (at first assembly); whereas the lower crosshead is moved by high pressurised oil. With this assembly there is an attachment to attach LVDT as shown in the Fig. 2.

The circular scale which gives load readings has two pointers, one is black coloured & another is red coloured. Red coloured pointer is just over the black coloured pointer & contains a retainer at its end & in front of black coloured pointer. So when the high pressure oil is allowed to flow into the second sub assembly the black coloured pointer is moved & it also moves the red coloured pointer till the load is increasing. When load starts decreasing black coloured pointer comes back but red coloured pointer remains at its final position. This facilitates in reading the maximum load value.

- **Linear Variable Differential Transformer (LVDT):**

The linear variable differential transformer (LVDT) is a type of electrical transformer used for measuring linear displacement. LVDT consists of a cylindrical former where it is surrounded by one primary winding in the centre of the former and the two secondary windings at the sides. The numbers of turns in both the secondary winding are equal, but they are opposite to each other, i.e., if the left secondary winding is in the clockwise direction, the right secondary windings will be in the anti-clockwise direction, hence the net output voltages will be the difference in voltages between the two secondary coil. An alternating current drives the primary and causes a voltage to be induced in each secondary proportional to the length of the core linking to the secondary. The frequency is usually in the range 1 to 10 kHz.

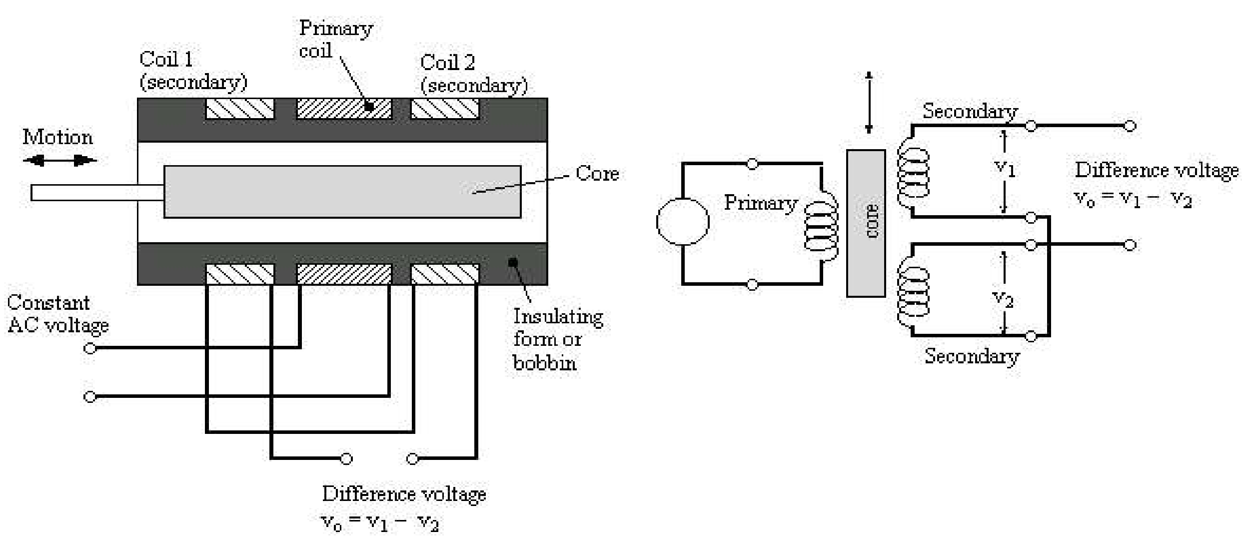


Fig. 6 Principle of LVDT
(Source: www.instrumentationandcontrollers.blogspot.in)

When the core is in its central position i.e. equidistant from the two secondary coils, equal voltages are induced in the two secondary windings and the output voltage is zero. As the core moves, the primary's linkage to the two secondary windings changes and causes the induced voltages to change. The phase of the output voltage determines the direction of the displacement (up or down) and amplitude indicates the amount of displacement.

- **Load Cell:**

A load cell is a transducer that is used to convert a force into electrical signal. There are many types of load cells available like strain gauge load cell, hydraulic load cell, piezoelectric load cell, capacitive load cell etc. Strain gauge load cells are the most common.

A strain gauge load cell usually consists of four strain gauges in a Wheatstone bridge configuration. Through a mechanical arrangement, the force being sensed deforms strain gauge and strain gauge measures the deformation (strain) as an electrical signal, because the strain changes the effective electrical resistance of the wire. The electrical signal output is typically in the order of a few millivolts and requires amplification by an instrumentation amplifier before it can be used. The output of the transducer is plugged into an algorithm to calculate the force applied to the transducer.

Fig. 7 Load cell

- **Experimental Procedure:**

1. Measure the height and diameter of the specimen.
2. Give some lubricant coating (if available) over the punch wall and inside wall of die block for easy removal of the component after extrusion.
3. Place the specimen in the die block and put the punch over it.
4. Place the die punch set up in between the two jaws of the compression testing machine. Care must be taken to place the set up coaxial with the machine central axis.
5. Reset the load cell and LVDT readings to zero.
6. Now give the load by the rotating the right hand wheel gradually and take the load readings up to 15 mm of punch displacement at an interval of 0.2 mm.
7. When the punch displacement reaches 15 mm, stop the machine, rotate the left hand wheel to release the load and take the total set up out of the machine to remove the extruded cup.

- **Observations:**

Table 1

Sl. No.	Punch displacement (mm)	Load (kg)

- **Results & Discussions:**

    - Graph to be plotted between the thicknesses of the bottom of the cup and load values.
    - Discussions to be made on the observed defects (if any) on the extruded cup.

  Some of the possible defects are:

    - Non uniform thickness of the cup.
    - Non uniform height of the cup.
    - Scratches on the surfaces of the extruded cup.
    - Cracks on the surfaces.

- **Conclusions:**

  Comment on:

    - Trends of the graph plotted.
    - Quality of the extruded cup.

- **Questions:**

    1. What material properties control extrusion?
    2. Differentiate between hot working and cold working?

- **References:**

    1. Metal Forming Handbook, Schuler, L. 671.02, SCH/M.
    2. Theory of Plastic Deformation and Metal Working, Masterov, V. And Berkovsky, V.
    3. Mechanical Metallurgy, Dieter, George E. 669, DIE/M.

- **Appendix I**

The force required for extrusion can be calculated approximately by equating specific internal strain energy to the external work per unit volume of the material extruded under the assumption of no losses

$$L \times p_{av} = V_m \times \int_0^{\bar{\varepsilon}} \sigma . d\varepsilon$$

where the integral represents the area under true stress-strain curve of the material. Now

$$\sigma = k\varepsilon^n$$

Hence,

$$\frac{L \times p_{av}}{V_m} = \int_0^{\bar{\varepsilon}} \sigma . d\varepsilon = \int_0^{\bar{\varepsilon}} K\varepsilon^n d\varepsilon = \frac{k\bar{\varepsilon}^{n+1}}{n+1} = \frac{\bar{\sigma} . \bar{\varepsilon}}{n+1}$$

Effective strain $\bar{\varepsilon}$ is calculated as

$$\bar{\varepsilon} = ln\left(\frac{l_2}{l_1}\right) = ln\left(\frac{D_d^2}{D_d^2 - D_p^2}\right) = ln\left(\frac{A_0}{A_1}\right)$$

Where

$k =$ Strength coefficient, n = strain harden ability coefficient, $\sigma =$ true stress, $\varepsilon =$ natural strain, $p_{av} =$ average load on punch, $V_m =$ material volume, $D_d =$ die diameter, $D_p =$ punch diameter.

The value of p_{av} thus, obtained underestimates the pressure because shearing work and friction has been neglected in this expression. The error may be of the order of 40 to 50 %. The extrusion pressure changes considerably when, the bottom of the cup becomes thin. The extent of redundant work can be studied by the split specimens where a uniform gridline is scribed before the extrusion operation is carried out.

Metal Forming Laboratory

Experiment No. 04: Hydraulic Bulge Test

- **Objective:** To find out the flow stress behavior of sheet metal under equi-biaxial stress condition.

- **Equipments Required:**

1. Hydraulic bulge test-rig
2. Sheet metal blank of diameter 120 mm.
3. Scriber
4. Micrometer (screwgauge)
5. Depth micrometer
6. Spherometer
7. Flexible scale

Fig. 1(b) Scriber

Fig. 1(a) Hydraulic bulge test-rig

Fig. 1(c) Depth micrometer

Fig. 1(d) Spherometer

[**Note:** Detailed information on **'Spherometer'** can be seen in *'Appendix 2'*.]

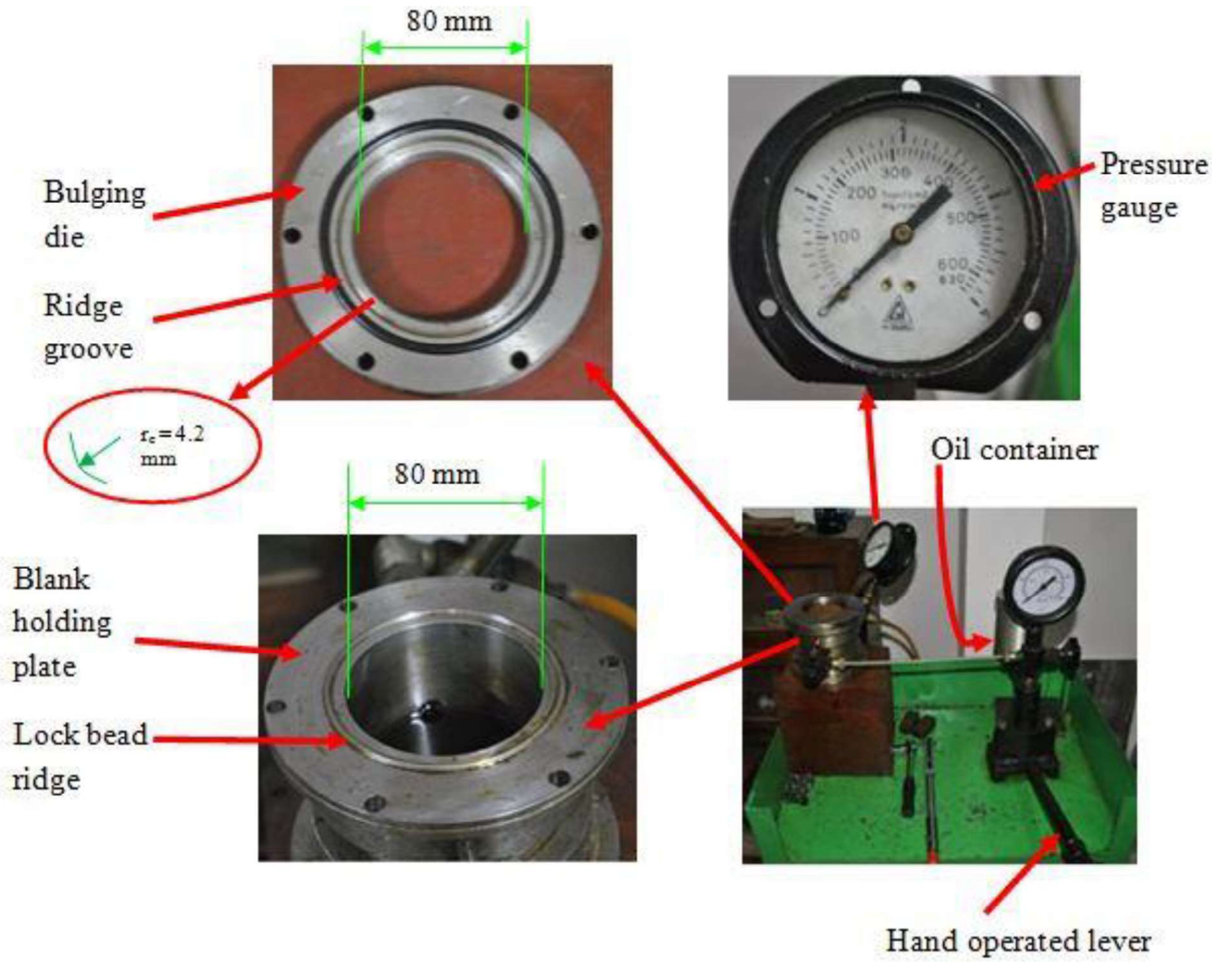


Fig.2.Various components of *'hydraulic bulge test-rig'*

- **Theory:** The stress-strain relationship of sheet metals are conventionally determined by tensile test, where the specimen is loaded uniaxially; but the range of stable uniform strain is restricted to approx 30% of the fracture value. Mostly the stress-strain states in actual sheet metal forming processes are biaxial but not uniaxial; so for finding out the biaxial stress-strain relationship of sheet metals '*Hydraulic bulge test*' is widely used, which gives flow curves for sheet metals with extended range of plastic strain up to 70% of fracture value. Another advantage of the process is that the deformation occurs isothermally [1].

- **Methodology:** In '*Hydraulic bulge test'* a thin metallic sheet is clamped at its periphery between circular die ring & blank holder and then uniform hydraulic pressure is applied at one side of the sheet; as shown in the figure 3. The edge of the dome is prevented from slipping by a lock bead placed in the die ring. It consists of a 'ridge' with small radii on one side and a 'matching groove' on the other. The constant parameter for die set is the die corner radius r_c; as it affects the bulged sheet`s shape & size. Initial thickness of sheet metal t_0 is another constant. As pressure is introduced, the metal starts to bulge to a hemispherical dome shape. Instantaneous variables of this bulging are the dome height h_d, pressure P, dome apex thickness t and bulge or dome radius R_d. In order to obtain the flow curve, these values should be measured at different stages of bulging, and then should be converted into strain and stress values. These values should then be plotted as a flow curve.

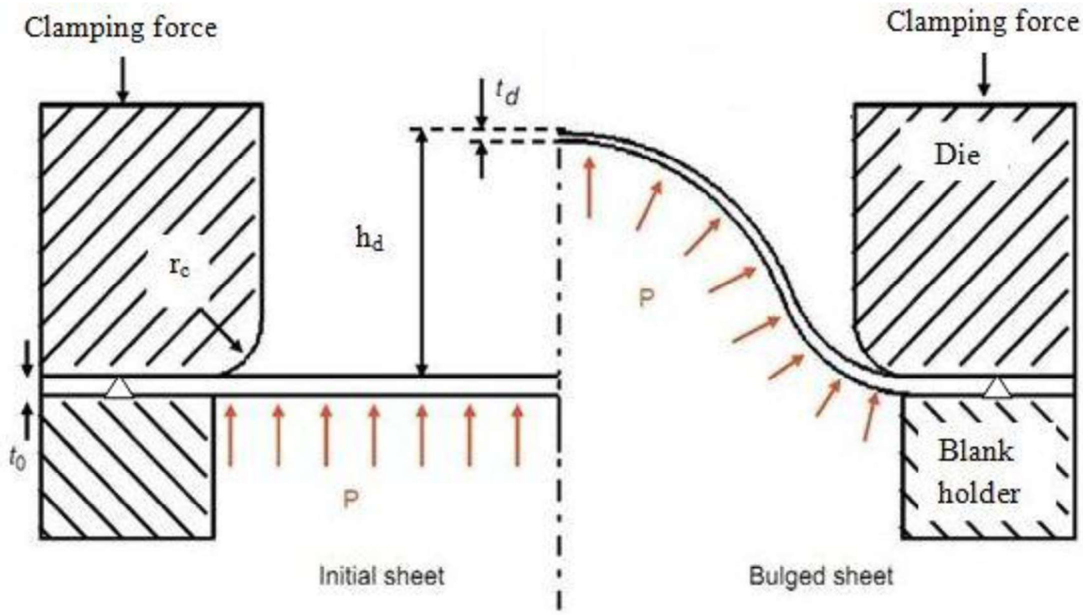


Fig.3. Geometry of '*Bulge test'*: Initial (left) and Instantaneous (right)

Since the bulge diameter is greater than 10 times of the sheet thickness, so the effect of bending of the sheet can be neglected & the bulged sheets can be treated as a *'membrane'* in which the stresses are tangential to the middle surface of the wall & uniformly distributed across its thickness [2]. Such stresses are called *membrane* stresses and can easily be calculated by applying *membrane* theory neglecting bending stresses as:

$$\frac{\sigma_c}{R_c} + \frac{\sigma_r}{R_r} = \frac{P}{t_d} \tag{1}$$

[Note: Derivation of equation (1) can be seen in '*Appendix 1*'.]

Where σ_c and σ_r are the principle stresses on the sheet surface along the circumferential & radial directions, R_c and R_r are the corresponding radii of the curved surface, P is the hydraulic pressure, and t_d is the thickness of bulged sheet. For axisymmetric case of the hydraulic bulge test, $\sigma_c = \sigma_r$ and radius of the bulged dome is $R_d = R_c = R_r$.

So,

$$\sigma_c = \sigma_r = \frac{PR_d}{2t_d} \tag{2}$$

In '*hydraulic bulge test'* initially both internal & outer sheet surfaces remain at atmospheric pressure. But once hydraulic pressure is applied the internal sheet surface experiences pressure P. Therefore the average stress σ_n in the sheet metal normal to the sheet surface will be:

$$\sigma_n = \frac{1}{2}(-P + 0)$$

$$\sigma_n = \frac{1}{2}(-P) \tag{3}$$

Now the effective stress $\bar{\sigma}$ can be calculated using *'Von Mises'* Plastic flow criterion as [1]:

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\sqrt{[(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\tau^2{}_{xy} + \tau^2{}_{yz} + \tau^2{}_{zx})]}$$

Substituting $\sigma_{xx} = \sigma_c$, $\sigma_{yy} = \sigma_r$, $\sigma_{zz} = \sigma_n$, $\tau_{xy} = \tau_{yz} = \tau_{zx} = 0$; and then simplifying the equation we get:

$$\bar{\sigma} = \frac{P}{2}\left(\frac{R_d}{t_d} + 1\right) \tag{4}$$

Similarly the strain normal to the sheet surface can be calculated using '*Volume constancy'* condition as:

$$\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = 0$$
$$\varepsilon_{xx} + \varepsilon_{yy} = -\varepsilon_{zz}$$

Substituting $\varepsilon_{xx} = \varepsilon_c$, $\varepsilon_{yy} = \varepsilon_r$ & $\varepsilon_{zz} = \varepsilon_t$ in the above equation we get;

$$\varepsilon_c + \varepsilon_r + \varepsilon_t = 0$$

$$\varepsilon_c + \varepsilon_r = -\varepsilon_t \tag{5}$$

Now similar to the effective stress; effective strain can also be calculated as:

$$\bar{\varepsilon} = -\varepsilon_t = -\ln\left(\frac{t_d}{t_0}\right) \tag{6}$$

- ## Experimental Procedure:

1. Mark a circle of 60 mm diameter exactly at the centre of the sheet blank & then divide its circumference into four equal quarters.
2. Measure the sheet thickness at three different places using 'screwgauge micrometer'. Take the average and note it on the observation table.
3. Keep the sheet on blank holder plate & put the die over the sheet such that the marked circle of the sheet should be exactly at the centre. Tight the complete setup by nuts & bolts using 'adjustable torque wrench', so that every bolts must be tightened by same torque.
4. Take the initial height of the sheet exactly at the centre of the marked circle using 'depth micrometer', assuming the die top surface as a reference.
5. Apply hydraulic pressure using 'hand operated lever' attached with the machine, shown in figure 1.
6. Simultaneously look at the 'pressure gauge', once the indicator comes to first division of the inner circular scale of pressure gauge (i.e. hydraulic pressure inside the sheet blank reaches to10 kgf/cm^2); stop applying more hydraulic pressure.
7. Again take the height of bulged shape using 'depth micrometer' assuming die top surface as a reference. Measure arc length of any one quarter along circumference of the marked circle,

using ‘flexible scale’. Also take the reading of ‘spherometer’.

8. Start applying hydraulic pressure till the pointer of pressure gauge reaches to next division. Take all the readings & repeat the process till bursting of the sheet or the shape of the dome becomes perfectly hemispherical.

• Observation Tables:

Initial thickness of the sheet blank t_0 =
[{Main scale reading + (Circular scale reading × Least count of micrometer)} – (± Zero error)]

Table No - 01.

Sr. No.	Main scale reading	Circular scale reading	Total value
1.			mm
2.			mm
3.			mm
Average value of initial thickness of the sheet blank t_0 =			mm

Table No - 02.

Length between two legs of spherometer (a_l) = 40mm

Diameter of circle marked on the sheet = 60mm

Initial depth micrometer reading (H_0) = ________ mm

Sr. No.	P (kgf/cm^2)	Depth micrometer reading H_i (mm)	Dome height $h_d = H_0 - H_i$ (mm)	Quarter circumference C/4 (mm)	Spherometer reading h' (mm)	Radius of bulged dome $R_d = \frac{{a_l}^2}{6h'} + \frac{h'}{2}$
01.	00					
02.	10					
03.	20					
04.	30					
05.	40					
06.	50					
07.	60					
08.	70					

Table No - 03.

Sr. No.	h_d	R_d	ε_r	C/4	ε_c	$\varepsilon_t = -\varepsilon_r - \varepsilon_c$	t_d	$\sigma_c = \sigma_r = \frac{PR_d}{2t_d}$	$\bar{\sigma} = \frac{P}{2}\left(\frac{R_d}{t_d} + 1\right)$	$\bar{\varepsilon} = -\varepsilon_t = -\ln\left(\frac{t_d}{t_0}\right)$
01.										
02.										
03.										
04.										
05.										
06.										
07.										
08.										

- **Calculations:**

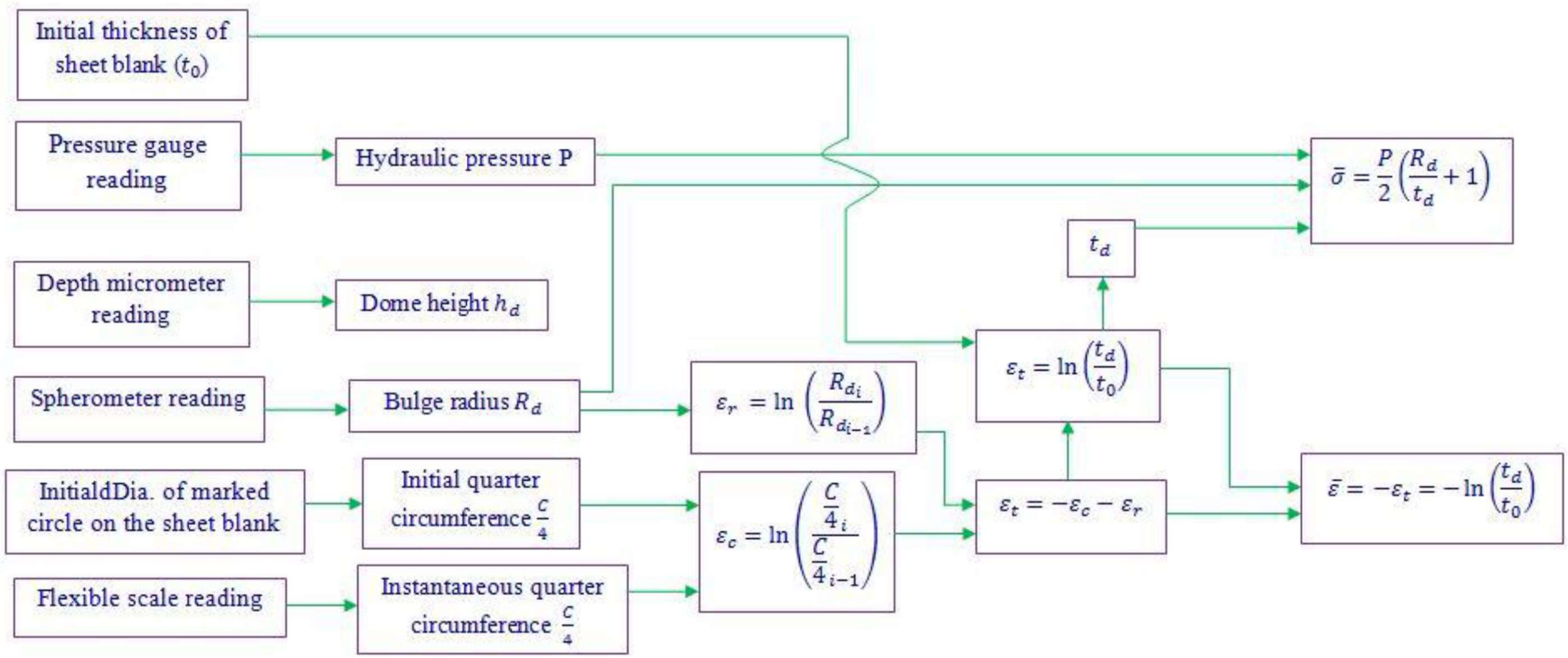
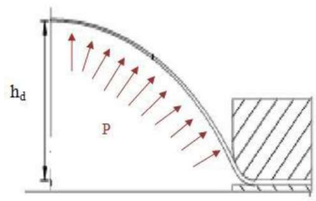


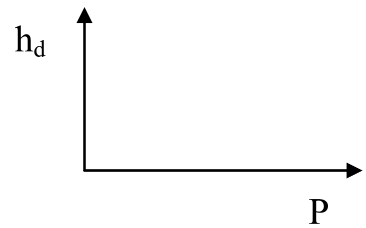
Fig.4. Steps to be followed for calculation of 'Effective stress' & 'Effective strain'

- ## Results:

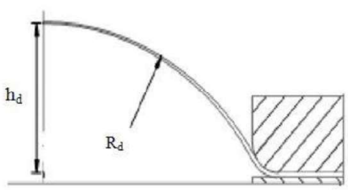
Plot a graph for following variations & give a proper justification for each variation.

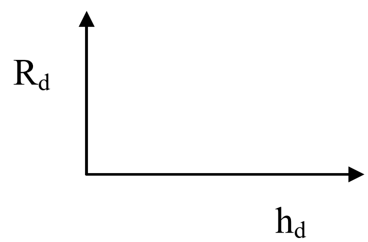
1. Variation of 'Dome height' with 'Hydraulic pressure'



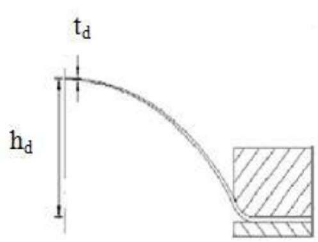


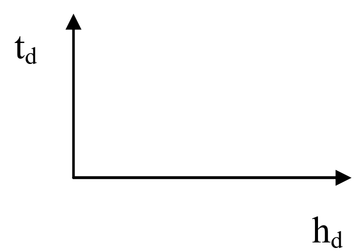
2. Variation of 'Dome bulge radius' with 'Dome height'





3. Variation of 'Dome apex thickness' with 'Dome height'

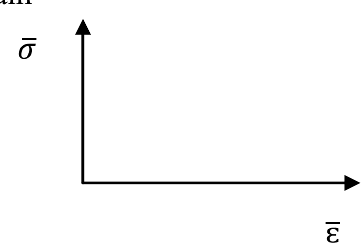




4. Variation of 'Effective stress' with 'Effective strain'

Effective stress $\bar{\sigma} = \frac{P}{2}\left(\frac{R_d}{t_d} + 1\right)$

Effective strain $\bar{\varepsilon} = -\varepsilon_t = -\ln\left(\frac{t_d}{t_0}\right)$



- **Discussion on Defects:** The *'Hydraulic bulge test'* would be defect less, if the sheet metal has smooth surfaces, has constant thickness throughout the surface area and does not have any sharp scratch mark on the surface; because these factors cause the defects. But mostly sheet metals are non isotropic in nature, which causes *'Earing'* defect. So to avoid this defect *'ridge impression'* & *'matching groove'* were made on the lock bead & die respectively. One more defect which generally appears on the bulged sheet blank at the flank region is *'Wrinkling'*. It occurs due to insufficient clamping force. For avoiding this defect, all the bolts should be tightened by same sufficient torque using 'adjustable torque wrench'.

Fig.5. Defective bulged sheets

Fig.6. Successfully bulged sheet

- **Conclusions:** Based on the conducted test following conclusions can be made:

1. The bulged dome shape has been found very near to hemisphere.
2. Due to equi-biaxial stress state the maximum achievable strain before necking/bursting was much larger.

- **Precautions:** Since the measured thickness and bulge radius values are used as parameters to calculate flow stress curve in the test, so measurement & calculation accuracy of these parameters directly affect the accuracy of the curve. Therefore the operator must follow few precautions as:

1. Before clamping the sheet blank, place it on the blank holder plate such that the marked circle on the sheet blank must be concentric with the bulging die internal periphery.
2. For clamping the sheet blank, all the bolts bust be tightened by the same torque; in order to achieve uniform strain during bulging.
3. Manually applied hydraulic pressure should be such that the strain rate has to be constant during bulging.

- **Applications:** '*Hydraulic bulge test'* is widely used for determining:

1. Flow stress or behavior at plastic stage of sheet metals.
2. *'Work hardening'* behavior of sheet metals.
3. *'Planner & Normal anisotropy'* of sheet metals; etc.

- ## References:

[1]. Johnson W., Mellor P. B., "Engineering Plasticity", 'Van Nostrand Reinhold Company Ltd.', 1st ed., p. 103, (1973)

[2]. Timoshenko, S. P., Young, D. H., "Elements of Strength of Materials", 'East-West Press Private Limited', 5th ed., p. 51, (1968)

- ## Questions:

1. What is 'Plane stress' & 'Plane strain'?
2. What is 'Principal stress' & 'Principal strain'?
3. What is 'Strain rate'?

Appendix 1

- **Stresses in a '*membrane*':**

To calculate 'Circumferential stress' & 'Radial stress' in a *membrane*, let us refer to fig. A-1.

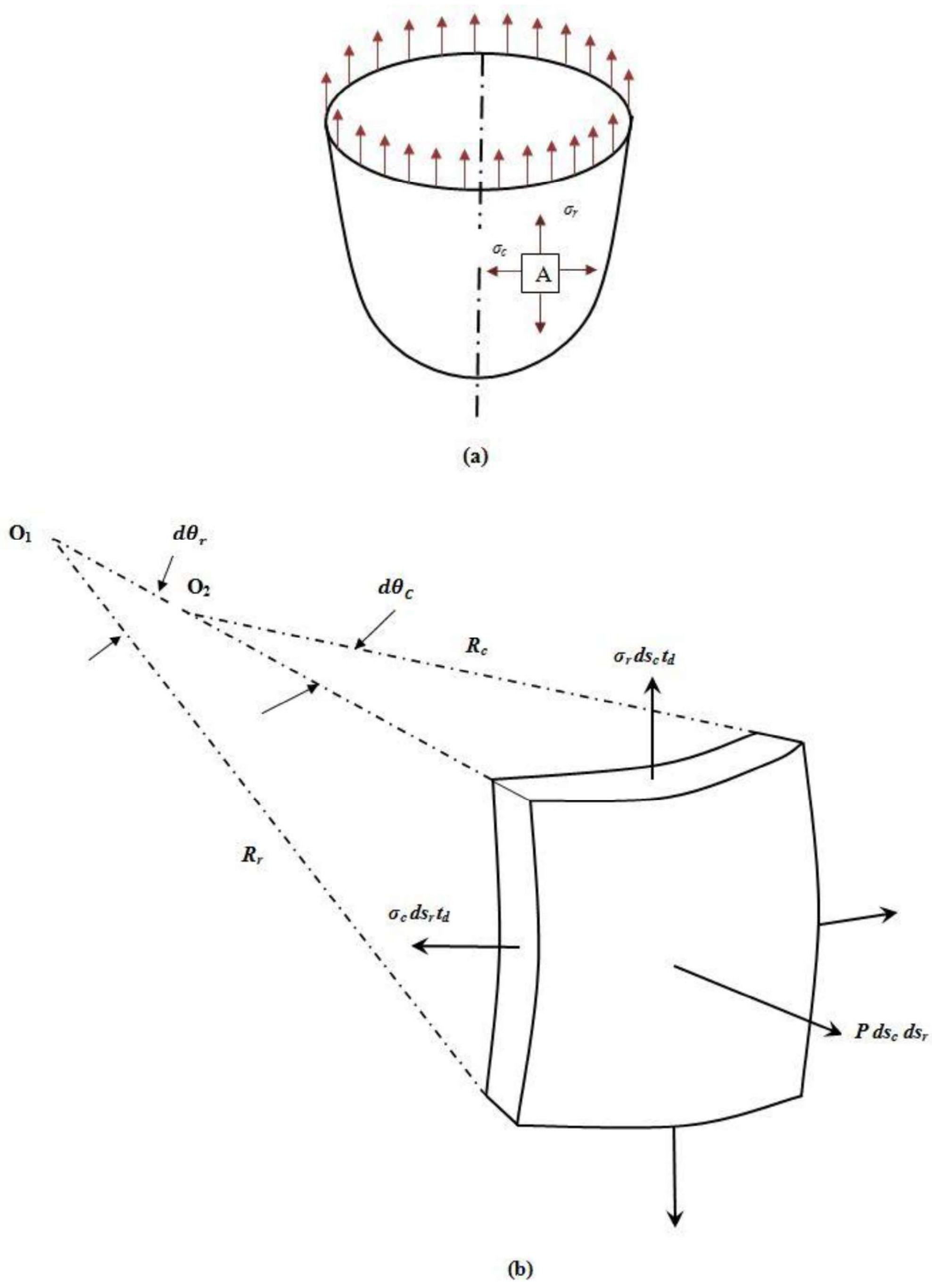


Fig. A-1. Stress state at an instant in finite small area of a *membrane.* [2]

Now, consider the following notations:

P = pressure inside the thin wall shell.

σ_c = tensile stress in circumferential direction or hoop stress.

σ_r = tensile stress in radial direction or meridional stress.

t_d = average thickness of shell wall.

R_c = radius of curvature perpendicular to meridian at 'A'.

R_r = radius of curvature of meridian at 'A'.

$d\theta_c$ = angle substended by arc normal to meridian at 'A'.

$d\theta_r$ = angle substended by meridian arc of element.

$ds_c = R_c d\theta_c$ = dimension of element in circumferential direction.

$ds_r = R_r d\theta_r$ = dimension of element in meridional direction.

Then the stress resultant acting on the edges of the element are $\sigma_c\, ds_r\, t$ and $\sigma_r\, ds_c\, t$ as shown in the fig. A-1. The two stress resultants in the circumferential direction have a resultant in the direction of the normal to the element equal to

$$\sigma_r\ ds_c\ t_d\ d\theta_r = \frac{\sigma_r ds_r ds_c t_d}{R_r}$$

In the same manner, the stress resultants in the meridional direction have a normal resultant equal to

$$\sigma_c\ ds_r\ t_d\ d\theta_c = \frac{\sigma_c ds_c ds_r t_d}{R_c}$$

The sum of these normal forces is in equilibrium with the normal pressure force on the inside surface of the element; thus

$$\frac{\sigma_c ds_c ds_r t_d}{R_c} + \frac{\sigma_r ds_r ds_c t_d}{R_r} = P\ ds_c\ ds_r$$

From which,

$$\frac{\sigma_c}{R_c} + \frac{\sigma_r}{R_r} = \frac{P}{t_d}$$

Appendix 2

- **Spherometer:**
- **Principle:**

Spherometer is an instrument based on the principle of micrometer screw. It is used for measuring radii of curvature of spherical surfaces accurately up to 0.01mm.

- **Construction:**

A spherometer consists of a triangular metallic frame F supported on three fixed legs whose tips from the vertices of an equilateral triangle. A vertical nut N is fixed at the centre of the triangular frame in which a uniformly cut screw S can be moved with the help of knob K having circular metallic disc D attached slightly below it. On the circumference of the circular disc D, circular scale is engaged dividing the circumference into 100 equal divisions. The lower end N of the screw S is made pointed on lowering it at the level of three legs, it touches at its centroid. On moving the screw clockwise or anticlockwise, the edge of the circular disc moves across a flat vertical metallic linear scale called main scale or pitch scale. The main scale has divisions marked in millimetres or half millimetres with zero at its centre.

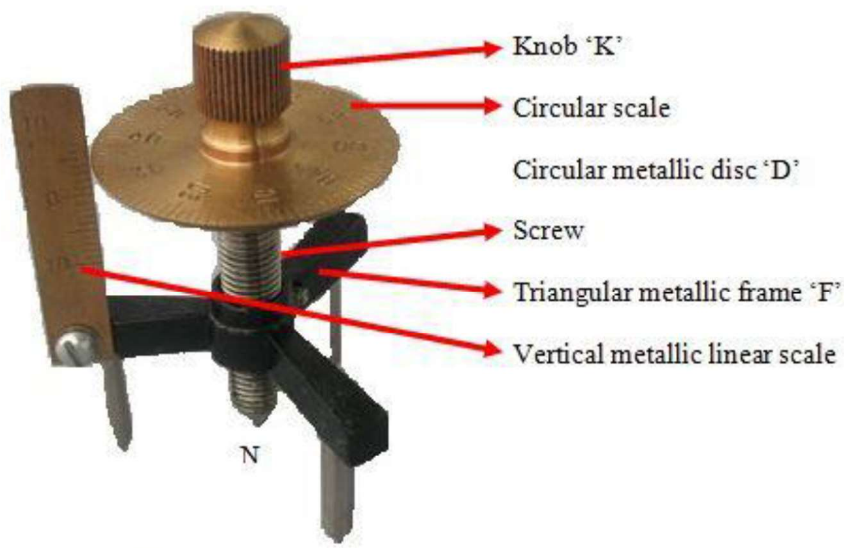


Fig.A-2.1. Spherometer

'Pitch' is perpendicular distance between any two consecutive threads provided that the threads on the screw are evenly spaced or it is the linear distance traversed by the screw in one complete rotation of its head, i.e.,

$$Pitch\ (P) = \frac{\text{Distance moved by the plane of the disc along the verticle scale}}{\text{Number of complete rotations given to the circular scale}}$$

'Least count' is the least measurement that can be measured accurately by the spherometer, i.e.,

$$Least\ count\ (LC) = \frac{\text{Pitch } (P)}{\text{Total number of divisions on the circular scale } (n)}$$

- **Zero error:**

After placing spherometer on a plane surface, if three fixed legs and the central screw are at the same level, i.e., touching the plane surface and the zero mark on the disc is in line with the zero mark on the main scale, then the instrument posses no zero error. Otherwise the instrument posses zero error. It may be of two types:

1. **Positive zero error:**

If the zero mark on the circular scale lies a little above the zero mark on the main scale (vertical scale), the zero error is positive. To determine the magnitude of this error, let the Nth division of circular scale lying in line with any graduation on the vertical scale is multiplied by the least count, i.e.,

$$\text{Positive zero error} = N \times LC.$$

2. **Negative zero error:**

If the zero mark on the circular scale lies a little below the zero mark on the main scale, the zero error is negative. To determine the magnitude of the negative zero error, read the division of the circular scale coinciding with the edge of the main scale (or pitch scale). Let it be N'. Then the

$$\text{Negative zero error} = -(n - N') \times LC.$$

- **Working:**

When a spherometer is placed on a spherical surface (a part of large sphere) such that, tips of three fixed legs are touching it. The tip of the screw S will be a little higher from the bulged out portion of the convex surface which is related to the radius of the curvature of the surface (radius of the large sphere whose part is the spherical surface).

From the geometry of fig. A-2.2. shows that

$$AO \times OB = QO \times OF$$

$$\Rightarrow r \times r = h' \times (2R - h')$$

$$\Rightarrow r^2 = 2h'R - h'^2$$

$$\Rightarrow R = \frac{r^2}{2h'} + \frac{h'}{2}$$

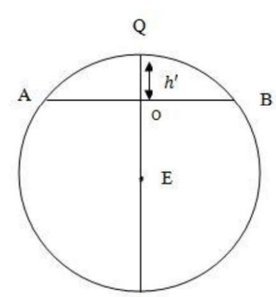


Fig.A-2.2. Measurement of radius of curvature of a convex surface using spherometer

If 'a_l' is the length between two tips of a spherometer, then $\frac{BD}{BO} = \cos 30°$

$$\Rightarrow \frac{a_l}{2} = \frac{r\sqrt{3}}{2}$$

$$\Rightarrow r = \frac{a_l}{\sqrt{3}}$$

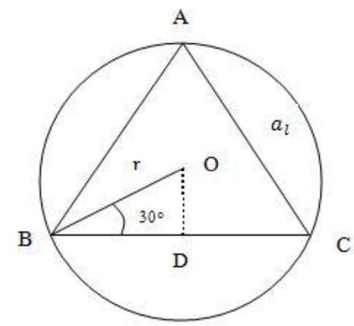


Fig.A-2.3. Section of the sphere cut by the plane containing tips *A*, *B*, & *C* of three legs

Hence, radius of curvature,

$$\Rightarrow R = \frac{\left(\frac{a_l}{\sqrt{3}}\right)^2}{2h'} + \frac{h'}{2}$$

$$\Rightarrow R = \frac{{a_l}^2}{6h'} + \frac{h'}{2}$$