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Research Article

Evaluation of Limiting Drawing Ratio (LDR) in Deep Drawing by Rapid Determination Method

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Abstract

At the outset, the number of stages in design of multistage deep drawing process must be evaluated in order to optimize the process conditions. The estimation of number of steps involved in accomplishment of the required shape of the component mainly depends upon the limiting drawing ratio (LDR). In deed, LDR is an essential design component to be familiarized by process engineers in minimization of forming steps for multistage deep drawing process in which the forming of finished component cannot be achieved in single stage deep drawing process. LDR is defined as the ratio of maximum diameter of the blank that can be successfully drawn under the given punch diameter. In essence, it establishes the maximum size of the blank that can be successfully drawn for the given punch diameter. The determination of LDR by traditional methods is a lengthy, costly. In contrast to that, the present method described here in this paper is often called as "rapid determination of LDR based on characteristic limit load". This method of LDR determination consumes less time. It is also fast and essentially needs only three sizes of test samples under the given process conditions. The experimental investigation of rapid determination of LDR had been performed on an automotive aluminum alloy sheet AA6111 and the procedure is based on characteristic limit load. The results are in good agreement with the traditional methods that are already established in industry.

Keywords: *Deep drawing, Rapid FLD, Normal anisotropy, Planar anisotropy, plastic strain ratio. Wrinkling*

1. Introduction

Deep drawing process of sheet metal is an essential means for forming of cup shaped components often having ample applications in automobile, beverage, aerospace, kitchen utensils, cartridge bases and zinc dry cells. At the outset, deep drawing process underwent lot of research in last two decades. In essence the competitive environment is still demanding further for high strength and light weight metal parts. It is seldom sought for careful and improved further study of deep drawing process with advanced methods of analytical, experimental as well as numerical methods such finite element methods. Deep drawing process can also be used as an assessment test of sheet metal formability. In general, deep drawing process can be used to produce from simple cylindrical, conical, box-shaped to even complicated intermediate shapes which normally require redrawing process using progressive dies. The deep drawing process had prominently acquired its popularity due to rapid press cycle times, requirement of semi skilled labor and simplicity of the process. The desired shape of the component can indeed be stored in the shape of punch and die and can be imparted the same to the blank when it passes through the clearance between the punch and die. In essence, punch forces the blank through the clearance between punch and die with or without the presence of blank holder force. Indeed a blankholder with suitable applied force or pressure can essentially postpone for initiation in wrinkles formation or tearing by suppressing these failures.

When single stage deep drawing process fails, tool design modification can be made by suitably increasing the punch diameter so that the drawn cup in first stage will have larger diameter with little wall height. If needed, secondary operation is performed on drawn cup with reduced punch size, so that the cup wall is further increased by further reducing the diameter of the cup and this method of obtaining the required size of the cup in two or more drawing operation is known as multistage deep drawing process. In multistage deep drawing process the final size of the cup can be made by the use of multiple tool sets of different sizes. More number of forming steps in multistage deep drawing process makes the component hard and needs intermediate annealing to reduce the hardness of the material. Hence, for optimization of the process it is essential to evaluate correct number of stages in multistep deep drawing process. In addition, the maximum diametrical reduction is usually limited by the maximum allowable drawing force at the region of punch nose radius. The most important parameters that are

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influencing of multistep deep drawing process are LDR, blank holder force, punch nose radius, die entrance radius, clearance between punch and die, friction coefficient between tool and blank material and also speed of the process. The proper assessment of LDR for the given material is an important aspect to be considered for proper utilization of blank material under minimum wastage of material so as to minimize production cost. The aim of this paper is to device a procedure for rapid determination of LDR based on characteristic limit load at the fracture in deep drawing of cup. The material selected for this experimental analysis is an automotive aluminum alloy AA6111. As aluminum is having high strength to weight ratio in comparison to steel and hence widely used in automobile and aerospace applications and hence AA6111 aluminum alloy material is used in determination of LDR by this method.

2. Literature Review

The comprehensive parametric study was conducted in finding out the effect of various process, design and material parameters such as strain hardening exponent, coefficient of friction, normal anisotropy, die arc radius in multistage deep drawing of axisymmetric components and also developed LDR model for multistage deep drawing process (Prakash Sonis *et al,* 2003). It performed Finite element simulations and experimental analysis on formability of magnesium alloy AZ31B and conclusions were made for isothermal deep drawing of AZ31 metal as LDR for this Magnesium allot AZ31B is higher than the conventional deep drawing process. It is 2.63 at 260^0 c is due to increased strength at punch corner (Tyng-Bin Huanga *et al*, 2006). Axisymmetric deep drawing tests on austenitic stainless steel 310 in worm forming process were conducted and reveled that LDR is higher at temperature of 300^0c (Syed Mujahed Hussaini *et al,* 2003). It is also revealed from the experimental study that in titanium sheet LDR increases with increasing temperature and it is maximum i.e., 2.9 at the temperature of 200^0c (Fuh-Kuo *et al,* 2005). From the study on the influence of sheet thickness on stainless metal foils under varying process conditions such as variation in co-efficient of friction, constant blank holder force and variable blank holder force and concluded that LDR increases as the thickness of the blank increases (Y. Marumo *et al,* 2005). The research in the analytical study of axisymmetric hydro-mechanical deep drawing process has resulted for higher drawing ratios and also established the relationships between fluid pressure, anisotropy and co-efficient of friction (A Fazil *et al,* 2006). The analytical results are in good agreement with experimental works in establishing relation between normalized fluid pressure and punch travel under different drawing ratios. An approach on application of response surface methodology (RSM) with Pareto based multi objective genetic algorithm for optimization of sheet metal forming process had developed (Parviz Kahhal *et al*, 2013). The optimization methodology had been used on cross-shaped cup drawing in order to get fracture and wrinkle free cross shaped cups. Computer aided process planning (CAPP) for deep drawing of non-axisymmetric deep drawn products were presented for construction of blank design module, drawing co-efficient, punch and die radii along with presentation of production rules to be followed in CAPP (Dong Hwan Park *et al,* 2004). A study on automotive aluminum alloys in evaluation of deep drawing characteristics in AA6111 and AA5754 materials were tested in revealing the relations between punch load and punch displacement, blank diameter and also established a rapid method of LDR determination (M Jain *et al*, 1998). It is concluded that LDR decreases with a decrease in the die profile radius and AA6111-T4 is much more sensitive than AA5754-O due to its low value of strain hardening exponent and lower bendability.

Study made for the influence of space variant blank holder force on strain path changes through numerical simulation of the entire deep drawing process (L Wang *et al,* 2005). An eight point BHF control system with six spatial schemes were adopted to compare their effects on the strain distribution and found that negative minor strain had been influenced much more in comparison to maximum major strain. It was established a mathematical model for finding limiting blank holder force in hydro-mechanical deep drawing and resulted in finding a safe zone for blank holding force (K S Deep *et al,* 2007). The safe zone for the blank holder force increases with an increase in normal anisotropy, die clearance and sheet thickness. Parametric study of the axisymmetric hydro-mechanical deep drawing process had been studied while consideration of tooling friction and revealed that increase in die friction leads to decreased drawing ratio (A Fazli *et al,* 2006). An efficient method had presented for optimization of the blank holder force in cup drawing process along with the significance of blank holder force window for defect free product (H Gharig *et al,* 2006). Flat nosed punch was used in evaluation of drawing force in axisymmetric deep drawing and established a rapid method of punch force determination (A S Korhonen *et al,* 1982). The importance of blank holder force in prevention of wrinkling as well as a simple relation between punch force and blankholder force had been established and concluded that the blank holder force is approximately proportional to the punch force (S. Thiruvarudchelvan *et al*, 2007).

3. Theoretical study

Forming of cup shaped articles by deep drawing process is actually one of the most complicated processes due to material properties such as planar anisotropy and normal anisotropy.

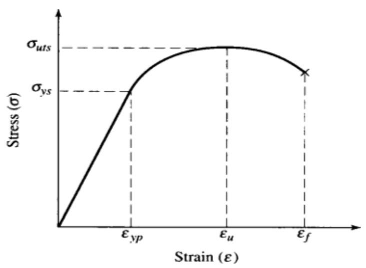

Fig. 1 Stress strain relations

Many researchers from industry and laboratory made large efforts in study of this complicated forming properties such as normal anisotropy, planar anisotropy and strain hardening effects on the limiting drawing ratio trough experiments and numerical models. In comparison to anisotropy, the effect of strain hardening is evidently insignificant in deep drawing of the material. An isotropic material under assumptions of rigid-plastic flow conditions can exhibit stress strain relations are as depicted in Fig 1.

When the material exhibits strain hardening property, the stress strain relations can be expressed in analytic form by equation 1.

$$\bar{\sigma} = K(\bar{\epsilon})^n \quad (1)$$

where K is the strength coefficient $\bar{\sigma}$ is the equivalent stress, $\bar{\epsilon}$ is the equivalent strain and n is the strain hardening exponent. The slope of log $\bar{\sigma}$ vs log $\bar{\epsilon}$ gives the value of strain hardening exponent and intercept on y-axis gives K. Anisotropic material is one which is having different yielding properties in different directions. The sheet material which is having more flow strength in thickness direction than width direction is more sought after material for deep drawing process. This anisotropy property induced due to rolling process helps in production of deeper cups without necking failure. This property of anisotropy can be expressed in terms of strain ratio (r) which is defined as the ratio between true strain in width direction to true strain in thickness direction as defined in equation 2.

$$r = \frac{\epsilon_w}{\epsilon_t} = \frac{\epsilon_w}{-(\epsilon_w+\epsilon_l)} = \frac{\ln(\frac{w_0}{w})}{\ln(\frac{wl}{w_0 l_0})} \quad (2)$$

The properties of the material are essentially assumed to be rotationally unsymmetrical and the material is having planar anisotropy in addition to normal anisotropy. Average value of normal anisotropy can be expressed by equation 3.

$$\bar{R} = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad (3)$$

where $r_0, r_{45} and\ r_{90}$ are the values of strain ratio at 0 degrees, 45 degrees and 90 degrees to the rolling direction. The variation of flow strength in the plane of the sheet is known as planar anisotropy ΔR leads to formation of ears. Planar anisotropy can be expressed as shown by equation 4.

$$\Delta R = \frac{r_0 - 2r_{45} + r_{90}}{2} \quad (4)$$

Ideally a sheet with high normal anisotropy and zero planar anisotropy is good for deep drawing. For isotropic material r = 1 and the Von Mises yield condition is expressed in equation 5.

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_{11}-\sigma_{22})^2 + (\sigma_{22-\sigma_{33}})^2 + (\sigma_{33}-\sigma_{11})^2 + 6({\sigma_{12}}^2 + {\sigma_{23}}^2 + {\sigma_{31}}^2)} \quad (5)$$

Anisotropic materials behavior is more appropriately described by hill criteria while considering the anisotropy parameters into account as described by Hill and the same were used by Tomasz Trzepiecinski (2011). This popular criterion described by Hill can be expressed in mathematical form as in equation 6.

$$\bar{\sigma} = \sqrt{\frac{F(\sigma_{11}-\sigma_{22})^2 + G(\sigma_{22-\sigma_{33}})^2 + H(\sigma_{33}-\sigma_{11})^2 + 2L{\sigma_{23}}^2 + 2M{\sigma_{31}}^2 + 2N{\sigma_{12}}^2)}{2}} \quad (6)$$

The constants F, G, H, L, M and N, defines the anisotropy of the material and are given by

$$F = \frac{1}{2}\left(\frac{1}{R_{22}^1} + \frac{1}{R_{33}^1} - \frac{1}{R_{11}^1}\right)$$

$$G = \frac{1}{2}\left(\frac{1}{R_{11}^2} + \frac{1}{R_{33}^2} - \frac{1}{R_{22}^2}\right)$$

$$H = \frac{1}{2}\left(\frac{1}{R_{11}^1} + \frac{1}{R_{22}^2} - \frac{1}{R_{33}^2}\right)$$

$$L = \frac{3}{2R_{23}^2}$$

$$M = \frac{3}{2R_{13}^2}$$

$$N = \frac{3}{2R_{12}^2}$$

The parameters R_{11}, R_{22}, R_{33}, R_{12}, R_{23}, R_{31} are ratios of yields stress in different directions with respect to reference stress can be expressed as follows.

$R_{ii} = \frac{\sigma_{ij}}{\sigma_0}$ and $R_{ij} = \frac{\sigma_{ij}}{\tau_0}$ where i= 1, 2, 3 and j= 1, 2, 3

The analytical model for determination of punch load can be found from various punch force analytical models. One model that used by F. Vollertsen et al highlighted that the maximum punch force F_{max} in deep drawing can be calculated by

$$F_{max} = \pi D t_0 \sigma_{Qmax} \quad (7)$$

where σ_{Qmax} can be defined as

$$\sigma_{Qmax} = k_f \left(ln \frac{D}{d} + \frac{2\mu F_n}{\pi D t_0 K_f} + \frac{t_0}{2r_z + t_0}\right) . (1 + 1.6\,\mu) \quad (8)$$

4. Deep Drawing set up

The experimental setup consists of 200T double acting press with in-built load cell for recording of the punch force as show in Fig 2. The punch load can be directly recorded under computerized recording system throughout the process from beginning of the punch while making contact with the blank till the end of cup formation. Cup drawing tests were conducted using die sets with die profile radius of 8 mm with 80 mm punch diameter having nose radius of 4 mm. All the tests of this experiment were conducted while keeping the punch nose radius, percentage of clearance, blank holder force, friction and other test conditions the same. The tool geometric parameters utilized in formation of different cups are as shown in table 1.

The speed of the ram was 600 mm per minute in forward stroke and 8100 mm/min in return stroke. The load verses punch displacement was recorded as shown in Fig 5. This method of rapid determination of LDR is based on the observation of the characteristics limit load at fracture was developed. In this method of testing, experiments were conducted on three different sized blanks, two are of undersized blanks and third blank is of oversized for deep drawing. The sizes of the blanks, maximum punch loads recorded are as shown in the table 2.

Fig. 2 Mechanical press used in deep drawing process

Table 1 Tool geometry for deep drawing

S. No	Parameter	Quantity
1	Sheet thickness, mm	0.9
2	Die opening diameter, mm	96
3	Die shoulder radius, mm	8
4	Punch Diameter, mm	80
5	Punch nose radius, mm	4
6	Die inner diameter, mm	83
7	Blank Holder opening diameter, mm	96
8	Gap between die and blank holder, mm	1.5

The commercially produced aluminum alloy AA6111 of gauge 0.9 mm was utilized in these tests. The blank sizes used were 100 mm, 140 mm and 250 mm. The tool geometry used is as shown in Fig 3. Firstly, the deep drawing tests were conducted with undersize blanks consisting of three blanks in each set. For each size of the blank the punch load verses punch displacement readings were made when the work piece underwent deep drawing process. The same test were also conducted for over size blank of 250 mm and punch load verses punch displacement recordings were made as depicted in Fig 5. The maximum punch load recordings for all sizes are as shown in Table 2.

In the case of 100 mm blank as well as 140mm blank, deep drawing tests were successfully performed and cups of wrinkle-free, fully drawn and without necking or fracture were produced. In contrast to the undersize blanks the oversize blanks of 250 mm diameter yielded fractured cups as shown in Fig 4. It had observed from load curve that the punch load drastically reduced to minimum in no time as soon as the fracture is initiated at punch nose region of the deep drawn cup. Fig 4 shows the photographs of the cups drawn while deep drawing process. For the under size blanks of 100 mm and 120 mm diameter, the maximum average load recoded was 90kN and 125kN respectively. Similarly the maximum load recorded for oversize blank of 250 mm diameter was 175kN.

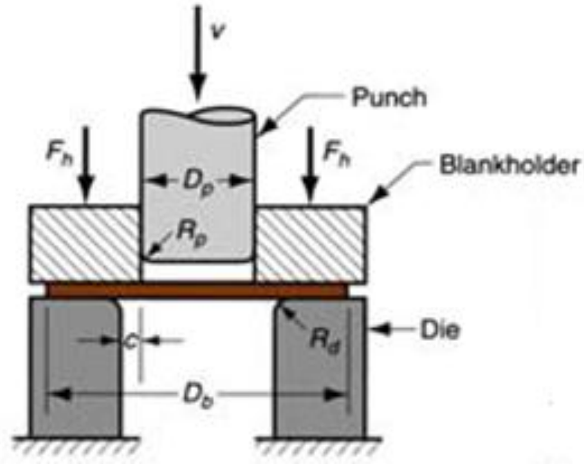

Fig. 3 Geometry of deep drawing process

5. Methodology for Rapid Determination method of LDR

The step by step procedure for rapid determination of LDR is as follows.

a. In the first step two sets of under size blanks are to be tested for deep drawing of cup and maximum punch loads were recorded for each test.
b. In the next step, again same test performed with oversize blank and noted for maximum punch load.
c. Plot readings for all sets of blanks as shown in Fig 6.
d. Draw a horizontal line passing through fracture load obtained for oversize blank.
e. Draw a trend line passing through maximum punch loads of undersized blanks and by extending it will intersect the fracture line
f. The point at which the extended inclined line intersects the fracture line is gives the maximum blank diameter that can be successfully drawn for the given punch diameter
g. The LDR is determined for the given material by dividing the maximum diameter of the blank to the diameter of the punch used in deep drawing process.

Table 2 Measured Punch Loads for different blanks

S. No	Dia. of the Blank (mm)	Max. load (kN)	Remarks
1	100.00	90	Fully drawn cup
	100.05	90.1	Fully drawn cup
	99.05	89.9	Fully drawn cup
2	140.00	125.0	Fully drawn cup
	140.20	125.1	Fully drawn cup
	139.80	124.9	Fully drawn cup
3	250.00	175.0	Fractured cup
	250.15	175.4	Fractured cup
	249.85	174.6	Fractured cup

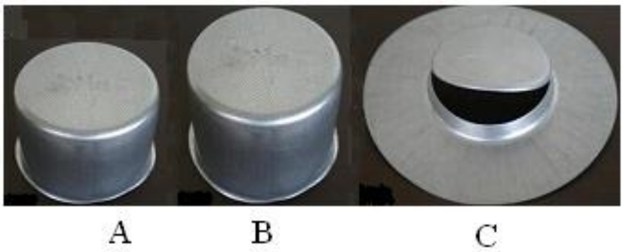

Fig. 4 Deep drawn cups A) undersized cup, B) undersized cup and C) oversized cup failed in drawing

6. Results

In this study it is evidently observed that the characteristic fracture load of aluminum alloy had been tested for determination of LDR by rapid method.

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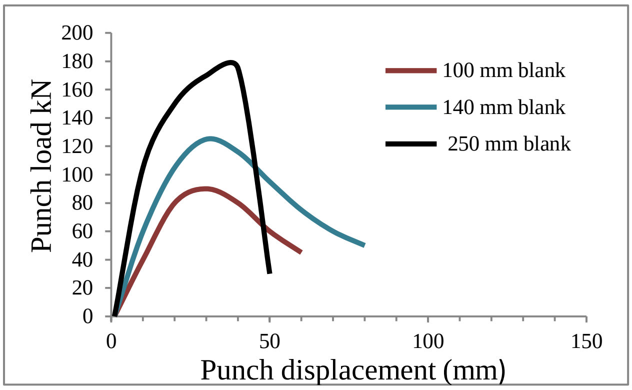

Fig. 5 Punch load verses punch displacement

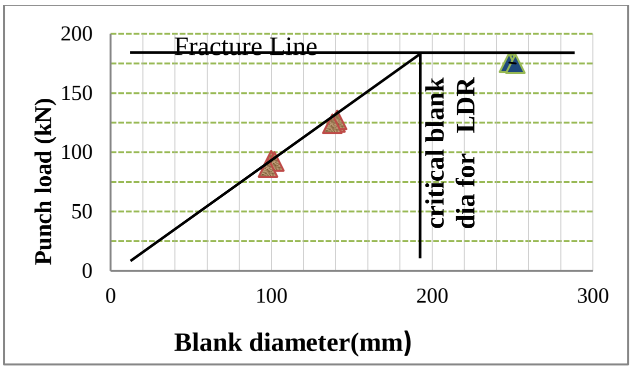

Fig. 6 LDR estimation on limit load at fracture

This method is indeed based on the fracture load limit and observed that the characteristic fracture load is really independent of blank size, die profile radius and blank holder force. Fracture of the cup occurs essentially when the fracture load limit exceeds the limit of the cup wall and it takes place very close to the punch profile radius. The LDR had found for aluminum alloy AA6111 in this test as 2.37 and it is indeed in good agreement with the results found elsewhere in the literature. Undoubtedly this method is simple and can be easily implemented in determination of LDR for any type of material.

Conclusions

In this paper a method of rapid determination of LDR is proposed and it is much useful in fixing the number of stages in multistage deep drawing process for estimation of number of stages by process engineers. This method is safe and supplies an accurate estimate of the LDR much useful in forming industry like automobile and aerospace industry. It is expected hat the present method will prove to be practically applicable, since it avoids the complex method of LDR estimation in which large number of blanks of different sizes needs to be tested which also involves lot of labor, time and cost.

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Nomenclature

D = blank diameter
d = punch diameter
k_f = flow stress
F_n = Blank holder force
r_z = drawing radius
μ = friction coefficient
t_0 = sheet thickness
r = strain ratio
F_{max} = maximum punch force
$\overline{\sigma}$ = Von mises stress
t_0 = initial thickness of the blank
$\bar{R}$ = normal anisotropy
ΔR = planar anisotropy