

Numerical Studies on Deep Drawability of the Aluminium Alloy, AA6082 and Parameters Affecting It

Srijan Bansal^{1,*}, Vijay Gautam², Ved Prakash³

Abstract

Deep drawing is a metal forming operation used for manufacturing sheet-metal components for application in the automobile, aerospace, and packaging industries. The objective of the present work was to study the various parameters influencing the drawability of AA6082. The deep-drawing process was modeled and simulated in Ls-Dyna Pre-Post(R) V4.6.17 software. The tensile test was performed according to the ASTM-E8M standard on AA6082-T6 material and subsequently annealed to attain higher ductility. The annealing was performed in an industrial furnace for a temperature range of 200°C–350°C and 350°C provided the best results. Further, to predict the accurate material behavior during deep drawing, Barlat-3 parameter anisotropic yield criterion was used. The material model parameters and constants were determined by conducting a uniaxial tensile test and anisotropy test on a universal testing machine, respectively. The experimental results revealed that annealing enhanced ductility and strain hardening exponent but reduced the strength of the sheet metal. It was observed that a higher blank holding force was required with lower sheet thickness to remove wrinkling. The nature of the load is tensile in the radial and compressive in the circumferential direction. An increase in the coefficient of friction decreased the sheet thickness in the wall section of the drawn cup. It was concluded that the limiting draw ratio increased with an increase in sheet thickness, coefficient of friction between punch and sheet, and an increase in die corner radius. The limiting draw ratio decreased with an increase in punch speed, blank holding force, friction between die and sheet, and punch radius.

Keywords: Limiting draw ratio, Barlat-3 parameter model, AA6082, LS-Dyna

INTRODUCTION

Deep drawing is a well-known sheet-metal forming process in which a flat sheet is drawn radially into a circular die to form a hollow component by the operation of a punch [1]. The deep-drawing process and its parts are shown in Figure 1. The sheet is deformed by the action of a punch pushing it against the frictional forces. After that sheet bends and slides over the surface of the die profile radius and then eventually takes the shape of the die it is been pushed into [2]. A blank holding load is applied on the blank holder which controls the flow of material and prevents wrinkling [3].

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M.T. Browne et al. [4] conducted a Taguchi L8 orthogonal array screening experiment for C.R.1 cups of 0.9 mm and found that top Ram Pressure of 70 kN, BHP of 18 kN, and speed of 100 mm/min were optimal parameters providing the least variation. Swadesh Kumar Singh et al. [5] examined forming of EDD steel at room temperature and 200°C. The LDR and coefficient of friction were calculated and it was inferred that there is a rise in LDR with an escalation in temperature because of relief in stress for both

simulations in LS-Dyna and experimental work. Liwen Y. gen WANG et al. [6] introduced a curved blank holder which improved the LDR to 2, and earing was also minimized. E. T. Harpell et al. [7] predicted the LDR of a cup-drawing for AA5754- in LS-Dyna explicit solver and found that Barlat-89 yield criteria gave more precise results than von-mises as well as hill's criteria. The predicted strain values under Barlat-89 were also within 5% of experimental values of von-mises and hill's criteria. Y. Marumo et al. [8] found that as the sheet thickness decreased, there was an increase in the blank holding force required to remove wrinkling. B. Rao et al. [9] tried to optimize blank holding force and concluded that punch diameter was the most influential parameter. It was then followed by the radius of the die, the radius of punch, clearance, and friction. He found that wrinkling is minimum at a 7 mm die radius, 1 mm punch radius, 7% of clearance, and 0.45 coefficient of friction.

In this paper, the influence of deep-drawing process parameters on drawability is presented. The model is developed as well as simulated with the help of the LS-Dyna explicit solver. AA6082 has been used for our research work which is annealed in an industrial muffle furnace to attain higher elongation. AA6082 being an anisotropic material, correct material characterization is essential to predict the behavior of the model as close to actual experimentation. Therefore, the use of the proper material model in LS-Dyna is of utmost importance and the Barlat-3 parameter is utilized for this purpose. The effect of sheet thickness, punch speed, coefficient of friction, and blank holding force with LDR are plotted.

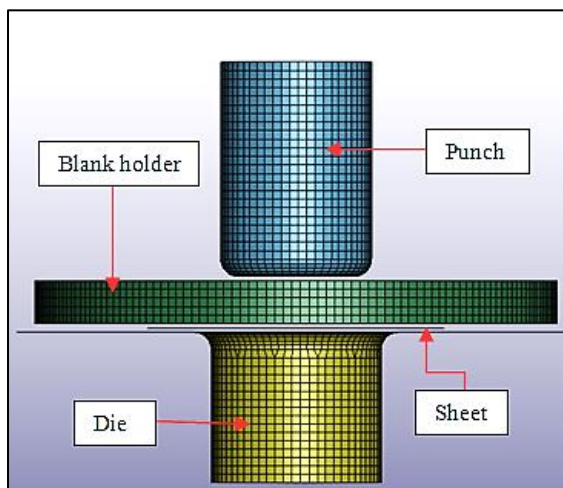


Figure 1. Deep-drawing FEA parts.

EXPERIMENTATION

Material Selection

Industries especially automotive's often require components to be lightweight, strong, corrosion-resistant, and durable. Therefore, AA6082 has been used for our research work as it is having highest strength among the 6000 alloys and is 15–20% higher than AA6061 alloy. [10]. The chemical composition of the AA6082 alloy is shown in Table 1.

Table 1. AA6082 alloy chemical composition.

Alloy	Mg	Si	Mn	Cu	Cr	Zn	Ti	Fe	Al
AA6082	0.6-1.20	0.70-1.30	0.40-1.00	0.10	0.25	0.20	0.10	0.50	Remainder

Tensile Test

The specimen was designed as per ASTM standard CAD as shown in Figure 2(a) and the HS-G3015C laser cutting machine was used to machine the tensile specimen. The tensile test was performed according to the ASTM-E8M standard as shown in Figure 2(b) in Tinius Olsen uniaxial tensile testing machine.

Initially, AA6082-T6 material was tensile tested on a UTM machine, and the yield stress and ultimate tensile stress were found to be 276.535 and 323.605 respectively as shown in Figure 3(a). The strain value was only 4%–5%. The $\ln(\text{True Stress})$ vs. $\ln(\text{True Strain})$ graph is depicted in Figure. 3(b) gave strength coefficient 'K' and strain hardening exponent 'n' reading to be 666.0735 and 0.2628 respectively.

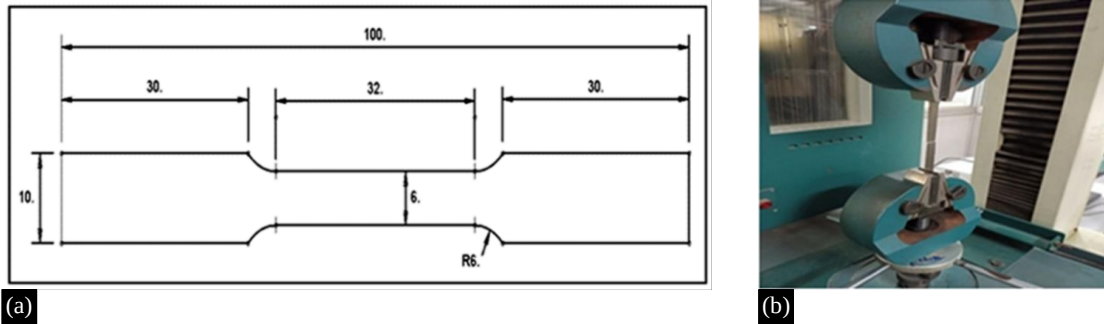


Figure 2. (a) Tensile testing specimen as per ASTM-E8M standard; (b) universal tensile testing machine and the crossheads.

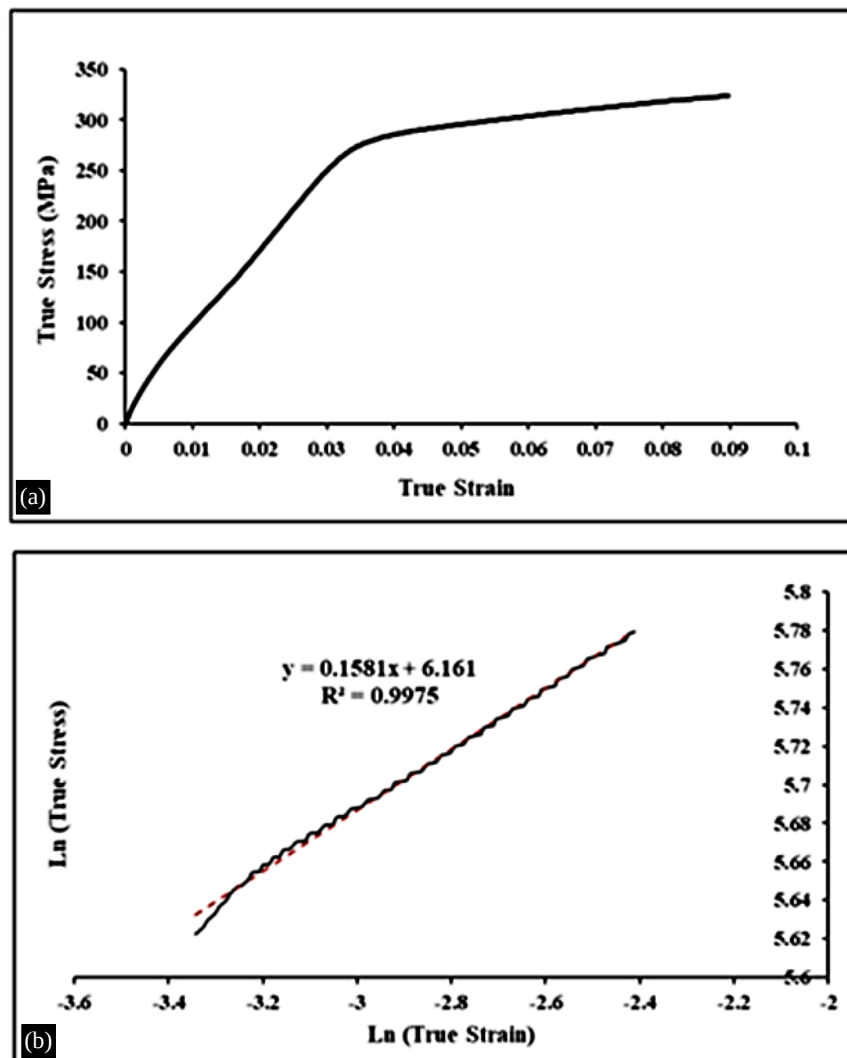


Figure 3. (a) True stress vs. true strain of AA6082-T6; (b) $\ln(\text{True Stress})$ Vs $\ln(\text{True Strain})$ of AA6082-T6.

To attain higher elongation, annealing needs to be performed on the material which can be done in an industrial muffle furnace as seen in Figure 4(a). The temperature of the furnace was increased from 200°C to 350°C as shown in Figure 4(b). After again tensile testing of the above samples, 350°C gave the best results for both ductility and strength and was therefore chosen for further analysis.

After annealing, the results of the tensile test observed in Figure 5(a) show that the elongation was now increased by 15% hence ductility of the material was improved. Then again $\ln(\text{True Stress})$ vs. $\ln(\text{True Strain})$ graph was plotted as shown in Figure 5(b) and the strength coefficient 'K' and strain hardening exponent 'n' reading was observed to be 205.696 and 0.246 respectively.

Anisotropy Calculation

Anisotropy is a material property where materials like aluminium show distinct properties in different directions and these materials are referred to as anisotropic materials [11]. The Lankford coefficients or the plastic strain ratio in the 0°, 45°, and 90° direction and normal anisotropy is shown in Table 2.

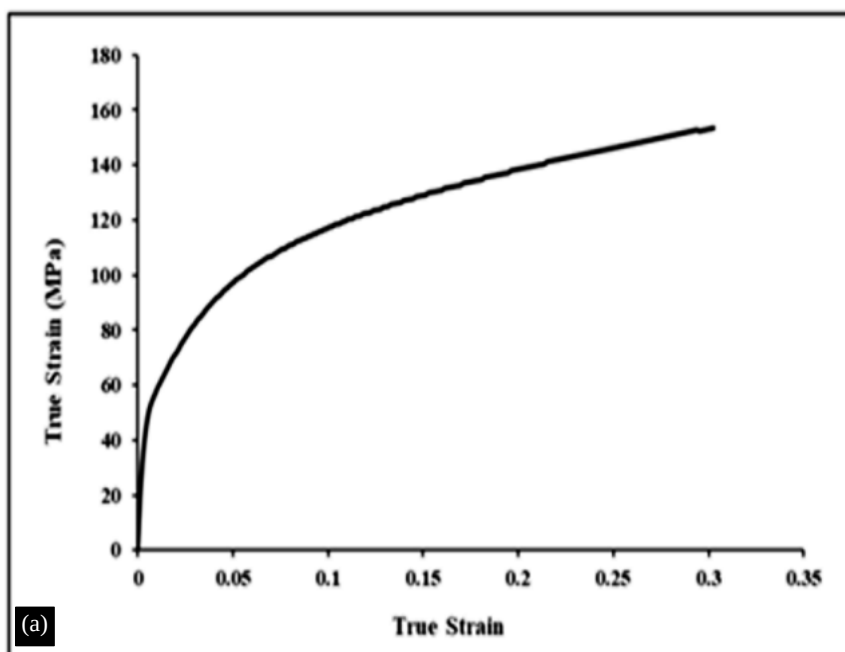


(a)



(b)

Figure 4. (a) Industrial Muffle Furnace; (b) at 350°C temperature.



(a)

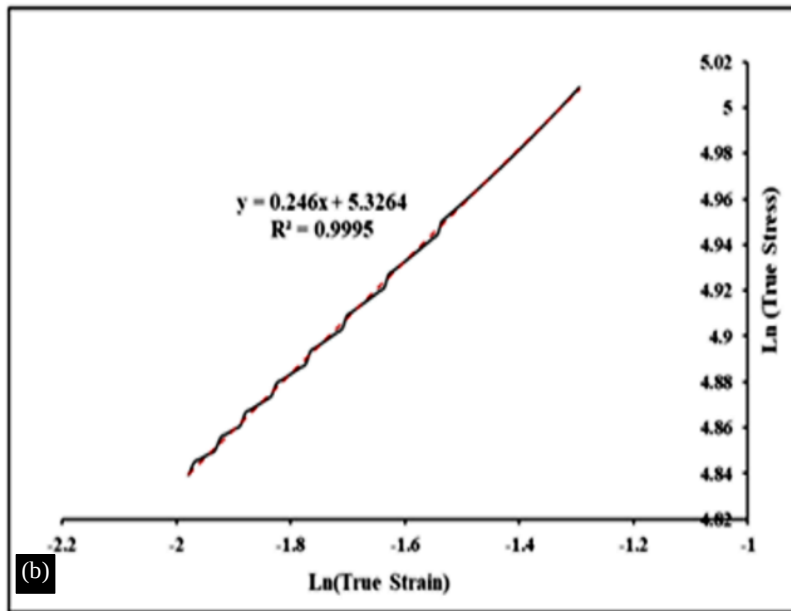


Figure 5. (a) True stress vs. true strain of AA6082-O; (b) Ln(True Stress) Vs Ln(True Strain) of AA6082-O.

Table 2. Lankford coefficients and normal anisotropy calculation

r_0	r_{45}	r_{90}	r_m
0.610	0.636	0.738	0.655

Barlat 1989 Material Model

Barlat and Lian [1989] presented this model which is generally used for anisotropic material in plane stress conditions for modeling sheets in the presented deep-drawing process given in Eq. 1. [12]

$$\phi = a|K_1 + K_2|^m + a|K_1 - K_2|^m + c|2K_2|^m = 2\sigma_Y^m \quad (1)$$

Where, K_1 , K_2 are given by Eq. (2) and Eq. (3) respectively

$$K_1 = \frac{\sigma_x + h\sigma_y}{2} \quad (2)$$

$$K_2 = \sqrt{\left(\frac{\sigma_x - h\sigma_y}{2}\right)^2 + p^2\tau_{xy}^2} \quad (3)$$

The parameters such as a , c , and h can be found by considering the plastic strain ratio as shown in Eqs. (4), (5), and (6).

$$a = 2 - 2\sqrt{\frac{R_{00}}{1+R_{00}} \cdot \frac{R_{90}}{1+R_{90}}} \quad (4)$$

$$c = 2 - a \quad (5)$$

$$h = \sqrt{\frac{R_{00}}{1+R_{00}} \cdot \frac{1+R_{90}}{R_{90}}} \quad (6)$$

Where, m is the non-linear relationship coefficient, a , c , h , p , and m are the anisotropic material parameters, σ_Y is the yield stress of material and K_1 , K_2 , K_3 are the principle deviatoric stress.

FEA Simulation Using LS-Dyna Pre-Post (R) V4.6.17

The geometric model, as well as the simulation of the deep-drawing process, was performed in LS-Dyna. The dimension of the model for sheet thickness of 1 mm and blank radius of 70 mm is shown

in Figure 6. The die clearance is taken according to the formula which states that die clearance should be 20% of the sheet thickness. The load on a blank holder or the blank holding force (BHF) in deep-drawing operation is calculated by the standard formula for a blank of 70 mm given in Eq. 7. [13]

$$\text{BHF} = 2\% * \left(\frac{\sigma_y + \sigma_{UTS}}{2} \right) * \text{Area} = 2\% * \left(\frac{88.389 + 153.464}{2} \right) * \frac{\pi}{4} * 70^2 = 4.653 \text{ kN}. \quad (7)$$

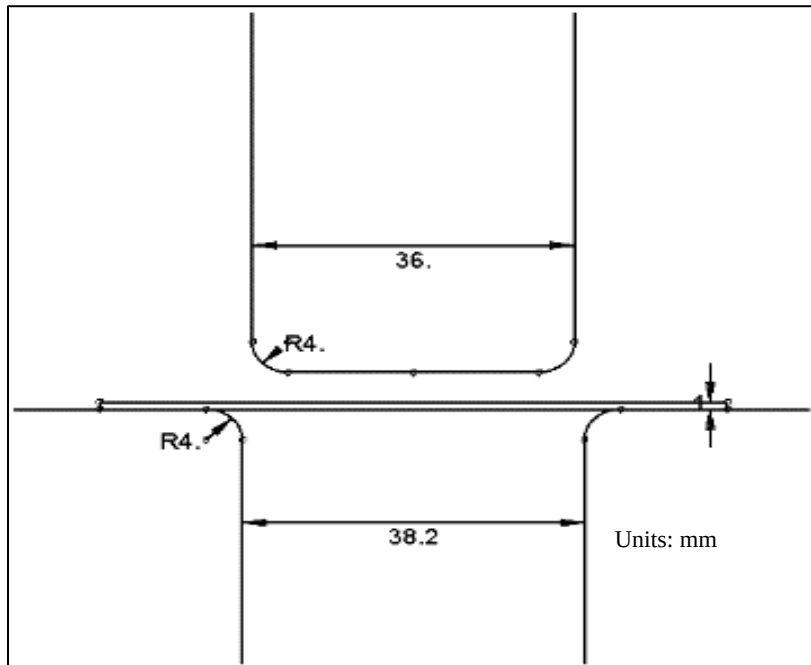


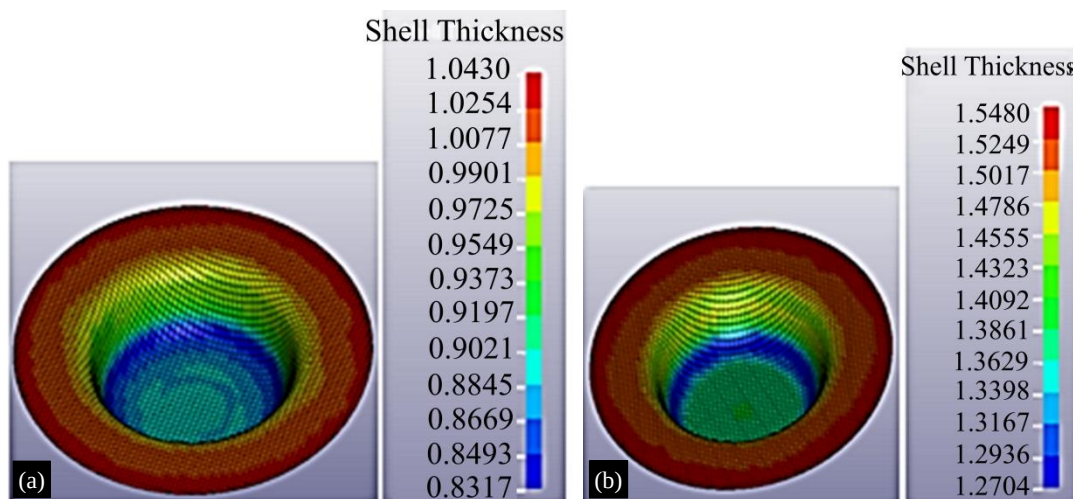
Figure 6. Deep-drawing setup.

RESULTS AND DISCUSSION

Thickness Variation During Sheet Deformation

Thickness of Flange at Different Sheet Thickness

The flange region experiences two opposite natures of stress namely hoop or circumferential stress and radial stress. So, the nature of the load is tensile in the radial direction and compressive in the circumferential direction. As a result, thickness in the area flank region increases as seen in Figure 7(a) to (c). The second zone of deformation is the transition between the wall of the cup and the radius of the punch profile. The region undergoes uniform axial stretching which will lead to thinning in this portion.



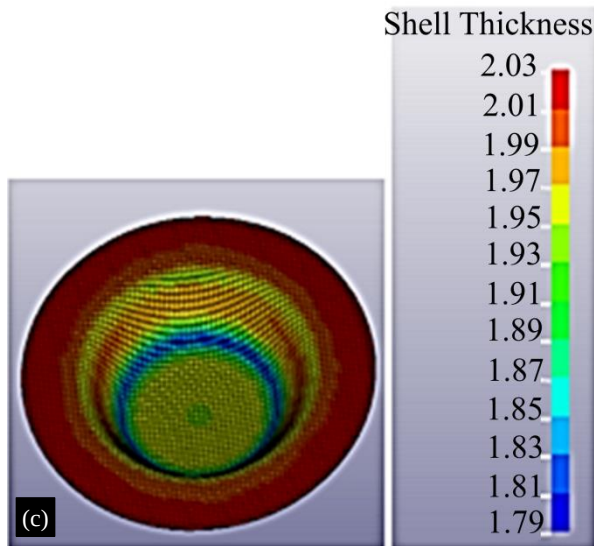


Figure 7. (a) Thickness variations on a sheet of 1 mm; (b) thickness variations on a sheet of 1.5 mm; (c) thickness variations on a sheet of 2 mm.

Wall Thickness During Sheet Deformation at Various Coefficients of Friction

The sheet thickness after the deep-drawing operation can be seen in Figure 8(a) to (d). It is visible that with the rise in the coefficient of friction, there is a decrease in sheet thickness at the wall section. If only the wall is considered, the thickness is reduced to 0.9753 for $\mu = 0.1$ in Figure 8(a), 0.9631 for $\mu = 0.15$ in Figure 8(b), 0.9604 for $\mu = 0.2$ in Figure 8(c), and 0.8869 for $\mu = 0.25$ in Figure 8(d). If the coefficient of friction increased any furthermore it will result in necking and eventually fail due to a severe reduction in thickness.

Blank Holding Force During Sheet Deformation

It is already known that a blank holding force is required to eliminate wrinkling or buckling [2]. In Figure 9, cups were drawn at different blank holding forces for sheet thicknesses of 1 mm and 1.5 mm. For a sheet of 1mm, wrinkling was seen at 0.75 kN of BHF and as the BHF increased to 0.8 kN wrinkling was not seen as seen in Figure 9(a) and (b). Now, for a sheet of 1.5 mm, wrinkles are observed at a BHF of 0.52 kN and wrinkles were prevented at a BHF of 0.55 kN as seen in Figure 9(c) and (d). It was seen that as the sheet thickness is decreased there is an increase in blank holding force required to remove wrinkling.

Determination of LDR at Various Process Parameters with the Barlat-3 Parameter Model

Variation of LDR with Sheet Thickness

In Figure 10(a), a curve is drawn between LDR and sheet thickness. The different sheet thicknesses taken are 1, 1.5, and 2 mm. At every particular sheet thickness, LDR was found and then plotted with sheet thickness. It was seen that with the addition of sheet thickness the LDR increases. As the thickness of the material decrease, the load-carrying capacity of the material also decreases. Therefore, it is difficult with the decrease in thickness of sheet metal to avert failure. With the increase in thickness of the sheet, stiffness also increases which is related to buckling. As a result, wrinkles are suppressed on the walls and there is an increase in LDR. The readings were also taken at the coefficient of friction $\mu = 0.1$ and 0.15. It was found that with an increase in friction, LDR decreases as the sheet thickness is increased.

Variation of LDR with Punch Speed

It was seen in Figure 10(b), that the curve between the variation of LDR and speed is plotted. The speeds which are considered in the calculation are 3000 mm/s, 4000 mm/s, and 5000 mm/s. At

different speeds, a particular LDR value was calculated which came out to be 1.969, 1.965, and 1.959 with increasing speed. It is observed that as the speed value increased from 3000 mm/s to 5000 mm/s, the calculated LDR decreases. The calculations were performed on a 1 mm sheet. The lesser the sheet thickness, the higher will be the radial and tangential compressive stress. To encounter the increased stresses, a higher amount of blank holding force is required to avoid wrinkling.

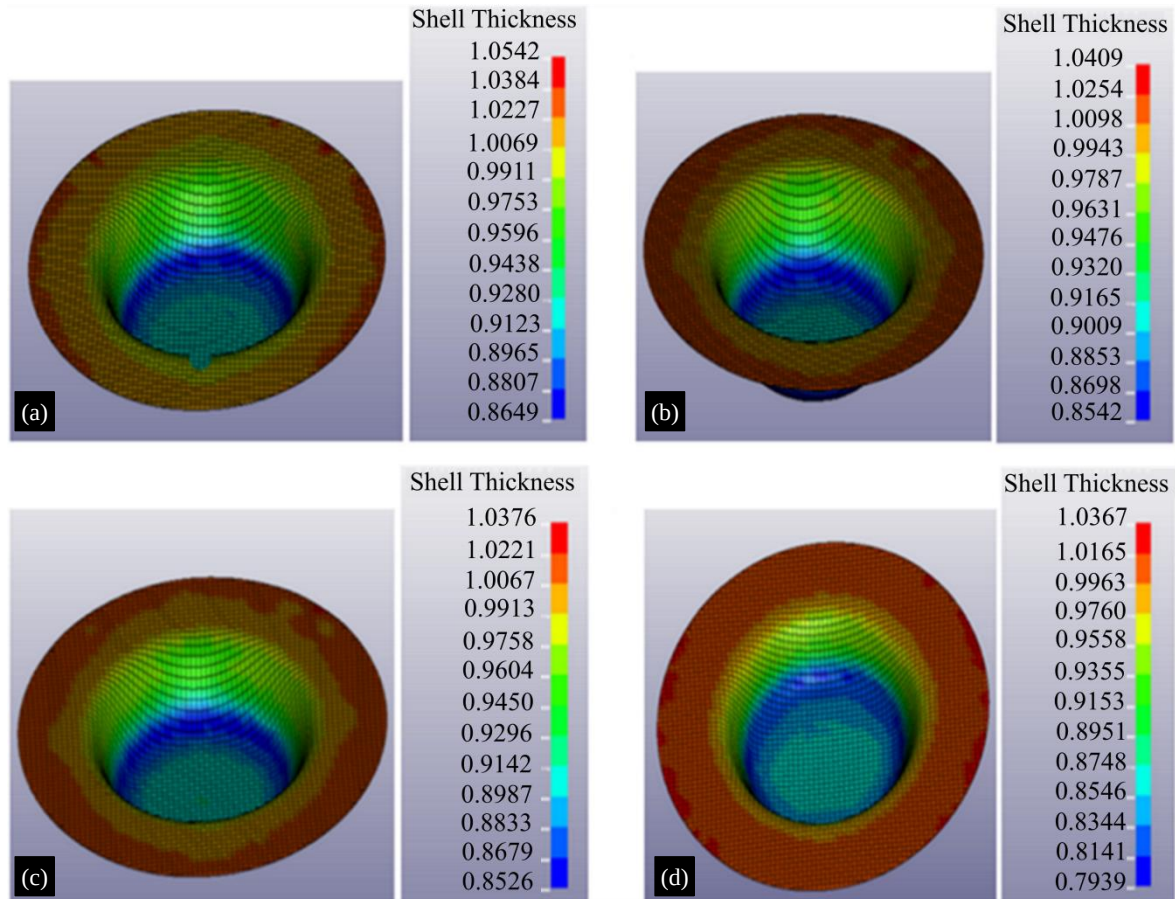


Figure 8. (a) Wall thickness at $\mu = 0.1$; (b) wall thickness at $\mu = 0.15$; (c) wall thickness at $\mu = 0.2$; (d) wall thickness at $\mu = 0.25$.

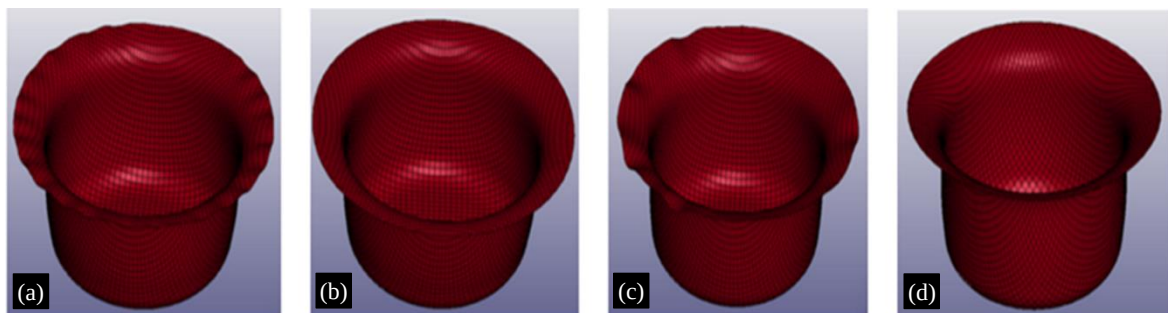


Figure 9. (a) Wrinkling at BHF of 0.75 kN for 1 mm; (b) No wrinkling at BHF of 0.8 kN for 1 mm; (c) Wrinkling at BHF of 0.52 kN for 1.5 mm; (d) No wrinkling at BHF of 0.55 kN for 1.5 mm.

Variation of LDR with BHF

The blank holding force is required to prevent wrinkling on the flange as well as the wall region. In Figure 10(c), the graph between LDR and blank holding force is drawn. The various BHF values taken were 5 kN, 10.4 kN, 20 kN, and 30 kN. After finding values of LDR at different BHF's it was

seen that LDR values decrease with an increase in BHF. If the BHF is of less value, more material will be drawn in thereby stress reduces on the wall surface. As the BHF is increased, it prevents the excess flow of material, and stress values increases. Therefore, with a low value of BHF, there will be deeper cups drawn and the value of LDR is increased, and vice versa.

Variation of LDR with Coefficient of Friction of Sheet-Die

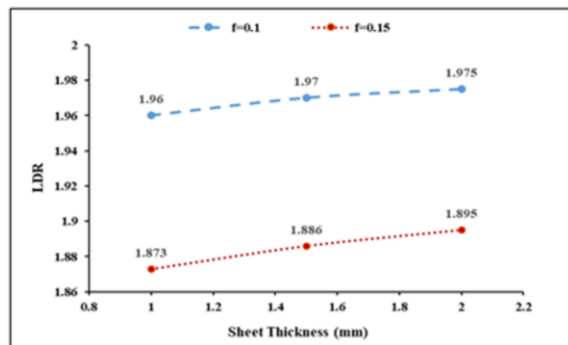
The variation of LDR was plotted in Figure 10(d) with an increased coefficient of friction between the sheet and die. The value of LDR for 0.1 was 1.969, 0.15 for 1.873 and 0.2 for 1.784, and 0.25 for 1.706. It was observed that with the increase in the coefficient of friction between the sheet and the die, LDR decreases. It can be inferred from the fact that as the friction between the sheet and the die is increased there is a resistance to motion. As the punch load increase and the sheet impending movement, the tendency to necking increases which results in an increase in thinning on the wall of the cup; hence, drawability decreases.

Punch Sheet

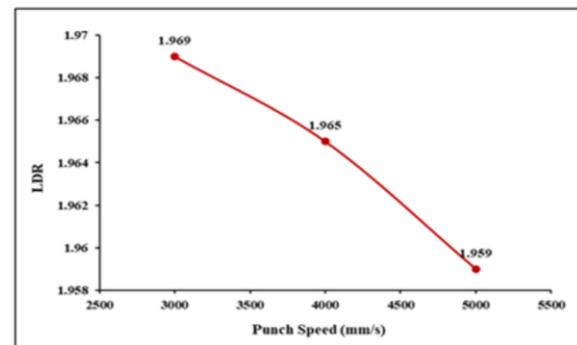
The variation of LDR was plotted in Figure 10(e) with an increased coefficient of friction between the sheet and punch. The coefficient of friction was taken as 0.01, 0.05, and 0.1, and the respective LDRs were found to be 1.9104, 1.9695, and 2.025. It is observed from that figure that high friction at the punch and cup interface leads to larger achievable LDRs.

Variation of LDR with Die Corner Radius

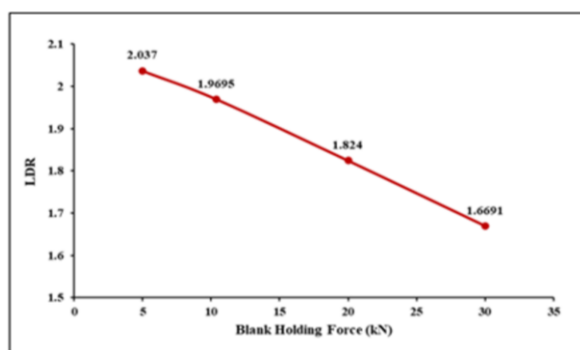
The variation of LDR was plotted in Figure 10(f) with an increase in die corner radius. The die corner radius was taken as 4, 6, and 8 with an increasing LDR of 1.9695, 1.9841, and 2.01. A large die radius is preferred for decreasing the drawing load and increasing drawability. If the die radius is too small, a fracture can occur. However, the contact area between the blank holder and the flange becomes smaller with increasing die radius, which may result in wrinkles in the die radius region. The recommended values of die radii for aluminium alloys are about 4 to 8 blank thicknesses.



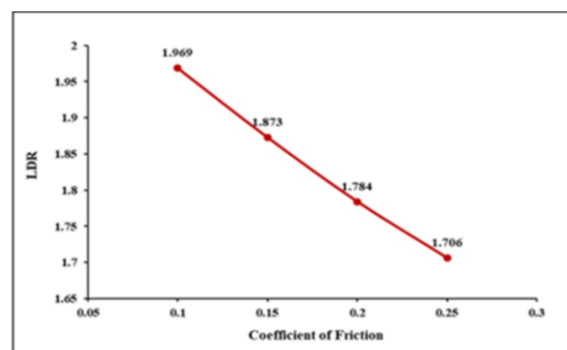
(a)



(b)



(c)



(d)

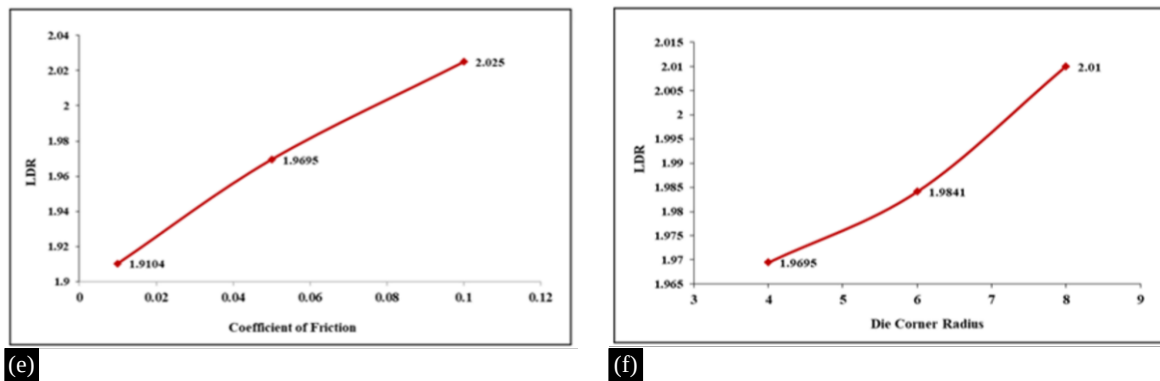


Figure 10. (a) Variation of LDR with sheet thickness; (b) variation of LDR with punch speed; (c) variation of LDR with BHF; (d) variation of LDR with a coefficient of friction between sheet and die; (e) variation of LDR with a coefficient of friction between sheet and punch; (f) variation of LDR with die radius.

CONCLUSIONS

The focus of this study was to study finite element analysis of the deep-drawing model and its parameters. Different parameters such as blank position, speed, sheet thickness, clearances, coefficient of friction between die-sheet as well as punch-sheet, blank holding force, etc. were varied and the drawability of the sheet was calculated. To take into account the behavior of anisotropic materials like AA6082, Barlat-3 parameters were employed in the LS-Dyna material model characterization.

The results depicted that annealing increased elongation by 15% which was earlier in the range of 4–5%. The thickness in the flank region increased as the flange region experienced two opposite natures of stress and the punch radius undergoes thinning due to thinning. As the sheet thickness is decreased, BHF to remove wrinkling also increased. With an increase in the coefficient of friction of the sheet, sheet thickness decreased at the wall section.

While finding drawability it was found that there was an increase in the LDR with the increase in sheet thickness as the load-carrying capacity of the material increases with sheet thickness. The LDR value is decreased with the increase in the punch speed. With the escalation in blank holding force from 5–30 kN, the decrease in the LDR was observed to be from 2.037 to 1.6691. The friction also affects LDR between sheet-punch and sheet-die. The variation of LDR with an increased coefficient of friction between sheet and punch and it is observed that high friction at the punch and cup interface leads to larger achievable LDRs. It was observed that with the increase in the coefficient of friction between the sheet and the die, LDR decreases. The die corner radius was taken as 4, 6, and 8 with an increasing LDR of 1.9695, 1.9841, and 2.01. A large die radius is preferred for decreasing the drawing load and increasing drawability.

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