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Spring-back prediction based on a rate-dependent isotropickinematic hardening model and its experimental verification

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Abstract. This paper deals with spring-back prediction with a rate-dependent isotropickinematic hardening model with tension/compression in high speed U-draw-bending tests. In order to verify the validity of the present model, spring-back simulation is carried out and its results are compared with experimental results. A rate-dependent isotropic-kinematic hardening model has been proposed by combining the rate-dependent function of material parameters and the Chaboche type model for the TWIP980 steel sheet under tension and compression. The proposed model can accommodate the strain rate effect on the material properties by providing rate-dependent hardening curves under loading and reverse loading condition. This change of the rate-dependent material properties is important to predict springback under high speed deformation in practical sheet metal forming undergoing tension and compression during the deep-drawing forming. High speed U-draw-bending tests have been performed to investigate the strain rate effect on spring-back of the TWIP980 steel sheet after draw-bending at intermediate strain rates of up to a hundred per second. The experimental results have been compared with simulation results of high speed U-draw-bending and springback analysis with four hardening cases: isotropic; isotropic-kinematic; rate-dependent isotropic; rate-dependent isotropic-kinematic hardening models. It is demonstrated with the comparison that the rate-dependent isotropic-kinematic hardening model proposed provides the best prediction of spring-back after U-draw-bending at intermediate strain rates among the four hardening cases.

1. Introduction

Spring-back prediction is important to fabricate accurate shapes of automotive panels and related numerical simulation is widely utilized to predict sheet metal forming and spring-back. The accuracy of numerical simulation is based on an appropriate hardening model to describe the accurate material properties of sheet metals. In sheet metal forming and spring-back, the material properties are involved in loading–reverse loading condition. In order to express the material properties under loading–reverse loading, Chaboche has suggested an isotropic–kinematic hardening model [1] and it has been improved by many researchers [2–4]. These models, however, cannot describe the strain rate effect in high-speed sheet metal forming and spring-back. To consider the strain rate effect, a rate-dependent isotropic–kinematic hardening model has been proposed based on tension-compression test results of the TWIP980 steel sheets at various strain rates ranging from 0.001 s⁻¹ to 100 s⁻¹ [5].

This paper provides comparison of experimental results and spring-back prediction with four hardening cases: isotropic; isotropic-kinematic; rate-dependent isotropic, rate-dependent isotropic-kinematic hardening models. An experimental setup has been established for a high speed U-draw-

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bending test to evaluate the strain rate effect on spring-back of the TWIP980 steel sheet. In the comparison, the accuracy of prediction is evaluated with the four hardening models for high speed U-draw-bending and spring-back analysis.

2. Rate-dependent isotropic-kinematic hardening model

The rate-dependent isotropic-kinematic hardening model has been proposed to describe hardening behaviours of the TWIP980 steel sheet in tension–compression at a wide range of the strain rate [5]. This model has been extended from the Chaboche type model improved by Zang et al. [4]. The rate-dependent isotropic-kinematic hardening model has been illustrated on the reference paper [5] in detail and the formulations are summarized as below:

$$f(\boldsymbol{\sigma} - \boldsymbol{\alpha}) - \bar{\sigma}_{iso} \left(\bar{\varepsilon}^{p}, \dot{\bar{\varepsilon}}^{p} \right) = 0 \tag{1}$$

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$$\bar{\sigma}^{iso} = \sigma_{y}(\dot{\bar{\varepsilon}}^{p}) + \frac{Q}{b(\dot{\bar{\varepsilon}}^{p})} (1 - e^{-b(\dot{\bar{\varepsilon}}^{p})\bar{\varepsilon}^{p}}) - \frac{C_{1}}{\gamma_{1}(\dot{\bar{\varepsilon}}^{p})} (1 - e^{-\gamma_{1}(\dot{\bar{\varepsilon}}^{p})\bar{\varepsilon}^{p}})$$
(2)

$$d\boldsymbol{a} = d\boldsymbol{a}_{1} + d\boldsymbol{a}_{2},$$

$$d\boldsymbol{a}_{1} = C_{1} \frac{(\boldsymbol{\sigma} - \boldsymbol{a})}{\overline{\boldsymbol{\sigma}}} d\overline{\boldsymbol{\varepsilon}}^{p} - \gamma_{1} (\dot{\overline{\boldsymbol{\varepsilon}}}^{p}) \boldsymbol{a}_{1} d\overline{\boldsymbol{\varepsilon}}^{p} \qquad (3)$$

$$d\boldsymbol{a}_{2} = C_{2} (\dot{\overline{\boldsymbol{\varepsilon}}}^{p}) \frac{(\boldsymbol{\sigma} - \boldsymbol{a})}{\overline{\boldsymbol{\sigma}}} d\overline{\boldsymbol{\varepsilon}}^{p}$$

where $\sigma_{\nu}(\dot{\bar{\varepsilon}}^{p}), b(\dot{\bar{\varepsilon}}^{p}), \gamma_{1}(\dot{\bar{\varepsilon}}^{p})$ and $C_{2}(\dot{\bar{\varepsilon}}^{p})$ are expressed as rate-dependent functions as follow:

$$\sigma_{y}(\dot{\varepsilon}) = \sigma_{0}(1 + K_{y}(\ln(\dot{\varepsilon} / \dot{\varepsilon}_{0}))^{p_{y}})$$

$$b(\dot{\varepsilon}) = K_{b}(\ln(\dot{\varepsilon} / \dot{\varepsilon}_{0})) + b_{0}$$

$$\gamma_{1}(\dot{\varepsilon}) = K_{\gamma}\ln(\dot{\varepsilon} / \dot{\varepsilon}_{0}) + \gamma_{0}$$

$$C_{2}(\dot{\varepsilon}) = C_{0}(1 + K_{C2}(\ln(\dot{\varepsilon} / \dot{\varepsilon}_{0}))^{p_{C2}})$$
(4)

Fig. 1 illustrates true stress-true strain curves of the TWIP980 steel sheet in tension-compression and monotonic tension from experiment and model prediction with the rate-dependent isotropic-kinematic hardening model (I+K+R model) at various strain rates ranging from 0.001 s⁻¹ to 100 s⁻¹. The experimental and numerical prediction results are adopted from the reference paper [5] and the material parameters are tabulated in Table 1. From the plots in Fig. 1, it is confirmed that the model prediction has a good agreement with experimental results at all intermediate strain rate conditions. The rate-dependent isotropic-kinematic hardening model can be utilized with numerical simulation to predict the deformed shape of high speed sheet metal forming and its spring-back.

 Table 1. Material parameters of the rate-dependent isotropic-kinematic hardening model for the TWIP980 steel sheet.

Material	σ_0 [MPa]	K_y [MPa]	p_y	Q [MPa]	K_{b}	b_0
	C_1 [MPa]	K_{γ}	${\gamma}_0$	C_0 [MPa]	K_{C2}	p_{C2}
TWIP980	601.3	8.57×10^{-3}	1.35	2,770	0.257	4.46
	21,200	2.752	110.1	718.0	2.03×10 ⁻⁴	2.86



Figure 1. True stress-true strain curves of the TWIP980 steel sheet from experiment and model prediction at each strain rate: (a) 0.001 s^{-1} ; (b) 0.1 s^{-1} ; (c) 1 s^{-1} ; (d) 10 s^{-1} ; (e) 100 s^{-1} .

3. Verification of the rate-dependent isotropic-kinematic hardening model

This paper deals with verification of the rate-dependent isotropic-kinematic hardening model for spring-back prediction after a high speed U-draw-bending test.

3.1. High speed U-draw-bending test

U-draw-bending tests have been widely utilized as a practical example for spring-back prediction. In this paper, a high speed U-draw-bending test has been performed to involve the strain rate effect on spring-back of sheet metals. The high speed U-draw-bending test has been established with a high speed crash testing machine [6] as depicted in Fig. 2. The specimen material is the TWIP980 steel sheet and the punch impacts the specimen at an initial velocity of 1.96 m/s. Fig.3 depicts deformed shape of the specimen after the high speed U-draw-bending test.



Figure 2. Experimental Setup of a high speed U-draw-bending test

Figure 3. Deformed shape of the specimen after a high-speed U-draw-bending test



Figure 4. Deformed shapes of the specimen before and after spring-back

When the holder is separated from the die, spring-back of the specimen takes places and deformed shapes of the specimen are acquired before and after spring-back as described in Fig. 4. The result is compared with spring-back prediction results in section 3.2.

3.2. Spring-back prediction after the high speed U-draw-bending test

The high speed U-draw-bending test has been simulated by the ABAQUS/Dynamic Explicit program and then spring-back simulation has been performed by the ABAQUS/Static General to acquire the final shape of the specimen after spring-back. The spring-back simulation is involved in elastic recovery from the final stress state of the specimen at the end of the high speed U-draw-bending simulation.

Fig. 5 demonstrates a schematic view of a FE half model for the high speed U-draw-bending simulation. The punch, die and holder are modelled as analytic rigid surfaces. The initial size of the specimen is 320 mm in length and 60 mm in width and the specimen is modelled consisting of reduced 4-node shell (S4R) elements. The number of shell elements is 160 in length and 30 in width. In addition, the shell element has 5-node integration points through the thickness of 1.17 mm.



Figure 5. Schematic view of the high speed U-draw-bending simulation.

Figure 6. Hardening model comparison: (a) I model; (b) I+K model; (c) I+R model; (d) I+K+R model.

The gap between the blank holder and the die is 1.18 mm and the blank holding force is not exerted because the gap is larger than the thickness of the specimen. In experiment, the gap is maintained by inserting a plate of 1.18 mm thickness. The initial velocity of the punch is imposed as 1.96 m/s as acquired from the experiment. Because the die is not an ordinary closed shape, the punch movement is only interrupted by the specimen and the bending stroke is dependent on hardening behaviors of the specimen. When the specimen has higher strength, the bending stroke becomes smaller. In similar sense, when the hardening model can be adapted to describe higher strength, it can lead a smaller bending stroke.

The specimen material is the TWIP980 steel sheet identical to that of the experiment. For the elastic material properties of the specimen, Young's modulus and Poisson's ratio are assigned as 210 GPa and 0.3 respectively. In order to describe the plastic material properties of the specimen, four hardening models are utilized such as Isotropic(I model), Isotropic-Kinematic(I+K model), Rate-dependent Isotropic(I+R model), Rate-dependent Isotropic–Kinematic(I+K+R model) hardening cases as shown in Fig. 6. The hardening models are implemented to ABAQUS/Dynamic Explicit program with VUMAT codes and they adopted a stress update algorithm based on the tangent cutting plane method [7].

The accuracy of spring-back prediction is evaluated by comparing the final deformed shapes of the specimen obtained from simulation and experiment. Spring-back simulation has been conducted with ABAQUS/Static General program by utilizing the final stress state of the specimen of the high speed U-draw-bending simulation. Fig. 7 exhibits the final deformed shapes of the specimen from the experiment and spring-back simulations with the four hardening models. Spring-back simulation results with the I and I+K models have a large discrepancy compared to the experimental result. The main reason is that the two rate-independent models can not accommodate the strain rate hardening effect and thus they provide low flow stresses during deformation. As a result, the two models overestimate the bending depth of the specimen during the high speed U-draw-bending process and underestimate the amount of spring-back. On the other hands, it is confirmed that the rate-dependent I and I+K models.



Figure 7. Comparison of spring-back prediction with experiment and simulation



Figure 8. Graphical definition of spring-back parameters

	Experiment	I model	I+K model	I+R model	I+K+R model
θ [°]	61.5	64.4	65.2	65.4	62.8
$\Delta Z \text{ [mm]}$	31.1	41.9	48.6	32.2	31.2

Table 2. Spring-back parameters measured from experiment and simulation.

In order to evaluate spring-back prediction quantitatively, spring-back parameters are defined as illustrated in Fig. 8 and the amounts of measured parameters are tabulated in Table 2. From the measured results, the spring-back parameters from the I+K+R model demonstrates a good agreement with that of the experimental result within a deviation of 2.1%. The I and I+K models, however, cannot predict spring-back parameter of ΔZ properly with a large deviation over 34% compared to the experimental result. Although the I+R model show a similar level of ΔZ with the experimental result, the I+R model underestimate θ with a deviation of 6.3% which is related to the different shape of the side wall of the specimen. It is because that the I+R model does not provide the difference between the flow stress in tension and that in compression while the I+K+R model considers the difference of the flow stress between tension and compression.

4. Conclusion

This paper investigates spring-back prediction of a high speed U-draw-bending process with the four different hardening models and evaluates the spring-back prediction in comparison with the experimental result. A high speed U-draw-bending test has been performed with a specimen of the TWIP980 steel sheet in order to acquire the spring-back parameters for evaluation. From comparison of spring-back simulation and experimental results, it is concluded that the present rate-dependent isotropic-kinematic hardening model can provide correct spring-back prediction with best performance. It is because the present model considers the strain rate hardening effect and the difference of the flow stress between tension and compression under loading–revere loading, which is close to the actual material properties under a high speed U-draw-bending process.

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