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Material modelling and springback analysis for multi-stage rotary draw bending of thin-walled tube using homogeneous anisotropic hardening model

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Abstract

The aim of this paper is to compare several hardening models and to show their relevance for the prediction of springback and deformation of an asymmetric aluminium alloy tube in multi-stage rotary draw bending process. A three-dimensional finite-element model of the process is developed using the ABAQUS code. For material modelling, the newly developed homogeneous anisotropic hardening model is adopted to capture the Bauschinger effect and transient hardening behaviour of the aluminium alloy tube subjected to non-proportional loading. The material parameters of the hardening model are obtained from uniaxial tension and forward-reverse shear test results of tube specimens. This work shows that this approach reproduces the transient Bauschinger behaviour of the material reasonably well. However, a curve-crossing phenomenon observed for this material cannot be captured by the homogeneous anisotropic hardening model. For comparison purpose, the isotropic and combined isotropic-kinematic hardening models are also adopted for the analysis of the same problem. The predictions of springback and cross-section deformation based on these models are discussed.

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Keywords: Thin walled tube;Rotary draw bending;Springback

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1. Introduction

The significant springback of aluminum tubes manufactured using rotary draw bending becomes a big obstacle for high production rate and low cost automated processes. Many efforts have been conducted to improve springback prediction of thin-walled tube in rotary draw bending. Liu et al. (2012) improved the springback prediction of a thick-walled TA18 tube by considering the strength-differential effect of the material. Zhu et al. (2013a) showed that springback accuracy for rectangular H96 tube in rotary draw bending process can be improved with the Yoshida-Uemori hardening model, compared with the isotropic and mixed kinematic-isotropic hardening models. Zhu et al. (2013b) indicated that the influence of material constitutive model on the accuracy of springback prediction after rotary draw bending was greater than that caused by simplifying FE model or using different mass scaling factors. In this paper, the springback of an industrial asymmetric aluminum tube (as later shown in Fig. 2) after multi-stage rotary draw bending is analyzed using a novel hardening law, namely, the homogeneous anisotropic hardening model. This model is adopted to capture the Bauschinger effect after reverse bending processes. The results of the material modeling and springback analysis of the aluminum tube are discussed.

Nomenclature

E	Young's modulus
v	Poisson's ratio
r	Plastic strain ratio
α , α_{1-8}	Coefficients of yld2000-2d
k , k_{1-5}	Coefficients of HAH model
σ_0	Initial yield stress along extrusion direction of the tube
Q, b	Coefficients of Voce hardening model
R	Bending radius of the tube

2. Material characterizing and constitutive modeling

2.1. Material tests

The material of the asymmetric tube is aluminum alloy AA6060-T4, which is commonly used for automotive frame components. To test the tube under different stress and strain paths, mechanical tests were performed through uniaxial tension, and monotonic and forward-reverse shear tests (i.e., Bauschinger shear tests).

In order to characterize the anisotropic behavior of the tube sample, uniaxial tension tests were conducted in the extrusion direction (0°), transverse direction (90°) and at 45° from the extrusion direction. The yield stress ratio and plastic strain ratio r were calculated from the tension test in different direction, as listed in Table 1.

For multi-stage bending, it is of vital importance to accurately model the mechanical behavior of the tube in reversal loading. Therefore, monotonic and forward-reverse shear tests were conducted along the extrusion direction for the tube in order to analyze the Bauschinger effect of this material. The 2 mm thick shear specimen was 50×15mm with a shear zone width of 3 mm. Strain reversal is achieved by reversing the motion of the mobile grip. More details concerning these tests were reported in Rauch et al. (2002).

Table 1. Mechanical properties and anisotropic data of the AA6060-T4.

E(GPa)	v	σ_0/σ_0	σ_{45}/σ_0	σ_{90}/σ_0	σ_b/σ_0	r_0	r_{45}	r_{90}	r_b
51	0.33	1	0.865	0.791	1	0.492	0.367	1.277	1

2.2. Constitutive modeling

To accurately capture the anisotropic hardening behavior of the tube in the multi-bending process, the yield criterion Yld2000-2d integrated with the homogeneous anisotropic hardening (HAH) model is adopted. This advanced model has been successfully applied to springback prediction of high strength steels (Lee et al., 2012). A brief review of this model is presented below, followed by the description of parameter identification for the models.

The homogeneous anisotropic hardening model can be seen as a distortional hardening framework for any yield locus description. Its initial version, suitable mainly for reversal loading, is described by the following equation：

$$\Phi(\mathrm{s})=\left(\phi^{q}+\phi_h^{q}\right)^{\frac{1}{q}}=\bar{\sigma}\,, \tag{1}$$

where ϕ is a stable component, which can be any isotropic or anisotropic yield function. ϕ_h is a fluctuating component which is defined as

$$\phi_h=f_1\left|\hat{\mathbf{h}}^{\mathrm{s}}:\mathbf{s}-\left|\hat{\mathbf{h}}^{\mathrm{s}}:\mathbf{s}\right|\right|+f_2\left|\hat{\mathbf{h}}^{\mathrm{s}}:\mathbf{s}+\left|\hat{\mathbf{h}}^{\mathrm{s}}:\mathbf{s}\right|\right|\,, \tag{2}$$

where q , f_1 and f_2 are three parameters and $\hat{\mathbf{h}}^{\mathrm{s}}$ is the microstructure deviator, which represents the prior deformation history and can be viewed as a continuum representation of a given set of active slip systems, irrespective of the slip directions. The normalized quantity $\hat{\mathbf{h}}^{\mathrm{s}}$ is defined as:

$$\hat{\mathrm{h}}_{\mathrm{ij}}^{\mathrm{s}}=\frac{\mathrm{h}_{\mathrm{ij}}^{\mathrm{s}}}{\sqrt{\frac{8}{3}\mathrm{h}_{\mathrm{kl}}^{\mathrm{s}}\mathrm{h}_{\mathrm{kl}}^{\mathrm{s}}}}\,, \tag{3}$$

More details about the model can be found in Barlat et al. (2011).

The yield function coefficients describing plastic anisotropy are decoupled from the coefficients expressing anisotropic hardening. In this work, the coefficients of the yield function Yld2000-2d were determined using the results of the three uniaxial tension tests presented above. Since the balanced biaxial tension experiment was not available due to the restriction on the sample size, the stress and r-value measured along the extrusion direction was arbitrarily used instead. The stress-strain behaviour measured in the extrusion direction was used to express the hardening of the material using the Voce law.

Table 2. Material coefficients corresponding to yld2000-2d and HAH model.

Yld2000-2d	α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	α
	0.426	1.806	0.875	1.051	1.034	0.952	0.924	1.487	8
HAH	σ_0	Q	b	k	k_1	k_2	k_3	k_4	k_5
	111.8	128.61	16.64	30	60	80	0.5	1	0

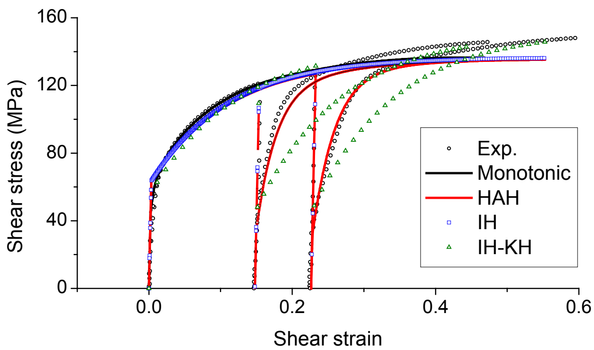


Fig.1. Calculated and experimental stress and strain curve of the AA6060-T4 in forward and reverse shear test

$$\bar{\sigma} = \sigma_0 + Q(1 - e^{-b\bar{\varepsilon}^p}). \tag{4}$$

The input data for the yield function are listed in Table 1 and the anisotropy parameters in Table 2. The hardening coefficients of the HAH model are determined from the forward-reverse shear tests, as listed in Table 2. The predicted stress-strain curves for the simple shear tests are compared with the experiments in Fig. 1. For comparison purpose, the yld2000-2d yield function with isotropic and combined isotropic-kinematic hardening models are also adopted for this case. Fig. 1 indicates that the material exhibits a Bauschinger effect after reverse shear. After this transient behaviour, a curve-crossing phenomenon is observed, i.e., at large cumulated strain levels, the flow stress of the sample reloaded in the reverse direction exceeds that pertaining to the sample deformed monotonically. This phenomenon is probably due to crystallographic texture evolution since a similar phenomenon was also observed by Rauch et al. (2007). The isotropic and combined isotropic-kinematic hardening models cannot capture either the transient Bauschinger effect or the curve-crossing phenomenon with sufficient accuracy, although the combined isotropic-kinematic hardening model is in better agreement with the experimental curve in the large strain range. In contrast, the transient hardening behaviour after load reversal is not very well captured by the combined isotropic-kinematic hardening model. The homogeneous anisotropic hardening model captures the transient Bauschinger effect accurately but cannot predict the permanent over-shooting behaviour either.

3. Finite element modeling of the aluminum tube in multi-stage rotary draw bending

A 3D FE model, presented in Fig. 2(a), is developed to simulate the multi-bending process of the aluminum tube using ABAQUS/Explicit and Implicit codes. S4R shell elements are adopted for the tube. The Explicit dynamic code with the VUMAT constitutive subroutine is used to simulate the bending simulation process while the Implicit static code with UMAT is employed to simulate the springback phenomenon. The whole process includes five steps: (1) First, the tube is bent -45 degrees along a big bend die (with a radius R116); (2) Second, the mandrel inside the tube is withdrawn; (3) The specimen is moved to the small die sets and the tube is bent 135 degree along the die (with R78); (4) The mandrel is withdrawn again; (5) Unloading. The final product is shown in Fig. 2 (b). The forming and contact interface parameters are summarized in Table 3.

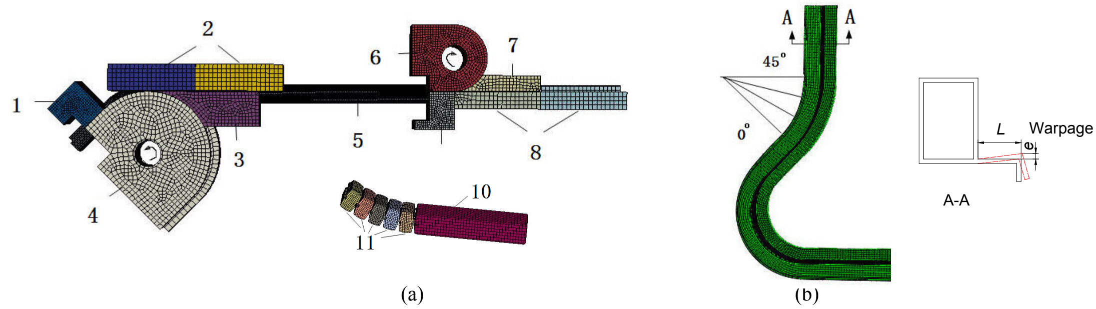


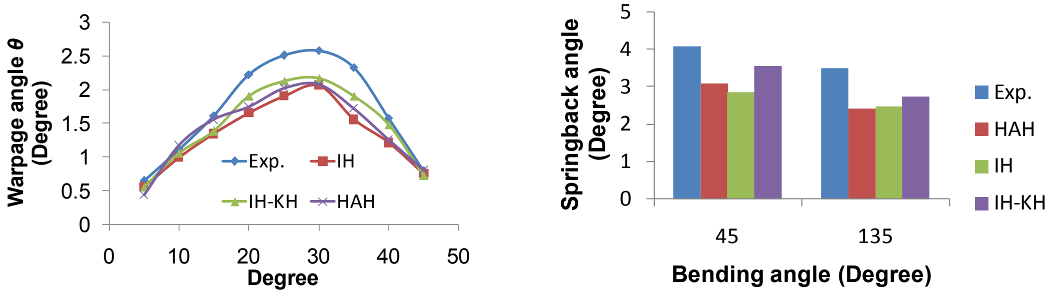
Fig. 2. (a) FE model of the aluminum tube in multi-stage rotary draw bending (1. Clamp die-big; 2.Pressure die-big; 3.Wiper die-big; Bend die-big; 5.Specimen; 6.Bend die-small; 7.Wiper die-small; 8.Pressure die-small; 9.Clamp die-small; 10.Mandrel; 11.Flexible cores).(b) Final product after multi-bending process.

Table 3. Process parameters of the rotary draw bending

Process parameters	Bending speed (rad/ s)	Pressure die speed (mm/s)	Die clearance (mm)	Mandrel extension (mm)
	0.523	65	0.1	2
Contact interfaces	Tube-Clamp die	Tube-Bending die or Wiper die	Tube-Pressure die	Tube-Mandrel or Cores
	Rough	0.15	0.1	0.05

4. Results

After the bending process, significant warpage occurs in the open flange of the tube cross section in the first bending area (as shown in Fig. 2(b)). Fig. 3(a) shows the predicted warpage angle θ ($\theta = \arctan(e/L)$) along the longitudinal direction of the tube using isotropic, combined isotropic-kinematic and homogeneous anisotropic hardening models. It is observed that the trends for the warpage predicted by all three constitutive models are in good agreement with the experimental result. The maximum warpage occur for an angle of about 30 degree. However, the warpage is underestimated using all the models. Fig. 3(b) represents the springback angles obtained by the three models which, again, are underestimated. The predicted errors for the first bending (-45 deg.) with isotropic and homogeneous anisotropic hardening models are 30% and 24%, respectively. The predicted difference between the two models is not very large. The error obtained using combined isotropic-kinematic hardening model is 13%, which is smaller than that of isotropic and homogeneous anisotropic hardening models. Since the amount of springback is closely related to the residual stress created during bending, it is useful to compare the stress-strain curves of Fig.1. The underestimation of springback can probably be attributed to the poor estimations of the curve crossing phenomenon after reversal for all isotropic hardening and homogeneous anisotropic hardening models. It is also observed that the predicted flow curve for combined isotropic-kinematic hardening model is closer to the experimental curve in the large strain range after load reversal. This might be the reason why the combined isotropic-kinematic model predictions lead to the lowest error of springback and warpage.



(a) (b)

Fig.3. (a) Predicted and experimental warpage of the asymmetric tube (b) Predicted and experimental springback angle of the tube.

5. Conclusion

A3D FE model of a multi-stage rotary draw bending process for an asymmetric aluminum tube, 6060-T4, is developed. The springback is analyzed based on three hardening models, i.e., isotropic hardening, combined isotropic-kinematic and homogeneous anisotropic hardening models. A transient Bauschinger effect and the curve-crossing phenomenon are observed for the aluminum tube deformed in forward-reverse simple shear tests. The transient Bauschinger effect can be captured by the homogeneous anisotropic hardening model very well but not the curve-crossing behavior. The results show that the hardening model plays an important role in springback prediction for this multi-bending process. It is also found that the warpage and springback of the aluminum tube are under-predicted by all three models. This correlates well with the prediction of the curve-crossing phenomenon, which leads to an underestimated flow stress for the three models. Improvement in the description of the anisotropic hardening behavior of this material is in great demand.

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