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Effect of Recrystallization Temperature on Formability of Hot Deep Drawn Cylindrical Cups from 6082 Al Alloy

Chennakesava Reddy A[1]

1.Professor, Department of Mechanical Engineering, JNTUH College of Engineering, Kukatpally, Hyderabad – 500 085, Telangana, India

☼Corresponding author:
Professor, Department of Mechanical Engineering, JNTUH College of Engineering, Kukatpally, Hyderabad – 500 085, Telangana, India, e-mail: chennakesava@jntuh.ac.in

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ABSTRACT

Deep drawing process is employed for the fabrication of products such as beverage cans, pots and pans, containers of variety shapes and sizes, sinks and automobile panels. Distinctive applications of 6082 Al alloy are trusses, ore skips, beer barrels, milk churns, etc. The major problem of 6082 Al alloy is the production of thin walled and complicated deep drawn shapes. In the present work, influence of recrystallization temperature on the formability of cylindrical cups from 6082 Al alloy was carried out by the finite element analysis. The expected size of cylindrical cup is 60 mm diameter and 75 mm height. The presence of precipitations of Mg_2Si and β-Al_5FeSi influences the size of grains in 6082 AL alloy during the deep drawing process of cylindrical cups. The cup drawn at temperature 200°C resembles the cold forming behavior. The low-angle grain boundary nets cause the formation of tear in the flange area of the deep drawn cups at recrystallization temperature of 6082 Al alloy. The softening effect is observed owing to the hot deep drawing behavior of 6082 Al alloy at 400°C above recrystallization temperature.

Keywords: 6082 Al alloy, cylindrical cups, recrystallization temperature, damage factor, formability, finite element analysis.

Abbreviations:
C_d is the clearance,
t is the thickness of blank sheet,
μ is the coefficient of friction,
D_f is the damage factor,
σ^* is the tensile maximum principal stress,
σ_{vm} is the von Mises stress,
$d\varepsilon$ is the effective strain increment,
T_m is the melting temperature in Kelvin,
$T_{recryst}$ is the recrystallization temperature.

1. INTRODUCTION

Semi-finished and finished products are manufactured in a bulk by metal forming processes. For this purpose, it is worthwhile to take on large scale research and development projects because a small saving per ton augments to huge amounts. Deep drawing is one of the metal forming processes for the manufacturing of products such as beverage cans, pots and pans, containers of variety shapes and sizes, sinks and automobile panels.

The 6082 Al alloy is identified as a structural alloy and substitutes to the 6061 Al alloy in many applications. The 6082 Al alloy has outstanding corrosion resistance as compared to 6061 Al alloy. Lassance et al. (2007) have stated that the presence of coarse and elongated particles is the key microstructural feature affecting the fracture behavior of 6xxx Al alloys. Also, they concluded that the ductility increases with decreasing amount of β particles, increasing temperature and strain rates, and decreasing stress triaxiality. Typical applications of 6082 Al alloy are trusses, ore skips, beer barrels, milk churns, etc. The major problem of 6082 Al alloy is the production of thin walled and complicated deep drawn shapes. The extruded surface finish is not as smooth as other similar strength alloys in the 6xxx series of Al alloys. Deep drawing process, wherein the product shapes are formed by plastic deformation (Reddy et al., 2012). Hence, it is important to know the plastic flow properties of 6082 Al alloy for optimizing the warm deep drawing process to produce cylindrical cups. Biroli et al. (1998) have observed a relationship between deformation mechanisms and softening effect of Mg alloys at low deformation temperatures. Also, mentioned by Nowotnik and Sieniawski (2005) that high magnesium content tends to increase strength properties of hardened alloy formation of Mg_2Si phase.

In the present work, the formability of cylindrical cups from 6082 Al alloy was carried out by the finite element analysis. The recrystallization temperature was considered to influence of the formability of 6082 Al alloy. Hence, the hot deep drawing process was implemented using D-FORM software.

The organization of the paper is as following: A procedure of the finite element modelling (FEM) of deep drawing of a cylindrical cup and material properties are presented in in Section 2. The main findings obtained in the present work are presented in Section 3 and discussed in Section 4. In Section 5, the main conclusions resulted from the present work are highlighted. Section 6 gives the summary of the salient points of the work emphasized in this paper.

2. MATERIALS AND METHODS

For the warm deep drawing process of cylindrical cups, the sheet material was 6082 Al alloy. The material properties of 6082 Al alloy are as follows:

Ultimate tensile strength: 300 MPa
Tensile yield strength: 255 MPa
Elongation at break: 9%
Modulus of elasticity: 68.9 GPa
Thermal conductivity: 200 W/m-K
Coefficient of thermal expansion: 25.6 μm/m-^{o}C.

The finite element modeling and analysis was carried using D-FORM 3D software (Reddy, 2015a and Alavala, 2016a). The circular sheet blank was created with desired diameter of 148.38 mm and thickness of 1.5 mm to get a target cylindrical cup of 60 mm diameter and 75 mm height. The cylindrical top punch and cylindrical bottom hollow die were modeled as shown in figure 1 with appropriate punch radius of 9.75 mm and die corner radius of 10.96 mm as found in the earlier publications (Reddy, 2015b and Alavala, 2016b). The clearance between the punch and die was calculated using Eq. (1).

$$\text{Clearance, } c_d = t \pm \mu\sqrt{10t} \quad (1)$$

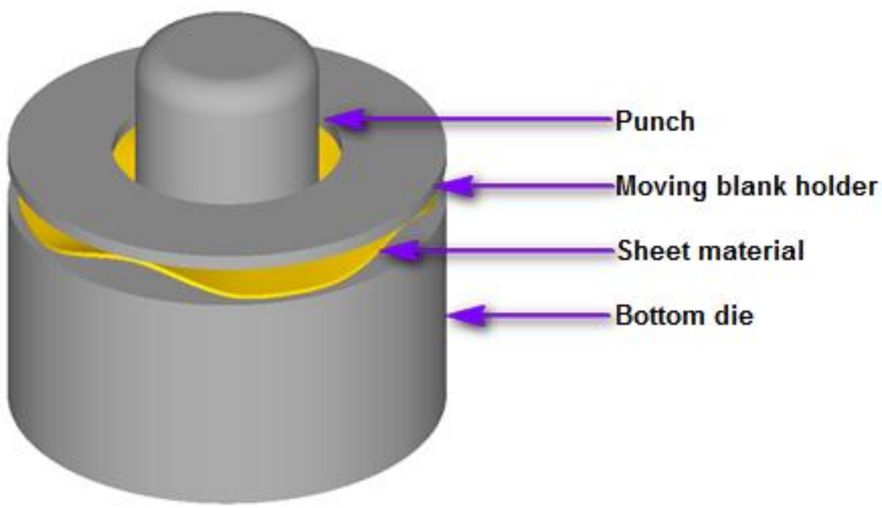

Figure 1
Formation of cylindrical cup at different steps of FEA simulation

The sheet blank was meshed with tetrahedral elements as shown in figure 2. The number of nodes for the blank were 4676. The number of elements for the blank were 12805. The contact between blank and punch, die and blank holder were coupled as contact pair. The mechanical interaction between the contact surfaces was assumed to be frictional contact. The finite element analysis (FEA) was chosen to find the effective stress, effective strain, shear stress, damage factor, and formability of the cup. The formability of the cylindrical was determined using major and minor strains (Reddy, 2015c and Alavala, 2016c).

3. RESULTS

Figure 3 describes the punch load as a function of stroke length and temperature resting the other parameters unchanged. The punch load decreased with an increase in the operating temperature. However, the decrease in the punch load was very small for the change of temperature from 275^{o}C to 400^{o}C. For the drawing operation at temperature, 200^{o}C, the punch load was increased continuously up to stroke length of 25 mm; and it was fallen down from 45 kN to 22 KN. The punch load was again raised to 48 kN at stroke length of 27 mm. Thereafter, the punch load was continuously decreased till the entire drawing operation at temperature, 200°C, was completed. For the drawing operation at temperature, 275°C, the punch load was uninterruptedly increased up to stroke length of 30 mm; and it was fluctuated till the deep drawing operation was completed. For the drawing operation at temperature, 400°C, the punch load was uninterruptedly increased up to stroke length of 60 mm; and it was gradually decreased till the deep drawing operation was completed.

Figure 2
Discretization of sheet material

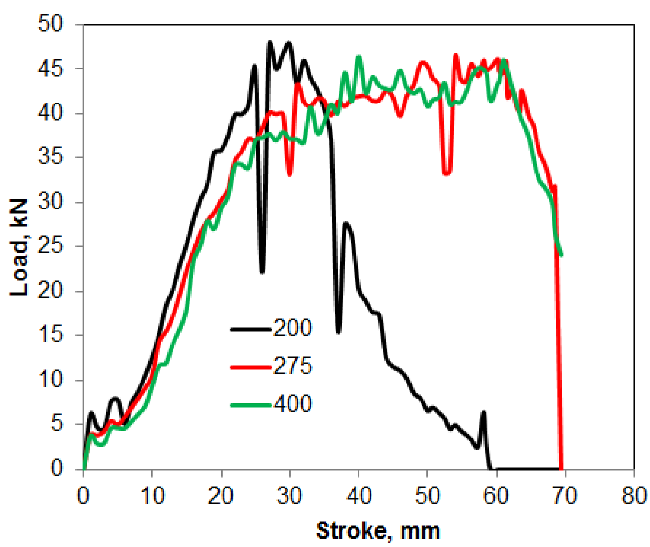

Figure 3
The punch load as a function of stroke and temperature (the other parameters are maintained at constant levels).

Figure 4 presents the von Mises stress as a function of von Mises strain at different temperatures keeping the values of other process parameters: strain rate at 1.0 s^{-1}, coefficient of friction at 0.15 and punch velocity at 2.0 mm/s. The von Mises stress was proportional to von Mises strain up to 1.0 and later on it was nearly constant irrespective of operating temperature. It was observed that the von Mises stress was found to be higher at 200ºC than that at 275ºC and 400ºC. The von Mises stress was not influenced for the change in operating temperature from 275ºC to 400ºC.

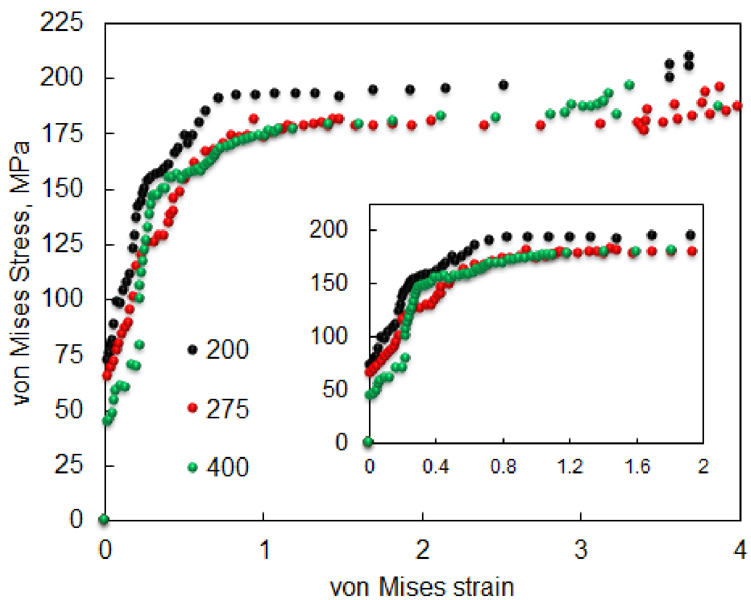

Figure 4

The von Mises stress as a function of temperature (the other parameters are maintained at constant levels).

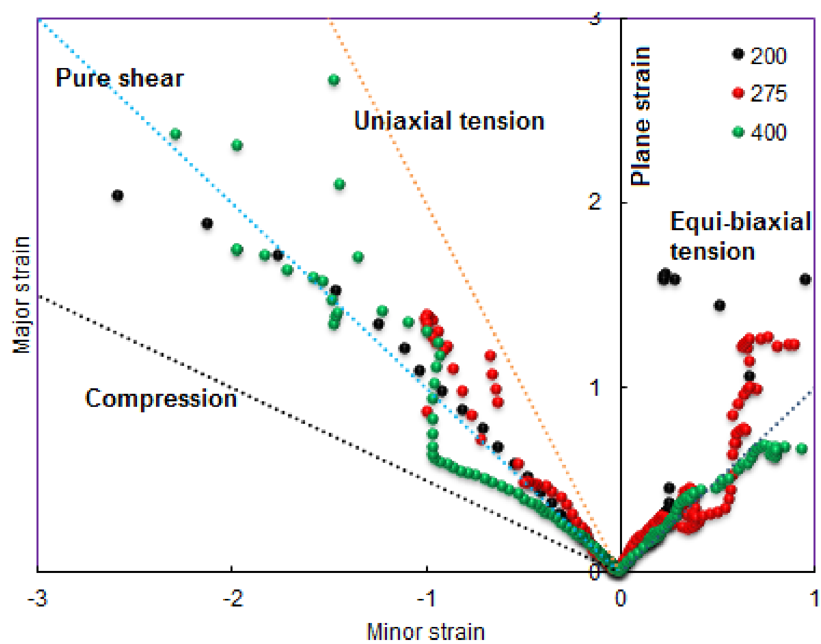

Figure 5

Forming limit diagram of the cups drawn at different temperatures

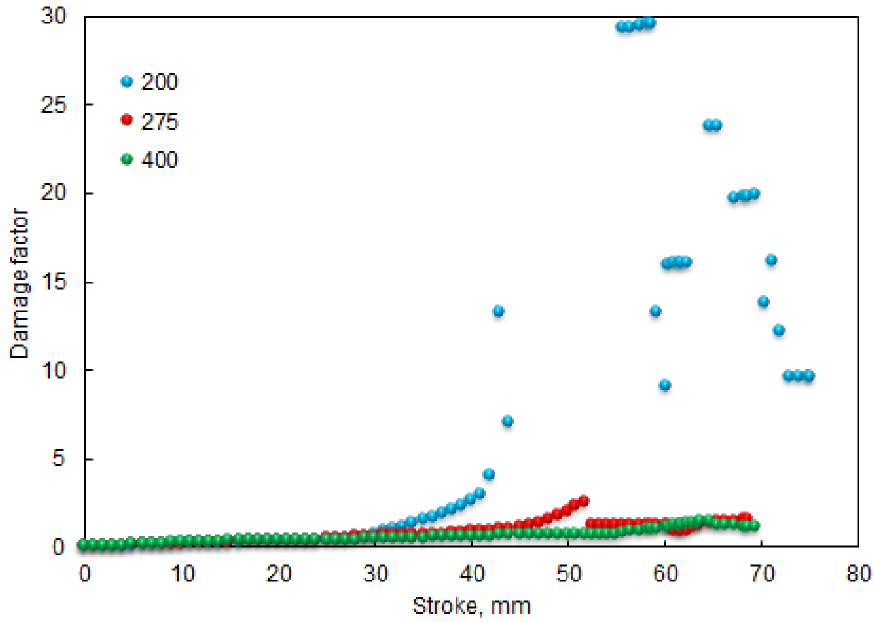

Figure 6

Effect of temperature on the damage factors of 6082 Al alloy cups

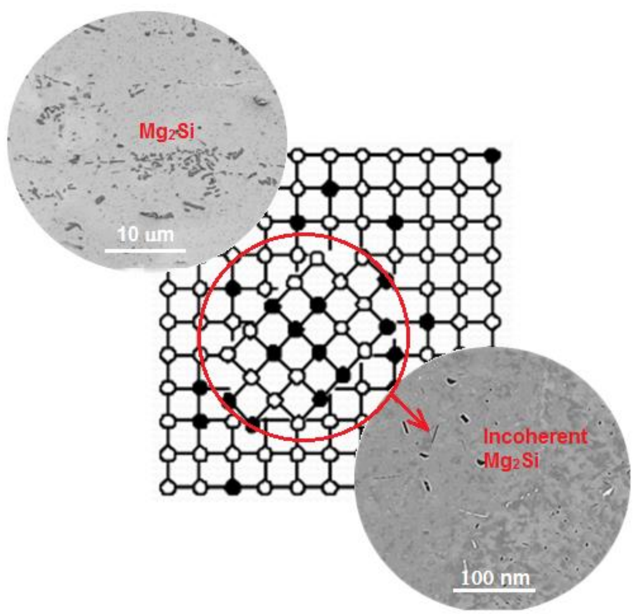

Figure 7

Micrograph of 6082 Al alloy showing precipitation of Mg2Si due to increased temperature.

Figure 5 shows the forming limit diagram (FLD) for the cylindrical cups drawn from 6082 Al alloy sheets at three temperatures. The cylindrical cups drawn at temperature 200°C and 275°C had experienced equi-biaxial tension. The hot deep drawing of 6082 Al alloy at 400°C above recrystallization temperature had yield the good quality cup as shown in figure 5.

In the present work, the critical value of the damage factor is defined as follows:

$$D_f = \int \frac{\sigma^*}{\sigma_{vm}} d\epsilon \quad (2)$$

The damage factors of the cups drawn at different temperatures are illustrated in figure 6. The damage factor decreased with an increase in temperature of the deep drawing process.

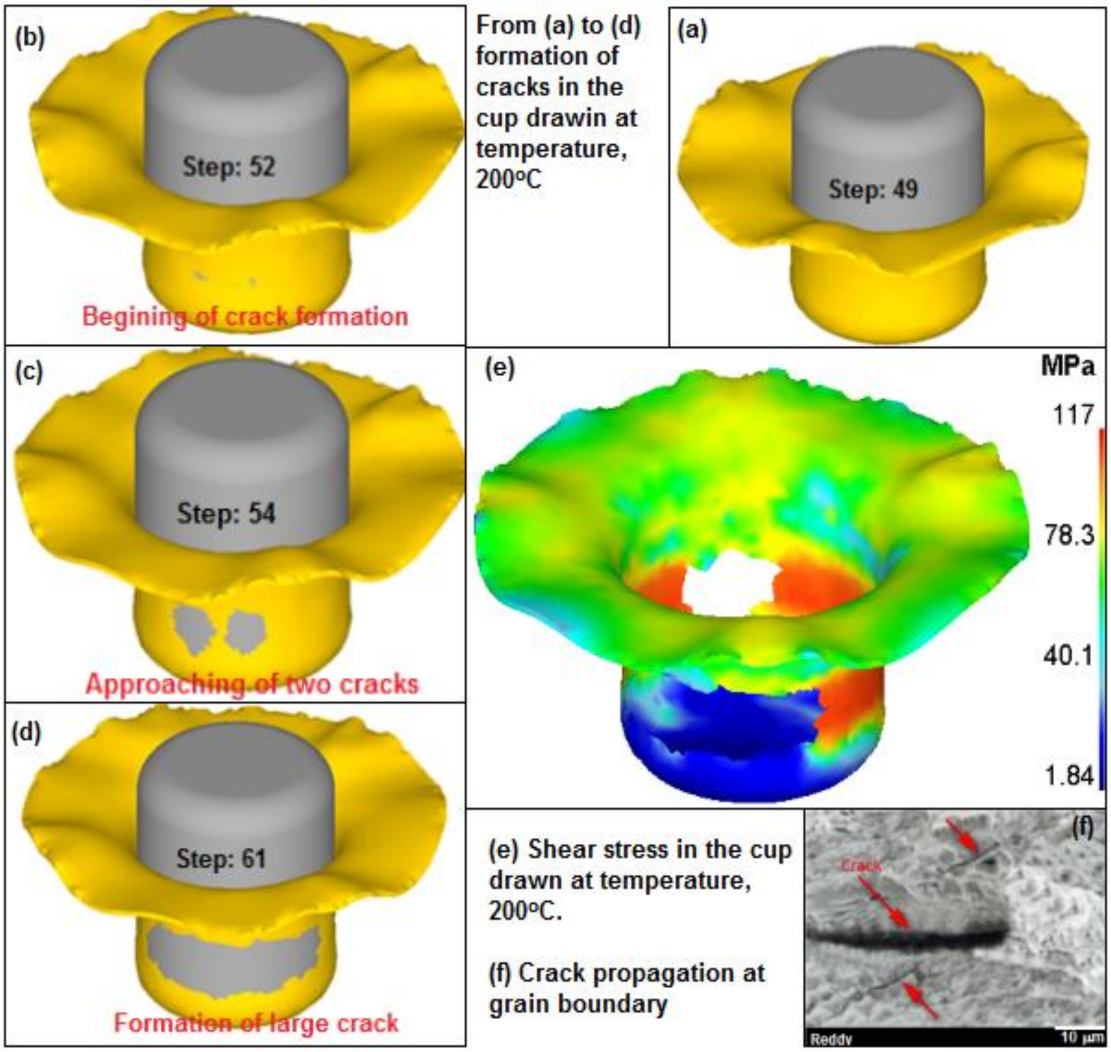

Figure 8

Important features of the cup drawn at temperature 200°C

4. DISCUSSION

The melting point of 6082 Al alloy is 555°C. The rule of thumb for the recrystallization temperature is that $T_{recryst}$ equals about 0.4 - 0.5 T_m. The presence of precipitations of Mg_2Si and β-Al_5FeSi influences the size of grains, avoiding the excessive growth of grain as shown in figure 7. The majority of the grains are slightly elongated, indicating the sustained presence of plastic deformation in the warm deep drawing of 6082 Al alloy. At 400°C temperature, a superposition of events (precipitation kinetics and grain growth processes) is likely to occur with the possibly formation of precipitates that leads to reduction of ductility. Formation of incoherent precipitates of Mg_2Si leads the reduction of strength of 6082 Al alloy. The temperature increase activates the dislocation motion and dislocation-dislocation interactions that result in a viscosity decreases.

At step 49 of deep drawing process, the cup does not have any cracks as shown in figure 8(a). For the deep drawing at 200ºC, the initiation of cracks is observed at step, 52 as shown in figure 8(b). These cracks are grown up towards each one to form big crack at step 61 as shown in figure 8(d). The shear strength at fracture is found to be 117 MPa as shown in figure 8(e). In recrystallization, new equiaxed and stress-free grains are formed, replacing the older grains. On account of incomplete recrystallization of 6082 Al alloy, the stress in the grains is not totally relieved, consequently, leading to the formation of cracks in the side walls of the cups. As seen from figure 8(f), cracks are propagated along the grain boundaries in the cup drawn at temperature 200ºC owing to cold forming behavior below the recrystallization temperature.

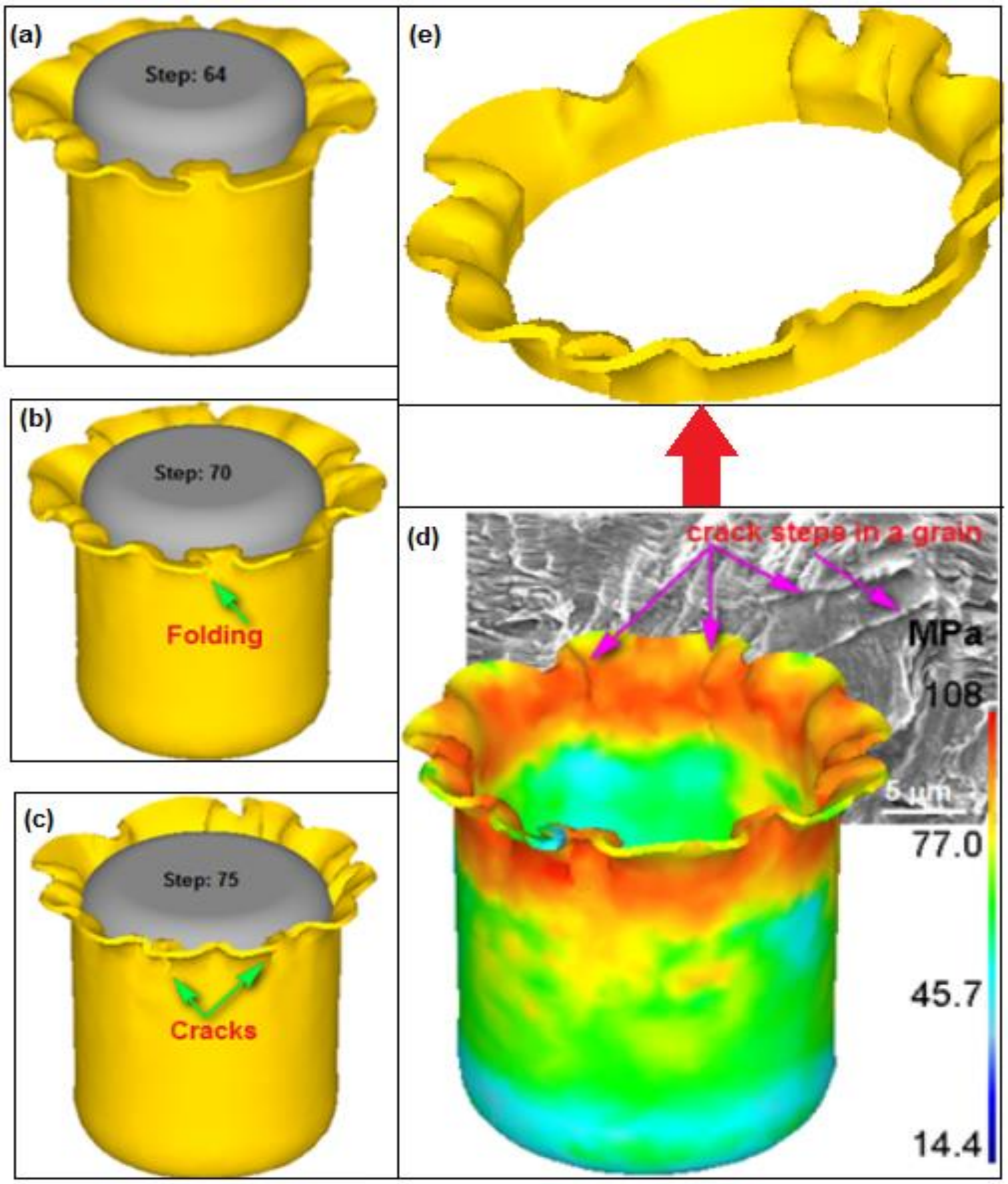

Figure 9

Formation of folds and cracks in the cup drawn at temperature 275ºC

At step 70 of the deep drawing process of 6082 Al alloy heated to 275ºC which is nearly equal to recrystallization temperature, folding of sheet material is observed in the flange area of the cup as shown in figure 9(b). Due to folding of the sheet material, the cracks are observed in flange area as shown n figure 9(c). The compression is highly predominant in the flange area of deep drawn cups due to blank holder force. Twins in the grains become recrystallized grain chains after compression. Dislocations formed by cross slip and climb could lead to the creation of low-angle grain boundary net as shown in figure 9(d) resulting the formation of tear in the flange area of the deep drawn cups at recrystallization temperature of 6082 Al alloy. The shear stress is 108 MPa in the cups drawn at the recrystallization temperature of 6082 Al alloy.

Only folds have been observed in the cylindrical cups drawn at temperature of 400°C as seen from figure 10(b). During the hot deep drawing of 6082 Al alloy cups, material softening occurs due to dynamic recovery or dynamic recrystallization as observed in the earlier works of Galiyev et al. (2001) and Alavala (2016d). The grains of 6082 Al alloy get elongated along direction normal to applied punch load, giving raise to anisotropy as shown n figure 10(c). At the flow of 6082 Al alloy is constrained to die profile, the sheet material gets folded in the area of punch radius. During recovery process, locked up dislocations get released due to adiabatic condition that prevailed under large deformation and large rise in temperature of the sheet material. In dynamic recovery, dislocation cross-slipping, climbing occurs resulting the formation of folds as detected in the previous works of Li et al. (2004) and Alavala (2016e). Normally, the flow stress behavior is a significant characteristic of the hot deep forming process, which can be described by the thermally activated stored energy established during the deformation controlled softening mechanism. With increasing temperature, the strain hardening effect becomes deteriorate while the degree of strain softening becomes prominent. Due to softening effect, the shear stress is reduced to 98.9 MPa in the deep drawn cups at 400°C.

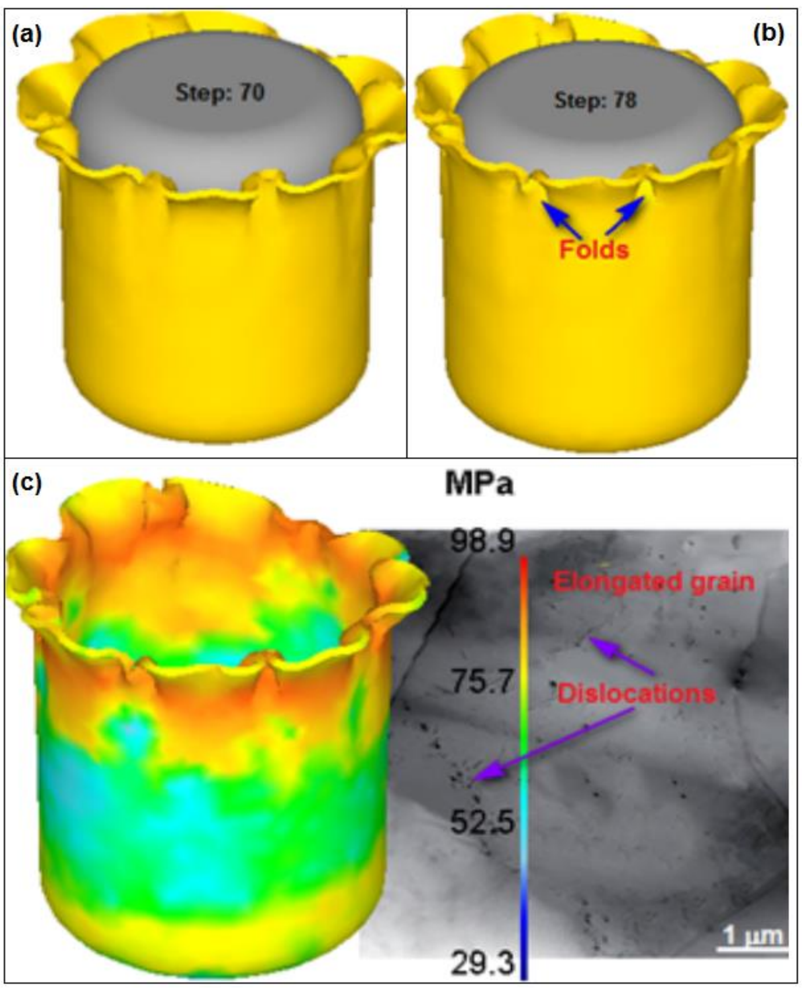

Figure 10

Formation of folds in the cup drawn at temperature 400°C

5. CONCLUSION

In this paper, the cylindrical cups of 6082 Al alloy sheet have been formed numerically using D-FORM software. The von Mises stress was least at operating temperature of 200°C below recrystallization temperature of 6082 Al alloy. The quality of cylindrical cups was good above the recrystallization temperature.

SUMMARY OF RESEARCH

1. Finite element analysis of the hot deep drawing process could predict efficiently the influence of recrystallization temperature on the formability of cylindrical cups from the 6082 Al alloy.
2. The formability of cylindrical cups was highly influenced by the equi-biaxial tension below and at recrystallization temperature of 6082 Al alloy.
3. Incomplete recrystallization of 6082 Al alloy was attributable to the formation of cracks in the side walls of the cups. Dislocations formed by cross slip and climb could lead to the formation of folds and tears in the flange area of the deep drawn cups at recrystallization temperature of 6082 Al alloy. The release of locked up dislocations could yield good quality cylindrical cups due to adiabatic condition that prevailed under large deformation and large rise in temperature above the recrystallization temperature of 6082 Al alloy.
4. The damage factor in the cylindrical cups would decrease with an increase in temperature of the deep drawing process.

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