INTRODUCTION TO DEEP DRAWING

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INTRODUCTION TO DEEP DRAWING

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Since the beginning of the 21^{st} Century, society has witnessed a great increase in technological advancement and it has been influencing the lifestyle of the people in various ways. In the present scenario of globalisation, advanced technology is at the forefront in all areas of the engineering world. The evolution of this technology in the mechanical engineering industry is glaringly evident in various metal forming operations.

Metalworking is one of the important processes used in shaping of the metals in addition to casting, welding, machining, and powder metallurgy. However, the metal forming may be considered as the earliest metalworking operation evolved through the simple hammering of gold and copper [1–5]. It is playing a central role and industry is actually progressing mainly due to the evolution of this technology [6, 7]. Essentially, the main aim of metal forming operations is to work for transformation of a metal billet into a component with the desired geometry. The demand for further research in lightweight sheet metals and their use in the automobile sector is increasing rapidly due to the shortage of petroleum products.[8–10],

conduct-begConducting an experimental study by developing a tool setup to evaluate LDR and testing with commonly available blank material, so as to help the manufacturing industry by using these results as reference, during product design and development stage at low volume of scrap generation. Though the method of estimation of LDR is based on extrapolation of maximum punch load until the intersection with the constant punch load line of failure giving some error can help the industry in assessment of number of stages in forming operation during the product development stage. The method is widely used among researcher

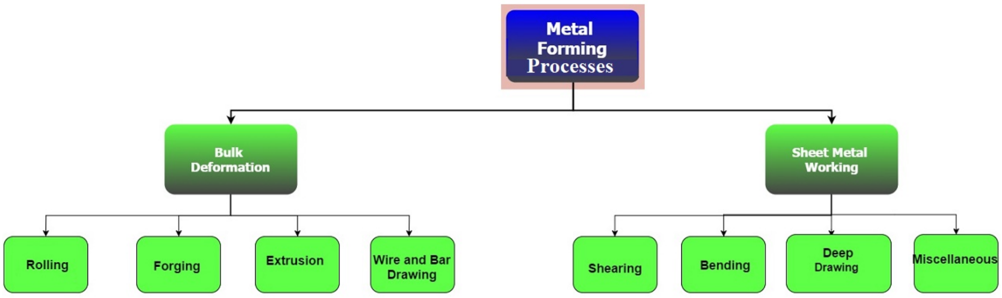

Fig. 1: Classification of metal forming processes [11]

Sheet Metal Forming

In a broad sense, metal forming operations are classified into different types, such as bulk-forming and sheet forming as shown in Fig. 1. Rolling, extrusion and forging are examples of the bulk-forming processes, whereas shearing, bending, stretching, spinning and deep drawing are examples of the sheet metal forming process.

Sheet metal forming is used for manufacture of quality products at low manufacturing costs. It is essential to produce 2D or 3D components for automobile bodies, railroad cars, aeroplanes, farm and construction equipment, office furniture, electronic instruments, computer appliances, etc. while using a minimum number of forming operations. The kitchen sink is the best example of the deep drawn component as it is both deep and seamless. Other notable articles produced in the deep drawing are cans, boxes, bottles, battery cells, etc.

The major reasons for advancement in R&D for sheet metal forming operations are:

1. Emphasis on the pollution-free environment is the need of the hour through the use of lightweight high strength structures in the automobile industry while maintaining safety standards and comfort levels. The usage of lightweight metals is contributing to environment-friendly products at low energy consumption in different application areas such as automotive, aerospace, beverage and domestic.
2. Minimising the emissions into the atmosphere is a dominant issue in developing countries like India. The rapid industrialisation is increasing

the applications of sheet metal and this is expected to increase in the future [12].

3. The consumer wants vehicles built for safety and less fuel consumption while retaining the current levels of performance, size, comfort and utility. The climate change, scarcity of resources, globalisation and increased market demand are driving towards the manufacture of automotive appliances in less time and at low cost using less material and energy [13].
4. Next-generation has to benefit substantially from the developments of the research carried out in the field of advanced forming technologies, such as superplastic forming, deep drawing, flow forming, laser forming and hydroforming.
5. The sheet metal forming process has to play a key role in the manufacturing industry and needs continuous development concerned with materials, processes, tool design and equipment manufacture.
6. The ever-increasing requirement in the automotive industry is another major driving factor for sheet metal forming innovations.

Deep Drawing Process

The process of deep drawing was studied extensively for the past couple of decades due to its importance in a variety of industrial applications. The International Deep Drawing Research Group (IDDRG) is working to unite different research groups worldwide to study sheet metal forming activities including materials, formability issues, tooling and tribology. It is also coordinating all-over the world for bringing scientists, researchers, and industrialists together for sharing scientific knowledge of deep drawing and other sheet metal forming operations. The IDDRG and other international industry, and institutional research groups concluded that further continuous research is essential in the sheet forming process with new alloy grades that are continuously entering into the market.

The usage of lightweight materials such as aluminium, copper and magnesium in complex component configuration system is rapidly increasing, and it is essential for a thorough knowledge of the technical process as well as the influence of parameters involved in it, i.e., type of lubrication, clearance between die and punch, a profile of die and punch, blank holding type, blank holding force, blank holding mechanism, blank thickness and material properties. Further, there is a demand for quick assessment of formability for sheet metal, such as Forming Limit Diagram (FLD) and Limiting Drawing Ratio (LDR) to bring down design costs and rejections. The new manufacturing technologies for deep drawing are developing in the present decade due to the challenges taking place with sheet forming. The deep drawing process is a complex plane strain deformation process subjected to biaxial stresses and strains and it is essential that the designer needs to know thoroughly about the process and its limitations. This knowledge comes only from experience and involves considerable time and experimental tests.

According to DIN 8584 standard, the deep drawing process is a tensile-compressive forming of a plane sheet into a hollow body open on one side, or the forming of a pre-drawn cup into another cup with a smaller cross-section without an intentional change in thickness of the sheet [14, 15]. It is a widely used sheet metal operation involving the use of a punch and die setup and the desired shape is obtained by pressing the blank sheet through the die. If the depth is greater than or equal to the radius of the cup, then it is known as the deep drawing process. Fig. 2 shows a sectional view of deep drawing operation comprising of punch, die and blankholder.

It is a known fact that technology is the main source of modern and advanced facilities of human life and hence the progressive development is widely noticed in the present manufacturing industries. To meet the technological advances and to stand in the competitive environment, the manufacturing companies are developing new techniques for improving the quality of products and production rates at low costs. Further, it is a very tough job to measure the quality of the components manufactured in a deep drawing process without the knowledge of blank metal deformation behaviour at a micro-level. Creating a proper simulation model of a process provides prior knowledge in predicting the influence of operating parameters.

In deep drawing operation, a two-dimensional plane sheet, known as blank,

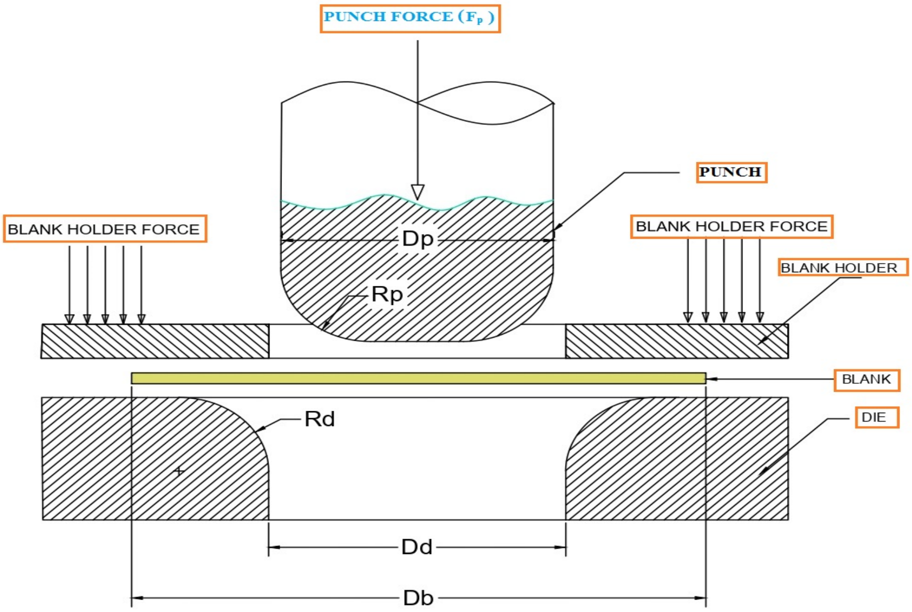

Fig. 2: Principle of Deep drawing [2]

transforms into a three-dimensional component. It involves forcing the blank gradually into the die cavity with a punch while holding the flange region between the blank holder and die shoulder [16] to regulate the flow of blank material. [17].

Fig. 3: Range of Components produced in deep drawing [18–20]

Some of the components generally produced in deep drawing are shown in Fig. 3.

Deformation Phenomenon in Sheet Metal Forming Processes

All elements in cup drawing are deformed under membrane stresses σ_1 and σ_2 and the normal stress σ_3 is quite small and considered negligible. The sum of the true strains is zero [21] i.e.,

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \tag{1}$$

The effective stress is given in Eq.2 [21]

$$\overline{\sigma} = (\sqrt{1 - \alpha + \alpha^2})\ \sigma_1 \tag{2}$$

where, $\overline{\sigma}$ is the effective stress and α is the stress ratio, σ_1/σ_2.
The effective strain is determined using and Eqn. 3 [22]

$$\bar{\varepsilon} = \sqrt{\frac{4}{3}\ (1 + \beta + \beta^2)}\ \varepsilon_1 \tag{3}$$

where, $\bar{\varepsilon}$ is the effective strain and β is the strain ratio, $\varepsilon_1/\varepsilon_2$.

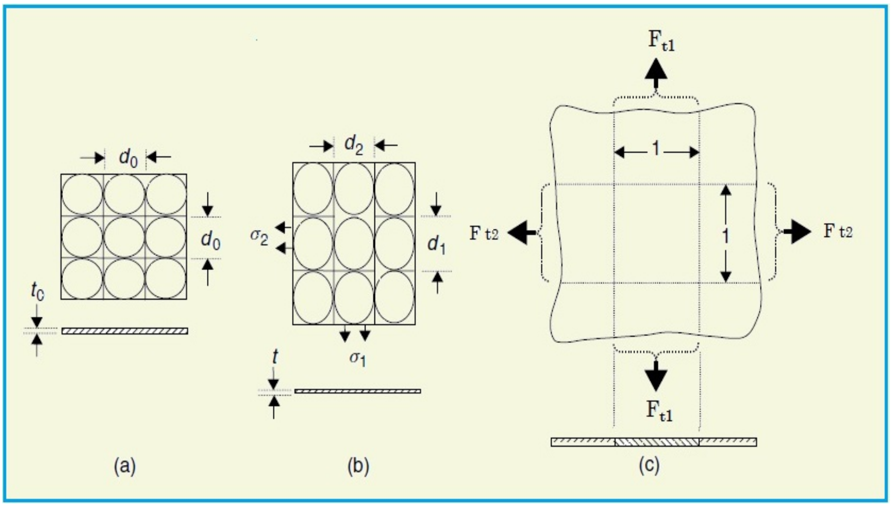

Fig. 4: (a) Grids marked on the sheet. (b) Deformed grid circles into ellipses. (c) Traction forces transmitted [22]

The strain values at different areas of deformation is to be determined through grid marks as shown in Fig. 4. By convention, the major principal direction is assigned to the greatest principal stress direction as well as the greatest principal strain direction. The minor principal direction is considered as perpendicular to the major principal direction.

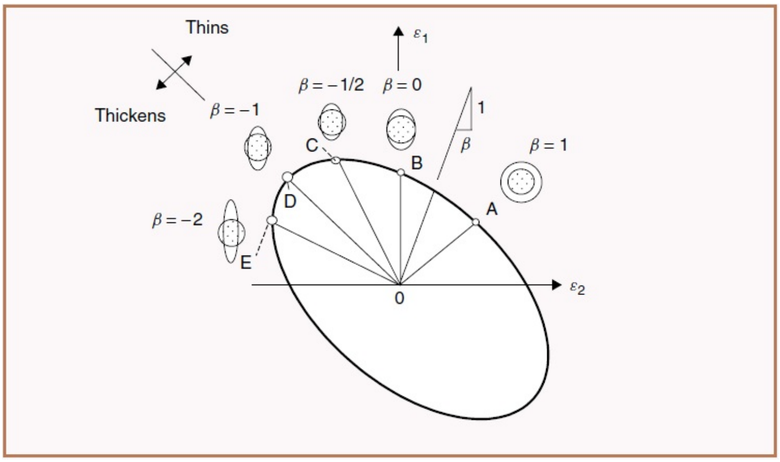

Fig. 5: Different modes of strain distribution [23]

Fig. 5 indicates the strain distribution of different modes.

Stress-Strain Laws

The deformation in sheet metal is done by stretching it between the punch and die set which is optimally designed. During the deformation, the blank is controlled by blank-holder.

The first step in the study of sheet metal forming is the determination of the stress state concerned with strain at every point. The engineering stress-strain plot diagram is characterised by an elastic part and a plastic part. To model the isotropic hardening behaviour, empirical effective stress-strain laws are necessarily used. The common applicable laws for sheet metal forming shown in Fig. 6

1. Power law: A power law or law of Hollomon's is defined as [25]

$$\overline{\sigma} = K_s \overline{\varepsilon}^n \tag{4}$$

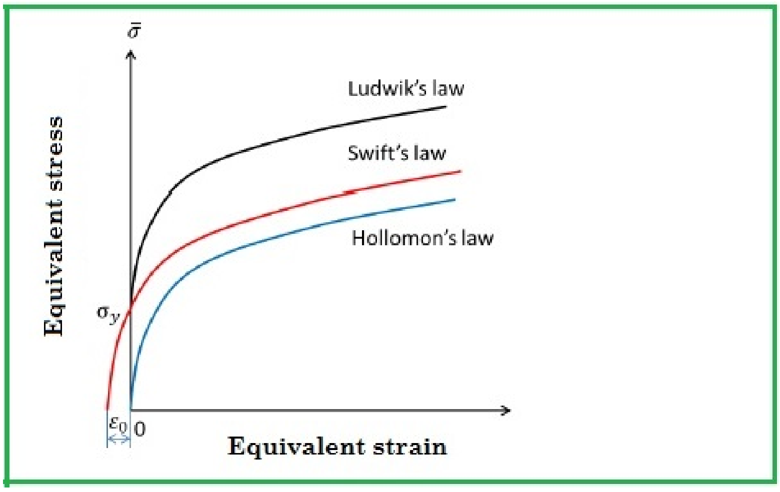

Fig. 6: Isotropic hardening constitutive laws [24]

where K_s is the strength co-efficient.

2. Law of Swift or law of Krupkowski is defined as [26]

$$\bar{\sigma} = K_s\,(\varepsilon_0 + \bar{\varepsilon})^n \tag{5}$$

3. Law of Ludwik is defined as [27]

$$\bar{\sigma} = \sigma_y + K_s \bar{\varepsilon}^n \tag{6}$$

Anisotropy

The blank used in deep drawing may be produced in cold rolling process and hence the blank may be of anisotropic in nature. Let l_1, w_1 and t_1 are length, width and thickness of un-deformed test specimen respectively and l_2, w_2 and t_2 are the corresponding values after elongation. The principal strains in three directions are $\varepsilon_l = \ln \frac{l_2}{l_1}$, $\varepsilon_w = \ln \frac{w_2}{w_1}$ and $\varepsilon_t = \ln \frac{t_2}{t_1}$. For a cold rolled sheet $\varepsilon_w \neq \varepsilon_t$. The anisotropy ratio is defined as [28]

$$r = \frac{\varepsilon_w}{\varepsilon_t} \tag{7}$$

The anisotropy ratio $'r'$ is calculated from the test results of specimens prepared by cutting in 0°, 45° and 90° to the rolling direction. The different values of r, i.e. r_0, r_{45} and r_{90} is determined. The

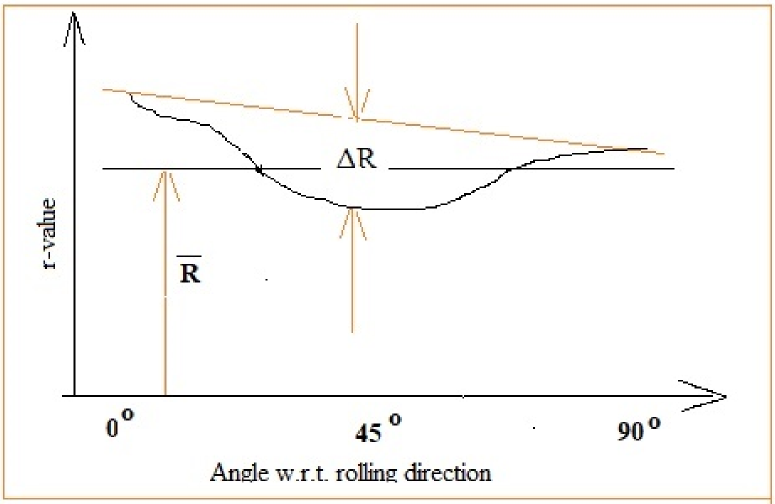

Fig. 7: Variation of anisotropy ratio *'r'* [22]

Δr is the indicator of planar anisotropy as shown in Fig. 7 and determined using the following equation.

$$\Delta r = r_{max} - r_{min} \tag{8}$$

The average variation is the best measure for planar anisotroy and is expressed as [22]:

$$\Delta R = \frac{r_0 + r_{90} - 2r_{45}}{2} \tag{9}$$

The average value of anisotropy ratio or normal anisotropy ratio is defined as [29]:

$$\overline{R} = \frac{r_0 + 2\, r_{45} + r_{90}}{4} \tag{10}$$

The value of r greater than 1 indicates a higher value of strength in the thickness direction than other directions. The higher value of r reduces the thinning effect and avoids the formation of the neck at stressed locations of the sheet and improves the drawability.

Mechanics of Deep Drawing Process

The deep drawing process involves different stages and begins with pushing of the blank by means of punch into the die and ends with an ejection of the complete drawn cup through a die cavity. The blank is subjected to a series of complex stresses of different nature such as radial tensile stresses at wall portion, bending stresses at punch nose region and die shoulder region and circumferential compressive stresses at the entire flange portion. Punch load causes the bending action of the blank around the punch nose and die shoulder regions. Different stages involved in deep drawing process are shown in Fig. 8.

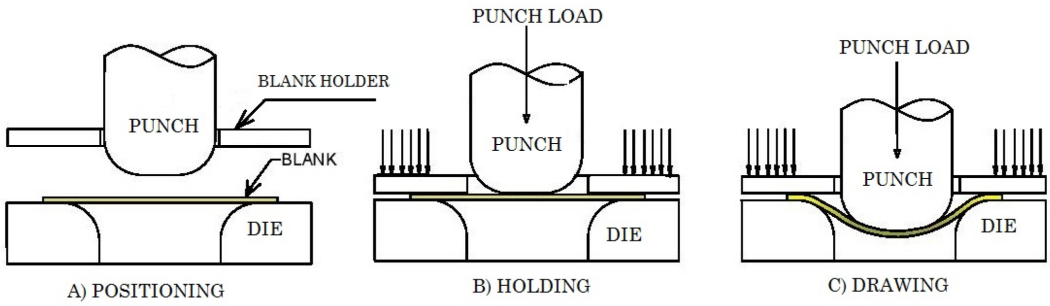

Fig. 8: Scheme of deep drawing process [30]

Downward travel of the punch makes the bent portion of blank further into the die and forms a shallow cup as shown in Fig. 8 (c). At the end of punch stroke, the shallow cup forms into a final cup by transforming the flange into a full wall portion of the cup [30]. During the process, the vertical wall is subjected to tensile stresses and the flange portion is subjected to circumferential compressive stresses and the bottom portion is subjected to biaxial tensile stresses. It is observed that the flange portion and the sidewall region of cup experiences deformation during the deep drawing process. At the flange, the friction force plays an important role in the successful operation of deep drawing.

When the drawing force overcomes the frictional forces between the contacting surfaces of different tool parts, the blank material moves towards the die cavity. The pulling tendency is generated when the blank is forced to move into the die opening while the frictional forces obstruct the material from moving into the die. The blank portion at the flange region is squeezed in the circumferential direction, creating hoop compressive stresses and a tendency for the development of wrinkles. The wrinkles are formed when the hold-down force is not sufficient or the frictional coefficient is less. Hence, the radial tension is the actual source for hoop compressive stresses [31].

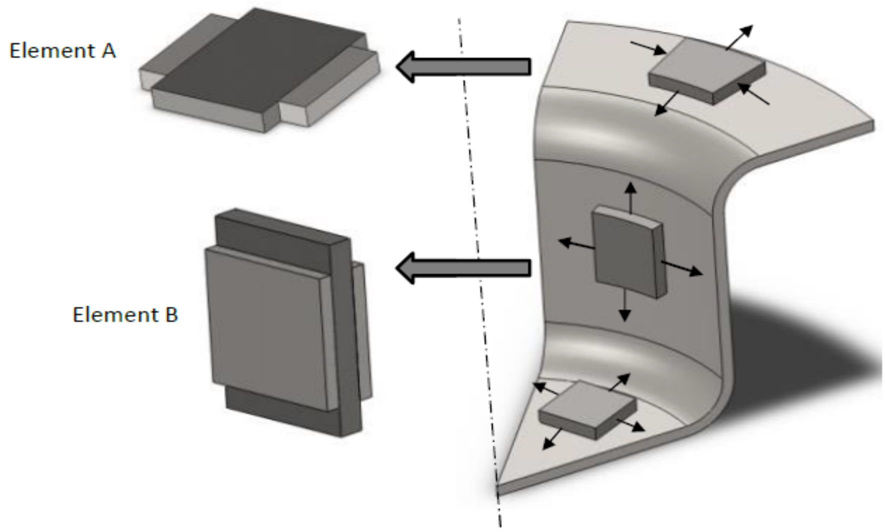

Fig. 9: Modes of deformation in deep drawing process [30]

The stress state during the formation of the cup wall is clearly understood by considering elements at different portions of the cup shown in Fig. 9. The tensile stresses are developed along the radial direction in the element A and element B due to transmission of drawing force from the side wall to the flange portion. It is to be noted that circumferential tensile stresses will be developed when the blank portion is properly stretched at die shoulder. At the flange, the wrinkling may occur if the blank holder force is low. The high blank-holder force obstructs for smooth flow of metal into the die and excessive stretching may take place leading to the neck formation and subsequent failure by tearing of the wall. It has been noticed that blank thinning is a normal phenomenon in the deep drawing, but it should not be more than 25 % of the blank initial thickness [11]. The deformation in deep drawing is summarised as follows.

1. Pure radial drawing of the blank between the die and blank holder.
2. Bending and sliding of blank over the die profile radius.
3. Stretching of blank at the gap between the punch and die.
4. Bending and sliding of blank over the punch profile radius.
5. Stretching and sliding of blank over the punch face.

This combination essentially influences the thickness variation of the drawn component. Therefore, it needs to understand that the process parameter values selected should be optimal such that the minimisation in the variation of thickness takes place. Otherwise, this variation leads to instantaneous changes in stress and stress concentration resulting in the wrinkled or fractured cup. It has to be noticed that the wall portion of the cup is subjected to circumferential tensile stresses and radial tensile stress and hence both stress components at wall portion along the cup wall plane are tensile.

Analytical model for the Max punch load vs. blank size

The analytical model for relationship between punch load and blank size is established by considering the assumptions followed by Fereshteh et al. [32] as described below.

1. The energy loss due to friction during bending and unbending is negligible.
2. The stress-strain exponent has a negligible effect upon LDR.
3. The material is considered perfectly plastic with strain hardening exponent, n is equal to zero.
4. No change in thickness of the sheet.

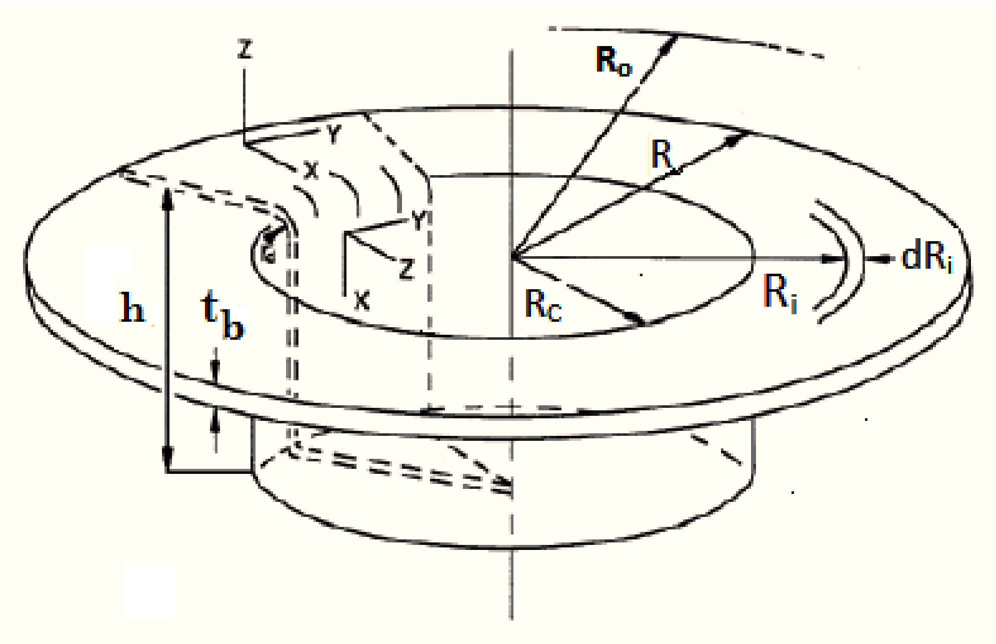

Fig. 10: Cup with flange [32]

5. Material exhibits planar isotropy. The process of deformation in deep drawing and its mechanism is shown in Fig. 10.

According to the principle of volume constancy, the initial blank volume and volume of cup formed is constant, i.e.,

$$\pi\, R_o^2\, t_b \;=\; \pi\, R_c^2\, t_b \;+\; 2\,\pi\, R_c\, h\, t_b \tag{11}$$

As the thickness assumed (t_b) is assumed to be constant in deep drawing operation, the Eqn. 11 can be simplified to

$$\pi\, R_o^2 \;=\; \pi\, R_c^2 \;+\; 2\,\pi\, R_c\, h \;=\; \text{constant} \tag{12}$$

The incremental reduction in area of the flange is equal to the incremental increase in the wall portion of the cup and it can be written as

$$2\,\pi\, R_i\, dR_i \;=\; 2\,\pi\, R_c\, dh \tag{13}$$

$$R_i\, dR_i \;=\; R_c\, dh \tag{14}$$

The strain variation over the flange portion in radial direction (i.e., along x direction in Fig. 10) can be written as

$$\frac{dR_i}{R_i} \;=\; \frac{R_c\, dh}{R_i^2} \tag{15}$$

The true strain in the radial direction of the flange is the ratio of the variation in radius with instantaneous radius at the given instant.
Hence,

$$d\varepsilon_x \;=\; \frac{dR_i}{R_i} \;=\; \frac{R_c\, dh}{R_i^2} \tag{16}$$

The incremental work done dW is the product of stress, strain and change in volume

$$dW \;=\; (\sigma_f)\,(\frac{R_c\, dh}{R_i^2})\,(2\,\pi\, t_b\, R_i\, dR_i) \tag{17}$$

The incremental punch load is

$$dF = \frac{dW}{dh} = \frac{2\,\pi\,R_c\,t_b\,\sigma_f}{R_i}\,dR_i \tag{18}$$

where,

R_i = Instantaneous radius of the blank

dh = Instantaneous increment in the height of the cup

R_c = Radius of the cup

σ_f = Flow stress of the material

For an ideally plastic material, the total work for punch travel is given by

$$\begin{aligned} F_p &= \int \frac{dW}{dh} = \int_{R_c}^{R_i} \frac{2\,\pi\,R_c\,t_b\,\sigma_f}{R_i}\,dR_i \\ &= 2\,\pi\,R_c\,t_b\,\sigma_f\,ln\,\frac{R_i}{R_c} \end{aligned}$$

where F_p is the punch load and it is maximum when $R_i = R_0$, i.e.,

$$F_{p(max)} = 2\,\pi\,R_c\,t_b\,\sigma_f\,ln\,\frac{R_o}{R_c} \tag{19}$$

As all the terms except R_o are constant in Eqn. 19 and it can be rewritten as

$$F_{p(max)} = K_p\,R_o \tag{20}$$

where K_p is the proportionality constant.

Hence, it is concluded that the maximum punch load is linearly proportional to the size of the blank up to the critical size, i.e.,

$$F_{p_{max}} = K_p\,R_0 \tag{21}$$

The equation 21 is valid for all sizes of blanks below the critical diameter. Above the critical size of the blank, tearing takes place and maximum punch load remains constant as tearing load does not vary with blank size above the critical diameter.

Common Failures in Deep Drawing

To produce a defect-free product having the symmetric shape, it needs to align the blank centre with die centre. The blank-holding force and punch load play a vital role in the successful drawing of cup.

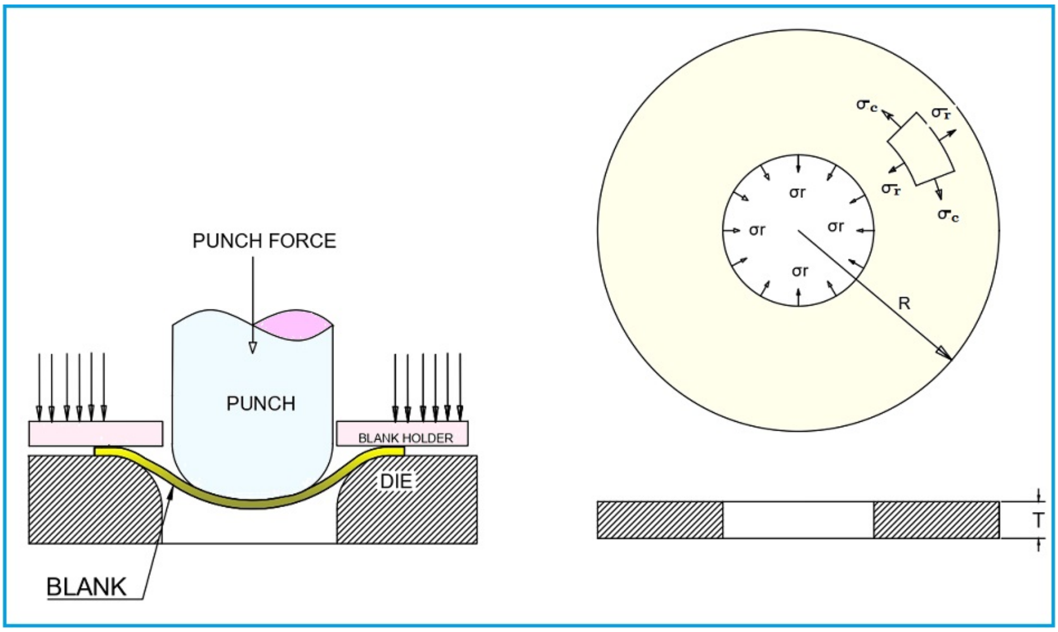

Fig. 11: Stress status on the flange portion of a formed cup [33, 34]

Various problems with reference to quality in the deep drawing process are

1 **Wrinkling**: The wrinkling is an important failure in the drawing process due to insufficient blank holder force. The unsupported region of the sheet subjected to compressible stresses as shown in Fig. 11 is the reason for formation of wrinkles [35]. Wrinkle develops on the flange or sidewall region of the drawn cup due to local buckling under excessive compression stresses [36]. If Drawing Ratio (DR) is too large, higher circumferential compressible stresses are generated, resulting in formation of the wrinkles.

2 **Earing** : The sidewall of the deep-drawn cup has a non-uniform height leading to the formation of ears. Earing is the waviness on the circular edge of the drawn cup. The ears on the cup wall are in even number such as four, six, or eight. Commonly four ears are formed on most of the cases. The planar anisotropic nature of the blank is the main cause of earing . The

formation of ears are minimised through proper modification in the blank shape to compensate anisotropy.

3 **Localized necking or tearing**: The appearance of any local neck that rapidly leads to tearing and failure will obviously terminate a forming operation. This is considered as local instability that is analysed by considering a local element without involving the whole process.

4 **Fracture**: There is a possibility of plastically deforming element to fracture in almost a brittle manner. This is not common in a sheet used for forming and is often preceded by some local instability.

Drawing Ratio and influencing Parameters

The depth of draw in deep drawing is the indicator of formability and higher the depth is possible with higher Drawing Ratio (DR). The DR as shown in Eqn. 22 is used to estimate the drawing performance. Various parameters such as metal flow geometry, material properties, and the design parameters of deep drawing tool setup limit the size of the blank to draw successfully. There is a limit to the amount of draw to perform on a sheet blank in a single operation. The drawing ratio helps to find the highest amount of draw possible [37].

$$\text{Drawing Ratio, DR} = \frac{D_b}{D_p} \tag{22}$$

To assess the formability in sheet metals, finding the LDR for a given material is an important task for bringing down the tooling cost and rejections. The LDR is defined as the ratio of successfully drawn largest size of the blank without failure to the size of the punch used in the drawing operation [38]. The LDR is estimated using the Egn. 23.

$$\text{LDR} = \frac{(D_b)_{max}}{D_p} \tag{23}$$

Many parameters concerned with the tool setup design and drawing process influence the quality of the drawn cup in the deep drawing process [39]. The main parameters involved in the deep drawing process are needed to be selected for minimising the problems in the deep drawing process. According to the recent work of Zhou et al. [40], LDR is a function of normal anisotropy, friction coefficient, strain hardening exponent, die shoulder radius and blank thickness.

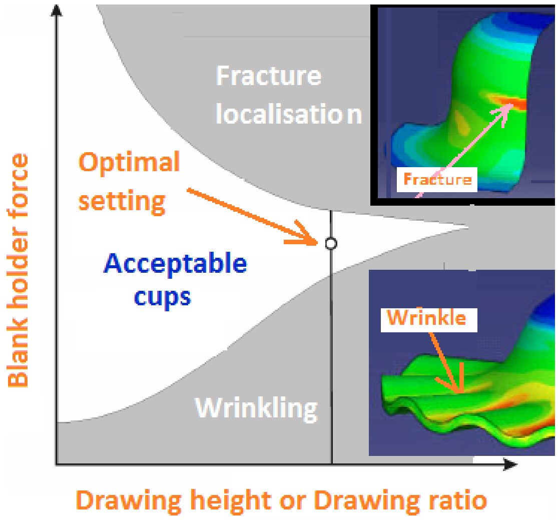

Fig. 12: Technological window [41]

1. **Blank Holder Force (BHF)**: From the past research it is found that the BHF improves the quality of the drawn parts [42–46] and in most of the cases BHF is described by means of the technological window as shown in Fig. 12. Higher BHF causes fracture while lesser BHF causes wrinkles. A lot of research was carried out on BHF, metal flow, stress distribution, strain path, wall thinning, flange thickening, etc. In the absence of blank-holding force, wrinkles appear at the flange. A suitable range is found for the BHF and it depends on different factors such as punch-die clearance, punch nose radius, die shoulder radius, punch speed, lubrication system, yielding properties, strain hardening and geometry of the blank/cup [47].
2. **Type of Blank Holder Mechanism**: Different types of blank holding mechanisms are available for selection. It is essential to select a suitable blank holding mechanism for the production of deep drawing product without defects. Various types are :
   (a) Constant BHF mechanism
   (b) Constant blank holder pressure (BHP) mechanism
   (c) Variable blank holder pressure mechanism
   (d) Segmented blank holder mechanism
   (e) Constant gap blank holder mechanism

(f) Vibration blank holder mechanism.

Constant blank holding mechanism is preferred in majority of the cases due to its simplicity [48].

3. **Punch Load and Speed**: The punch load in the deep drawing process is proportional to punch travel until maximum load and it helps in the selection of suitable deep drawing press. It has been observed that if Young's modulus and yield stress or strain hardening exponent of a material increases, it results in an increase in the punch load. It is to be noted that the value of strain hardening exponent ≥ 0.3 produces wrinkles during the drawing process. When the wrinkle development increases, the punch force required becomes erratic [49]. Basically, the drawing operation should be slow and gradual, where the blank material tends to suffer a critical strain. The blank material needs to be allowed into the die with a uniform speed. Therefore, the draw speed is also considered to be one of the highly influencing parameters during the design of deep draw tool setup [50].
4. **Friction and Type of Lubricant**: The friction is another important parameter that essentially influences the deep drawing operation. The quality of the product produced and the life of the tool are highly dependent on the lubricating film conditions between the contact surfaces [51]. The static friction force at the blank-die interface must be lower than the punch load applied for the inception of the deep drawing operation. The BHF influences static friction and the draw takes place once the punch load overcomes the static friction force. The continuous movement of the punch is quite important after the punch load overcomes the static friction in order to use the advantage of the dynamic friction since the dynamic friction force will be less than the static friction force. A definite lubricating oil film thickness can improve the surface finish of the deep drawn cup. It is revealed from the earlier research that a larger area of full film lubrication region results in the uniform strain distribution [51]. The proper lubrication conditions are needed for deep drawing process in order to get quality surface.
5. **Punch-Die clearance**: The intentional space provided between the punch and die is the die clearance and it is one of the critical factors to

be considered. Radial clearance of 7 - 14% of the sheet thickness is recommended. Insufficient clearance may cause shearing of the blank. It is to be kept in mind while designing the tool setup that if the radial clearance is less, the cup tends to fail due to ironing action. The die inner diameter is based on the gap required between the punch and die. This gap between punch and die depends upon the blank thickness and material, surface finish and lubricant used.

6. **Punch Nose and Die Shoulder Radii**: Sharp corner or less Punch Nose Radius (PNR) could cause fracture of the cup and larger PNR causes wrinkles on the flange. A less die corner radius causes fracture of the flange. For large values of punch nose radii, the material lying at the punch region deforms more than the other regions of the cup wall. It produces more thinning, leading to high-stress concentration at the PNR due to excessive bending and stretching of metal. This thinning phenomenon increases with an increase of PNR and the maximum thinning occurs at the punch nose region. The PNR has a considerable effect on shear strain, and the shear stress distribution. It is to be noted that an increase in the PNR, results in significant variation in shear stress and/or shear strain. In the deep drawing process, the tearing starts nearer to the upper edge of the PNR. It has been shown that the PNR less than four times the blank thickness or greater than 10 times the blank thickness will not have much influence on LDR. The Die shoulder Radius (DSR) generally depends upon the size of the workpiece and its thickness. The increase in DSR increases LDR as well as the punch load [52]. The increase in die shoulder radius leads to a decrease in the contact area between the blank and blank holder. It increases the chance of the formation of wrinkles [53]. According to Zaid et al. the maximum size of die shoulder radius should not be more than 15 times of blank thickness. The die shoulder radius should be in the range of 6 - 10 times the blank thickness [54, 55].
7. **Blank Heating System**: An appropriate heating system is used to raise the temperature of blanks for conducting experiments at warm forming conditions. In case of external heating, the blanks are heated in a furnace, and transferred to the press without any loss of temperature for deep drawing operation. During this process, any heat loss at transit may cause

a reduction in temperature. In the internal heating process, the blank is heated in the press itself through which a close control on temperature is possible. As the temperature gradient is essential for warm drawing operation to achieve higher LDR, the tool setup has to be heated uniformly using cartridge or band type heater while keeping the punch at room temperature. Though the heating may be either external or internal, the internal heating method is preferred to heat the blank in the tool setup itself due to its simplicity.

8. **Blank Shape**: To reduce the defects, thorough knowledge of the influence of blank shape is essential. The blank optimisation process can be carried out using the Finite Element Method (FEM) coupled with Taguchi DoE method. In cases, where the elliptical or square cup deep drawing process is performed under multistage operation, it requires to configure the blank shape correctly, as it largely influences the strain distribution all over the blank and at the corners, in particular. The blank shape optimisation can be done by various techniques with the use of FEM, Artificial Neural Network (ANN) models, etc. For optimisation, a meta-model can be developed and coupled with an optimisation algorithm using numerical methods. It helps to find the optimum shape of the blank in comparison to the experimental method which involves more time and cost.

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