Cup drawing or deep drawing

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1. Cup drawing or deep drawing

1.1 Deep drawing process

Cup drawing or deep drawing is one of the widely used sheet metal forming operations. Cup shaped objects, utensils, pressure vessels, gas cylinders, cans, shells, kitchen sink etc are some of the products of deep drawing. In this process, a sheet metal called blank is placed on a die cavity, held in position using a
holding plate or holding ring and pressed against the die cavity using a solid punch. The sheet metal attains the shape of the die cavity with flat bottom. Both die and punch should be provided with corner radius in order to avoid shearing of the sheet.

During drawing of sheet into the die, there is thickening of the sheet upto 12%. Therefore, clearance is provided between the punch and die. The radial clearance therefore is equal to the sheet thickness plus the thickening of sheet. Punch pushes the bottom of the sheet into the die cavity. The flat portion of the sheet under the holding plate moves towards the die axis, then bends over the die profile. After bending over the die profile the sheet unbends to flow downward along the side wall. The vertical portion of the sheet then slips past
the die surface. More metal is drawn towards the center of the die in order to replace the metal that has already flown into the die wall. Friction between holding plate and blank and that between die and blank has to be overcome by the blank during its horizontal flow.

Fig. 1.1.2: Redrawing of cup
1.2 Analysis of Cup Drawing:

Tensile stress is induced on the sheet at various locations within the die cavity. Maximum tensile stress is caused near the end of punch, at the profile of punch, because the sheet bends over the edge of the punch due to tensile stress. The sheet unbends along the cup wall. Necking of the sheet takes place near the punch profile due to excess tensile stress, resulting in fracture. The sheet under the holding plate, namely, the flange undergoes compressive hoop stress, radial tensile stress and compressive stress due to blank holding plate. Thickness of the cup wall increases from bottom to top. The die-punch clearance, usually, taken as 1.1t, where t is thickness of the sheet.
Fig. 1.2.1: Stresses in deep drawing process

Stresses acting on the sheet at various locations are shown in figure. The flange portion of the blank is subjected to a compressive hoop stress due to it being drawn towards the center. It is also subjected to radial tensile stress. The compressive stress of the hold down plate will be acting in the axial direction. If the hoop compressive stress is high or if the metal in the flange is not restrained wrinkling of the metal in the flange happens. To prevent wrinkling, the hold down plate is used. The material of the flange undergoes compressive hoop
strain and a radial tensile strain. The result is the metal in the flange, as it flows towards the center, tends to thicken – due to circumferential shrinking. However, due to bending under the punch and die profile, the metal undergoes thinning. The metal at the center of the blank, which is getting pressed by the punch bottom, is subjected to biaxial tensile stress due to the punch. The metal in the gap between die wall and punch is now subjected to longitudinal and hoop tensile stresses. If the clearance is less than the metal thickening on the flange side, the metal in the cup wall is squeezed. This process of thinning of the cup wall is called ironing. In order to reduce thickness and to cause uniform thickness on the cup, ironing is used in some drawing process, employing smaller clearances between die and punch.

The drawing force required under ideal frictionless flow conditions will increase linearly with punch stroke – due to increase in strain on the metal and also because the material gets strain hardened. Friction due to hold down pressure as well as sliding tends to increase reach a peak value and decreases early during the drawing. This is due to the fact that after certain amount of drawing the amount of material under the hold down plate reduces. Ironing force operates during the later part of the process, as sufficient thickening has to occur. About 15% of the total force is spent on bending and unbending of the blank on the die and punch profile. 70% of the total force is required for radial drawing of the material. 10% of the energy goes for overcoming friction.

If the blank hold down force is too high or if draw beads are used under the hold down ring, the material around the punch will begin to stretch instead of being drawn. This may lead to localized necking or diffuse necking depending on strain rate sensitivity, lubrication, punch geometry. On the other hand, a lower hold down pressure makes the metal flow freely into the die cavity.

The material which occupies the length represented by the difference between the die and punch radii is likely to undergo wrinkling – folding due to hoop compressive stress. This is due to the fact that the diameter of the blank has become sufficiently smaller. Therefore, the smaller material is unable to support the hoop stress and hence wrinkles. This happens especially when the hold down
pressure is insufficient and the thickness of sheet is too small and the material flow is pure drawing mode.

Sachs has given an approximate expression for total drawing force, which is given below:

\[ F = \left[ \pi D_p t \cdot 1.1 \ln \left( \frac{D_o}{D_p} \right) + \mu (2H \frac{D_p}{D_o}) \right] e^{\frac{\pi \mu}{2}} + B \]  \hspace{1cm} 1.1

- \( D_p \) is punch diameter
- \( D_o \) is blank diameter
- \( H \) is hold down force
- \( B \) is force for bending and unbending
- \( T \) is blank thickness
- \( Y \) is yield strength of the material

In deep drawing material just above the bottom of the punch is subjected to circumferential tensile stress and longitudinal tensile stress. Punch force acting on the bottom of the cup is transferred to the side of the cup. The narrow ring of metal just above the bottom of the cup is subjected to plane strain condition. As a result, failure of the cup easily happens in this zone due to necking induced by the tensile stress, leading to tearing. Punch force is shown to vary with the stroke of the punch. It is difficult to predict the punch force in deep drawing. However, an expression for maximum punch force is given by:

\[ F_{\text{max}} = \pi D_p t_o UTS \left( \frac{D_o}{D_p} - 0.7 \right) \]  \hspace{1cm} 1.2

- \( UTS \) is ultimate tensile strength of the material
- \( t_o \) is initial thickness of blank

The maximum tensile force on the cup which causes tearing can be estimated form the plane strain condition as:
\[ F_{\text{max}} = \frac{2}{\sqrt{3}} \text{UTS} \pi D_p t \]

In wire drawing the strain hardening exponent \( n \) has significant influence on deformation and draw force. Whereas in deep drawing strain hardening does not affect significantly both draw stress and deformation.

Clearance between die and punch is a critical factor in deep drawing. Normally, radial clearances of 7 to 14% of the sheet thickness is common. Too small a clearance may cause shear on the blank. Sharp corner on the punch could cause fracture of the cup along the corner. Too large a radius on the corner of punch may cause wrinkles on the flange. Similarly die corner radius, if small, can cause fracture on the flange. Corner radius is normally 5 to 10 times the sheet thickness.

Blank holder pressure is another important factor. 0.5 to 1% of the ultimate strength of the sheet material is normally taken to be the hold pressure. Too large a hold pressure results in tearing along cup wall. Too low a value leads to wrinkling in flange. An approximate expression for holding force is given based on the initial area of the blank and assuming that the holding pressure is 0.015 times yield strength.

\[ \text{Hold force} = 0.015\pi (D_b^2 - (D_p + 2.2t + 2R_d)^2) \]

\( R_d \) is die corner radius.

Thick sheets could be drawn without blank holder. In such case, the limit on the diameter of sheet is governed by: \( D_o - D_p < 5t_o \)