Forming of Al 5182-O in a Servo Press at Room and Elevated Temperatures

Aluminum alloys are increasingly used in automotive manufacturing to save weight. The drawability of Al 5182-O has been proven at room temperature (RT) and it is also shown that formability is further enhanced at elevated temperatures (ETs) in the range of 250–350°C. A cost effective application of ET forming of Al alloys can be achieved using heated blank and cold dies (HB–CD). In this study, the material behavior of Al 5182-O is characterized using tensile test and viscous bulge test at RT. The nonisothermal finite element model (FEM) of deep drawing is developed using the commercial software PAMSTAMP. Initially, deep drawing simulations and tests were carried out at RT using a 300 ton servo press, with a hydraulic cushion. The predictions with flow stress curves obtained from tensile and bulge tests were compared with experimental data. The effect of punch speed and temperature rise during forming at RT is investigated. The warm forming simulations were carried out by combining material data at ETs obtained from the literature. The coupled effects of sheet temperatures and punch speeds are investigated through the finite element analysis (FEA) to provide guidelines for ET stamping of Al 5182-O. [DOI: 10.1115/1.4030334]

Keywords: warm forming, aluminum alloy, deep drawing, nonisothermal FEA

1 Introduction

The use of aluminum alloys is increasing in automotive stamping, because of aluminum’s low density and high strength to weight ratio. However, stamping of Al alloys presents new challenges in obtaining good part definition and formability at RT.

Recent studies have indicated the workability and formability can be increased considerably at ETs [1]. However, this process also has its own challenges, such as heating the blank, controlling the die temperature, lubrication, selection of the appropriate forming press, cycle time, and increased cost [2]. Considerable R&D has been conducted in North America in warm forming (around 250–400°C) of “soft” nonage hardenable 5xxx series alloys. Studies covered: determination of material properties, lubrication, FEA, various forming methods such as super plastic forming, quick plastic forming (developed by GM), and development of warm forming cells [3,4]. In a major study conducted by USAMP (U.S. Automotive Materials Partnership), extensive investigations and prototype trials have been conducted in warm forming of Al 5xxx and 6xxx series alloys, mostly on 5754 and 5182. In these studies, sheet material was formed at around 275°C while the dies were heated in some cases [5] and were kept at RT in most recent studies [4,6]. HB–CD stamping process, with blank heated only, can provide an efficient and economic approach to form Al alloys [7].

Servo presses, having the capability to enable infinitely variable and controllable ram speed and dwell at bottom dead center (BDC), offer a potential improvement in forming quality at both RT and ET [8]. The application of servo presses is continuously increasing in drawing, blanking, and warm forming processes [9]. By using servo presses, the drawability and productivity of deep drawn parts, such as door panels and fenders, were found to be improved with optimized punch speed profiles at RT [10–12].

Regarding to warm drawing of Al–Mg alloys, with specially designed slide motions in a servo press, the blank holder pressure and punch speed were found to have significant effects on heat transfer between interfaces and thickness distribution of the formed part [13].

A number of previous studies have focused on FEA simulations of warm forming process by using isothermal and nonisothermal models. Kay et al. [13] conducted cup drawing simulation of Al sheet forming at ET (250–300°C). The warm forming process of Al 5754-O was simulated using a nonisothermal FEM to study the complex interactions between material properties, temperature, and punch velocity (strain rate). Kim et al. [14] investigated thermomechanically coupled FEM, which was performed for forming of Al rectangular cups at ETs. The effects of some major factors (i.e., forming speed, blank holder pressure, and friction condition) on forming performance were reviewed and discussed. Abedrabbo et al. [15] developed a temperature-dependent anisotropic material model for use in a coupled thermomechanical FEA of the pure stretch forming of Al 5182 and Al 5754. The failure locations of simulation results at RT and ET matched well with the experiments.

The major conclusions of these studies were that (a) due to increased formability Al 5182-O could be successfully warm formed at about 250°C, (b) the cycle time for the operation could be kept to less than 15 s per part, and (c) most importantly, to reduce production costs, it is preferred to use nonheated dies, and provide quick transport of the heated blank from heater into the press, in the forming cell [2].

In this paper, based on previous material characterization and lubricant study, forming of Al 5182-O at both RT and ET is discussed. The nonisothermal FEA simulations are carried out using commercial software PAMSTAMP. Deep drawing experiments were performed at RT in a 300 ton servo press. The effects of forming speed at RT were evaluated and presented in detail. HB–CD warm forming was simulated with different blank temperatures and forming speeds. The thickness distribution along critical sections in the formed part was predicted and compared with results at RT.
Table 1 Material property of Al 5182-O from tensile test (conducted at Honda R&D)

<table>
<thead>
<tr>
<th>Direction (deg)</th>
<th>Uniform elongation (%)</th>
<th>Yield stress (MPa)</th>
<th>Tensile stress (MPa)</th>
<th>Lankford value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>21.9</td>
<td>126.9</td>
<td>291.2</td>
<td>0.71</td>
</tr>
<tr>
<td>45</td>
<td>22.7</td>
<td>121.3</td>
<td>279.8</td>
<td>1.09</td>
</tr>
<tr>
<td>90</td>
<td>22.0</td>
<td>123.9</td>
<td>285.4</td>
<td>0.84</td>
</tr>
</tbody>
</table>

2 Al Alloy 5182-O Properties

Aluminum alloy 5182-O has an extensive application in automotive industry, due to its light weight and good drawability. The chemical composition and tensile properties of Al 5182-O are given in Refs. [15,16].

2.1 Flow Stress at RT—Tensile Test/Bulge Test. The standard uniaxial tensile test is the most widely used method to characterize the mechanical properties of engineering materials in industry [17]. The material properties of Al 5182-O obtained from tensile test are summarized in Table 1. However, for the FE simulation of actual sheet metal forming operations, the tensile test has two main limitations: (1) the true strain before instability and necking is relatively small, and (2) the uniaxial stress state does not represent practical forming conditions. Viscous pressure bulge (VPB) test, developed at the Center of Precision Forming, provides higher strain values under biaxial state of stress [18]. The schematic of VPB test is shown in Fig. 1. The flow stress of the sheet material can be obtained by using inverse FEA, while measured bulge pressure and bulge height are used as inputs. As shown in Fig. 2, with the VPB test, the flow stress of Al 5182-O could be obtained at true strain about 0.5, while tensile test data are available only for strains of 0.2 and must be extrapolated to conduct FE simulations.

2.2 Flow Stress at ETs, Effect of Strain Rate. The formability of Al 5182-O is improved with increasing temperature and decreasing strain rate under warm forming conditions. The results of tensile tests show that temperature and strain rate have almost no effects on the flow stress at temperature range (25–100°C) [7,15,19]. Thus, the power law can be applied to describe the hardening behavior at this temperature range

$$\sigma = K \cdot e^n \quad 25^\circ C < T \leq 100^\circ C$$  

(1)

As shown in Fig. 2, based on the bulge test result at RT, the strength coefficient $K$ and the strain-hardening exponent $n$ are 487.6 MPa and 0.263, respectively. However, the flow stress data obtained from tensile test must be extrapolated to conduct FE simulations. Only the plastic deformation of the data, shown in Fig. 2, can be used in the FE simulation. The elastic portion of the curve is subtracted for this purpose.

Zhang and Abu-Farha [7] proposed a phenomenological constitutive model to describe the plastic deformation of Al 5182-O, with a wide range of temperatures (25–300°C) and strain rates (0.001–0.1 s⁻¹), as shown in Fig. 3. At temperature range (100–300°C), the constitutive model is expressed as follows:

$$\sigma = \sigma_{peak} - \sqrt{a e^b - 100^\circ C < T \leq 300^\circ C}$$  

(2)

where $a$ and $b$ were obtained by curve fitting the tensile tests data at different temperatures and strain rates. The peak stress $\sigma_{peak}$ is expressed as a function of Zener–Hollomon factor $Z$

$$a = 141.14 \cdot [\ln(Z)]^2 - 6301.6 \cdot \ln(Z) + 69623$$  

(3)

$$b = (-0.0099T + 1.5796) \cdot [\ln(\dot{\varepsilon})]^2 + (-0.0977T + 14.844) \cdot \ln(\dot{\varepsilon}) + (-0.1966T - 2.0188)$$  

(4)

$$\ln(\sigma_{peak}) = -0.5285 \cdot [\ln(Z)]^2 + 47.808 \cdot \ln(Z) - 744.47$$  

(5)

and

$$Z = \dot{\varepsilon}^Q / RT$$  

(6)

The gas constant $R$ is 8.31 J/mol K and the activation energy $Q$ is 142 kJ/mol.
3 Deep Drawing Tests

3.1 Description of the Die Set and Press. The schematic of deep drawing tooling is illustrated in Fig. 4. This die was originally designed to form advanced high strength steels. The die cavity was assembled by several inserts with different radii and curvilinear shapes. The clearance of punch and die was kept at 1.6 mm. The allowable drawing depth of this die is about 80 mm.

In the current study, a 300 ton mechanical Aida servo press with 25 ton hydraulic Computer Numerical Control (CNC) cushion was used to conduct the deep drawing tests. The ram movement could be programmed to obtain any desired ram speed versus stroke profile. Using the CNC die cushion, the press has the capability to control the forming speed and blank holder force (BHF) during forming. In order to reduce the contact impact and bending affects, the press also has the pre-acceleration function.
with several levels (strong, medium, and weak). The data measurement system of the press can record positions, speeds, and load data for the punch and die cushion.

Two types of speed profiles are analyzed, including (1) mechanical crank motion (1 SPM, 10 SPM, and 18 SPM) and (2) constant speed during deformation (50 mm/s and 310 mm/s). As seen in Fig. 5, the mechanical crank motion is a basic sine curve. However, for constant speed profile, the ram speed could not be kept constant during the whole forming stroke, because at a certain stroke position it is necessary for the slide to decelerate to the BDC.

3.2 Evaluation and Selection of Lubricants for RT Forming. In a previous study, the performances of 14 lubricants, including oil based, water based, and dry film lubricants, were evaluated by using cup drawing test. The Al 5182-O sheets were available with two different surface textures, including mill finish and electrodischarge texturing (EDT). The performance of the lubricants was determined by measuring (1) maximum applicable BHF for cup drawing without defects, and (2) the draw-in length of the flange perimeter of formed cups at each BHF. As illustrated in Fig. 6, it was found that dry film lubricants performed better in deep drawing of 5182-O with EDT surface texturing.

4 FEM of the Deep Drawing Operation

In order to understand the complex interactions between material behavior, friction conditions, and temperature effects on deep drawing of Al alloys at both RT and ET, it is necessary to analyze the process using a nonisothermal FEM. In the current study, the nonisothermal FEM was developed using commercial software PAMSTAMP, as illustrated in Fig. 7(a). The sheet, with 1.2 mm thickness, is designed with rectangular shape (720 mm × 500 mm) with chamfered corners, as shown in Fig. 7(b). Four-node shell elements were used to simulate the deformation and heat transfer. The tools are considered as rigid bodies with 6 mm thermal thickness, to enable the calculation of temperature gradient. Initial temperature of the tools is assumed to be 25°C, while the sheet will be assumed to be heated to various initial temperatures ranging from 25°C to 300°C. In the FEM, Eqs. (1) and (2) are used to define the flow stress at temperature ranges 25–100°C and 100–300°C, respectively. The heat transfer coefficient (HTC) varying with contact pressure (Fig. 8) is applied between the contact interfaces [20]. The thermal–mechanical properties and simulation inputs are summarized in Table 2.

5 Results and Discussion

5.1 Validation of the FEMs at RT. Figure 9(a) shows the part drawn to 75 mm under BHF 150 kN at a forming speed of 18 SPM. In order to investigate the input flow stress curves on the accuracy of FE predictions, the data obtained from tensile test and VBP test (Fig. 2) were used in the simulations, respectively. The load–stroke curve and thinning distribution along the critical selected corner section, obtained in experiments, were measured and compared with predicted results.

As shown in Fig. 9(b), by using COF 0.1, the predicted load–stroke curves with tensile test data and VBP test data can
both give a good match with the experimental result. As seen in Fig. 10(b), more accurate thickness variation was predicted with VPB test data for COF 0.1.

5.2 Effect of Forming Speed at RT. Deep drawing tests were conducted at various punch speeds. The speed profiles are illustrated in Fig. 5. The sheet samples were precoted with dry film lubricant. The forming stroke was set to 60.8 mm and BHF was 125 kN. The test results at 50 mm/s and 310 mm/s are shown in Fig. 11. Due to the convex shape and the smaller corner radius (R₃ shown in Fig. 4), the cracks always initially occurred at the lower right corner (Fig. 11(a)). It was found that the part could be formed without cracks when applying a higher ram speed (310 mm/s), as shown in Fig. 11(b).

Figure 12 illustrates the punch load for various ram speeds mentioned above. It is seen that the load drop during deformation
is observed at forming speed of 50 mm/s, which indicates the occurrence of fracture. In this case, the maximum draw depth is approximately 53.6 mm at 50 mm/s punch speed. It is also seen in Fig. 12 that the maximum punch load decreases with increasing forming speed. By using COF 0.12 and 0.1 in the FEM, the predicted stroke–load curves show a good match with the experimental results at 50 mm/s and 310 mm/s, respectively. It can be seen that the friction condition in the contact interfaces may change with different forming speeds at RT. This observation is subject of ongoing study by the authors.

5.3 Prediction of Temperature Distribution During Forming at RT. During forming, plastic deformation and friction cause temperature increases in the part as well as at the die and punch surface. The proposed nonisothermal FEM was able to predict these temperature distributions. Figure 13 shows the predicted nodal temperature distribution in the deformed part. The higher temperature is found around the die-shoulder corners, where material flows under high contact pressure and friction work. Sections E–J (Fig. 13) are selected to evaluate the effect of forming speed on the temperature distributions. As illustrated in Fig. 14, the punch maximum temperatures are 77.3°C at 310 mm/s, 52°C at 50 mm/s, and 34.8°C at 10 mm/s and they are at location I. In the drawing tests, the temperature rise on the drawn part was moderate and probably not too severe to change the performance of the lubricant during the tests.

The highest temperatures 27°C and 32°C were predicted in the punch and die, respectively, at forming speed of 310 mm/s. The peak temperature in the die occurred at the corner regions. However, it was found that the location of peak temperature in the punch moved from the corner to the wall with forming stroke. It should be noted, however, that the estimated temperatures are for one stroke operation only. Under production conditions, when 10–20 parts per minute are formed, the die temperatures will be higher.

5.4 Deep Drawing at ET Using HB–CD. Using the constitutive model proposed by Zhang and Abu-Farha [7], ET forming simulations were carried out with heated 5182-O sheets at temperatures 100°C, 200°C, and 300°C, while the initial temperature of the tools is set to 25°C (RT). Figure 15 shows the effect of sheet initial temperature on the thinning distribution in the selected corner with constant forming speed 310 mm/s. It can be noted that there was almost no difference in thinning distribution at 100°C compared parts formed at RT (Fig. 10(b)) and the maximum thinning in the drawn part occurred around punch corner (location B in Fig. 10(a)). However, at ET forming, as the heated blank contacts the cold punch, a lower temperature gradient was established in the deformed part around the punch corner, where the material has greater strain hardening than hotter wall area. From Fig. 15, it can be seen that the maximum thinning values 12.8% and 15.4% at 200°C and 300°C, respectively, occurred on the wall (between B and C) instead of corner area.

Further simulations were carried out to evaluate the part quality at different forming speeds 50 mm/s and 310 mm/s (initial blank temperature 200°C) under ET forming conditions. With a higher forming speed, the part is deformed under higher strain rate; thus the material is stronger due to increased strain rate hardening effect. However, as illustrated in Fig. 16, it is found that more uniform thickness distribution could be achieved at 50 mm/s. Figure 17 shows the predicted temperature distributions in the deformed part at forming speeds 50 mm/s and 310 mm/s with the same initial blank temperature (200°C). The temperature decrease is approximately 80°C in the part corner regions when forming at 50 mm/s. It should be noted that lower ram speed provided more time for interface heat transfer between the heated sheet and the dies. As a result, the plastic behavior was locally affected by different temperature gradient across the part during deformation.

Fig. 13 Estimated temperature distribution in the drawn part at forming speed 310 mm/s, stroke = 60 mm

Fig. 14 Predicted temperature distributions in the drawn part along the selected sections E–J (Fig. 13) at different forming speeds, stroke = 60 mm

Fig. 15 The effect of initial sheet temperature on the thinning distribution in the part corner, forming speed 310 mm/s, punch stroke 75 mm (locations A, B, C, and D are shown in Fig. 10(a))

Fig. 16 The effect of forming speed on the thickness distribution in the part corner, initial sheet temperature 200°C, punch stroke 75 mm (simulation)
Although forming at low speed is not efficient and leads to greater heat loss, better part quality could be achieved by combined effects of sheet temperature and punch speed at ET forming condition. However, the variability in temperature and thickness distributions in the manufactured parts could be obvious in stamping cycles. More investigations, such as lubrication, die temperature control in mass production, and process optimization, are necessary for the application of the proposed process under production conditions.

6 Summary and Conclusions

The drawability of aluminum alloy 5182-O under cold and warm conditions was discussed in detail. The material behavior is characterized using tensile test and viscous bulge test at RT. By utilizing the 300 ton servo press, the deep drawing tests were conducted at different forming speeds at RT. The nonisothermal FEM was developed to help analyze the drawing process at RT, including experiment design, model validation, friction investigation, and temperature prediction. In addition, a more detailed understanding of the warm forming process (with sheet heated only) was provided by utilizing the nonisothermal simulation analysis. The effects of temperature and punch speed were investigated. Following conclusions can be drawn from this study:

1. Regarding material testing methods, comparing to tensile test, VBP test could provide a more accurate prediction of thickness distribution across the critical corner section in the drawn part. However, a good match in load-stroke curves could be achieved with both flow stress data by using a proper coefficient of friction.

2. The effect of forming speed on the part drawability is found to be significant at RT. Results indicated that the better part quality could be achieved with a higher forming speed, which could also be considered in production for a more efficient process. By using the nonisothermal FEM, the peak temperature rise was predicted to be 73 °C in the drawn part around die should at the highest forming speed 310 mm/s. However, in the single stroke condition studied here, there was no significant temperature rise in the die and punch.

3. Temperature gradient is found to have a great effect on the thickness distribution of the drawn part under warm forming conditions. The maximum thinning was predicted to occur in the wall when forming at 200 °C and 300 °C, while it was found to be in the corner area under cold forming condition (25–100 °C). The combined effects of temperature and punch speed could help to obtain a better thickness distribution in the deformed part under warm forming conditions.

Acknowledgment

The authors would like to extend special thanks to the member companies of the Center of Precision Forming (CPF) that funded this study. Special thanks are due to Shiloh Industries, Inc. (Cliff Hoschouer) and Honda Engineering (Dennis O’Connor) for supporting this project.

References