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ORIGINAL ARTICLE

Formability studies of ASS 304 and evaluation of friction for Al in deep drawing setup at elevated temperatures using LS-DYNA

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Abstract Deep drawing is a sheet metal forming operation which involves conversion of flat thin sheet blanks drawn into desired cups. Forming of high strength sheet metal and low weight alloys under warm conditions is in great demand now-a-days and its application has great importance in nuclear plants, cryogenic vessels, heat exchangers, pharmaceutical industries etc. In the Present investigation the austenitic stainless steel (ASS)-304 of different blank diameters is deep drawn under warm condition. It is observed that there is a significant improvement in limiting drawing ratio (LDR) from 2.16 at room temperature to 2.5 at 150 °C and drawn cups are determined. In this investigation blanks of different diameters are deep drawn to determine LDR at various temperatures and it was found out that under warm conditions there is a significant improvement in limiting drawing ratio from room temperature to 300 °C. In the present investigation the other material IS 737 grade aluminum alloy is drawn at elevated temperature and its formability was investigated in warm condition and it was found that there was a substantial increase in the formability of commercial pure aluminum when drawn at 350 °C.

For a successful design and simulation by finite element (FE) analysis, it is important to determine reliable friction data for a given lubrication system. Especially when the deep drawing operation is being performed under warm conditions, the prediction of friction becomes complex as its value increases with temperature. By inverse analysis of relating the predicted and measured values

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of the load-stroke curve this paper presents a practical methodology using the deep drawing test and finite element (FE) analysis to evaluate the coefficient of friction between blank and tooling.

1. Introduction

In recent years great improvement has occurred in bulk and sheet metal forming. Sheet metal forming has an important role in manufacturing of simple to complex parts in automotive and other sheet metal components. In sheet metal forming, a thin sheet is subjected to plastic deformation using a tool by a process to a desired shape before fracture occurs. Factors like mechanical properties, metallography, lubrication, with blank, die and punch geometry, process parameters like punch speed, Blank holding force (BHF) etc., will contributes the success or failure of the component (Ravi Kumar, 2002). Recent researchers are tending toward the development of new and improved alloy materials which are more important along with understanding the formability of improved material at elevated temperatures which is more essential. So materials like austenitic stainless steels, interstitial-free steels, deep drawing quality (DDQ), Extra deep drawing(EDD) steel sheets and various non-ferrous alloys like aluminum, magnesium alloys are developed (Fekete, 1997; Wang et al, 2001; Swaminathan et al., 1991; Sachdeva, 1990). Austenitic stainless and Al alloy grades are most commonly used for applications like kitchen ware, cookery items, bath and sink units, hollow ware. The common austenitic alloys are iron chromium-nickel steels as 300 series. The austenitic stainless steels are high chromium and nickel based alloys which are most corrosion resistant of the stainless group with fine mechanical properties. They have high strength, and temperature resistance among the commercially available alloys. Grade 304 is used in architectural trim appliances, chemical equipment, cryogenic components, dairy equipment, kitchen equipment, food handling equipment, pressure vessels, marine, sanitary fittings, shipping drums, chemical processing, pharmaceutical and paper industry equipment. The basic test for cup drawing is the deep drawing and it is a complex forming process which involves tension in the center of the cup (biaxial tensile stress), bending (punch and die corners) and compression at the outer section of the blank. Deep drawing at room temperature has many drawbacks like large flow stresses and deformation (Bolt et al., 2001).

Aluminum is very ductile in nature but its poor formability restricts its use in most of the industrial applications which requires forming e.g. in automobile engineering. In recent years there is an effort to increase the material formability by increasing the temperature of material before and during forming. (Bolt et al., 2001) applied coupled FEM for simulating the warm sheet forming process of aluminum alloys using the commercial code MARC. They concluded that, compared to experiments, numerical simulation results underestimated the punch load vs. stroke. In their study, DEFORM 2D and 3D, coupled thermo-elastic-visco-plastic commercial FEM codes have been used to analyze warm forming of magnesium alloys. They reported that the predicted drawability of cylindrical cups was in good agreement with the corresponding results.

(Lee et al., 2007) investigated the warm formability of a commercial Mg–Al–Zn alloy. The relationship between strain rate and formability was used to predict the failure occurred on square cup deep drawing. The measured flow stresses from 200 °C to 400 °C were used in FEM analysis for square cup drawing. (Toros, 2008) investigated on aluminum–magnesium (Al–Mg) alloys (5000 series). They observed that formability and the surface quality of the final product of these alloys are not good if processing is performed at room temperature, after the tests in warm conditions the formability of these alloys is increased at temperature range from 200 °C to 300 °C and better surface quality of the final product has been achieved.

Li and Amit (2003) investigated that as the forming temperature increases under the given tooling geometry, the values of strength coefficient (*K*) and hardening exponent (*n*) of aluminum alloys generally decrease and the behavior of three aluminum sheet alloys, Al 5182 + 1% Mn, Al 5754 and Al 6111-T4, is studied in the warm forming temperature range of 200–350 °C and in the strain rate range of 0.015–1.5 s^{-1}. The total elongation in uniaxial tension is found to increase with increasing temperature and to decrease with increasing strain rate. Li and Amit (2004) investigated that the formability for all the three aluminum alloys (Al 5754, Al 5182 + 1%Mn and Al 6111-T4) improves at elevated temperatures, the strain hardened alloys Al 5754 and Al 5182 + 1%Mn show considerably greater improvement than the precipitation hardened alloy Al 6111-T4. Temperature effect on drawing of the sheet was found to have a large effect on formability. Setting die temperature slightly higher than punch temperature was favorable in promoting formability. Tebbe and Kridli (2004) investigated that the under warm forming process is intended to draw complex shapes by using an elevated temperature which is below recrystallization. Recently (Singh 2010a,b) investigated the formability of extra deep drawing (EDD) steel at elevated temperature and it was found that there was a drastic increase in the formability of material when the temperature of the material increases. Since aluminum IS 737 40800 grade material is very important due to its commercial use, so in the present investigation, its formability is investigated which was not studied by any other author.

2. Methodology

2.1. Determination of LDR

An induction furnace (Fig. 1) was developed to heat the blank at elevated temperature. This system is designed to heat iron blanks maximum up to 700 °C. Besides heating the blank, the lower die was also heated by providing another induction coil around it (Fig. 1). This is to maintain a uniform temperature of blank and avoid thermal shock. This die gets heated to a predetermined temperature so that the drawing process can be done at a particular temperature. Coolant water is supplied continuously to the heaters of die and blank. Non contact pyrometers are used to measure

Figure 1 Induction furnace developed to draw the materials at elevated temperature.

the temperature of the blank during drawing as the area becomes inaccessible. Pyrometer works on the principle of catching the wave length of the radiation that is emitted by any material. The complete test rig is designed for forming operations like deep drawing, stretching operations etc., but in this investigation a new die is specially designed for deep drawing operations at elevated temperatures shown in Fig. 2. A data acquisition system is used to obtain punch load applied to blank, punch displacement, blank holding pressure from the hydraulic press and the computer system with software is connected to obtain graphs like punch load with displacement and blank holding pressure and punch displacement.

Circular blanks of 1 mm thickness were made on a wire cut EDM machine of different diameters. The die is heated to required temperature and when it reaches, lubricant is applied so that friction at higher temperature is reduced and simultaneously on other heater blank is heated and placed on the die and drawing operations are performed on the setup shown in Fig. 2.

Figure 2 Complete experimental test rig.

2.2. Deep drawing experiments

2.2.1. LDR-Al alloy

Circular blanks of both the material were made on a wire cut EDM machine of different diameters and were drawn on the setup shown in Fig 2. Limiting draw ratio (LDR) from room temperature to 350 °C is calculated and through this investigation it shows that LDR has significant improvement as the temperature of the material increases. The cups drawn at these temperatures are shown in Fig. 3, Fig. 4 and Fig. 5. Calculated LDR values at these temperatures are presented in the Table 3.

2.2.2. LDR- ASS 304 alloy

Similarly for ASS- 304 alloy the deep drawing experiments are conducted for the blanks (60–75mm) diameter range. The maximum blank diameter which is successfully drawn from room temperature to higher temperature is presented in Table 4. Through experiments for both materials it was found out that the maximum limit reached when cup fractured little above the punch corner radius. The cups drawn at these temperature are showed in Fig. 4a. Through experiments at room temperature the maximum blank drawn is 65mm and at 150 °C and 300 °C the maximum blank size is 75 mm. As explained in the above methodology for Al, similarly for ASS-304 also there is significant improvement of LDR at higher

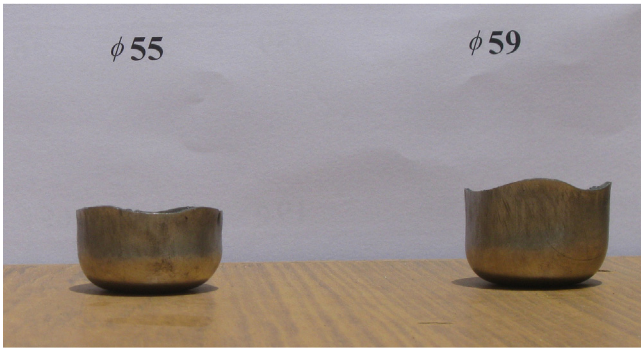


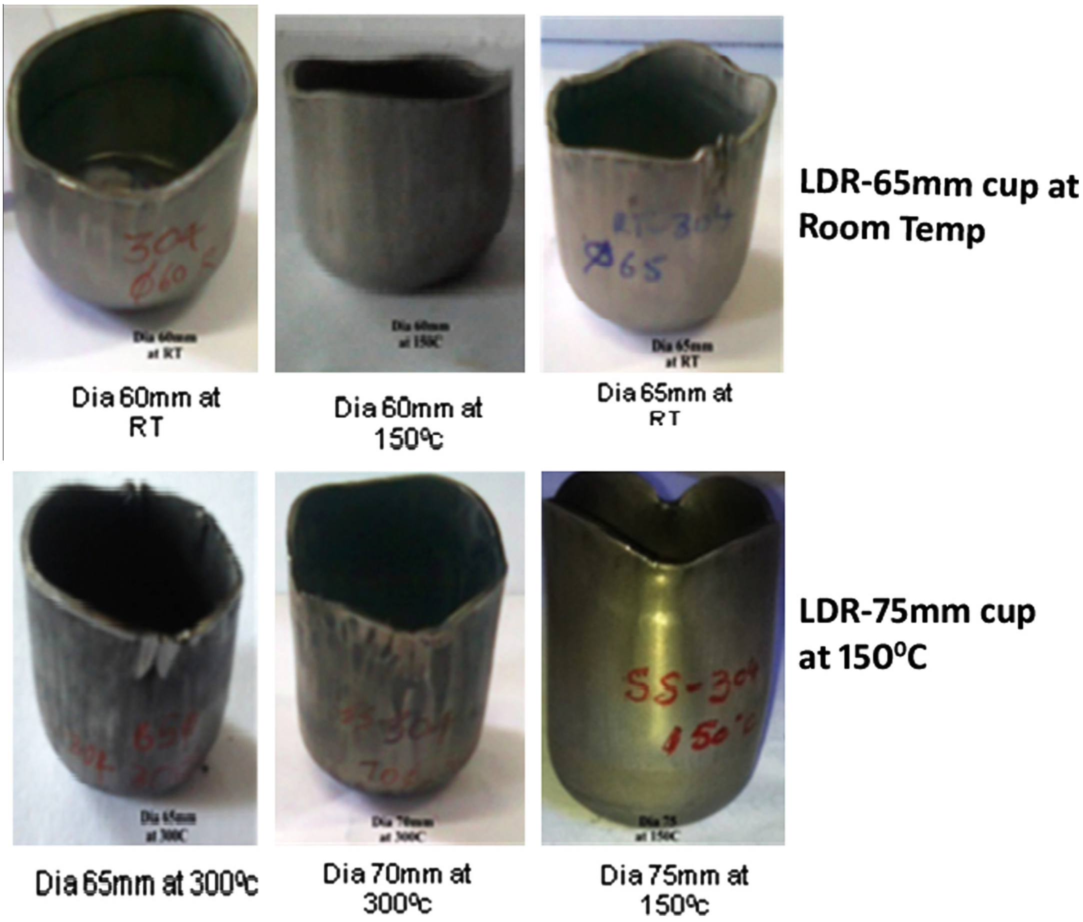
Figure 3 Drawn cups of Al IS 737 alloy at room temperature.

Figure 4 Drawn cups of Al IS 737 alloy at 200 °C.

temperature. At a temperature close to 350 °C there is both stressed induced martensite deformation and also the ASS 304 material is approaching towards the dynamic strain regime. That is the reason there is drastic reduction in the drawability of this material after 350 °C.

2.3. Determination of tensile properties and anisotropy

The chemical composition of Al alloy sheets was analyzed by a spectrometer. These analysis results are shown in Table 2. The five ton electronically controlled UTM is used to determine the common tensile properties of these Al alloy sheet materials at elevated temperature by uniaxial tensile tests. The test specimens were made of Al alloy sheets of 1 mm thickness according to DMRL standards. The test specimens were wire cut to present the tensile properties at elevated temperatures in three rolling directions i.e., in 0° (parallel to axis), 45° (diagonal) and 90° (rolling direction). Tensile tests were carried out on the specimens at room temperature, 200 °C and 350 °C. A constant cross head speed of 1 mm/min was employed. The study of strain rate deformations is important in sheet metal forming



Dia 60mm at RT
Dia 60mm at 150⁰c
Dia 65mm at RT
Dia 65mm at 300⁰c
Dia 70mm at 300⁰c
Dia 75mm at 150⁰c

Figure 4a ASS-304 cups drawn at different temperatures for various diameters.

Figure 5 Drawn cups of Al IS 737 alloy at 350 °C.

Table 1 Mechanical properties of material at various temperatures.

Temperature	Mass density	Hardening modulus	Strain ratio			Yield strength (Mpa)
			R_0	R_{45}	R_{90}	
Room	$2.7*10^{-9}$	50	0.241	0.359	0.468	34
200	$2.7*10^{-9}$	45	0.209	0.65	0.418	30
350	$2.7*10^{-9}$	80	Isotropic	Isotropic	Isotropic	25

Table 2 Composition of material for Al alloy.

Material	Composition
Si	0.79
Cu	0.008
Mg	0.21
Ni	0.25
Ti	0.056
Fe	0.74
Mn	0.15
Zn	0.087
Cr	0.013
Al	Rest

operations because they influence the strain distributions. The power law of true stress–strain relationship is:

$$\sigma_f = K\varepsilon^n \dot{\varepsilon}^m,$$

where, σ_f is true or flow stress, K is strength coefficient, ε is true strain, n is work or strain hardening exponent, is strain rate and m is strain rate sensitivity index. All these properties are functions of temperature. Singh et al. investigated the mechanical properties of steel from room temperature to 700 °C. The properties of Al alloy material found from experimentation at different temperatures are presented in Table 1.

3. Results and discussions

3.1. Drawability at various temperatures

As discussed in the previous sections ASS-304 and Aluminum IS 737, 40800 grade materials are very important for automobile industries. In the present investigation Al alloy material shows poor formability i.e. at room temperature only 55.5 mm blank could be successfully drawn into the cup (LDR = 1.85) but when it was drawn at 350 °C in a single stage LDR was observed to be as high as 2.45.

Similarly for ASS-304 at room temperature 65 mm blank was drawn successfully (LDR = 2.1) and at higher temperature i.e., at 150 °C in a single stage LDR is more than 2.1 and increased to 2.5. This indicates that by controlling the design and process parameters in warm deep drawing, the LDR of the material which has poor formability can also be drawn successfully. These drawn cups are presented in Figs. 3–5. Punch load and displacement data were recorded for the cups drawn at room temp, 200 °C and 350 °C for Al alloy and similarly for ASS-304 the deep drawn cups are drawn at room temp, 150 °C and 300 °C.

Different punch load vs. displacement graphs are shown in Figs. 6–9. Generally it can be observed from these graphs that as the temperature increases, there is a decrease in the load requirement. As it can be seen from Figs. 6 and 7 that to draw 59 mm Al alloy blank at room temperature requires around 3.6 KN of load but to draw the same diameter blank at 200 °C requires only 2.6 KN of load and 73 mm diameter Al alloy blank can be drawn successfully at 350 °C and the load appears to be same as that of room temperature drawing of 59 mm Al alloy blank. This is due to a decrease in mean flow stresses of material at elevated temperatures and it is because the larger the diameter the more will be the drawing force. At room temperature necking appears at the punch corner radius due to appearance of maximum load. Usually in any material with the increase in temperature the mean flow stress decreases. So forming load will also decrease. As it was investigated by Singh et al. (2010a) that increase in the temperature of material not only decreases the flow stress of material at which the material can be deformed but also there is an in-

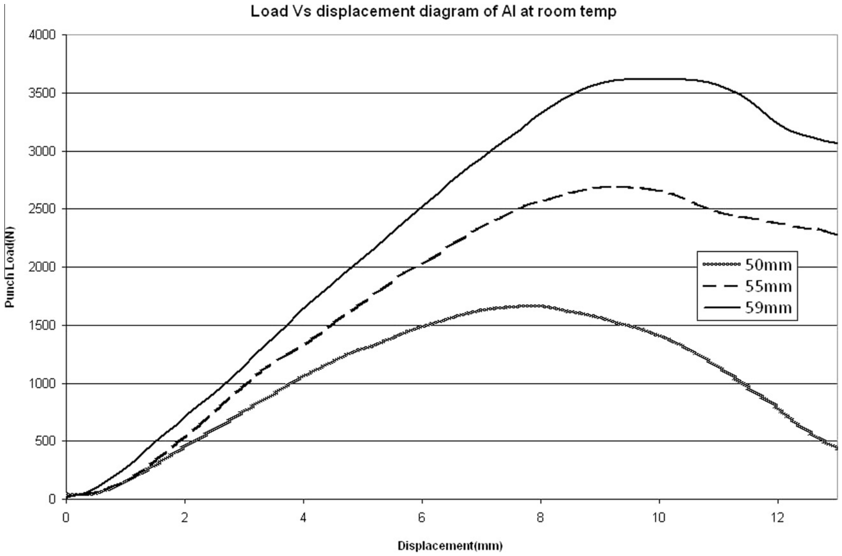


Figure 6 Punch load vs. displacement diagram of Al at room temperature.

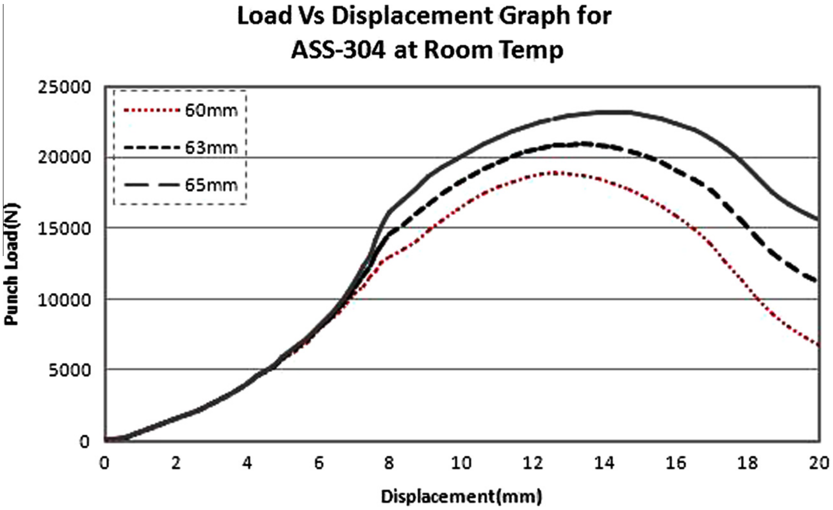


Figure 6a Punch load vs. displacement diagram of ASS-304 at room temperature.

crease in the ductility of material and there will be a range in which the material can be drawn safely.

It can be observed from the load displacement curves that at a particular temperature there is a sharp decline in the load values. This represents fracture. So as represented in Fig. 8 the fracture appears at 75 mm diameter blank so LDR at 350 °C is 2.46, which shows good improvement of formability for this material. The LDR observed at 200 °C was 2.1. There are many automobile components which are produced by this method and hot/warm forming will decrease the number of redrawing stages in the manufacturing of these components.

3.2. Preprocessing and material properties

An explicit finite element code LS-DYNA is used to simulate the process both at room temperature and under warm conditions. LS-DYNA 2D is a non linear dynamic simulation package which can simulate different types of sheet metal processes like deep drawing, stretching, bending, hydroforming etc. to predict the stresses, strains, thickness distribution etc. and the effect of various design parameters of tooling on final product can be studied. Input models were constructed in the pre-processor (DYNAFORM 5.6.1). The relevant properties of aluminum found out at room temperature, 200 °C and at 350 °C are shown in Table 1. Four node quadrilateral and triangular shell elements of thickness 1.0 mm were used for the blank and the tool components were treated as rigid bodies. Blank was discretized into 400 elements. The preprocessor file of the complete tooling is presented in Figs. 10 and 10a represent the stress-strain diagram of Al alloy at various temperatures. These diagrams are input to the FE code LS-DYNA. As it can be observed from this diagram that there is a small amount of work hardening at lower temperatures in the material.

Material characterization was performed to identify the properties of material. These properties are input as boundary

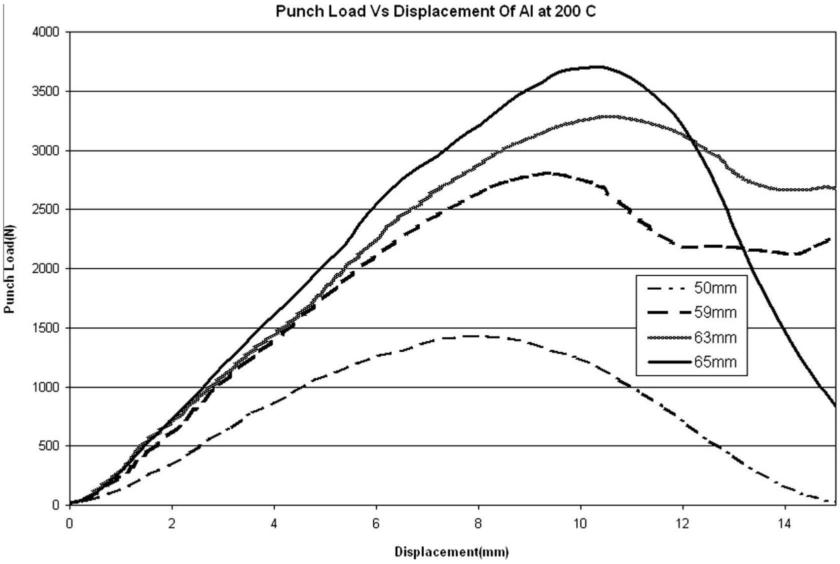


Figure 7 Punch load vs. displacement diagram of Al at 200 °C.

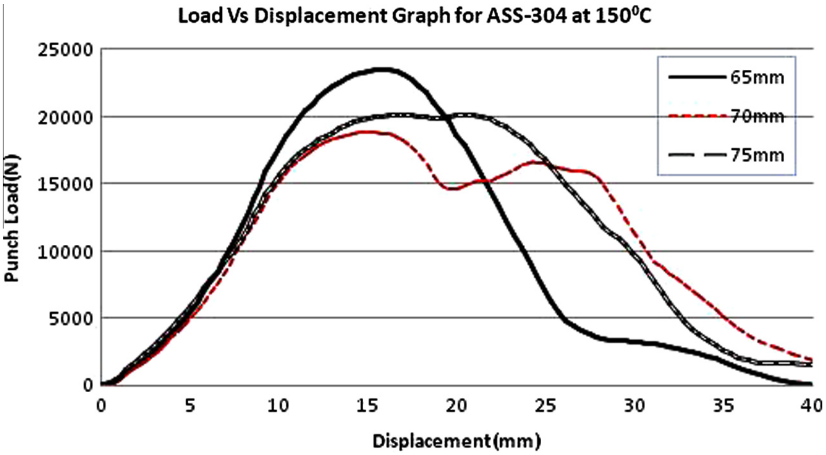


Figure 7a Punch Load Vs Displacement diagram of ASS-304 at 150 °C.

conditions to the simulation. Table 1 presents the properties of Al at room temperature, 200 °C and 350 °C. It can be observed that as the temperature increases, yield stress and UTS (Ultimate Tensile Stress) of the material decrease and when the temperature reaches 350 °C, percentage elongation suddenly increases. Beyond this temperature Al deforms like superplastic flow. The composition of the material is presented in Table 2.

3.3. Material models

It was observed during the characterization of material that up to 200 °C, the material shows small regions of work hardening and there is also some anisotropy related to the material (Table 1) so during simulation at room temperature and at 200 °C, transversely anisotropic elastic plastic model was used to simulate the process and also to calculate the friction in the deep drawing process.

3.4. Friction

In deep drawing, the most severe friction takes place at the flange area. The lubrication in the flange area influences the thinning and, possibly, failure of the side wall in the drawn cup. In the present study, the draw ratio (diameter of blank/ diameter of punch) was selected to be 2.0. material with rounded blanks of 60 mm diameter and 1 mm thickness prepared for experimentation. These blanks were drawn into cups both at room temperature, 200 °C and at 350 °C and their punch-displacement curves were recorded using the data acquisition system. Since the sticking tendency of blank due to friction increases by an increase in temperature especially in the case of aluminum this tendency is very high, so a Mo base lubricant Molycote is used between the blank and tooling both at different temperatures.

It is reported by researchers (Chung et al., 1998; Kim et al., 2002, 2004, 2007) that explicit analysis can be accelerated by

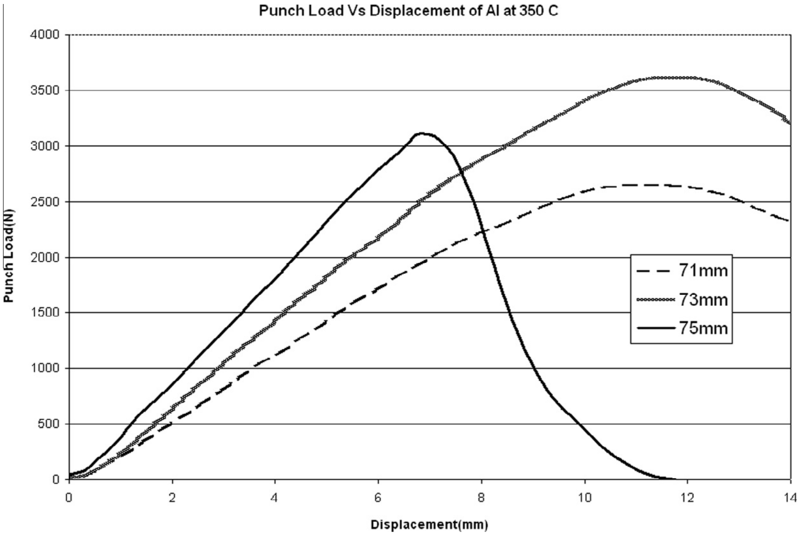


Figure 8 Punch load vs. displacement diagram of Al at 350 °C.

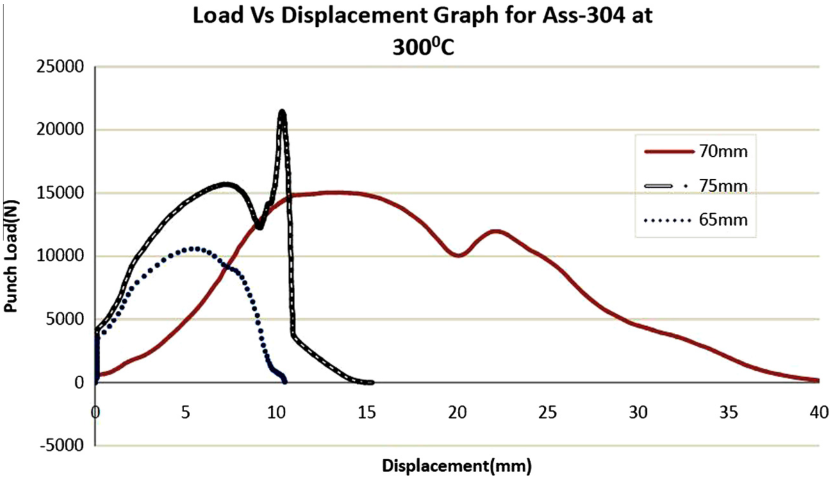


Figure 8a Punch load vs. displacement diagram of ASS-304 at 300 °C.

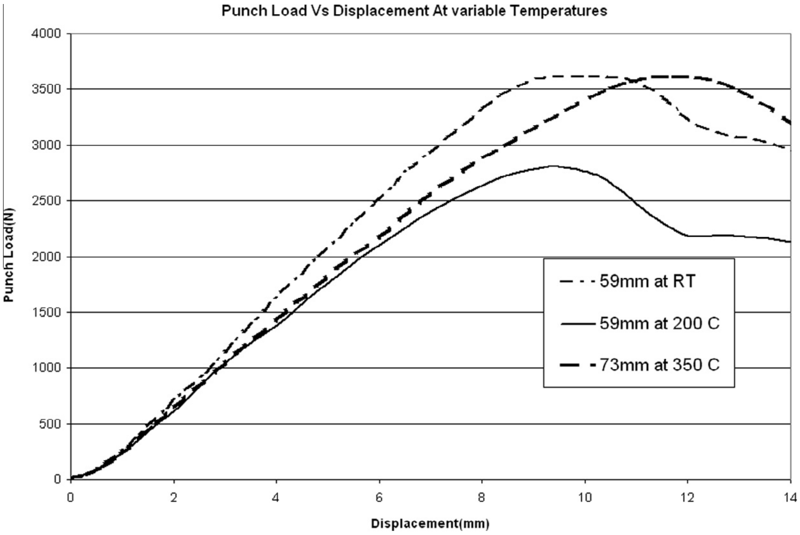


Figure 9 Comparison of load vs. displacement graphs at different temperatures.

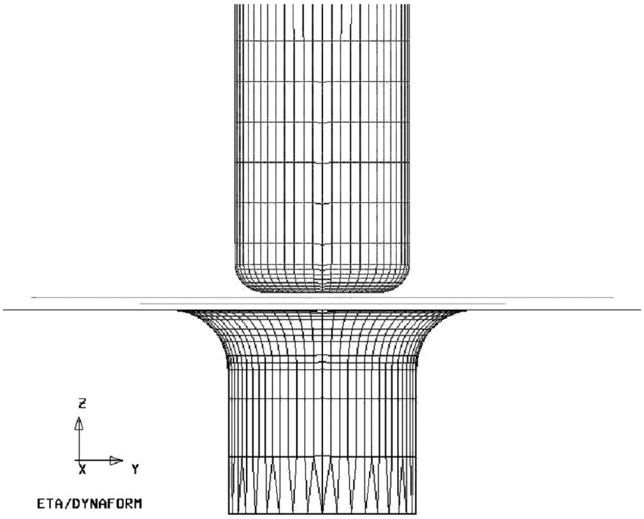


Figure 10 Discretization of tools in the pre-processor of LS-DYNA.

Table 3 Limiting drawing ratio at room temp & elevated temp for Al alloy.

Room Temperature	200 °C	350 °C
1.85	2.1	2.46

Table 4 Limiting drawing ratio at room temp & elevated temp for ASS-304.

Room Temperature	200 °C	350 °C
2.16	2.5	2.5

increasing the process speed, for instance, by increasing the punch speed in stamping or the pressurizing rate in a hydro-mechanical forming operation, which is called the time scaling technique. In the present investigation simulations were performed by varying the punch speed by keeping the other parameters same. The blank holding force, blank diameter was taken as used in the experiments. (Singh et al., 2010a) established from simulations that punch speed during simulations affect the load calculations. Similar investigations were reported by Taylan Altan (Kim et al., 2007) that tests should be conducted by taking into account the real production conditions in terms of ram speed and blank holding force, the simulations in the present investigations were carried out under realistic conditions.

In the present investigation simulations were performed by varying the punch speed by keeping the other parameters same. The blank holding force, blank diameter was taken as used in the experiments. The ram speed used in the experiment was 5 mm/s and after giving all the material properties to the code like UTS, YS, strength coefficient, strain hardening exponent and anisotropies in three different directions, on a dual core 2.2 GHz processor with 4 GB ram one simulation took around 26 h with 30 mm punch displacement and writing 100 plot states. Punch load vs. displacement graph from the experiments were superimposed with simulations at a different coefficient of friction at room temperature, 200 °C and at 350 °C given in Figs. 11–13 respectively. The small fluctuation in the load vs. displacement graph observed in simulation is due to oscillation of nodes (Singh et al., 2010a) in contact with the punch. The coefficient of friction under the forming conditions is calculated by selecting the appropriate graph produced by simulation which gives a good match with the maximum punch force and the overall trend. The forming conditions taken at room temperature and 200 °C are on a 50 mm blank diameter and at 350 °C, are on 73 mm blank diameter. It can be observed that at room temperature the coefficient of friction between aluminum and Inconel dies is 0.1 (Fig. 11). At 200 °C drawing conditions along with molycote lubricant, the coefficient of friction between blank and dies is 0.05 (Fig. 12) and at 350 °C it is 0.06 (Fig. 13). Although the coefficient of fric-

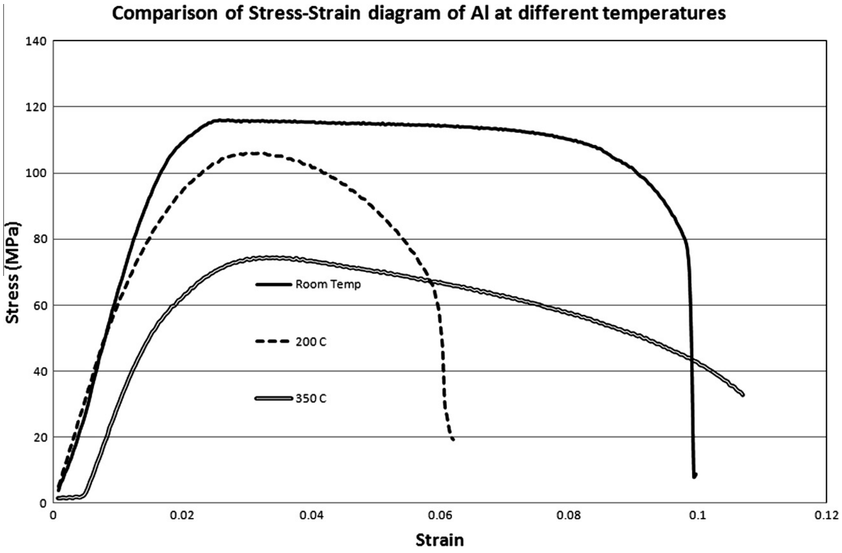


Figure 10a Stress vs. strain diagram for Al-alloy at different temperature.

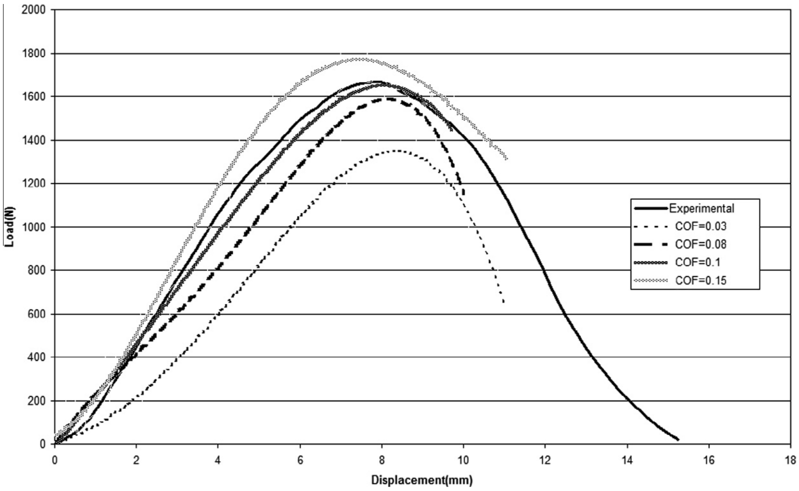


Figure 11 A comparison of punch load vs. displacement diagram from the simulation at different coefficient of friction and from experiments at room temperature.

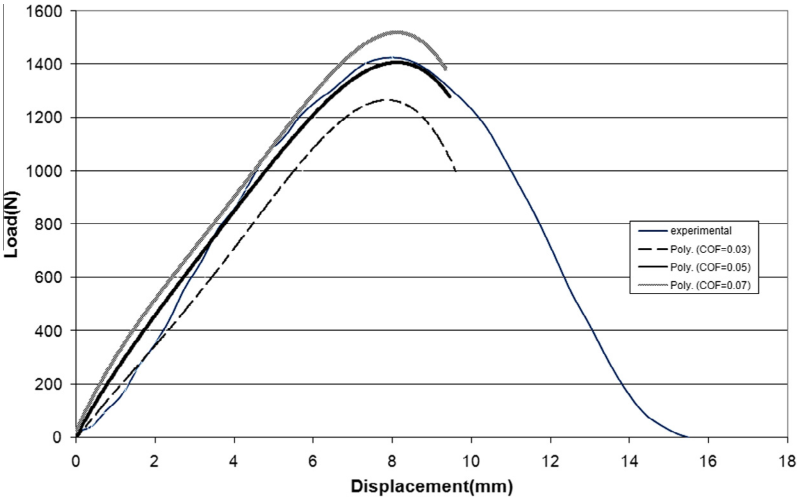


Figure 12 A comparison of punch load vs. displacement diagram from the simulation at different coefficient of friction and from experiments at 200 °C.

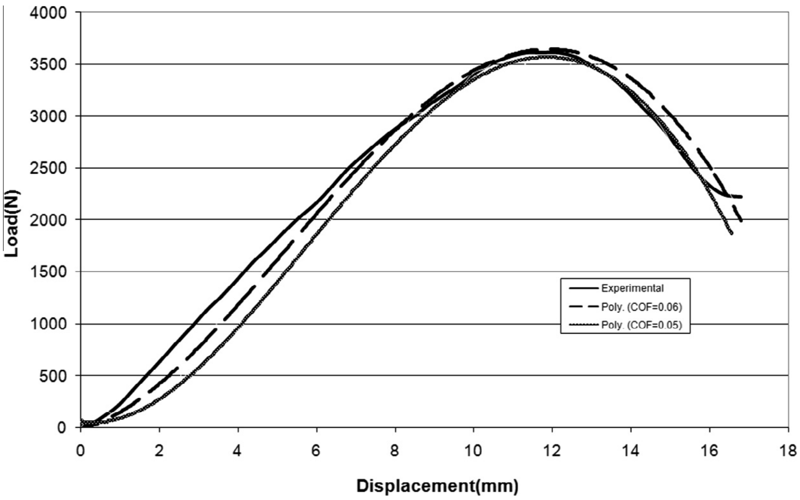


Figure 13 A comparison of punch load vs. displacement diagram from the simulation at different coefficient of friction and from experiments at 350 °C.

tion value increases by increasing the temperature the effectiveness of lubricant used in the present deep drawing operation depends upon the temperature. Molycote is a very effective lubricant at elevated temperature. These friction values were used for further simulations to identify thickness and stress distribution in the drawn cup.

4. Conclusions

The warm deep drawing process is a very attractive process for sheet metals. Main advantages of this process are high drawability (higher limiting draw ratio), reduced friction, lower residual stresses in the drawn cup etc., which result in better product quality and higher productivity. This process is having large potential to be used in industries to produce different types of components. It can be extended to numerous other products, and it has a prosperous future. The design considerations involved in the process were discussed and it was observed that for commercial Al alloy there was drastic improvement in the drawability by increase in the temperature of material. It was also observed by experimentations that there is a drastic reduction in the load requirement during drawing due to decrease in the flow stresses. As aluminum is known for high friction at higher temperatures the friction is expected to increase. The friction was controlled by using a high temperature lubricant Molycote and this friction was successfully calculated by finite element procedure. In the present investigation, drawability of ASS-304 material was also discussed at elevated temperature. It was found that there was a significant improvement in the formability by increasing temperature. As the load–displacement curve predicted by increasing temperature there was a decrease in the load during forming due to a decrease in the mean flow stresses.

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