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].

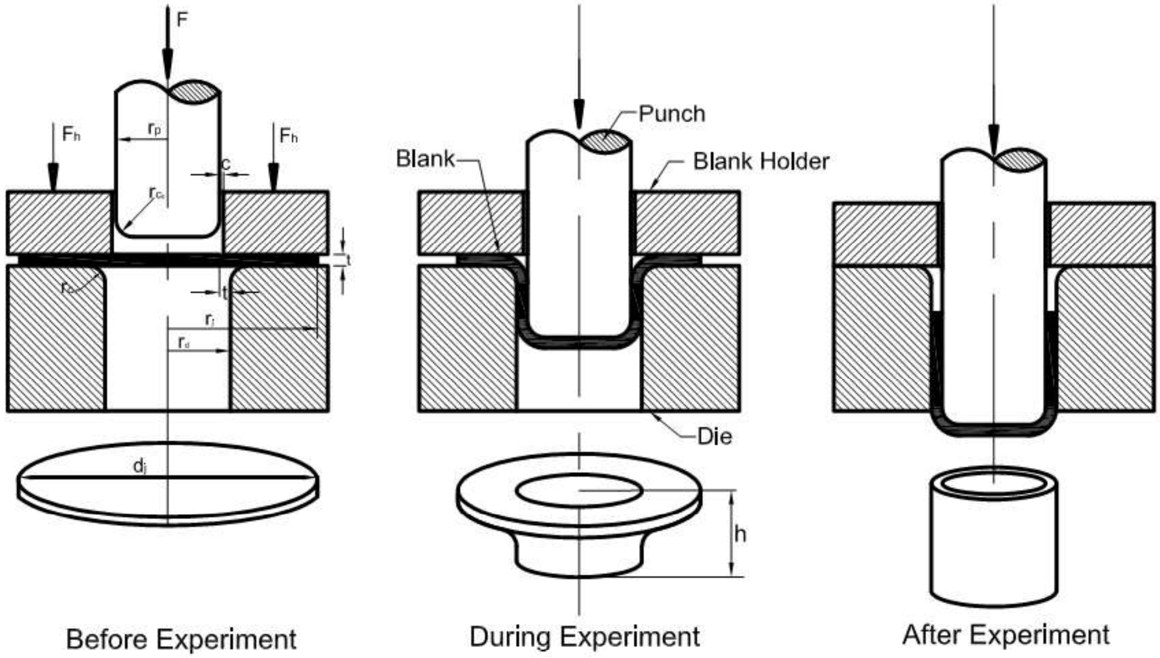


Fig.1. Schematics of deep drawing: **(a)** Die-Punch combination and position of Blank before drawing, **(b)** Drawn cup with flange, and **(c)** Drawn cup without flange

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 $(\boldsymbol{r_d} - \boldsymbol{r_p})$ 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:**

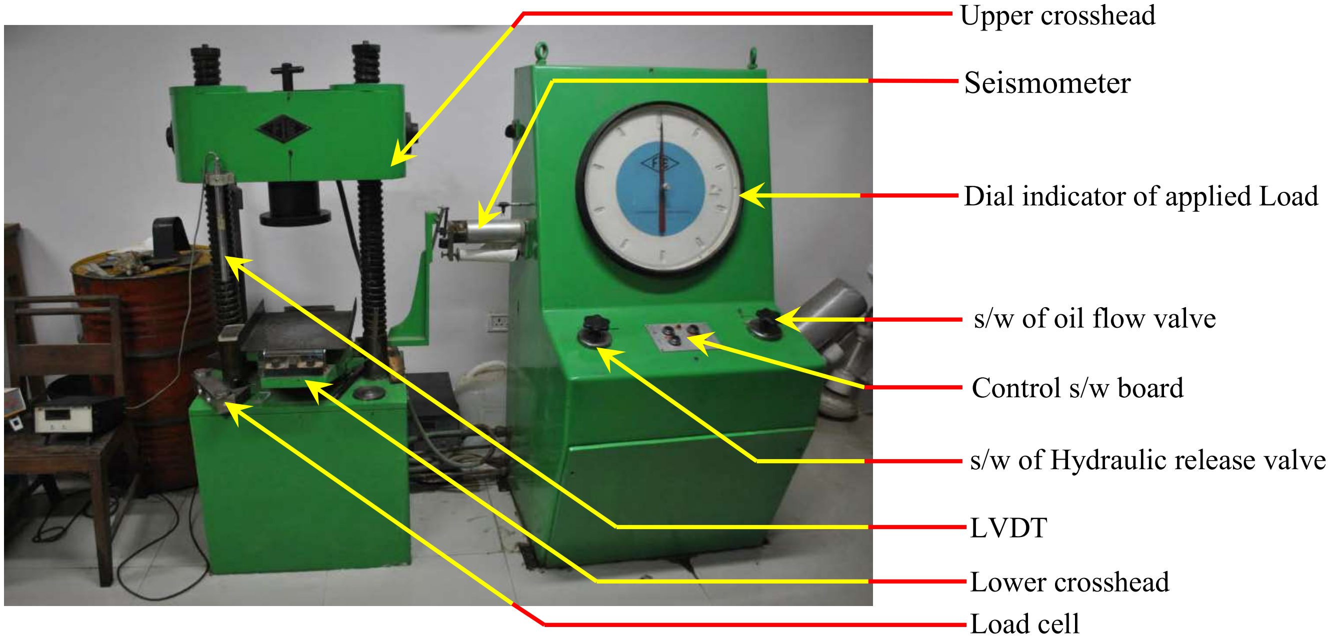


Fig.2. Compression Testing Machine

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, ***h*** *(in mm)*	Applied Load, ***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											$d_{i\text{-}1}$ =											$d_{o\text{-}1}$ =
2											$d_{i\text{-}2}$ =											$d_{o\text{-}2}$ =
3											$d_{i\text{-}3}$ =											$d_{o\text{-}3}$ =

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 **(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 ***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.

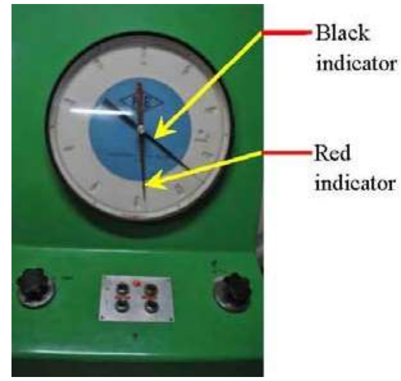
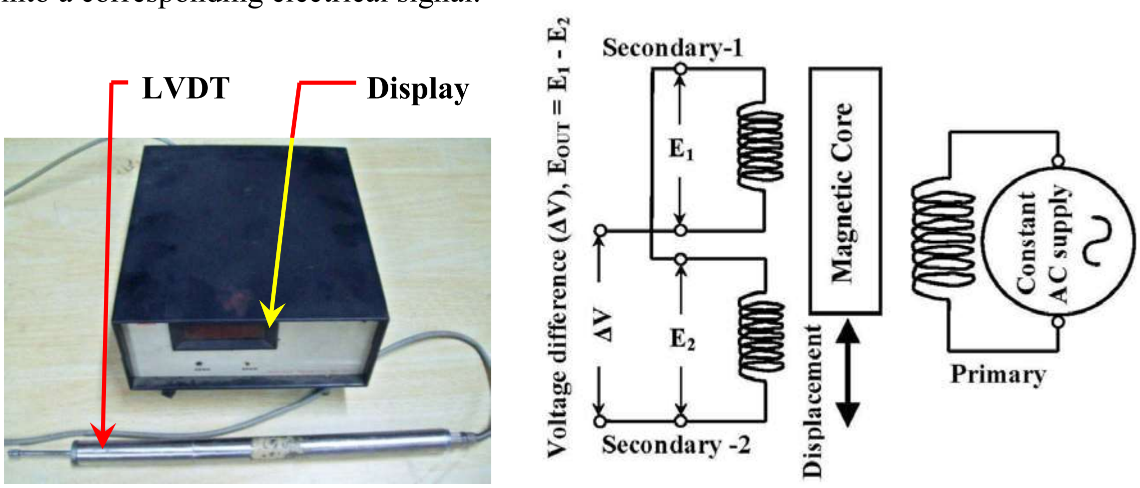


Fig.4. Main control unit of Compression Testing Machine

- ## 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.



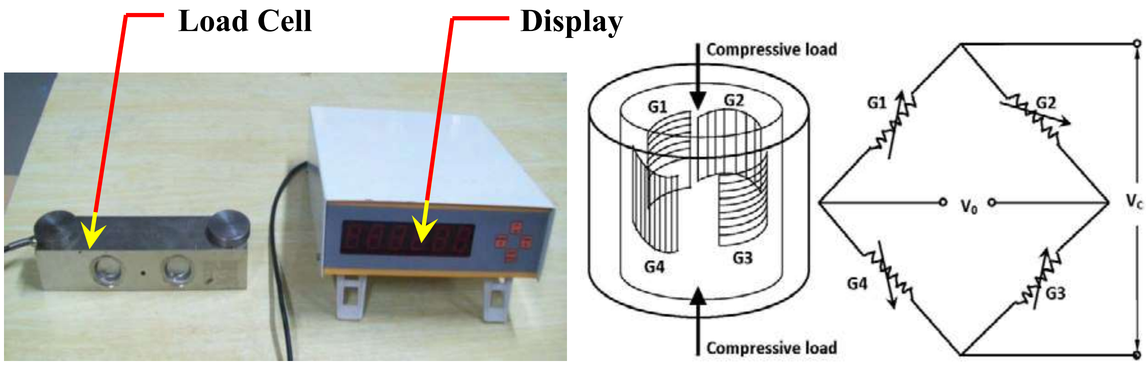
(a) **(b)**

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].

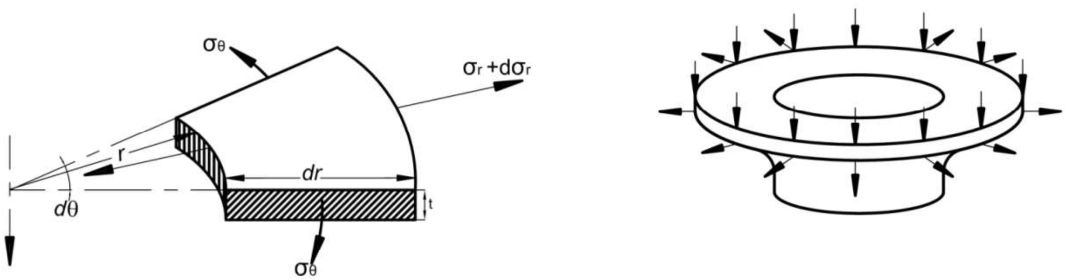


Fig.8. Analysis of deep drawing operation:
(a) Stress acting on element during drawing, and **(b)** Radial stress due to blank holding pressure

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

$$r d\sigma_r + \sigma_r dr - \sigma_\theta dr = 0 \tag{2}$$

As σ_r and σ_θ are the principal stresses, the equation we obtain by using *Tresca's yield criterion* is

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

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

$$\frac{dr}{r} + \frac{d\sigma_r}{2K} = 0 \tag{4}$$

Integrating, we obtain

$$\frac{\sigma_r}{2K} = C - \ln r. \tag{5}$$

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

Hence,

$$C = \frac{\mu F_h}{2\pi K r_j t} + \ln r_j \tag{6}$$

Using this in the expression for σ_r , we have

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

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

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

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.

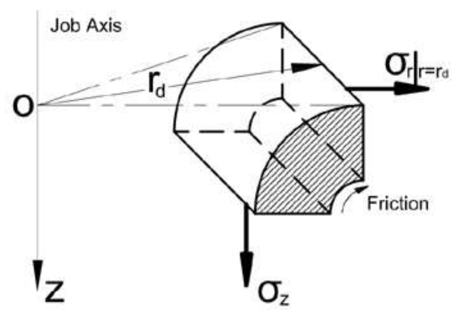


Fig.9. Effect of friction at corners.

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

Thus,

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

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

$$F_h = \xi\, \pi r_j{}^2 K \tag{10}$$

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

$$F \approx \sigma_z 2\pi r_p t \tag{11}$$

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