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Experimental and simulation study on the warm deep drawing of AZ31 alloy

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ABSTRACT

The presented work aimed at studying the deep drawing process of a magnesium alloy sheet at elevated temperatures. This is because magnesium is being considered as a promising alternative for high strength steel and aluminium within many applications because of its low density and high specific strength. It is a well-known and recognised fact that fracturing and wrinkling during the deep drawing process can be minimised or eliminated by selecting an appropriate warm-forming temperature of the magnesium, as the formability of magnesium increases considerably as the temperature increases. Hence a warm formability study of AZ31 was performed and tested by experimental and simulation methods and resulted in superior formability at elevated temperatures in both cases. A 3D Finite element model was developed for the simulation of circular cup deep drawing and tested for different temperatures ranging from room temperature to 300 °C and it was found that the limiting drawing ratio (LDR) increased significantly with any increase in temperature. The experimental and simulation results were found to be in good agreement.

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1. Introduction

It had been realized that the use of lightweight structures for aerospace, automotive and other industrial usage are vividly increased for economising the fuel consumption and minimizing the emission of hazardous gases into the atmosphere. Indeed, among the light weight metals, magnesium has gained much attention in recent years due to its light weight, i.e. 36 % lighter (by unit volume) than aluminium and 78 % lighter than iron. When magnesium is properly alloyed, attains the highest strength-to-weight ratio among all the structural metals [1]. In addition, it is having superior qualities like easy of recycling, better thermal properties, better manufacturability and close dimensional stability. As magnesium is having superior formability at higher temperatures is thus necessary to activate deformation mechanism at higher temperatures during forming process [2]. There are many significant forming parameters that are influencing of deep drawing process and they are punch nose radius, die shoulder radius, blank holder force, coefficient of friction, strain hardening exponent, strain rate sensitivity index, forming temperature and clearance between punch and die. Among these, forming temperature plays a vital role in warm forming process and needs to study the formability by means of limiting drawing ratio which is one of the formability assessment methods for deep drawing process.

Many research activities [3, 4] were aimed at investigating the improvement of the drawability and the formability of the magnesium alloy when working in warm condition. Gao En Zhi et al. [5] studied for the influence of material parameters on deep drawing of thin walled hemispheric surface part and revealed that higher punch force as n, E, σ_s increases and the influences of n and σ_s on punch force are more notable.

Warm deep drawing of magnesium alloy sheets had been performed by Ren et al. [6] using experimental method and finite element analysis. It has concluded that magnesium alloy AZ31 is sensitive to the temperature and formability is high in the temperature range 200-250 °C. Finite element simulation of deep drawing of aluminium alloy sheets at elevated temperatures by Venkateswarlu et al. [7] showed that the formability of aluminium 7075 is good in the temperature range of 150-250 °C and again from 400-500 °C.

Huang et al. [8] conducted experimental deep drawing tests on magnesium AZ31B sheets. The experimental results indicate that for 0.58 mm thinness, the highest limiting drawing ratio (LDR) is 2.63 at forming temperatures of 260 °C and for 0.50 mm thinness, highest LDR is 2.5 at 200 °C. FEM of warm forming of aluminium alloys by Kim et al. [9] was performed for forming aluminium rectangular cups at elevated temperature levels of 250 °C, 300 °C, 350 °C and observed that an increasing limiting strain with increasing forming temperature both in FEA and experiments. Forming of aluminium alloys through experimental methods by Erdin et al. [10] evaluated and concluded that as the deformation temperature increases, there is decrease in flow stress, maximum strength, hardening parameter (n), strength factor (K) but increased maximum strain. Palumbo et al. [11] did experimental analysis of worm deep drawing for Mg alloys highlighted that an improvement of LDR from 1.8 to 2.6 is feasible when adopting a draw die temperature equal to 170 °C. Deep drawing of square cups with Magnesium alloy AZ31 sheets by Chen et al. [12] revealed that both the tensile tests and forming limit tests indicate an inferior formability of AZ31 sheets at room temperature. However the formability could considerably improve when the AZ 31 sheet is stamped at elevated temperatures of 200 °C. Reddy et al. [13] demonstrated the rapid determination of LDR in order to reduce the large number of experiments and cost involved in it. The method is being well accepted by the industry in recent years. Reddy et al. [14] also conducted experiment for assessment of magnitude of the influence of different process parameters in deep drawing and concluded that blank holder force has more influence in comparison to punch nose radius and die profile radius. Patil et al. [15] conducted warm deep drawing by numerical methods and revealed that the worm temperature enhances the formability of sheet metal.

2. Yield functions

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. 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 can be expressed as shown in Eq. 1.

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2+6(\sigma_{12}^2+\sigma_{23}^2+\sigma_{31}^2)} \quad (1)$$

The anisotropic materials behaviour is more appropriately described by Hill criteria while considering the anisotropy parameters into account as described by Hill. This popular criterion described by Hill can be expressed in mathematical form as in Eq. 2.

$$\bar{\sigma} = \sqrt{\frac{F(\sigma_1-\sigma_2)^2+G(\sigma_2-\sigma_3)^2+H(\sigma_3-\sigma_1)^2+2L{\sigma_{23}}^2+2M{\sigma_{31}}^2+2N{\sigma_{13}}^2}{2}} \quad (2)$$

The F, G, H, L, M and N are constants specific to the anisotropy state of the material and 1, 2 and 3 are the principal anisotropic axes. If the tensile yield stress in the principal anisotropy directions is denoted by σ_{y1}, σ_{y2} and σ_{y3} it can be shown that

$$\left.\begin{aligned}\frac{1}{\sigma_{y1}} &= G + H\\ \frac{2}{\sigma_{y2}} &= H + F\\ \frac{3}{\sigma_{y3}} &= F + G\end{aligned}\right\} \tag{3}$$

for the ideal case of isometric materials subjected to plane stress conditions, the Mises yield criteria can be expressed as follows.

$$\sigma_f^2 = \sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2 \tag{4}$$

Similarity for material subjected to plane stress, the Hill proposed enhanced criteria for anisotropic materials while evaluating Lankford parameters in parallel and transverse to the rolling direction. The yield stress under such anisotropic conditions can be expressed as shown in Eq. 5.

$$\sigma_f^2 = \sigma_1^2 + \big((1 + r_{90})/(1 + r_0)\big)\sigma_2^2 - \big(2r_0/(1 + r_0)\big)\sigma_1\sigma_2 \tag{5}$$

If there is an effect of planar anisotropy, the quadratic Hill criterion reduces to and termed as Hasford – Backhofen equation and is as shown in Eq. 6.

$$\sigma_f^2 = \sigma_1^2 + \sigma_2^2 - \big(2r/(1 + r)\big)\sigma_1\sigma_2 \tag{6}$$

3. Determination of material properties

The Magnesium alloy AZ31 sheet had been investigated for determining the effect of temperature, anisotropy, strain hardening, strain rate sensitivity, flow stress in conjunction with evaluation of sheet metal behaviour under varying conditions. As stress-strain relations are the basic information necessitated for the study of sheet metal forming behaviour and accordingly uniaxial tensile tests were conducted while maintaining wide range of forming temperatures in concern with different strain rates. The thickness of the sheet considered were 0.9 mm and flat specimens of dog-bone shape were prepared as shown in Fig. 1 for revealing the material properties.

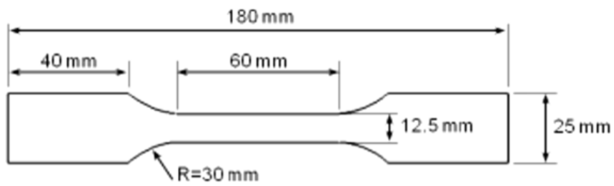

Fig. 1 Tensile test specimens used in uniaxial testing

It is also established from the literature that the AZ31 sheets exhibit anisotropic nature at lower temperatures and become isotropic over 250 °C. In order to assess anisotropic property of AZ31, samples were also prepared along 0°, 45° and 90° to the rolling direction by means of EDM cutting in order to avoid influence of edge effects due to poor cutting profile. The gauge length of 60 mm were distinguished by imprinting two marking points and was measured and recorded in order to calculate the final elongation.

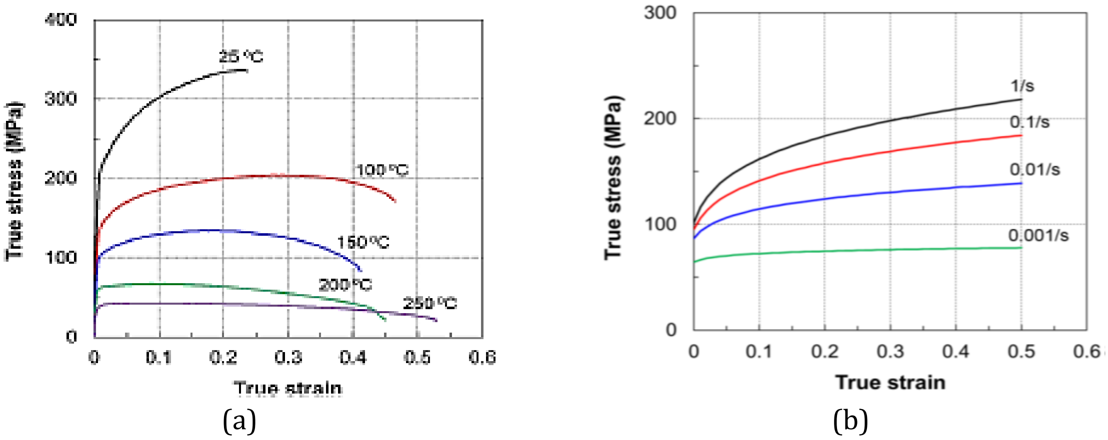

Fig. 2 a) Stress-strain curves in uniaxial tension test at different temperatures;
b) Effect of strain rate on the flow stress at 250 °C [16]

The tests were performed on an Instron 5582 universal testing machine with a capacity of 10 ton and a maximum crosshead speed of 500 mm/min. The tests were conducted at room temperature, 100 °C, 150 °C, 200 °C, 250 °C, 300 °C and 350 °C with the tensile axes of the test specimens aligned along the rolling direction (RD), diagonal direction (DD), and transverse direction (TD). A heating time of more than 20 min were maintained to reach the desired temperature before testing and the temperature in the chamber kept constant during each test.

The precise temperature control as well as uniform temperature distribution was maintained for accurate results. The crosshead speed of 0.06 mm/s, and strain rate of 0.001/s were applied. The variation in length, width and thickness corresponding to each load were measured for each test and ε_l, ε_w and ε_t were also evaluated. The true stress strain curves were plotted as shown in Fig. 2 and strain hardening exponent n was computed by incorporation of test results in the flow relation $\sigma = K\varepsilon^n$. The normal anisotropy can be determined with the use of expression 0.25 $(r_0 + r_{45} + r_{90})$, where r_0, r_{45}, and r_{90} orientation along 0°, 45°, and 90°, respectively.

It can be observed from Fig. 2(a) that yield stress decreases and elongation increases as the temperature increases. It is also observed that the strain hardening decreases with increase in temperature. The Fig. 2(b) illustrates the nominal stress strain relationships at 250 °C for different strain rates. It is established that higher strain rate leads to higher yield stress but reduced elongation. From the production lot, test samples were collected and upon testing observed for three types of chemical composition as shown in Table 1.

Table 1 Chemical composition of specimens (% by weight)

Specimen	Al	Zn	Mn	Fe	Ni	Mg
Type A	3.1	0.9	0.36	0.0025	0.0008	Balance
Type B	3.02	1.06	0.39	0.004	0.0005	Balance
Type C	3.09	0.83	0.38	0.0032	0.001	Balance

4. Experimental deep drawing

A preliminary experimental activity on the warm deep drawing (WDD) process of AZ31 magnesium alloy sheet was performed on 10 ton mechanical press provided with a circular tool setup consisting of axisymmetric punch, die and blank. WDD tests were performed by heating of die and while keeping the punch cool by passing cool water through the water circulation system provided in the form of passage as shown in Fig. 3.

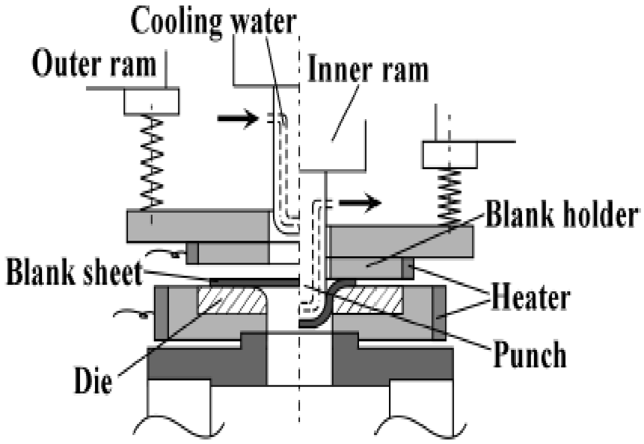

Fig. 3 Schematic representation of warm deep drawing

It shows the schematic diagram of the experimental set up used for WDD to study the forming behaviour at different temperatures. The tooling material was H13 tool steel hardened to 52 HRc. Both the die and clamp contain four 867 W electrical resistance cartridge heaters.

Embedded thermocouples were used to control the die and clamp temperature, between room temperature and 350 °C. Chilled water at a constant temperature of 10 °C was circulated through channels machined into the punch to maintain its temperature at about 14 °C. The punch temperature was also monitored using embedded thermocouple. The drawing tests were conducted for different blank sizes ranging from 150 mm to 210 mm diameter blanks with 10 mm increase in size for different worm temperatures ranging from 25 °C to 350 °C. The tool and process parameters were as depicted in Table 2.

In deep drawing test conducted at room temperature found that the induced strains in accomplishing a complete cup had crossed safe limits and hence cracks were induced as shown in Fig. 4(a). On the other hand for 300 °C temperature test of the blank observed for forming of defect free cup by maintaining all induced strains within the limiting strains as shown in Fig. 4(b).

Table 2 Tool and process parameters for experimental and simulation

Variable	Experiment	Finite element model
Blank Material	AZ31	AZ31
Blank Diameter (mm)	150 to 210 mm	150 to 210 mm
Blank Thickness (mm)	0.9	0.9
Blank Temperature (°C)	25, 100, 150, 200, 250, 300, 350	25, 100, 150, 200, 250, 300, 350
Punch Diameter (mm)	80	80
Punch nose radius (mm)	5	5
Punch temperature (°C)	25 °C	25 °C
Die opening diameter (mm)	96	96
Die Inner Diameter (mm)	83	83
Die shoulder radius (mm)	10	10
Blank holder opening diameter (mm)	96	96
Die temperature (°C)	100	100
Blank Holder force (kN)	10	10
Punch speed (mm/s)	5	5
Friction coefficient	Not reported	0.1
Contact heat transfer coefficient (W/m^{2}K)	Not reported	1000
Convective heat transfer coefficient (W/M^{2}K)	Not reported	10
Anisotropy parameters of blank	Not reported	r_0 = 1.30, r_{45} = 2.5, r_{90} =1.05

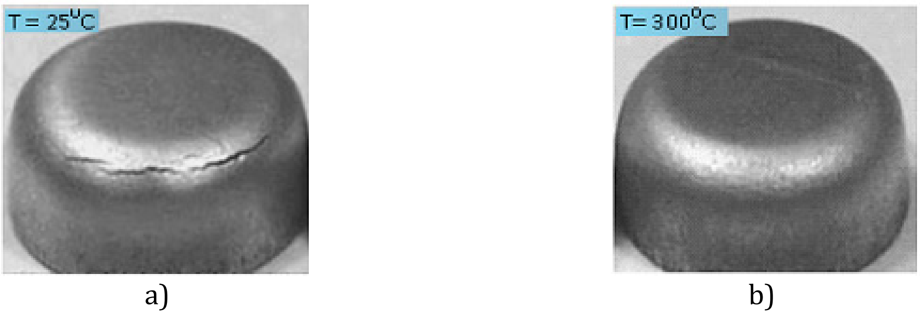

Fig. 4 a) Cups produced at room temperature, and b) cup produced at 300 °C

Experimental tests revealed that deep drawing at higher temperature gives increased formability. The LDR increased as the temperature increases and the LDR values obtained for different blank temperatures are as shown in Table 3.

Table 3 LDR for different temperatures of blank

S. No.	Temperature (°C)			LDR
	Blank	Die	Punch	
1	25	100	25	1.86
2	100	100	25	2.05
3	150	100	25	2.2
4	200	100	25	2.48
5	250	100	25	2.59
6	300	100	25	2.61
7	350	100	25	2.05

5. FEM study

Finite element analysis (FEA) technique had become a rapid and cost-effective tool for forming process and it significantly reduces the development time and cost associated with it. In essence, in-depth research has been focused on development of proper FEA models in order to accurately predict the forming behaviour and failure modes. Determination of optimal temperature for warm forming of sheet material is indeed essential requisite in order to achieve desired size, process robustness and productivity.

Experimental trial and error methods had been used in determination of appropriate temperature distribution on tooling and blank is not an easy task to achieve due to high cost, time and complexity of the process. As the complex interactions are involved among material, tooling and process, the experimental study is limited only to lab scale prototypes of industry.

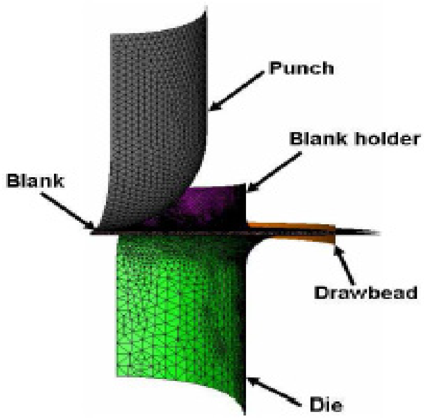

Fig. 5 Finite element mesh model for simulation

To widen the scope of warm deep drawing and to reduce product and process design lead times, essentially FEM came as an alternative in recent decades. FEM with DOE, and various optimization techniques such as artificial neural networks, genetic algorithm, multi-fidelity optimization techniques have been increasingly applied in metal forming process design and control. In this study, the worm forming of circular cup deep drawing had been analysed using commercially available FEA software ABACUS/Explicit. The tooling geometries were constructed using CAD program PRO/Engineer and were eventually converted into the finite element mesh as shown in Fig. 5.

The material properties of the AZ31 sheet obtained from the tensile tests were essentially used in the finite element simulations. The tool parameters used for simulations were die clearance of 0.6 mm on each side, blank-holder force of 2.5 kN, coefficient of friction of 0.1 and punch speed of 3 mm/s. The tooling was modelled as perfectly rigid but non-isothermal while the blank was considered as rigid visco-plastic with isotropic hardening law and following hills anisotropic yield criterion. Due to the symmetric boundary conditions and to reduce computational time, a quarter of the geometries were only modelled. The both used model have temperature and displacement as their degrees of freedom to predict both deformation and temperature variation during the process. The other input parameters for finite element simulations are as shown in Table 2.

6. Results and discussion

The formability is the ability of the sheet metal to be formed or stamped without developing any failure, and the formability increases as the temperature increases. The basic forming characteristics of sheet metals are obtained with simple tension tests. These results have been used for formulation of numerical results. The experimental result from Fig. 4 indicates that the test fails at room temperature while the cup drawn at 300 °C can be successfully dawn without any defects. The LDR increased gradually as the deep drawing temperature increases in warm forming the LDR starts decreases after 300 °C as shown in Table 3.

The finite element tests have been conducted for the 150 mm blank diameter using FEA software ABACUS/Explicit. The deep drawn cups are produced without any incipient necking or fracture and the LDR in considerably high at the temperature of 300 °C.

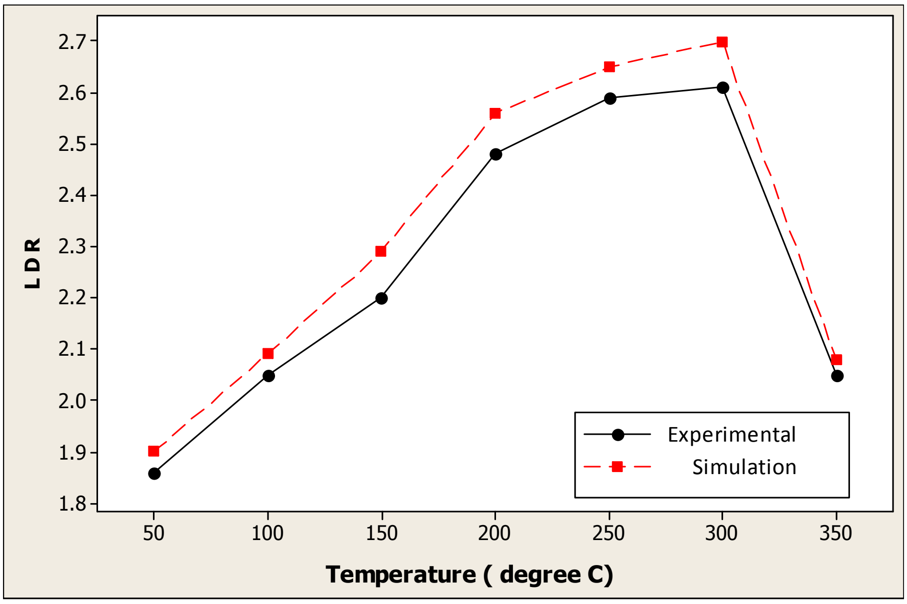

Fig. 6 LDR for experimental and simulation for different temperatures of the blank

The Fig. 6 shows the comparison of the experimental and simulated results and found that LDR increased significantly as the temperature increases from ambient temperature to 300 °C in both experimental and simulation results. The reason for poor formability above 300 °C is due to the tendency of sheet for localised necking and limits the formability in deep drawing of cups especially at the regions very close to punch nose radius. Once this instability occurs, the load carrying capacity decreases gradually due to decrease in thickness of the material and hence reduced LDR. The onset of localized necking needs to be predicted accurately in order to determine the forming limits of the material. It have be observed that the LDR can be significantly achieved about 2.6 at 300 °C and hence warm forming can be successfully used for deep drawing at elevated temperatures. In addition to that the amount of blank holder force required also decreases due to decreased flow stress at higher temperatures.

It can be observed from simulation results that the LDR obtained from simulation are slightly higher than that of the experimental results. This might be due to the complexity involved in the finite element models in selecting an appropriate and correct model for simulation results. The accuracy of FE simulation results are highly dependent on the type yielding and temperature dependent flow stress models used in describing the flow properties of the material.

7. Conclusion

In this study, formability of AZ31 studied both experimentally and numerically using FEM software ABAQUS. In both cases LDR increased significantly as the temperature increases. The deep drawing tests were conducted at 25 °C, 100 °C, 150 °C, 200 °C, 250 °C, 300 °C and 350 °C. Hence proper temperature selection is very essential for deep drawing of AZ31 cups without incipient necking and cracks.

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