Influence of hardening model on draw-bending springback prediction of DP980 dual-phase steel

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Abstract. Springback is a key factor affecting the dimensional and shape accuracy of cold-formed high-strength steel parts, and the accuracy of high-strength steel springback prediction depends on the accurate material constitutive model. Therefore, it is important to study the influence of the constitutive model on springback prediction accuracy. In this paper, the parameters of the Yoshida-Uemori (Y-U) dynamic hardening model of DP980 dual-phase steel were determined through tension-compression tests with two different strain levels and multicycle tension-compression tests. Based on the draw-bending test platform, the influence of roll radius and normalized back force on the springback of DP980 was investigated. Additionally, the effect of different hardening models (Swift model, Y-U model) on the prediction of draw-bending springback was studied by using Abaqus finite element analysis software. The results show that increasing the bending radius and normalized back force can reduce the springback angle and side wall crimp. The tension-compression testing strategy shows little effect on the calibrated Y-U model parameters of DP980 dual-phase steel. The Y-U model can achieve better prediction accuracy for draw-bending springback angle and curvature compared to the Swift isotropic hardening model.

Introduction

Advanced high strength steels (AHSS) are highly promising materials for lightweight vehicle structures. In recent years, advanced high strength steels (AHSS) are being used in the automotive industry in an effort to reduce vehicle weight and increase fuel efficiency without sacrificing passenger safety [1]. DP (Dual Phase) steels exhibit continuous yielding behavior, a low yield to tensile strength ratio, a high work-hardening rate, relatively high elongation, bake hardenability and cost efficiency, the use of DP steels has increased [2-3]. However, the practical application of these materials has been hampered by the technical challenges of understanding and accounting for springback behaviour after forming [4]. AHSS components are often modified via trial-and -error, which is not only costly but also inefficient. The application of finite element (FE) methods to predict springback of sheet products and compensate for the design of stamping dies can effectively reduce the expense of die tryout and improve the dimensional accuracy of parts.

There are many examples of predicting springback after simple forming operations such as cylindrical tool bending, V-die bending, U-channel forming and stretch bending[5]. These test methods can characterise test conditions such as pure bending or bending with a small tensile force.

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It was concluded that springback increased with the increase of material yield strength and the tool radius, but decreased with increasing elastic modulus for an elastic perfectly plastic material after pure bending. However, among all the process variables that affect springback, sheet tension has the most prominent effect in reducing springback [6]. While stretch bending test is unable to represent the complex deformations that occur in the practical forming processes in which a sheet metal slides over a rigid tool surface as it is drawn into a die cavity. However, the draw bending test overcame this shortcoming and provided a better way of studying springback behavior [7-9].

The accuracy of high-strength steel springback prediction largely depends on the accurate material constitutive model [10]. In recent studies, attention has been drawn to the importance of material constitutive models for FE formability and springback analysis. Yoshida and Uemori [11-12] implemented a back stress idea to develop a theory (the Y-U model) for cyclic plasticity that describes the Bauschinger effect as well as an effect of hardening stagnation that has been observed in some materials upon reverse loading. Lin et al. [13] investigated the effect of the Y-U model on the springback prediction accuracy of MP980 advanced high strength steel and AA6022-T4 aluminium alloy in U-bending. For MP980 advanced high strength steel exhibiting a clear Bauschinger effect but insignificant texture anisotropy, the springback prediction accuracy can be significantly improved by using the Y-U model in combination with the Hill48 yield criterion, and for the AA6022-T4 aluminium alloy with significant texture anisotropy, it is more important to improve the springback prediction accuracy by using the YLD2000-2D yield criterion. Min et al. [14] investigated the effect of tension-compression testing strategy on calibration of Y-U model parameters and on the springback prediction accuracy of advanced high-strength steels. For QP980 advanced high-strength steel, which has a phase transition induced plasticity (TRIP) effect, the tensile-compression strategy has a significant effect on the parameters of the Y-U model and on the springback simulation results. The HAH model developed by Barlat et al [3] was able to describe the complex material behavior such as Bauschinger effect, transient hardening and permanent softening and was in good agreement with experimental data for both cases with and without pre-strain. Barlat et al. [15] developed the HAH model was able to describe the complex material behavior such as Bauschinger effect, transient hardening and permanent softening and was in good agreement with experimental data for both cases with and without pre-strain. Lee et al. [16] applied the HAH model for springback predictions in U draw of as-received and pre-strained DP780 steel sheets. Chaboche [17] developed the Chaboche model and proposed the decomposition of the nonlinear kinematic hardening into several kinematic rules used for the description of special ranges of strain.

In this work, the parameters of the Yoshida-Uemori (Y-U) dynamic hardening model of DP980 dual-phase steel were determined by tension-compression tests. The influence of roll radius and normalized back force on the springback of DP980 was investigated using a draw-bending test platform. The influence of different hardening models on drawing-bending springback prediction was studied by using Abaqus finite element analysis software.

Experimental details

Materials. The material used in this study was hot-dip galvanized DP980 dual-phase steel sheets with a thickness of 1.2 mm. The typical microstructure of dual-phase steel sheets is ferrite and martensite islands. The strength of DP steels is achieved by the presence of martensite, and the ductility is due to the presence of ferrite. The chemical composition of the DP980 dual-phase steel used in this study is given in Table 1.

Table 1. Chemical composition of DP980 steel.

Steel	C	Si	Mn	S	Alt	Cr	Mo	Ti
DP980	0.095	0.4	2.4	0.003	0.035	0.5	0.2	0.025

Uniaxial tensile tests. The mechanical properties of the materials were characterized by uniaxial tensile tests. The tests were carried out on standard GB/T228.1-2010 with a strain rate of 0.01/s. The specimens were tested along the rolling direction (RD), diagonal direction (DD) and transverse direction (TD) with a gauge length of 80 mm. The directional r-values were measured by two extensometers. The true stress-true strain curves are plotted in Fig. 1 and the corresponding mechanical properties of the DP980 dual phase steel are summarized in Table 2.

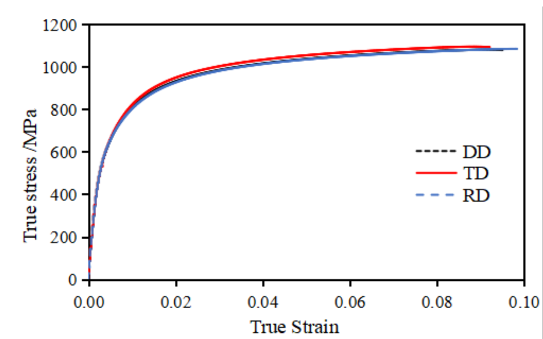


Fig. 1. True stress-true strain curves in RD, TD and DD directions for DP980 steel.

Table 2. The mechanical properties of DP980 steel.

Direction	Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)	n value	r value
RD	638	1008	10.5	0.094	0.96
TD	638	1008	10.5	0.094	0.96
DD	640	993	11	0.096	0.94

Tension-compression tests. It has been shown that the Bauschinger effect and cyclic hardening behavior are significant factors in the prediction of springback for automotive sheet materials. To determine the parameters of the Y-U model, the experimental method in reference [13] was used for the tension compression test of DP980 dual phase steel. Strain was measured using the digital image correlation (DIC) method at room temperature. The crosshead speed was set at 2 mm/min for both tension and compression tests. A lateral force fixture with a nominal force of approximately 2 kN was designed to prevent specimen buckling. Polytetrafluoroethylene (Teflon) sheets 0.8 mm thickness were adhered to both surfaces of each specimen with lubricating grease to minimize friction between the specimen and the fixture. The dimension of the specimen for the tension compression test was shown in Fig. 2.

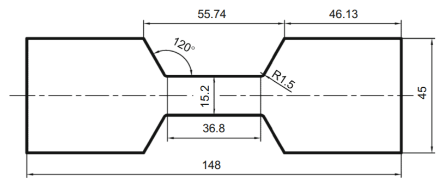
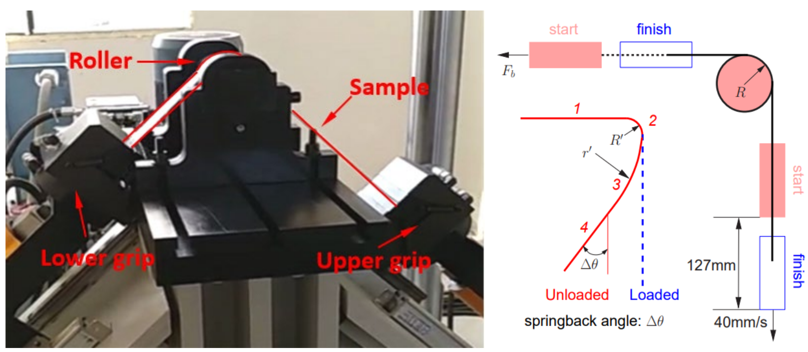


Fig. 2. Dimensions of specimen for tension-compression test (mm).

Draw-bending tests. The draw-bending test and schematics of the test procedure are shown in Fig. 2. During the test, the strip was drawn over a fixed or rotating cylindrical roller at a speed of 40 mm/s for a total travel of 127 mm, while the back force was maintained constant. A typical unloaded specimen is shown schematically in Fig. 3(b), from which four distinct regions of deformation were identified. The material in regions 1 and 4 only experienced pure stretching and these two regions were not considered in this experiment. Regions 2 was in contact with the forming tool before unloading, and its radius of curvature changes from R to R' after springback. The material in region 3 has undergone sequential bending and unbending with superposed stretching and has a radius of curvature r' after unloading. The parameter Δθ has been used to characterize the amount of springback for draw bending tested specimens.



(a) (b)

Fig. 3. Draw bending experiment: (a) equipment, (b) schematics of test procedure.

FE modeling of springback

Y-U model parameter fitting. The Y-U model uses two surfaces to describe the hardening rule, wherein the yield surface moves within the bounding surface [11]. In this work, a single-element model was built to optimize the Y-U model parameters [14] . An sequence optimization response surface method (SRSM) was used to minimize the difference between experimental and calculated stresses with a mean square function as follows,

$$\delta = \frac{1}{P}\Sigma_{p=1}^{P} W_p \left[\frac{f_p(x) - G_p}{S_p}\right]^2 = \frac{1}{P}\Sigma_{p=1}^{P} W_p \left[\frac{\delta_p(x)}{S_p}\right]^2 \quad (1)$$

where G_p, $p = 1 \cdots P$ is the number of the experimental curve, G, fp(x) is the corresponding component value of the curve f calculated by the response surface, x is the vector of design variables and W_p is the weight coefficient. In addition, an identification process based on the feedforward neural network method was carried out to investigate the influence of the optimization method on the parameter identification.

Springback prediction with Abaqus. The finite element analyses for the tension-bending tests were performed in ABAQUS. The draw-bending and springback simulations were conducted using ABAQUS/Explicit and ABAQUS/implicit, respectively. The Y-U model was implemented into ABAQUS through the user material subroutines UMAT and VUMAT. The Coulomb friction law with a friction coefficient of 0.1 was used for the contact between the tools and the blank. For the simulation, the forming tools were defined as rigid analytical surfaces and four-node shell elements (S4R) with 8 integration points through the thickness were used for the blank. The Hill48 yield criterion was used for the simulated material, and the Swift and Y-U models were compared to determine their effect on the accuracy of springback prediction.

Fig. 4. The 3D-FE model of Draw bending test and mashing.

Results and Discussion

Tension-Compression test results. To investigate the influence of the tension-compression test strategy on the Y-U model parameters, the tension-compression-tension (TCT) tests under two pre-strains of 0.03 and 0.05, and the multi-cycle tension-compression-tension (MTCT) tests under three pre-strains of 0.02, 0.035, and 0.05 were conducted on the DP980 dual phase steel. Experimental true stress vs. true strain curves of DP980 are shown in Fig. 5. It can be illustrated that both methods can well describe the deformation behaviour of DP980. The Y-U model can describe the transient Bauchinger effect and permanent softening phenomenon of the material during cyclic loading by introducing the parameters C and h. Therefore, the Y-U model has a high fitting accuracy compared with the test curve. Table 3 shows the parameters of the Y-U model obtained by fitting single-cycle tensile-compression test curves and multi-cycle tensile-compression test curves, respectively, with fitting errors of 0.2%.

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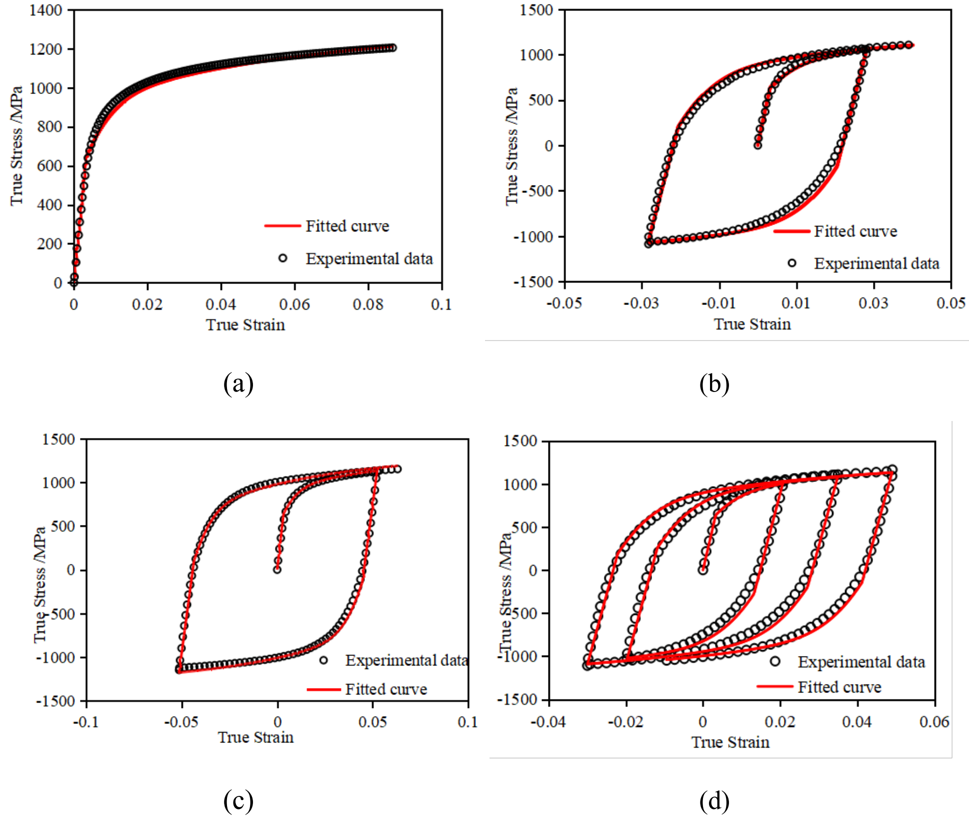

Fig. 5. Experimental and curve fit data of DP980: (a) tensile test, (b) 0.03 pre-strain, (c) 0.05 pre-strain, (d) multi-cycle pre-strain of 0.02, 0.035, and 0.05.

Table 3. Fitted parameters of the Y-U model for DP980.

Strategy	*Y* (MPa)	*B* (MPa)	*R*sat (MPa)	*m*	*h*	b (MPa)	C_1	C_2
TCT	583.7	862.4	604.5	31.1	179.1	378.0	0.87	0.0233
MTCT	637.9	941.6	810.2	15.8	142.0	376.3	0.69	0.0002

Draw-bending test results. Since the sheet tension played a dominant role in reducing springback, multiple tests were conducted with the normalized back forces ranging from 0.2to 1.2, at an increment of 0.05-0.1 to improve resolution.The normalized back force is calculated using equation as follows,

$$\overline{F}_b = \frac{F_b}{\sigma_s \times a_0 \times b_0} \tag{2}$$

Where σ_s is the yield strength of the material, a_0 is the thickness of the specimen, b_0 is the width of the material.

Fig. 6 shows the results of the tests with tool radius of 6.2 and 12.7 mm, respectively, from which it can be seen that the stretching force plays an significant role in reducing the springback. For the same bending radius, the springback angle $\Delta\theta$ decreases with the increase of Normalized back force. Therefore, in the actual stamping process, the method usually used to reduce springback is to increase the binder force. For the same stretching force, the total springback angle decreases as the bending radius increases. By increasing the bending radius and stretching force, both side wall curling and springback can be reduced. Accordingly, R' has the same tendency as the springback angle, while r' has the opposite tendency. In addition to this commonly observed trend, a dramatic drop in the springback angle occurs near F_b = 1.1- 1.2, which is associated with a sudden increase in the anticlastic curvature. It is noted that the critical back force, at which the fast decline of springback angle occurs, weakly depends on tool radius.

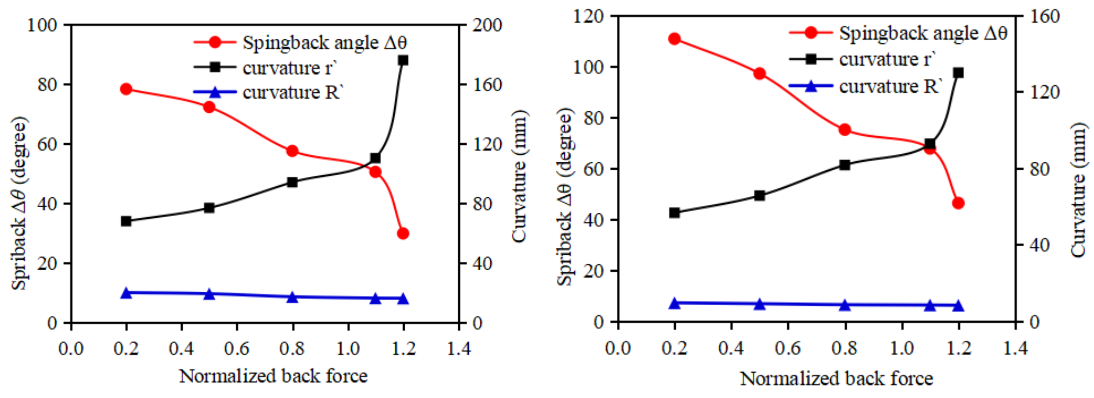

Fig. 6. Effect of normalized back force on the springback angle and the curvature: (a) R6.2 mm, (b) R12.7 mm.

Springback prediction. The effect of the Swift isotropic hardening model and the Y-U kinematic hardening model on the springback is investigated by using the bending radius of 6.2 mm in the draw-bending test, and the comparison of the predicted results with the test results is shown in Fig. 7. It can be seen that a better prediction accuracy of springback angle Δθ and radius of curvature r' can be obtained using the Y-U model, with the corresponding prediction errors of 5.3% and 4.6% respectively. The prediction errors of the Swift hardening model for springback angle Δθ and radius of curvature r' are 28.7% and 22.8% respectively. This suggests that the prediction of springback in draw-bending can be significantly improved by using the Y-U model. The elastic modulus decreases with the increasing of cyclic load strain, and the Y-U model uses an exponential function to describe the relationship between the elastic modulus and the equivalent plastic strain, which improves the accuracy of the springback prediction.

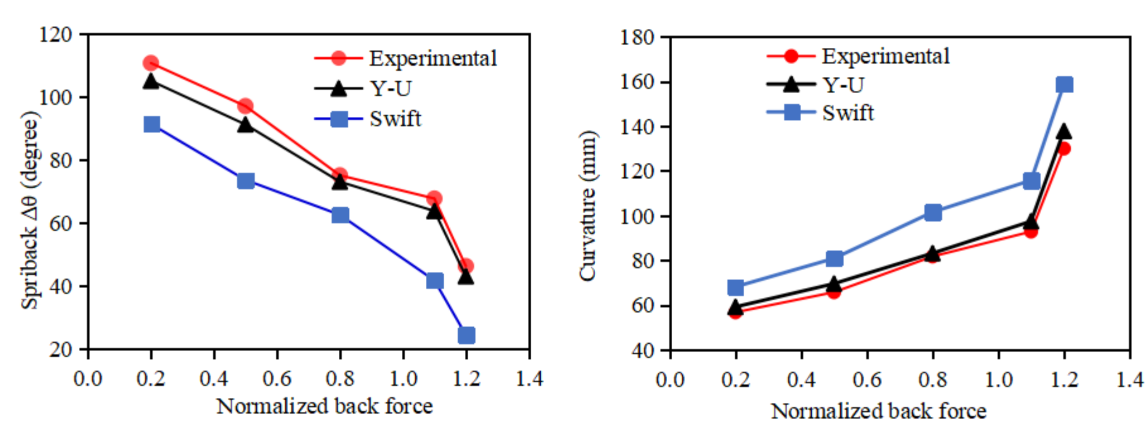

Fig. 7. Comparison of the simulation results with the experimental data: (a) the springback angle, (b) the unloaded anticlastic curvature

Conclusions

(1) The springback angle and side wall crimp decrease with increasing normalized back force, and there is a dramatic decrease in the springback angle at normalized back force close to 1.1- 1.2, which is associated with a sudden increase in the anticlastic curvature.
(2) The tension-compression testing strategy shows little effect on the calibrated Y-U model parameters of DP980 dual-phase steel.
(3) The Y-U model can achieve better prediction accuracy for springback angle and curvature compared to the Swift isotropic hardening model.

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