Kinematic hardening performance of 5052 aluminium alloy subjected to cyclic compression-tension

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Abstract. In order to study the kinematic hardening performance of 5052 aluminium alloy, experiments of cyclic compression-tension were conducted in this work. The kinematic hardening performance including the Bauschinger effect, transient hardening and permanent softening shown by the forward-reverse stress-strain curves was discussed. The famous Yoshida-Uemori hardening model was adopted to characterize the kinematic hardening behaviour of AA5052. The parameters in Yoshida-Uemori hardening model were identified with an inverse method composed by experiments, finite element simulation and optimization. Experiments of cyclic loading-unloading uniaxial tension were also performed to identify the degradation of the elastic modulus of AA5052 with the plastic strain. U-bending springback simulation using the Yoshida-Uemori hardening model was conducted. The results showed that the investigated AA5052 has strong Bauschinger effect, transient hardening and permanent softening. The percentage of elastic modulus degradation could reach 16.7% at 8.8% plastic strain. The Yoshida-Uemori hardening model can capture the kinematic hardening behaviour of AA5052 very well.

1. Introduction

As the problems of energy consumption and environmental pollution are increasingly urgent, light-weighting has been a crucial way for the sustainable development of automotive industries. Replacing conventional steels by aluminium alloys is an effective approach to achieve light weighting. Correspondingly, aluminium alloys have been extensively applied in the automobiles. During the stamping processes, aluminium alloys have more serious springback problems than steels have. Precise springback simulation is crucial to the springback control for aluminium alloys. Correct springback simulation need correct materials parameters and suitable material model including a yield criterion, a hardening model and a flow rule. Among which, a suitable hardening model combined with a correct elastic modulus model have been proved to be effective in improving the precision of springback simulation [1,2]. Commonly used hardening models can be classified as the isotropic, the kinematic and the combined hardening types. The isotropic hardening theory regards the subsequent yield surface only has size change without location change. This type of models was unable to describe the Bauschinger effect of some metals because they can’t reproduce the material behaviour during reverse loading. In order to solve this problem, the kinematic hardening models consider the movement of the yield surface while neglect the size change as the plastic deformation advances. This theory can predict some kinematic hardening phenomenon very well, such as,
Bauschinger effect, permanent softening, and transient hardening and cross hardening.

One of the best known kinematic hardening models was presented by Armstrong and Frederick [3]. After that much efforts have been put into developing advanced hardening models for sheet metals, such as, the Geng-Wagoner’s model[4], Chun’s ANK model[5], Chaboche multi-backstress model[6,7], Yoshida-Uemori two-surface model[8,9] and so on. The Geng-Wagoner’s model can reproduce the Bauschinger effect, transient hardening and permanent softening very well but can’t capture the cross hardening effect. The ANK model can’t produce the permanent softening effect. Chaboche model is very effective in the ratcheting effect for the materials subjected to cyclic loading. Yoshida-Uemori model adopted two surfaces to describe the yielding behaviour. It assumed that the yielding surface is smaller than the boundary surface, which makes it possible to capture the Bauschinger effect and the subsequent transient hardening effect. The bounding surface can represent the global workhardening and permanent softening effect. Yoshida-Uemori model has been proved to work well in capturing the kinematic hardening behaviour for some high strength steels and aluminium alloys.

On the hardening performance of aluminium alloys, Jordon [10] investigated the Bauschinger effect of a cast A356-T6 aluminium alloy and a rolled 7075 aluminium alloy from the interaction of particles and dislocation. Cardoso [11] adopted a phenomenological two yield surface model to study the Bauschinger effect of aluminium alloy. Yilamu [12] adopted the Y-U model to simulate the Bauschinger effect of a steel-aluminium clad sheet in draw bending. Proudhon [13] investigated the kinematic hardening performance of AA6111 subjected to cyclic tension-compression. It was shown that the Bauschinger effect depends strongly on the precipitation state. Taherizadeh [14] combined the non-associated flow rule with anisotropic-directional hardening and nonlinear kinematic hardening law and proposed a new constitutive model. Experiments showed that significant improvements in springback prediction were made for both DP steel and AA 6022 in terms of sidewall curvature. Tamura [15] investigated the elastoplastic properties of AA5052 and AA6016 sheets under in-plane cyclic tension-compression. Both the sheets showed strong cyclic hardening with weak Bauschinger effect. Recently, Uemori et al. [16] simulated the springback of aluminium alloys considering the effect of initial anisotropy and the Bauschinger effect. They concluded that the springback simulation using the Yoshida yield function and the Yoshida-Uemori model showed an excellent agreement with the experimental data. Muhammad et al. [17] pointed out that the deformation-induced-dislocation microstructures can induce intragranular backstess due to blockage of dislocation passage. Generally speaking, springback simulation precision for aluminium alloys is still unsatisfied because aluminium alloys have complicated hardening and anisotropic properties.

Besides the hardening model, the elastic modulus was another important material parameter for the springback simulation. Furthermore, the elastic modulus of aluminium alloys changed with the plastic deformation. As a matter of fact, the elastic modulus was regarded as a constant in most of the available references, which had been proved to be an important error source for springback prediction.

The aim of this work was to identify the effect of the degradation of the elastic modulus on springback and the applicability of the Y-U hardening model for the AA5052. In section 2, experiments of cyclic compression-tension were conducted and the kinematic hardening performance shown by the forward-reverse stress-strain curves was discussed in detail. Cyclic loading-unloading uniaxial tension was performed to study the degradation of elastic modulus with plastic strain. In section 3, Yoshida-Uemori model parameters was identified by an inverse method. In section 4, the U-bending springback simulation in Numisheet2011 was adopted to check the precision of Yoshida-Uemori model in the springback prediction of aluminium alloys.

2. Experiments
2.1. Materials

The investigated 5052 aluminium alloy sheets were supplied by Southwest Aluminium (Group) Co., Ltd. The thickness was 1.0mm. Besides the aluminium element, the additive chemical composition were Mg(3.41%), Fe(0.49%), Si(0.25%),Mn(0.1%),Cu(0.1%),Zn(0.1%) and C(0.01%). Figure 1 showed the engineering stress-strain curves of the AA5052 sheet. From Fig.1, one can identify the yielding stress at 0.2% strain was 160.1MPa. The ultimate strength was about 220MPa.
2.2. Cyclic compression-tension

Cyclic tension-compression can provide a chance for sheet metals to show the kinematic hardening behaviour. As shown in figure 2, a new dog-bone specimen was designed. The uniform deformation was assumed to happen within a rectangle region of 36.8mm×15.2mm to hold an anti-buckling fixture. The strain was measured using the digital image correlating (DIC) system\cite{18,19}.

Because thin sheets subjected to compression are easily buckled out of the sheet plane, a special fixture was designed to reduce the risks of buckling. In this study, an anti-buckling fixture which was protected by a patent was adopted, as shown in figure 3. The fixture is activated by an air pump. The driving force can be adjusted according to the size of the specimens. Between the specimen and the fixture, a thin layer of aviation lubricating oil was coated on the contact surfaces to minimize the friction. The specimen surfaces were covered by the fixture, so the strain can be measured from the side surface of the specimen.

As shown in figure 1, the uniform elongation of the investigated AA5052 was about 10%. The plastic strain of the first knee point from compression to tension was assumed to be at 0.03 strain. The initial side supporting force was 2kN and after several trials this force was adjusted to be 1.5kN. In order to obtain the actual load for the deformation of the specimen, the friction force should be subtracted from the measured load from the load cell of the machine. The friction force was calculated according to the Coulomb friction law, \( F = \mu N \), where the friction coefficient \( \mu \) was assumed to be 0.08 since the contact surface was coated by aviation lubricating oil. The value of \( N \) was 1.5kN. Because the elongation of AA5052 was very small and the specimens were easily fractured, the sequence of testing was compression-tension instead of tension-compression.

Figure 4 showed the true stress-strain curves obtained from the experiments of cyclic compression-tension. It showed that the two curves almost coincided during the first two cycles. For the simplicity of studying the kinematic hardening performance, the stress-strain curve of the 1# specimen was rotated to the first quadrant by plotting stress versus the accumulated strain, as shown in figure 5. From which, one can identify the yielding stress at forward compression and at reverse tension is 146.7MPa and 107.5MPa, respectively. The initial yielding stress of the monotonic tension curve is 167.1MPa. The yielding stress at reverse tension is smaller than that at forward compression. This hints the existence of Bauschinger effect. Furthermore, the reverse loading curve has a rounder corner at the elastoplastic part than the forward loading curve has, which is the characteristic of the transient hardening. After 0.04 accumulated strain, the reverse loading stress-strain curve is permanently lower than the monotonic curve. This indicated that the permanent softening phenomenon happened after transient hardening.
2.3. Cyclic loading-unloading uniaxial tension

The specimens adopted in the cyclic loading-unloading uniaxial tension were prepared according to the ASTM-E8 standard. The specimen was loaded to some plastic strain with the velocity of 0.5mm/s and then it was unloaded to zero. After that, the same specimen was loaded to 2.8% strain and then it was unloaded to zero again. This specimen was loaded to another plastic strain 4.7%, and then it was unloaded once more. According to this rule, one single specimen was loaded and unloaded four times at plastic strain 2.8%, 4.7%, 6.7% and 8.8%.

Figure 6 showed the engineering stress-strain curves of AA5052 subjected to cyclic loading-unloading. From which, one can obtain the elastic modulus according to the standard ASTM-E8. The elastic modulus under different plastic strain was plotted in figure 7. The initial value of elastic modulus is 69.4GPa and it becomes 57.8GPa at 8.8% plastic strain. The decrease percentage reaches 16.7%. Using the Yoshida’s elastic modulus function to fit these data, one can obtain equation (1).

\[
E = 51.2 + 18.7\exp(-9.95\varepsilon_p) \quad \text{GPa}
\]  

(1)

Where \(\varepsilon_p\) is the equivalent plastic strain and the unit of the elastic modulus calculated by equation (1) is giga pascal (GPa).

3. Identification of Yoshida-Uemori model parameters

In order to describe the deformation behaviour of aluminium alloys and steels under stress reversals, Yoshida et al. proposed a two-surface hardening model\(^{[8]}\). They assumed only the kinematic hardening for the yield surface while mixed isotropic-kinematic hardening for the bounding surface. At the initial state, the general form of the yield function \(f_0\) was assumed to be as equation (2)

\[
f_0 = \Phi(\sigma) - Y = 0
\]  

(2)
where $\phi$ denotes a function of the Cauchy stress $\sigma$, and $Y$ is the initial yield strength, the subsequent yield function $f$ is given by equation (3).

$$f = \phi(\sigma - \alpha) - Y = 0$$  \hspace{1cm} (3)

where $\alpha$ denotes the backstress. The bounding surface $F$ is expressed by equation (4).

$$F = \phi(\sigma - \beta) - (B + R) = 0$$  \hspace{1cm} (4)

where $\beta$ denotes the center of the bounding surface, and $B$ and $R$ are its initial size and the isotropic hardening component. During uniaxial tension, the bounding stress can be expressed by equation (5).

$$\sigma_{\text{bound}} = B + R + \beta = B + (R_{\text{sat}} + b) \left(1 - \exp(-m \varepsilon_p)\right)$$  \hspace{1cm} (5)

In Eq. (5), there are six parameters, namely, $Y$, $C$, $B$, $R_{\text{sat}}$, $b$ and $m$ need to be identified. In addition, another parameter $h$ was used to describe the rate of expansion of the non-isotropic surface. According to the method in reference $[9]$, the parameters $B$, $Y$, $C$, $m$, $R_{\text{sat}}$ and $b$ can be identified from the uniaxial tension and cyclic compression-tension stress strain curves. The parameter $h$ was obtained by numerical simulation using finite element software LSDyna combined with the optimization package LS-opt. The parameter $h$ was set as the only variable and the experimental stress-strain curve was regarded as the optimization object. The MAT_125 material model in LSDyna was adopted. This model adopts the Yoshida-Uemori hardening model. After five iterations, $h$ reaches 0.031 and the simulated stress-strain curve is almost identical with the experimental curve. This demonstrated that the optimization has converged. Up to now, all parameters in Yoshida-Uemori model have been identified. The value of $B$, $Y$ and $C$ is 160.9MPa, 142.1MPa and 416, respectively. The value of $m$, $R_{\text{sat}}$, $b$ and $h$ is 15.5, 104.2MPa, 36.5MPa and 0.031, respectively.

### 4. Springback simulation

![Figure 8. Dimensions of the U-bending tools](image)

![Figure 9. Experimental U-bending parts](image)

#### Table 1. Simulated and experimental springback angles

| Data sources                      | $\theta_1^{\circ}$ | $\theta_2^{\circ}$ |
|----------------------------------|---------------------|---------------------|
| Voce Isotropic hardening model   | 103.7               | 83.0                |
| Yoshida-Uemori hardening model   | 108.6               | 73.2                |
| Mean value of the experimental measurement | 109.5               | 77.1                |

The 2D bending springback simulation in Numisheet 2011$[20]$ was conducted using the Yoshida-Uemori hardening model. The variable elastic modulus equation (1) was adopted. Dimensions of the tools were shown in figure 8. The stroke of punch was 71.8mm and the blank holder force was 2.5kN. The stamping velocity was 200mm/s. Full integrated shell element was assumed with 7 integration points in the thickness direction. The average element size was 3mm.

U-bending experiments were performed in a MTS universal machine. The process parameters and the specimen size were identical with those used in simulation. Five duplicated specimens were stamped and the average value of the measured data was adopted. Figure 9(a) showed the experimental parts. The two angles, i.e., $\theta_1$ and $\theta_2$, were measured using the method illustrated in figure 9(b) $[20]$. Table 1 showed the final data, in which the experimental results were the averaged value of the five parts. For
the angle $\theta_1$, the simulated result using the isotropic hardening model and the Yoshida-Uemori model is 103.7° and 108.6°, respectively. So the corresponding springback amount of $\theta_1$ is 13.7° and 18.6°. For the angle of $\theta_2$, its springback amount simulated by the Voce model and the Yoshida-Uemori model is 7° and 16.8°, respectively. The average springback amount of the experimental parts is 19.5° and 12.9° for $\theta_1$ and $\theta_2$, respectively. Therefore, for the investigated AA5052 sheet, the non-linear Yoshida-Uemori kinematic hardening model can predict a more precise springback than the isotropic Voce hardening model can.

5. Conclusions
In order to identify the applicability of Yoshida-Uemori hardening model in capturing the kinematic hardening behaviour of AA5052, experiments of cyclic compression-tension and cyclic loading-unloading uniaxial tension were performed. The parameters in Yoshida-Uemori model were calibrated with an inverse method. The degradation of elastic modulus with the plastic strain was also considered. The following conclusions were obtained.
(1) The Yoshida-Uemori hardening model can capture the kinematic hardening behaviour of the investigated AA5052 very well.
(2) The investigated AA5052 has strong kinematic hardening performance including the Bauschinger effect, transient hardening and permanent softening.
(3) A suitable hardening model considering the degradation of elastic modulus during plastic deformation is crucial to springback simulation. Degradation of elastic modulus of AA5052 during plastic deformation can reach 16.7% at 8.8% effective plastic strain.

Acknowledgments
This study was funded by the National Natural Science Foundation of China under grant No. 51175382.

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