

Numerical Simulation of Warm Forming Behavior of High Strength Aluminum Alloy 7075

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Abstract: Numerical analysis is critically important to understanding the complex deformation mechanics that occur during sheet forming processes. It has been widely used in simulation of sheet metal forming processes at room temperature in the automotive industry. However, material at elevated temperature behaves more differently than at room temperature and specific material parameters and models need to be developed for the simulation of warm forming. Based on the experimental investigation of material behavior of high strength aluminum alloy 7075 (AA7075), constitutive equations with strain rate sensitivity at 140, 180 and 220 °C are developed. Anisotropic yield criterion Barlat 89 is used in the simulation. Warm forming of limit dome height tests and limit drawing ratio tests of AA7075 at 140, 180 and 220 °C are performed. Forming limit diagrams developed from experiment at several elevated temperatures in the previous study are used to predict the failure in the simulation results. Punch force and displacement predicted from simulation are compared with the experimental data. Simulation results agree with experimental results, so the developed material model can be used to accurately predict material behavior during isothermal warm forming of the AA7075-T6 alloy.

Key words: high strength aluminum alloy; warm forming; numerical simulation; material model

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0 Introduction

Finite element analysis (FEA) has been widely used in automotive industry to predict deformation behavior during stamping operations^[1]. Use of these tools has dramatically shortened lead times to produce good die systems as well as to reduce the amount of try-out time required to reach a controlled forming process. An accurate material model is critical for accurate simulation of the forming process. For traditional forming processes, numerous material models have been developed and are available in commercial FEA codes^[2]. However, these FEA codes often do not offer highly specialized material models developed for specific materials and processes. The warm forming process which is essentially

stamping with a die at elevated temperature has been shown to enhance the formability of aluminum^[3,4]. While some research has been conducted for the development of warm forming material models, most of this work focuses on AA5××× and AA6××× series aluminum alloys. For example, Nader Abedrabbo used YLD96 and YLD2000 in warm forming of 5×××, 6××× and 3××× material^[5,6] and Bogard characterized the flow stress behavior of AA5754 with the modified power law model^[7]. All these works have greatly improved the simulation technology of the warm forming process.

For some automotive structural parts, e. g. the B-pillar, high strength aluminum alloys can potentially be used to replace steel for weight reduction. Aluminum alloy 7075 (Al-Zn-Mg-Cu)

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(AA7075) has wide applications in aircraft structural materials due to its high strength and low density^[8,9]. The conventional forming process of AA7075 part is forming annealed AA7075, followed by solution heat treating and then artificial aging. In most cases, this requires a secondary "calibration" process to fix the distortion due to the high temperature solution heat treat and quench process. For complicated deep draw parts, superplastic forming is often utilized^[10-14]. Superplastic forming is a low speed, high temperature process that also requires a high temperature heat treatment and perhaps calibration step after forming. Both of these technologies are not well suited to the high volume production rates of the automotive industry. One process that may be suitable for automotive manufacturing is warm forming. This process is targeted at a temperature in which the formability of the alloy is expanded sufficiently to stamp complex parts while not too high to destroy the T6 temper. Previous studies focused on the experimental study of formability at different temperatures^[15, 16]. The numerical simulation of the warm forming behavior of high strength aluminum alloys has not been fully explored. For optimization of the warm forming process of high strength aluminum, a suitable material model under warm forming conditions needs to be developed. A detailed experimental investigation on warm forming formability has been conducted in Part 1^[17] of this research. In the paper, a material model based on the experimental data is developed for simulation of warm forming of high strength AA7075. The limit drawing ratio (LDR) test and the limit dome height (LDH) test are simulated and compared with the experimental data.

1 Constitutive Equation Development

Flow stress represents the size of the yield function during deformation^[18]. To accurately simulate the sheet metal forming process, an ap-

propriate equation to describe the stress-strain relationship is required. The equation describing changes in the flow stress of the material depends on deformation conditions such as strain rate and temperature. For the isothermal warm forming processes, the temperature of the die and blank are kept constant during the process. Therefore, for the constitutive equation in isothermal warm forming, only strain rate is considered. As noted in Table 1 several equations have been used in describing the stress-strain relationship, such as, Ludwik equation, Swift equation, Ghosh equation, Voce and Hockett-Sherby equation, and so on.

Table 1 Constitutive equation for sheet metal forming

Name	Equation
Ludwik	$\sigma = A\epsilon_p^n$
Swift	$\sigma = A(\epsilon_0 + \epsilon_p)^n$
Ghosh	$\sigma = A(\epsilon_0 + \epsilon_p)^n - C$
Voce	$\sigma = A - (A - B)e^{-m\epsilon_p}$
Hockett-Sherby	$\sigma = A - (A - B)e^{-m\epsilon_p^n}$

Ludwik and Swift equation can be included in Ghosh equation and Voce equation can be included in Hockett-Sherby equation. A simplified Ghosh and Hockett-Sherby equation can be shown as follows

$$\text{Ghosh: } \sigma_Y(\epsilon_p) = k(\epsilon_0 + \epsilon_p)^n - p$$

$$\text{Hockett-Sherby: } \sigma_Y(\epsilon_p) = a - be^{-c\epsilon_p^n}$$

Stress-strain relationship from the experiment in Ref. [17] is used to fit the equation with a regression method. As shown in Fig. 1, the Ghosh equation predicts a higher stress than Hockett-Sherby after the ultimate stress is reached^[18].

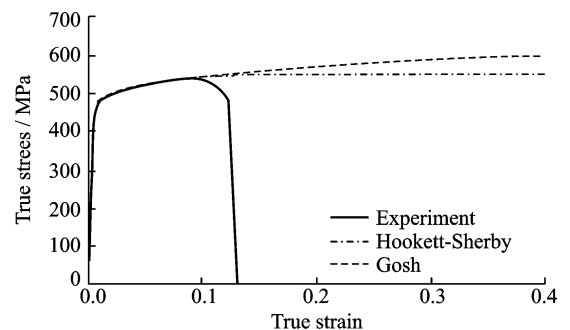


Fig. 1 Regression results of stress-strain relationship with different equations at 140 °C

The stress-strain relationship not only depends on temperature, but also strain rate at elevated temperature. The Cowper-Symonds model is used in the paper to describe the strain rate sensitivity. The constitutive equation form can be shown as

$$\sigma = (a - b e^{-c \dot{\epsilon}_p^n}) \left[1 + \left(\frac{\dot{\epsilon}}{C} \right)^{1/P} \right]$$

A regression method is used in determination of the parameters in this equation. Table 2 gives the parameters of the Hockett-Sherby and the strain rate Cowper-Symonds equation at temperatures of 140, 180 and 220 °C.

Table 2 Constitutive equation parameters of AA7075-T6 at different temperatures

Temperature/ °C	a	b	c	n	C	P
140	516.38	90.37	9.68	0.77	0.199	0.455
180	277	110.598	3.09	0.23	9.258	13.5
220	152	8.47	66	1.26	0.00029	18

2 Yield Function

The three-parameter yield function presented by Barlat is one of the most accurate yield functions for aluminum alloys^[19]. It simultaneously accounts for yield stress and R value directionalities. The yield function for plane stress can be defined as

$$\Phi = a |K_1 + K_2|^m + a |K_1 - K_2|^m + c |2K_2|^m = 2\sigma_Y^m$$

where σ_Y is the yield stress. K_1 , K_2 are given by

$$K_1 = \frac{\sigma_x + h\sigma_y}{2}$$

$$K_2 = \sqrt{\left(\frac{\sigma_x - h\sigma_y}{2} \right)^2 + p^2 \tau_{xy}^2}$$

The anisotropic material constants a , c , h , and p are obtained through R_0 , R_{45} and R_{90}

$$a = 2 - 2 \sqrt{\frac{R_0}{1+R_0} \frac{R_{90}}{1+R_{90}}}$$

$$c = 2 - a$$

$$h = \sqrt{\frac{R_0}{1+R_0} \frac{1+R_{90}}{R_{90}}}$$

The anisotropy parameter p is calculated implicitly. According to Barlat and Lian the R value (width to thickness strain ratio) for any angle φ can be calculated from

$$R_\varphi = \frac{2m\sigma_Y^m}{\left(\frac{\partial \Phi}{\partial \sigma_x} + \frac{\partial \Phi}{\partial \sigma_y} \right) \sigma_\varphi} - 1$$

where σ_φ is the uniaxial tension in the φ direction. This expression can be used to iteratively calculate the value of p . Let $\varphi = 45$ and define a function g as

$$g(p) = \frac{2m\sigma_Y^m}{\left(\frac{\partial \Phi}{\partial \sigma_x} + \frac{\partial \Phi}{\partial \sigma_y} \right) \sigma_\varphi} - 1 - R_{45}$$

From tensile test experiments, the following anisotropic material can be tested and used to calculate the yield surface of Barlat89. An iterative search is used to find p value as a function of temperature. R values for various temperatures are shown in Table 3.

Table 3 Anisotropic parameters of AA7075-T6 at different temperatures

Temperature/°C	R_0	R_{45}	R_{90}
140	0.43	0.69	0.69
180	0.50	0.74	0.69
220	0.51	0.77	0.68

3 Numerical Analysis

Finite element simulations of LDH and LDR tests are conducted using the commercial software LS-DYNA 971. A model of the die and blank are shown in Fig. 2. Hypermesh is used to create the finite element mesh, assign the boundary conditions and build the LS-DYNA input deck for the analysis. Only one-quarter of the geometry is modeled due to the symmetric boundary conditions. The constitutive equations and yield criterion shown in Sections 1 and 2 of the paper are used in the simulation. A friction coefficient of 0.06 is used in the simulation.

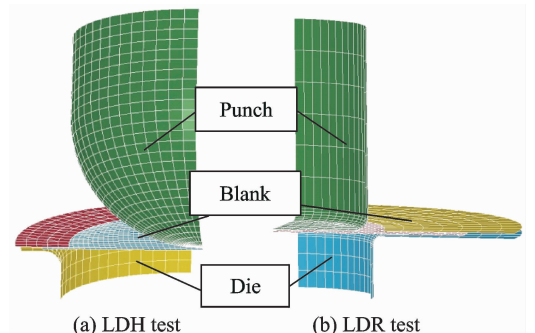


Fig. 2 FEM model of LDH and LDR tests

For the LDH processes, a blank with diameter of 140 mm is used and the boundary of the side is restrained with binder force of 100 kN, so no material is drawn in. For the LDR processes, blanks with different diameters are used to determine the LDR value.

4 Results and Discussions

4.1 LDH

Fig. 3 shows the experimental and simulation results of biaxial stretching at 180 °C. The forming limit diagram which is obtained from Part 1^[17] is used as a failure criterion. The simulation appears to be an accurate predictor of punch displacement. Similar results are also found at 140 and 220 °C.

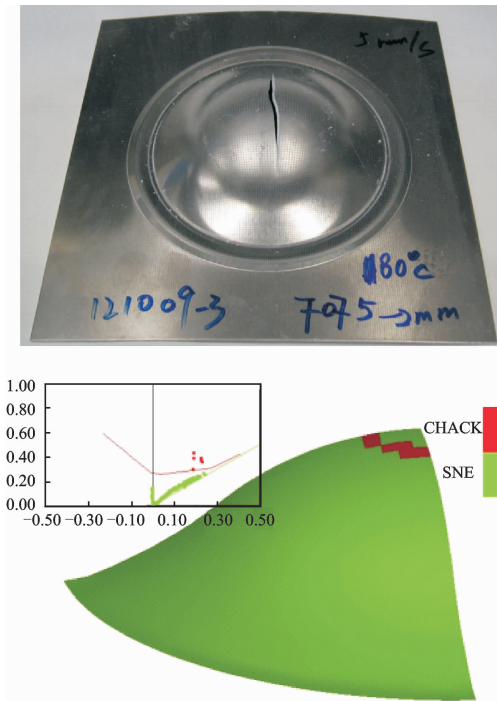


Fig. 3 Simulation and experimental results of LDH at 180 °C

Fig. 4 shows a comparison between experimental and numerical results of the punch load v. s. punch depth at three elevated temperatures. As seen in the plot, the simulated punch forces agree well with the experimental results at 180 and 220 °C. For the experiment performed at 140 °C, specimens fractured earlier than the prediction from simulation. This may be a result of the material model's inability to capture the fracture behavior at the lower temperature.

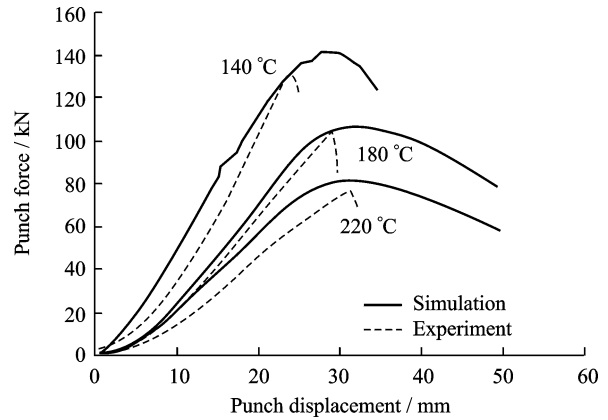


Fig. 4 Punch force plotted as a function of displacement at different temperatures (punch speed = 5 mm/s)

To investigate the strain rate sensitivity, the LDH process at 180 °C under different punch speeds is analyzed. Punch force and penetration curves are shown in Fig. 5. Results indicate the simulation captures the strain rate effect.

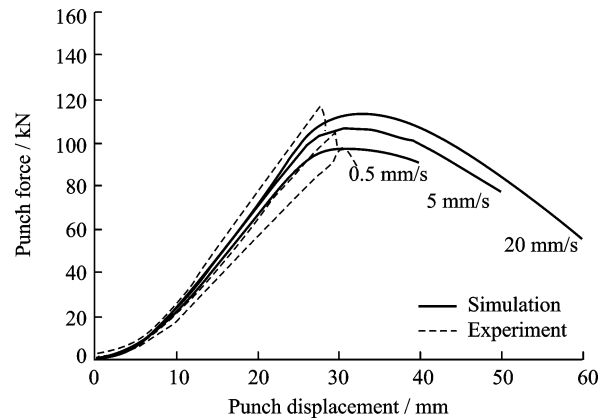


Fig. 5 Punch force plotted as a function of punch displacement for different forming speeds at 180 °C

4.2 LDR

The LDR value is defined as the maximum blank diameter which can be formed without fracture divided by the diameter of the punch. Fig. 6 shows both photographs of LDR samples and the corresponding simulation results for two different blank diameters at 140 °C. Simulations are performed with a friction coefficient of 0.04. Results indicate that a blank diameter of 190 mm can be formed but a blank diameter of 200 mm fractures during forming.

Fig. 7 shows the LDR values predicted from simulation and determined from experiment. Re-

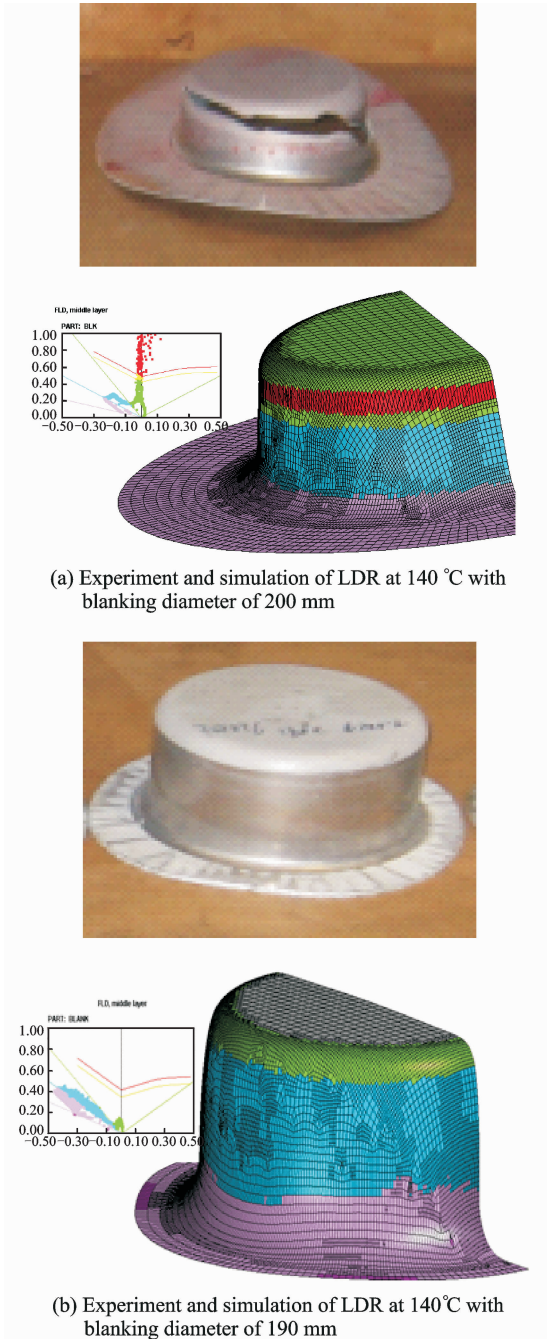


Fig. 6 LDR in experiment and simulation

results show that when the friction coefficient is 0.04, the experimental results agree with the predictions from simulation at a set temperature of 140 °C. However, simulation results over-predict LDR at the same coefficient of friction at the higher temperatures of 180 and 220 °C. When the friction coefficient is changed to 0.08, the simulation results at 180 °C are much closer to the experimental results. This may be a result of the sensitivity of the LDR experiment to friction coef-

efficient coupled with the temperature effect on the lubricant. To better understand the effect, more testing is required to better measure the friction coefficient as a function of temperature.

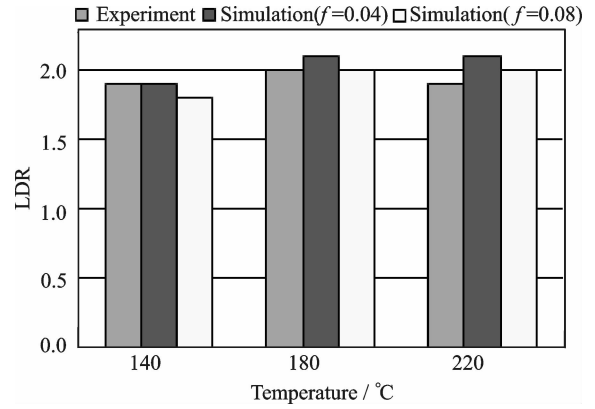


Fig. 7 LDR values tested and predicted by simulation for two friction coefficients

5 Conclusions

A strain rate dependent anisotropic material model for finite element analysis of warm forming of AA7075 is implemented into the finite element code LS-DYNA. The Hockett-Sherby hardening law is used to predict the flow stress at elevated temperature and anisotropic yield model parameters at elevated temperature are developed. The processes used in both LDH and LDR tests are simulated with the developed model. Forming limit diagrams developed from experiment at several elevated temperatures in a previous study are used to predict the failure in the numerical simulations. Simulation results accurately predicted the failure behavior of LDH and LDR tests indicate that this material model can be used to predict the material behavior of the AA7075-T6 alloy during isothermal warm forming.

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