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ARTICLE

Experimental and Numerical Investigation on Springback of Automotive Aluminum Alloy Sheet

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Abstract: In the forming process of automotive aluminum alloy, springback is one of the main defects and difficult to control. In this study, stress-strain curves of automotive aluminum alloy 6061 were obtained through tensile tests at room temperature and the constitutive model was established based on a modified Johnson-Cook equation. The model was used in finite element simulation of V-bending tests to investigate the effect of different anisotropic yield criteria on accuracy of springback prediction. Experimental and simulation results indicate that the prediction results are more accurate when YLD2000-2d yield criterion is applied and the efficacy of the model in springback analysis is verified. Furthermore, the effect of several different factors on springback behavior of aluminum alloy sheet was investigated, including deformation degree, drawing velocity, friction condition and blank holding force. The experimental and numerical investigation is applied in stamping forming process of aluminum alloy inner panel of engine cover and the springback is reduced effectively.

Key words: aluminum alloy; springback; V-bending test; constitutive modeling

Nowadays, lightweight has become an inevitable trend of the development of automobile industry, which is of great importance for resource conservation and environmental protection. The usage of lightweight materials is an important approach to achieve the lightweight of automobile. Thanks to specific advantages, aluminum alloy becomes a rather important lightweight material used in automobile industry. However, some weakness exists in the forming property of aluminum alloy under cold forming conditions, which restricts the application of aluminum alloy. In general, wrinkling tends to take place on aluminum alloy during stamping forming as well as crack, springback, etc. Springback, particularly is one of the main obstacles in the forming process, which is influenced by many factors[1], including sheet thickness, elastic modulus, yield stress and work hardening exponent, etc. Severe springback during unloading phase of sheet forming will influence the dimensional accuracy of workpiece to a great extent. Springback will also do harm to surface quality of formed parts and affect the component assembly. Meanwhile, aluminum alloys are rather more vulnerable to springback due to their low Young's modulus[2]. As a consequence, it is of vital importance to investigate the springback rules of aluminum alloy in the forming process and explore methods to solve this problem.

A large number of studies have been concentrated on the mechanical property of aluminum alloy[3-5]. Due to the more pronounced Bauschinger effect and reverse yields of aluminum, it is more complicated in the actual forming process to predict springback for aluminum than for steel[4]. A new model for springback was established by Gau et al[4], using a material parameter (CM) to handle the Bauschinger effect. Bending experiments for AA6022-T4 and AA6111-T4 were conducted and four different deformation processes were applied to investigate the influence of the Bauschinger effect on the springback phenomenon. Through comparison between experimental results and simulation, it is proved that the new

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model gets better results compared with the isotropic and kinematic hardening models and the Mroz multiple surfaces model. The modified form of asymmetric non-quadratic yield function (YLD96) for plane stress conditions was used in the prediction of springback of anisotropic sheet[5], which considers nonlinear isotropic and nonlinear kinematic hardening. The simulation process shows the necessity of considering the Bauschinger effect in the constitutive equations. Draw-bending tests on AA2024 and AA7075 were conducted and the prediction of springback shows good agreement with experimental results. These results confirm the efficacy of the yield surface model for predicting deformation subject to the Bauschinger effect.

Forming process condition is one of the direct factors that decide the forming quality. The change of process conditions has pronounced effects on springback behavior, which is the highlight of relevant researches all the time[1,6-10]. Research indicates that springback is more related to the thickness and bending angle while the length of workpiece has little effect on springback behavior[6]. V-bending process for 1050-H14 aluminum alloy was conducted by Erdin et al.[7] and various holding forces were applied at the end of the bending process. The result shows that the application of holding force can decrease springback dramatically and annealing can also decrease springback due to the removal of residual stresses. Through U-form stretch bending tests, the study of the effect on springback of different technological conditions such as blank holding force and die radius of curvature was conducted[8]. The results show that springback will decrease in a non-linear fashion with stretching height and an increase in blank holding force can also reduce springback by reducing sliding of the sheet between the die and the blank holder. Larger entrance radius of the die will also contribute to reduction of final springback.

Thanks to the development of finite element analysis (FEA) technology, numerical simulation has become a rapid and low-cost method for solving engineering problems[11] and optimizing forming process and mold design. In recent years, more and more research work have been concentrated on the application of numerical methods, which contribute to the prediction and analysis of springback behavior[12-19]. A mixed hardening model with combination of classical non-linear kinematic hardening model and isotropic hardening theory was implemented by Tang et al.[13] to consider cyclic behavior and the Bauschinger effect. The model was implemented into ABAQUS and the comparison between simulated results and experimental data show that the model can predict springback well. Tensile tests were performed by Toros[14] to obtain a cyclic stress-strain curve. The cyclic stress-strain curves and springback test results were implemented in optimization process to determinate Yoshida-Uemori two surface plasticity model parameters. A commercial LS-DYNA software was applied to 60° V-Die bending and U bending simulations. The results show that the prediction of springback will be more accurate when the model parameters are determined from both the definition of the hysteresis loops and springback target. A constitutive model based on artificial neural network (ANN) was also proposed and used in FE code for springback prediction in sheet metal forming[17].

In this study, stress-strain curves of AA6061-O were obtained by tensile tests at room temperature and the constitutive model was established based on a modified Johnson-Cook equation. The model was applied to finite element simulation of V-bending procedure. The effect of different anisotropic yield criterions on accuracy of springback prediction was studied based on V-bending process simulation and experimental investigation and the efficacy of this model could be verified. Simulation procedures were applied to investigate the effect of several different factors on springback. The experimental and numerical investigation was applied in stamping forming process of aluminum alloy inner panel of engine cover and the springback was reduced effectively.

1 Constitutive Modeling

1.1 Tensile tests at room temperature

The applied materials were obtained from a commercial company as sheet metal of AA6061, with the thickness of 1.2 mm and chemical composition shown in Table 1. The tensile test specimens were machined through wire cutting along the rolling direction (Fig.1). All the specimens were annealed in a resistance furnace. The tensile tests were conducted by a SANSCMT-6104 electronic universal testing machine at room temperature and the strain rates ranged from 2.8×10^{-4} s^{-1} to 2.3×10^{-1} s^{-1}.

1.2 Constitutive modeling

The true stress-strain curves under different strain rates are shown in Fig.2. According to the results we can notice that with the increase of strain, the true stress of the applied material increases rapidly at the beginning and then the change of stress tends to be gentle. Meanwhile, due to the effect of strain rate hardening, the true stress increases with the strain rate. Overall, the flow stress of material is influenced by strain hardening and strain rate hardening simultaneously.

In this study, a modified Johnson-Cook constitutive model was used to describe the stress-strain response. The fundamental form of the original model is described as

$$\sigma = [A + B\varepsilon^n][1 + C\ln\dot{\varepsilon}^*][1 - T^{*m}] \tag{1}$$

where σ and ε represent the stress and equivalent strain, A is the yield stress, B and n are coefficients which represent the effect of strain hardening, C is the coefficient of strain rate hardening effect, $\dot{\varepsilon}^*=\dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless plastic strain rate with $\dot{\varepsilon}_0$ being the reference strain rate, m is the thermal softening factor, $T^* = (T - T_r)/(T_m - T_r)$ is the homologous temperature with T_r being the room temperature and T_m being the melting

Table 1 Chemical composition of AA6061 sheet (wt%)

Cu	Mn	Mg	Zn	Ti	Si	Fe	Al
0.23	0.023	0.91	0.023	0.018	0.4	0.34	Bal.

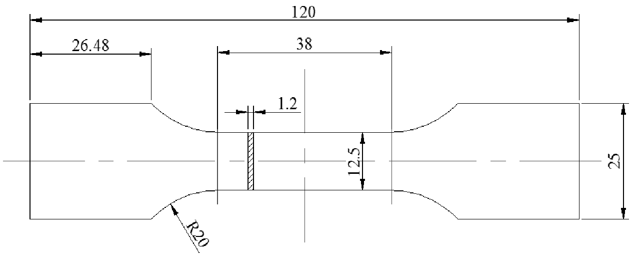

Fig.1 Tensile test specimen (mm)

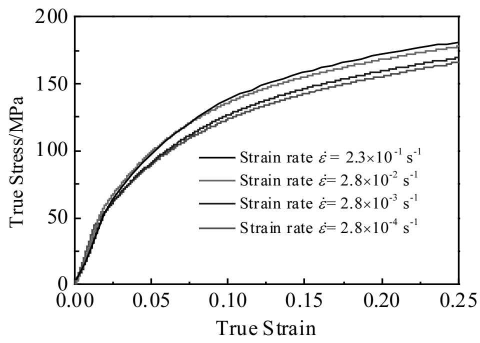

Fig.2 True stress-strain curves of AA6061-O under different strain rates

temperature. Under cold forming condition the equation can be described as

$$\sigma = [A + B\varepsilon^n][1 + C\ln\dot{\varepsilon}^*] \quad (2)$$

Based on the experimental data, the material constants can be obtained with the help of mathematic methods and software. Taking the $\dot{\varepsilon}_0$ = 2.8×10^{-4} s^{-1} as the reference strain rate, the influence of strain rate can be ignored when $\dot{\varepsilon} = \dot{\varepsilon}_0$, then the Eq.(2) can be simplified as

$$\sigma = A + B\varepsilon^n \quad (3)$$

The yield stress A can be gained from the tensile tests, by taking the natural logarithm of both sides of Eq.(3), the equation can be expressed as

$$\ln(\sigma - A) = \ln B + n\ln\varepsilon \quad (4)$$

It is obvious that the intercept of the curve of $\ln(\sigma - A)$ - $\ln\varepsilon$ is the value of $\ln B$ and the slope is the value of n, which is shown in Fig.3.

The original Johnson-Cook constitutive model is based on the assumption that the coefficient C is a constant that can be calculated by the formula $C=[\sigma/(A+B\varepsilon^n)-1]/\ln\dot{\varepsilon}$. However, as shown in Fig.4, the coefficient C is not a constant but a variable changing with strain and strain rate. In order to represent the change of hardening effect under different strain rates and deformation degree so that the constitutive model can describe the plastic flow behavior of material more accurately, a modified Johnson-Cook model was considered.

According to the results in Fig.4, the coefficient C can be described as quadratic function of ε(Fig.4a) and $\ln\dot{\varepsilon}^*$ (Fig.4b). Taking the interaction between the two independent variables into consideration, the coefficient C can be expressed as[20]:

$$C = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\ln\dot{\varepsilon}^* + C_4(\ln\dot{\varepsilon}^*)^2 + C_5\varepsilon\ln\dot{\varepsilon}^* \quad (5)$$

where $C_0 \sim C_5$ are constants to be solved. The values of C at different strains and strain rates are substituted into Eq.(5) and the constants can be determined using the least square method with the help of MATLAB software (Table 2).

Fig.5 shows the comparison between experimental and predicted curves under different strain rates. In general, the modified Johnson-Cook constitutive model can describe the plastic flow behavior of AA6061-O under cold forming condition.

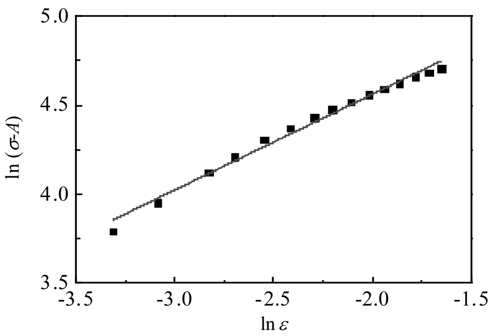

Fig.3 Relationship between ln(σ-A) and lnε

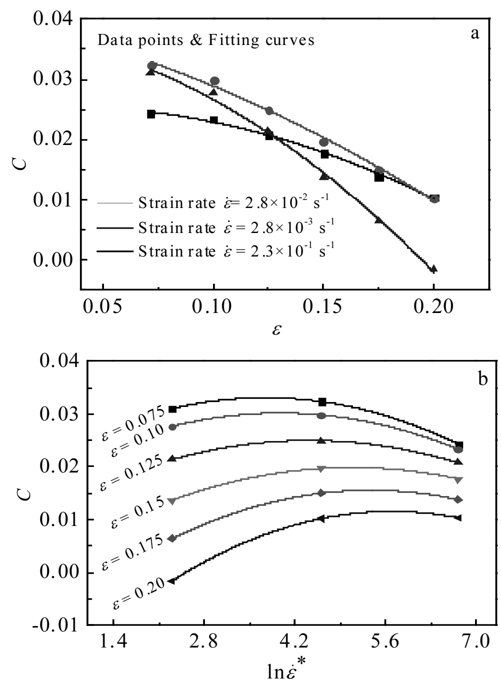

Fig.4 Relationship between C and ε (a), $\ln\dot{\varepsilon}^*$ (b)

2 Finite Element Simulation and Verification

2.1 Simulation procedure

Due to the pronounced anisotropy of aluminum alloy, different anisotropic yield criteria are proposed and considered in many studies. Hill 1948 yield criterion[21] was proposed by Hill in 1948 and it is suitable for orthogonal anisotropic materials. Barlat 1989 yield criterion[22] used a Lankford coefficient to determine the anisotropy of material and the plane anisotropy under plane stress condition was taken into consideration.

Due to lack of effective parameters, some yield criteria cannot describe the anisotropic characters completely. In 2003, Barlat et al.[23] proposed YLD2000-2d yield criterion, which can

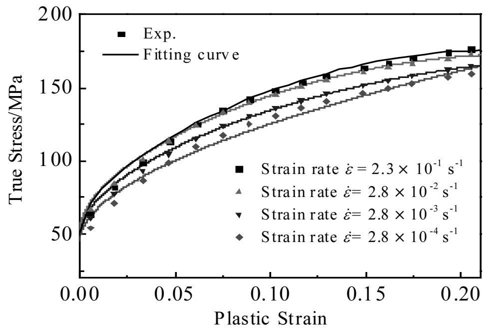

Fig.5 Comparison of experimental curves and predicted curves at different strain rates

Table 2 Parameters of the modified Johnson-Cook constitutive model for AA6061-O

Parameter	A/MPa	B/MPa	n	C_0	C_1	C_2	C_3	C_4	C_5
Value	45.919	281.851	0.53939	0.0226	-0.0216	-1.0262	0.0060	-0.0010	0.0279

be expressed as

$$\phi = |X_1' - X_2'|^a + |2X_2'' + X_1''|^a + |2X_1'' + X_2''|^a = 2\bar{\sigma}^a \quad (6)$$

where $\bar{\sigma}$ is equivalent stress, a is material coefficient, X_i' and X_i'' can be determined as

$$X' = C'S = C'T\sigma_c = L'\sigma_c \quad (7)$$

$$X'' = C''S = C''T\sigma_c = L''\sigma_c \quad (8)$$

where σ_c is Cauchy stress tensor, S is Cauchy stress tensor component matrix, C', C'' and T are linear transformation matrixes. L' and L'' contain eight independent anisotropic coefficients.

Three yield criteria were used to conduct V-bending simulation in LS-DYNA to explore their influence on the accuracy of springback prediction[24,25]. The constitutive model obtained above was applied in the simulation. In consideration of the experimental procedures, the finite element model is composed of upper die, lower die and blank sheet, which are defined as shell element (Fig.6). The material is defined as AA6061 and the elastic module is determined to be 69 GPa. Poisson ratio is set as 0.33. The element size of blank sheet is defined as 24 and the thickness is 3 mm. The friction coefficient is defined as 0.125 and the drawing velocity is set as 1 mm/s. Based on the geometric symmetry, the simulation process was conducted using 1/4 model in order to reduce the amount of calculation.

2.2 Experimental verification

6061-O aluminum alloy sheets were used in the V-bending tests. The dimensions of the specimens are 60 mm in length, 20 mm in width and 3 mm in thickness. The tests were carried out according to GB/T 232-2010 in a SANSCMT-6104 electronic universal testing machine with punch fillet radius of 5 mm, which is shown in Fig.7a. The punch span L=19 mm and different values of punch displacement was applied to change deformation degree of specimens (Fig.7b).

A GMASystem grid strain measurement and analysis system were used to obtain the strain value in deformation area, which represents the deformation degree of specimens. The solid model of V-bending specimens after springback could be obtained by a HandySCAN 3D scanner. Then the model of V-bending specimens before and after springback were imported into Geomagic software under the same coordinate system and variance analysis was conducted to get the springback value of specimens (Fig.8).

The simulation results based on three yield criteria are shown in Fig.9. Comparing the experimental data with the predicted results, we can notice that the accuracy of springback prediction behaves higher when YLD2000-2d yield criterion is applied. Meanwhile, the efficacy of the constitutive model was verified in development.

3 Analysis of Springback

Based on the material model verified in the previous section, springback behavior of aluminum alloy sheet in V-bending process was simulated under various kinds of forming conditions. The effect of deformation degree, drawing velocity, friction condition and blank holding force on springback was considered.

3.1 Effect of deformation degree

It can be obtained based on the results from Fig.9 that springback value increases with deformation degree increase. To investigate the reason for this phenomenon, this may result from the fact that with the increase of deformation degree, the length of deformation area will also increase and the deformation in unit length will decrease when the corner radius of mold is constant. In consequence, the proportion of elastic deformation will increase accordingly, which results in the increase of springback.

3.2 Effect of drawing velocity

The finite element model was applied to investigate the effect of drawing velocity on springback. The springback value of V-bending specimens under different drawing velocities are shown in Fig.10. We can notice that the springback value remain relatively stable with the change of drawing velocity.

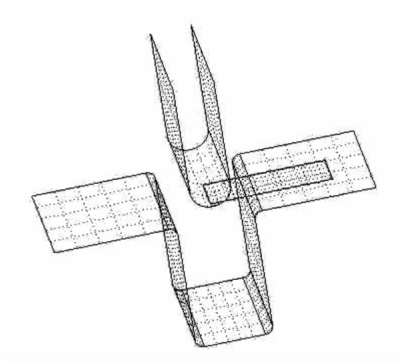

Fig.6 Finite element model of V-bending

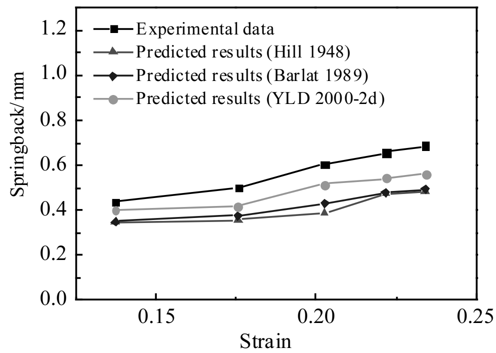

Fig.9 Influence of different anisotropic yield criterions on accuracy of springback prediction

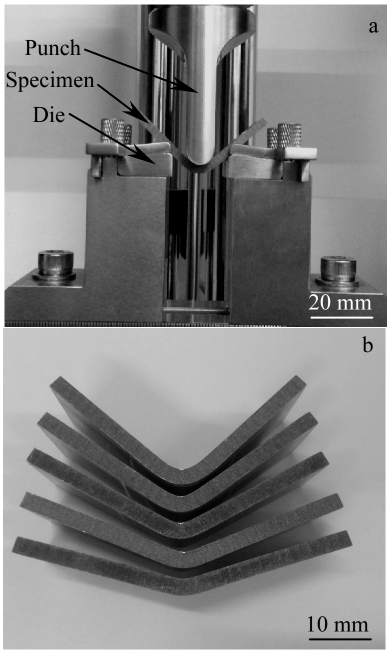

Fig.7 V-bending test setup (a) and specimens (b)

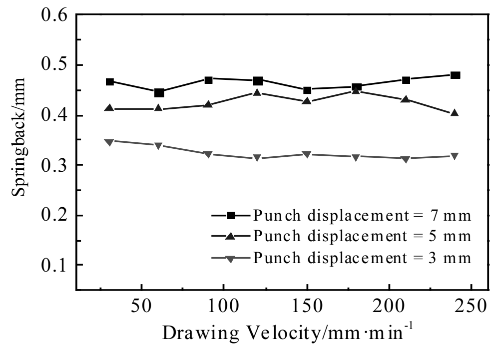

Fig.10 Effect of drawing velocity on springback

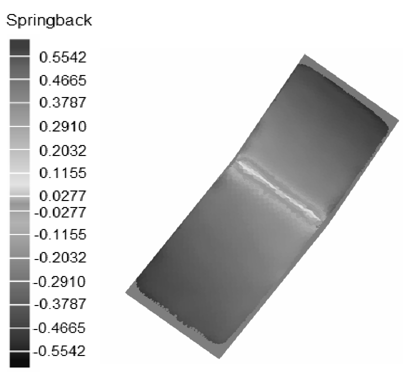

Fig.8 Measurement of springback of V-bending specimen

The influence of drawing velocity on springback is complex. On the one hand, the increase of drawing velocity enhances the work hardening effect, the plastic deformation resistance also increases and the springback is more pronounced accordingly. On the other hand, the increase of drawing velocity causes heat effect in some degree, which contributes to the reduction of springback through reducing the yield strength and plastic deformation resistance of material. Generally speaking, the effect of drawing velocity on material property is slight at room temperature and the change of springback value is inconspicuous.

3.3 Effect of friction condition

During forming process, the frictional resistance increases with the friction coefficient, which enhances the tension applied to the sheet metal. In consequence, the plastic deformation area extends and the springback is reduced. In this section, the friction coefficient was changed under different punch displacement and invariability of other processing parameters to investigate its influence on springback. The value of friction coefficient changed from 0.05 to 0.20 and the results of springback characterization are shown in Fig.11. It can be obtained that springback of formed sheet tends to decrease with the increase of friction coefficient.

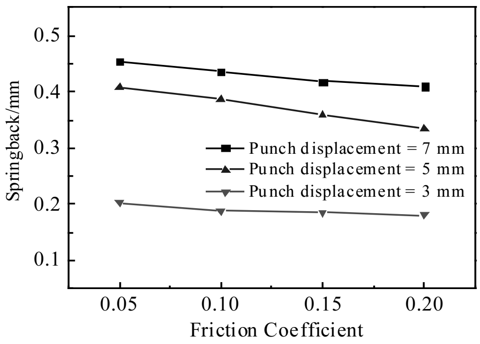

Fig.11 Effect of friction coefficient on springback

3.4 Effect of blank holding force

Blank holding force is another sensitive factor in sheet metal forming, which cannot be ignored. Based on the constitutive model verified above, further numerical simulation can be conducted to investigate the effect of blank holding force on springback. In this section, a blank holder was applied in the finite element model established above. The effect of blank holding force on springback was investigated under different punch displacements and the results are shown in Fig.12. It is obvious that springback is reduced effectively after blank holder is applied. Furthermore, the results indicate that springback value decreases with the increase of blank holding force. This may be explained by the fact that the flow resistance increases with blank holding force, which changes the stress-strain appearance of material. The deformation direction of inner and outer layer of sheet metal tend to be consistent and the springback can be reduced.

4 Application in Aluminum Alloy Sheet Forming

The experimental and numerical research on springback rules will serve in actual production. In this paper, an aluminum alloy inner panel of engine cover was taken as an example. The improvement of processing parameters and springback compensation were applied to reduce the springback so as to acquire better quality of products.

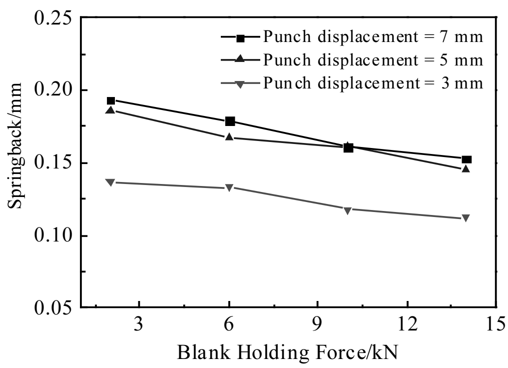

Fig.12 Effect of blank holding force on springback

Springback compensation is a common method to reduce springback in actual production and often conducted in combination with adjustment of processing parameters. In this section, an AutoForm software platform was applied to conduct analysis of springback compensation. The modified Johnson-Cook constitutive model was applied and the simulation element was defined as elastic plastic shell element. Processing parameters were adjusted through numerical simulation, including blank holding force, friction coefficient and drawing velocity, etc. As well as reduction of springback, the forming defects caused by irrationality of processing parameters should also receive enough attention. As previously mentioned, the springback of the component decreased with the increase of blank holding force and friction coefficient. However, partial crack occurred in the component when blank holding force was overloaded and the trend of wrinkle and crack occurred when lubrication was poor (Fig.13). Taking both the formability and springback of the component into consideration, an orthogonal test was conducted to determine the value of processing parameters. The blank holding force is defined as 1200 kN and the friction coefficient is set as 0.15. The drawing velocity is determined as 1 mm/s.

Based on the springback compensation and adjustment of processing parameters, stamping test for an aluminum alloy inner panel of engine hood was conducted and the springback was effectively controlled (Fig.14).

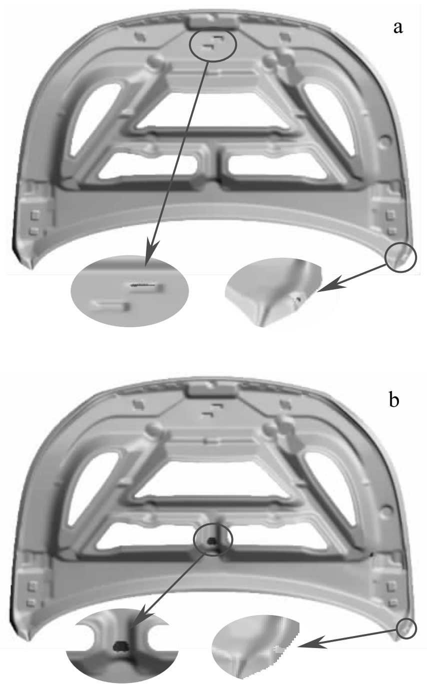

Fig.13 Forming defects caused by irrationality of processing parameters: (a) crack and (b) trend of wrinkle and crack

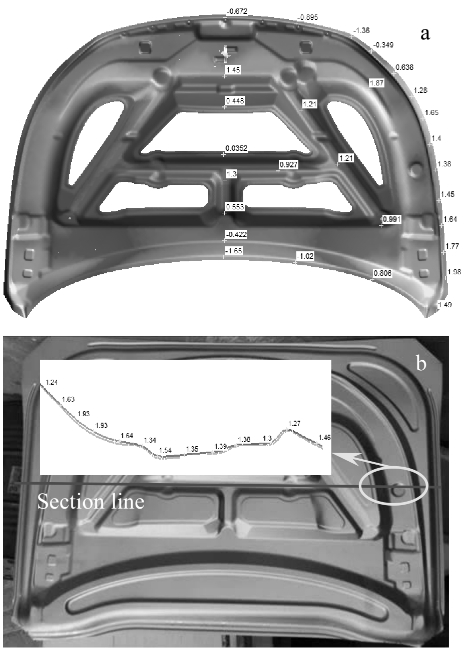

Fig.14 Springback compensation (a) and measurement of springback (b) for aluminum alloy inner panel of engine cover

5 Conclusions

1) A modified Johnson-Cook constitutive model was established based on the results of tensile tests for 6061-O aluminum alloy sheet. The influence of strain and strain rate on plastic flow behavior was considered more adequately.

2) Finite element simulation procedures were conducted based on three different anisotropic yield criterions and the constitutive model above was applied. The results indicate that the springback prediction is more accurate when YLD2000-2d yield criterion is applied and the efficacy of the model can be verified through comparison with experimental results.

3) The finite element model was used in simulation procedures to investigate the effect of different factors on springback. Several influential factors are considered in this section, including deformation degree, drawing velocity, friction condition and blank holding force.

4) Based on the analysis of experimental data and numerical simulation, the improvement of processing parameters and springback compensation can be used in stamping forming of aluminum alloy automotive part and springback can be reduced effectively.

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车用铝合金板材回弹规律研究

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摘　要：在车用铝合金材料的成形加工过程中，回弹是主要的成形缺陷之一并且较难控制。本研究对车用 6061 铝合金板材进行了室温拉伸试验获得其应力-应变曲线并建立改进的 Johnson-Cook 本构模型。该模型被应用于 V 形弯曲试验的有限元仿真中，研究不同各向异性屈服准则对板料回弹预测精度的影响。仿真结果表明，应用 YLD2000-2d 屈服准则时其预测精度较高，同时也验证了该模型用于回弹分析的有效性。进一步探究不同因素如变形程度，冲压速度，摩擦条件，压边力等对铝合金板材回弹行为的影响规律，并应用于铝合金发罩内板的冲压成形过程，能够有效减小工件的回弹。

关键词：铝合金；回弹；V形弯曲；本构建模

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