Forming of Al 5182-O in a servo press at room and elevated temperatures

Long Ju
School of Mechanical Engineering, University of Science and Technology Beijing
30 Xueyuan Road, Haidian, Beijing 100083, China
e-mail: ju.64@osu.edu

Shrinivas Patil
Aida-America Corporation
7660 Center Point 70 Blvd. Dayton, OH 45424, USA
e-mail: spatil@aida-america.com

Jim Dykeman
Honda R&D Americas, Inc.
21001 State Route 739 Raymond, OH 43067-9705, USA
e-mail: JDykeman@oh.hra.com

Taylan Altan¹
Center for Precision Forming, The Ohio State University
339 Baker Systems, 1971 Neil Avenue, Columbus, OH 43210, USA
e-mail: altan.1@osu.edu

ABSTRACT
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 (ET) in the range of 250-350°C. A cost effective application of elevated temperature 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 room temperature. The non-isothermal finite element model of deep drawing is developed using the commercial software PAMSTAMP. Initially deep drawing simulations and tests were carried out at room temperature using a 300 ton servo press, with a hydraulic cushion. The predictions with

¹ Corresponding author
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 room temperature is investigated. The warm forming simulations were carried out by combining material data at elevated temperatures obtained from the literature. The coupled effects of sheet temperatures and punch speeds are investigated through the finite element analysis to provide guidelines for ET stamping of Al 51821-

Keywords: warm forming, aluminum alloy, deep drawing, non-isothermal 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 room temperature.

Recent studies have indicated the workability and formability can be increased considerably at elevated temperatures [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°C to 400°C) of “soft” non-age hardenable 5xxx series alloys. Studies covered: determination of material properties, lubrication, FE analysis, 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 all these studies, sheet material was formed at around 275°C while the dies were heated in some cases [5] and were kept at room temperature in most recent
studies [4,6]. Hot blank-cold die (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 room and elevated temperatures [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 room temperature [10-12]. Regarding to warm drawing of Al-Mg alloys, with specially designed slide motions in a servo press, the blankholder 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 FE simulations of warm forming process by using isothermal and non-isothermal models. Kaya et al. [13] conducted cup drawing simulation of Al sheet forming at elevated temperature (25~300°C). The warm forming process of Al 5754-O was simulated using a non-isothermal FE model to study the complex interactions between material properties, temperature, and punch velocity (strain rate). Kim et al. [14] investigated thermo-mechanically coupled FE model which was performed for forming of Al rectangular cups at elevated temperatures. 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 thermo-mechanical finite element analysis of the pure stretch forming of Al 5182 and Al 5754. The failure locations of
simulation results at room temperature and elevated temperature 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 sec per part, and (c) most importantly, to reduce production costs, it is preferred to use non-heated 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 room and elevated temperatures is discussed. The non-isothermal FE simulations are carried out using commercial software PAMSTAMP. Deep drawing experiments were performed at room temperature in a 300 ton servo press. The effects of forming speed at room temperature was 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 were predicted and compared with results at room temperature.

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 several references [15,16].

2.1 Flow stress at room temperature (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 FE analysis, 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 is available only for strains of 0.2 and must be extrapolated to conduct FE simulations.

<table>
<thead>
<tr>
<th>Direction</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>

Fig. 1 Schematic of Viscous Pressure Bulge test [18]
2.2 Flow stress at elevated temperatures (ET), 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°C~100°C) [7, 15, 19], while the rate sensitivity is important at elevated temperatures [21]. Thus, the power-law can be applied to describe the hardening behavior at this temperature range.

\[
\sigma = K\varepsilon^n \quad 25^\circ C \leq T \leq 100^\circ C
\] (1)

As shown in Fig.2, based on the bulge test result at room temperature, 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°C ~ 300°C) and strain rates (0.001s⁻¹ ~ 0.1s⁻¹), as shown in Fig. 3. At temperature range (100°C ~ 300°C), the constitutive model is expressed as follows.

\[
\sigma = \sigma_{\text{peak}} - \sqrt{ae^{bg}} \quad 100^\circ C < T \leq 300^\circ C
\] (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 \( Z \):

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

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

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

and

\[
Z = \dot{\varepsilon} e^{\left(\frac{Q}{RT}\right)}
\]

The gas constant \( R \) is 8.31 J/mol·K and the activation energy \( Q \) is 142 kJ/mol.

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3. Deep Drawing Tests

3.1 Description of the die set and press

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![Fig. 3 Flow stress curves from tensile tests at different strain rates for elevated temperatures: (a) 100°C, (b) 200°C, (c) 300°C [7]](image-url)
The schematic of deep drawing tooling is illustrated in Fig. 4. This die was originally designed to form advanced high strength steels (AHSS). The die cavity was assembled by several inserts with different radii and curvilinear shapes. The clearance of punch and die was kept at 1.6mm. The allowable drawing depth of this die is about 80 mm.

![Diagram of deep drawing tooling](image)

**Fig. 4 Top and cross-sectional view of deep drawing tooling, dimensions are in mm (R₁=1501.6, R₂=1998.4, R₃=51.6, R₄=55.6, R₅=61.6, R₆=66.6, R₇=20, R₈=10)**

In the current study, a 300 ton mechanical Aida servo press with 25 ton hydraulic CNC cushion was used to conduct the deep drawing tests. The ram movement could be programmed to obtain any desired ram speed vs stroke profile. Using the CNC die cushion, the press has the capability to control the forming speed and blank holder force 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 bottom dead center (BDC).

![Fig. 5 Ram speed profiles with crank motion (1 SPM, 10 SPM and 18 SPM) and nearly constant (50 mm/s and 310 mm/s) punch speed during deformation (Aida 300 ton servo press)](image)

**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 (CDT). The Al 5182-O sheets were available with two different surface textures, including mill finish (MF) and electro discharge texturing (EDT). The performance of the lubricants was determined by measuring 1) maximum applicable blank holder force (BHF) for cup drawing without defects, and 2) the draw-in length or 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. FE modeling 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 room temperature and elevated temperature, it is necessary to analyze the process using a non-isothermal FE model. In the current study, the non-isothermal FE model was developed using commercial software PAMSTAMP, as illustrated in Fig. 7(a). The sheet, with 1.2 mm thickness, is designed with rectangular shape (720mm×500mm) with chamfered corners, as shown in Fig. 7(b). 4-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 FE model, Eq. (1) and Eq. (2) are used to define the flow stress at temperature ranges 25°C to 100°C and 100°C to 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.
Table 2 Input parameters of the non-isothermal FE models

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B - Flow stress curve</td>
<td>Tensile/VPB test data at RT (Fig. 2)</td>
</tr>
<tr>
<td></td>
<td>Tensile test data at ET (Fig. 3)</td>
</tr>
<tr>
<td>B - Young’s modulus ($)</td>
<td>70.6 GPa</td>
</tr>
<tr>
<td>B - Poisson ratio ($)</td>
<td>0.341</td>
</tr>
<tr>
<td>B - Sheet temperature ($)</td>
<td>25/100/200/300 °C</td>
</tr>
<tr>
<td>D - Thermal conductivity ($)</td>
<td>130 W/m·C</td>
</tr>
<tr>
<td>D - Specific heat capacity ($)</td>
<td>900 J/kg·C</td>
</tr>
<tr>
<td>D - Coefficient of friction (COF)</td>
<td>0.08~0.12</td>
</tr>
<tr>
<td>D - Die temperature ($)</td>
<td>25 °C</td>
</tr>
<tr>
<td>P - Blankholder force ($)</td>
<td>Max. 250 kN</td>
</tr>
<tr>
<td>P - Stroke ($)</td>
<td>Max. 80 mm</td>
</tr>
<tr>
<td>P - Ram speed ($)</td>
<td>As shown in Fig. 5</td>
</tr>
</tbody>
</table>

5. Results and discussion
5.1 Validation of the FE models at RT

Fig. 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 VBP test data for COF 0.1.

Fig. 9 Test results and predicted punch force at room temperature, (a) formed part, (b) comparison of punch forces between experiment and FEM

Fig. 10 Comparison of thickness variations, (a) selected corner section A-D, (b) thinning variations from experiment and FE simulations

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 pre-coated 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. 1. Due to the convex shape and the smaller corner radius (R5 shown in Fig. 4), the cracks always initially occurred at the lower right corner (Fig. 11a). 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).

Fig. 12 illustrates the punch load for various ram speeds mentioned above. It is seen that the load drop during deformation is observed at forming speeds 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 FE model, 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 room temperature. This observation is subject of ongoing study by the authors.

Fig. 11 Results of deep drawing tests with a dry film lubricant under different forming speeds at RT, stroke 60.8 mm: (a) 50 mm/s, crack at lower right corner, (b) 310 mm/s, defect free formed part
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 non-isothermal FE model was able to predict these temperature distributions. Fig. 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. The section E-J (Fig. 13) is 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.
Fig. 14 Predicted temperature distributions in the drawn part along the selected section E-J (Figure 13) at different forming speeds, stroke = 60 mm

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 to 20 parts per minute are formed, the die temperatures will be higher.

5.4 Deep drawing at ET using hot blank and cold dies (HB-CD)

Using the constitutive model proposed by from Zhang and Abu-Faha [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 are set to 25 °C (RT). Fig. 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 room temperature (Fig. 10b) and the maximum thinning in the drawn part occurred around punch corner (location B in Fig. 10a). 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.

![Figure 15](image)

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

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. Fig. 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.
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.

![Graph showing the effect of forming speed on the thickness distribution in the part corner, initial sheet temperature 200 °C, punch stroke 75mm (simulation)](image1)

**Fig.16** The effect of forming speed on the thickness distribution in the part corner, initial sheet temperature 200 °C, punch stroke 75mm (simulation)

![Graph showing temperature distribution in the part under forming speed (a) 50 mm/s and (b) 310 mm/s, initial sheet temperature 200 °C, punch stroke 75mm (simulation)](image2)

**Fig.17** Temperature distribution in the part under forming speed (a) 50 mm/s and (b) 310 mm/s, initial sheet temperature 200 °C, punch stroke 75mm (simulation)

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 room temperature. By utilizing the 300 ton servo press, the deep drawing tests were conducted at different forming speeds at room temperature. The non-isothermal FE model was developed to help analyze the drawing process at room temperature, including experiment design, model validation, friction and...
investigation and temperature prediction. In addition, a more detailed understanding of the warm forming process (with sheet heated only) was provided by utilizing the non-isothermal 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, VPB 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 room temperature. 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 non-isothermal FE model, 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 °C~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.

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References


Figure Captions List

Fig. 1 Schematic of Viscous Pressure Bulge test [18]

Fig. 2 Flow stress curves of Al 5182-O obtained from tensile test and VPB test

Fig. 3 Flow stress curves at different strain rates for elevated temperatures: (a) 100°C, (b) 200°C, (c) 300°C [7]

Fig. 4 Top and cross-sectional view of deep drawing tooling, dimensions are in mm

Fig. 5 Ram speed profiles with crank motion (1 SPM, 10 SPM and 18 SPM) and nearly constant (50 mm/s and 310 mm/s) punch speed during deformation

Fig. 6 Flange perimeters measured from formed cups with various lubricants at BHF 16 ton

Fig. 7 (a) 3D FE model of deep drawing process, (b) Blank dimensions (mm)

Fig. 8 Variation of Heat transfer coefficient with contact pressure [20]

Fig. 9 Test results and predicted punch force at room temperature, (a) formed part, (b) comparison of punch forces between experiment and FEM

Fig. 10 Comparison of thickness variations, (a) selected corner section A-D, (b) thinning variations from experiment and FE simulations

Fig. 11 Results of deep drawing tests with a dry film lubricant under different forming speeds at RT, stroke 60.8 mm: (a) 50 mm/s, crack at lower right corner, (b) 310 mm/s, defect free formed part

Fig. 12 Experimental and predicted load-stroke curves at forming speeds 50 mm/s and 310 mm/s

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 section E-J (Figure 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 75mm (location A, B, C, D are shown in Fig. 10a)

Fig. 16 The effect of forming speed on the thickness distribution in the part corner, initial sheet temperature 200 °C, punch stroke 75mm (simulation)

Fig. 17 Temperature distribution in the part under forming speed (a) 50 mm/s and (b) 310 mm/s, initial sheet temperature 200 °C, punch stroke 75mm (simulation)
Table Caption List

Table 1 Material property of Al 5182-O from tensile test (conducted at Honda R&D)
Table 2 Input parameters of the non-isothermal FE models