Parameter Identification of Chaboche Model for Aluminum Alloy Sheets Based on Differential Evolution Algorithm

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Abstract. *Springback prediction is one of the most challenging in finite element analysis for sheet metal forming processes. The demand requests the development of a kinematic hardening model and parameter identification. This study presents a schematic strategy to identify parameters of Chaboche's kinematic hardening model based on a differential evolution optimization method. To this goal, several tension-compression (TC) tests were conducted to observe the Bauchinger's effects and kinematic hardening behaviors of two aluminum alloy sheets: AA6022-T6 and AA7075-T76. A Python code is developed to apply the proposed method in identifying parameters of the kinematic hardening model. The calibrated material models were implemented in Abaqus software to simulate V-bending and U-bending tests for the investigated materials. The predictions for springback amount match well with the experimental measurements, which verifies the effectiveness of the presented identification strategy.*

Keywords

Springback, Aluminum alloy sheet, Kinematic hardening model, Parameter identification, Differential Evolution.

1. Introduction

Aluminum alloy sheets are widely used in automotive engineering owing to their lightweight and good formability [1] Sheet metal forming processes, such as stamping, rolling, and deep drawing are the most popular manufacturing methods for making car parts from blank sheets. During these manufacturing processes, the geometrical changes of the formed parts after releasing from constraints or so-called springback is the most common issue that affects the product qualities. Numerical simulation with the finite element (FE) method is an efficient tool for analyzing and predicting springback before experimental investigation. The simulation framework has been well developed in several application-specific software, for example, AutoForm, PamStamp, Simufact-Forming, etc. Thus, the most challenge in these simulations regards calibrating parameters of material models to secure accuracy.

The origins of springback are due to elastic strain recovery after removing all constraints made by forming tools. Previous studies have been conducted to characterize the springback appeared in forming aluminum panels [2, 3]. The most popular type of springback for visualization is the change of the bending angular, which is observed in almost stamped parts. Sidewall curl is another issue for thin-wall structures. Twists may occur in a formed long part. These different phenomena are commonly co-occurrent making the springback control more challenges.

From an engineering point of view, springback amounts increase with tensile strength but decrease with the elastic modulus and initial thickness. Different methods have been developed to reduce the springback. The first approach is to apply additional processes aiming to reduce elastic stresses. Post-stretching and over-forming operations are examples of this approach. Modifying the forming processes or tools is the second approach, of which drawbead controlling and binder force acting are applicants. The third approach is to modify product design to confront the change of deformed parts. Nowadays, FE simulation is a key for the success of all mentioned approaches. Implement of these simulations requires selecting a proper material model and calibrating its parameters accurately.

Armstrong-Frederick [4] and Chaboche [5] models are commonly used in simulating and predicting springback numerically. Conventionally, parameters of these models are identified step-by-step by using a systematic mathematical approach [6]. However, application of the approach for Chaboche model is time-consuming because of a substantial number of parameters. Inverse FE method has been used to this purpose [7] but involving an expensive computational cost. Recently, several advanced computational methods have been applied successfully to identify parameters of Chaboche model, for example, fuzzy logic analysis [8], genetic algorithm [9], particle swarm optimization [10]. These studies demonstrate the potential of advanced computational methods in identifying Chaboche model's parameters. However, implementation of these computational methods is complex that limits their applications in practice.

This study deals with calibration of Chaboche model for springback simulation of two aluminum alloys: AA6022-T6 and AA7075-T76 sheets. To the goal, uniaxial tensile and tension-compression tests are performed to achieve material behaviors observed during monotonic and reversal loadings. Constitutive equations are then developed based on both Armstrong-Frederick (AF) [4] and Chaboche [5] models to capture the experimental data. Parameters of these models are calibrated by a common method [6] and a differential evolution (DE) algorithm [11], respectively. The calibrated models of AA7075-T76 sheets are applied to simulate the U-bending and V-bending tests. Numerical predictions of the angular changes are compared to the experimentally measured data to clarify their accuracy. The comparison reveals that the Chaboche model calibrated by the DE algorithm provides a better prediction for the Bauschinger's effect compared to the AF model calibrated by the common one.

2. Experiment Procedure

Tested materials in this study are AA6022-T6 sheets with a thickness of 1.1 mm and AA7075-T76 sheets with a thickness of 1.6 mm. Both materials are supported by Hyundai Motor Group and are widely used in the automotive industry.

2.1. Uniaxial tensile test

Uniaxial tensile (UT) tests are conducted for both materials following the Korean standard KS B0810 13B to investigate the material behavior under a quasi-static uniaxial stress state. Furthermore, specimens were prepared in three orientations, including the rolling direction (RD), diagonal direction (DD), and transversal direction (TD). Fig. 1 shows an image of deformed specimens; meanwhile, Fig. 2 reports the stress–strain curves obtained from the tests.

According to these figures, a minor anisotropy effect is observed in the stress–strain curves of both two materials. Table 1 presents the material properties of the investigated materials directly obtained from these tests, which include

Tab. 1: Material properties determined from the uniaxial tensile tests.

	AA6022			AA7075		
	RD	DD	TD	RD	DD	TD
E (GPa)	69	69	70	68	69	70
σ_0 (MPa)	150.3	144.6	151.0	478.0	454.0	485.0
UTS (MPa)	277.3	275.5	281.0	555.6	530.1	559.2
R-value	0.76	0.70	0.59	0.78	1.02	0.80
ε^*	0.209	0.211	0.206	0.091	0.086	0.085
El (%)	32.3	31.6	31.2	13.5	11.0	10.3

Young's modulus (E), initial yield stress (σ_0), ultimate tensile strength (UTS), Lankford value (R-value), maximum uniform strain (ε^*), and total elongation (El).

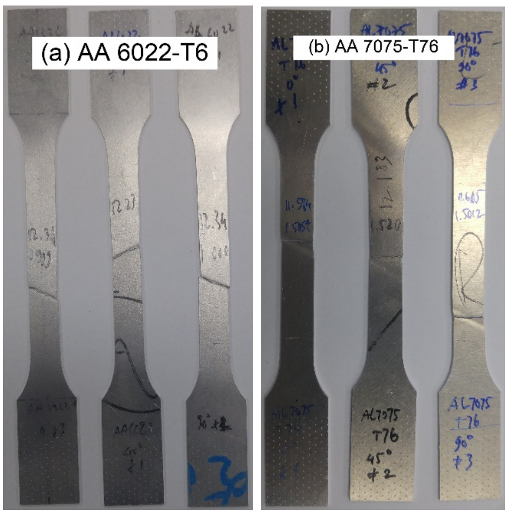


Fig. 1: Failure specimens obtained from uniaxial tensile tests.

2.2. Tension-compression test

Several tension-compression (TC) tests are carried out for the tested materials to characterize material behaviors observed during reversal loads. For this demand, specific zigs were designed to prevent bulking occurrence during compression. During the tests, specimens are first subjected to an amount of prescribed tensile strain. Then, in the second step, the specimen is compressed in the reversal direction until its original length. Fig. 3 compares the stress–strain curves obtained from the TC tests with the one obtained from the UT test. For both materials, the flow stresses obtained from

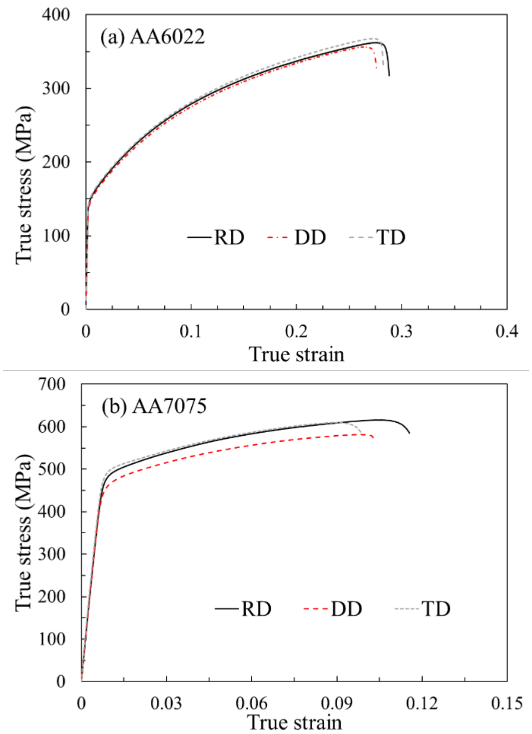


Fig. 2: Stress–strain curve obtained from uniaxial tensile tests.

the tension phase of the TC tests are agreed well with the curve observed in the UT test. Furthermore, the stress–strain curves in the compression phase indicate the Bauschinger's effect with early re-yielding, as shown in Fig. 3.

3. Constitutive Equation

3.1. Armstrong-Frederick model

Generally, an isotropic hardening law is frequently adopted to describe the hardening behavior of sheet metals subjected to a forming process. This hypothesis assumes an expansion of yield surface in the stress space during plastic deformations. However, previous studies pointed out that this hypothesis overestimates the springback because it overrates the re-yielding behavior in the reversal loads [3, 12]. Therefore, one may consider a kinematic hardening law for springback prediction. In this theory, the yield surface is assumed to translate purely

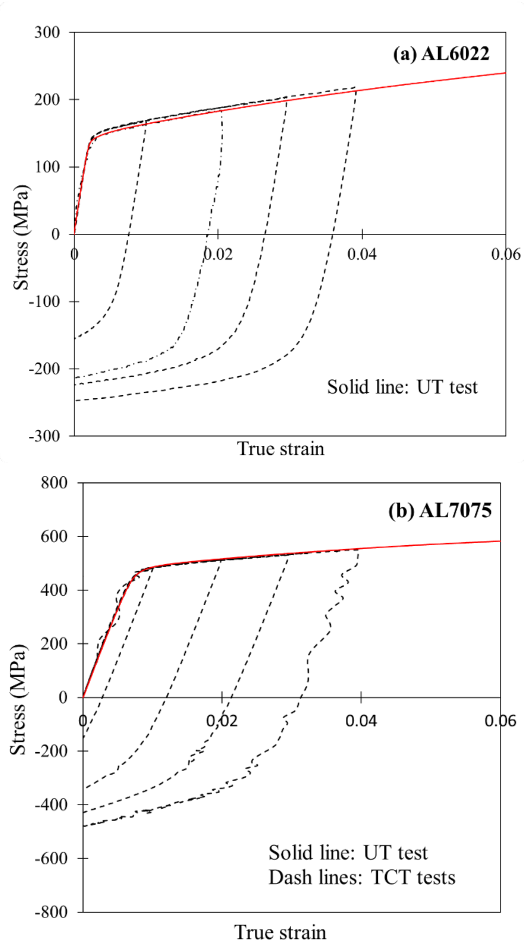


Fig. 3: Comparison between the stress–strain curves obtained from the tension-compression tests with those of the uniaxial tensile test for RD specimen.

in the stress space without reshape. Ziegler's and Prager's models [13] proposed linear movements of yield surface, which are the pioneering works in this topic. Armstrong and Frederick [4] presented a non-linear model of kinematic hardening law. Recently, a combination of an isotropic hardening law with the kinematic model of Armstrong and Frederick [4] is frequently used to improve the accuracy of the springback prediction. That model is so-called the Armstrong-Frederick (AF) model hereafter.

In the AF model, the yield criterion is expressed as:

$$F = \bar{\sigma}(\sigma - \alpha) - R \leq 0 \qquad (1)$$

where σ denotes the stress tensor, α (so-called the back stress) denotes the position of the center of the yield surface, $\bar{\sigma}$ is the equivalent stress, R denotes the hardening behavior or the expansion of the yield surface. Consequently, the expansion of yield surface is formulated by a hardening law:

$$R = \sigma_0 + Q(1 - exp(-b\bar{\varepsilon})) \qquad (2)$$

where σ_0, Q, and b are material parameters that need to be identified. The increment of the back stress is governed by the following equation:

$$d\alpha_{ij} = \frac{2}{3}Cd\varepsilon^p_{ij} - \gamma\alpha d\bar{\varepsilon} \qquad (3)$$

where C and γ are material parameters.

In the literature, the most common method to calibrate parameters of the AF model is the curve fitting method. In this method, the difference between the experimental stress, σ^{exp} and calculated stress, σ^{cal} is estimated by the cost function:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\sigma^{exp} - \sigma^{cal}\right)^2} \qquad (4)$$

Then, an optimization algorithm (i.e., generalized reduced gradient method) is applied to minimize the cost function and determine the parameters.

3.2. Chaboche model

Although the AF model is able to estimate correctly the re-yield stress in the reversal loading, it lacks the flexibility to capture the entire reverse stress–strain curves of many engineering materials [14, 15]. Chaboche [5] proposed to use multiple back stresses to improve the model's predictability. Thus, the back stress evolution in Chaboche's model is evaluated as:

$$\alpha = \sum_{i=1}^{m}\alpha_i \qquad (5)$$

where m is the number of imposed back stresses, α_i is individual back stress which is regulated by equation (3). A huge number of parameters involved to the Chaboche model raises difficulty in calibrating these parameters by the common method.

4. Parameter Identification

4.1. Differential evolution algorithm

Differential evolution (DE) proposed by Storn and Price [11] is a promising heuristic algorithm for global search. This algorithm has been applied to different engineering problems [16, 17, 18]. Fig. 4 shows a schematic of a generic DE algorithm. This study adopts the algorithm to identify parameters of the Chaboche model. It is worth to notice that there are three back stresses ($m = 3$) imposed in the Chaboche models.

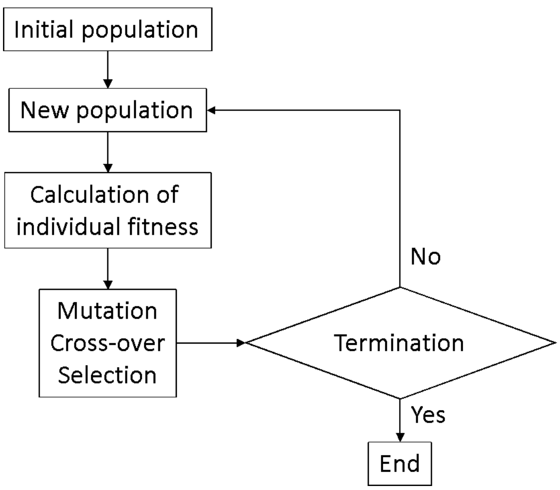


Fig. 4: A schematic of the differential evolution algorithm.

In this method, the fitness function is constructed as follows:

$$f = \sqrt{f_1 + w f_2} \tag{6}$$

where f_1 and f_2 are the differences between experimental and calculated flow stresses in the tension and compression phases, respectively; w is a weight factor determined by the reliabilities of the experimental data. It is noticed that f_1 and f_2 were determined in a similar manner of Eq. (4).

A Python script is developed to implement the algorithm using the *Scipy.optimize.DE* library. In this approach, the population is set to 50 individuals. Following preview work [19], the coefficient of mutation and cross-over rate are set to 0.8 and 0.5, respectively. This library provides several strategies for searching new candidates in each iteration. It is found that the "best1exp" strategy yields the best convergence for this particular engineering problem. The conclusion may not be true for other investigated materials.

4.2. Calibration results

The AF and Chaboche models calibrated in the previous sections are used to evaluate the material behavior obtained from the TC tests for two examined materials. It is reminded that parameters of AF model were calibrated by a common curve fitting method; and, those of Chaboche model were identified by the DE algorithm described in the previous subsection. Fig. 5 compares the experimental data with these models' predictions. Table 2 reports the determined values of these parameters. For AA6022-T6 sheets which exhibit less sensitive Bauschinger's effect, both models give similar predictions for the stress–strain curves. These predictions are in good agreement with the experimental data. However, a significant discrepancy is observed in their predictions for the case of AA7075-T76 sheets, which exhibits extreme reductions in the reversal yield stresses. The AF model calibrated with a common method overestimates significantly the experimental data in the compression phase. Fortunately, the Chaboche model calibrated by the DE algorithm provides good predictions of material behavior, especially in the early stages of compressions. The effect of their accuracy in predicting the stress–strain data on the springback prediction is discussed in the next section.

5. Application

5.1. Springback tests

V-bending and U-bending tests are frequently used to investigate the springback behaviors of sheet metals. The former requires the tested material to undergo different stress states (ten-

Tab. 2: Material properties determined from the uniaxial tensile tests.

Parameter	AA6022-T6		AA7075-T76	
	AF	Chaboche	AF	Chaboche
σ_0 (MPa)	135.17	120.22	463.84	360.49
Q (MPa)	405.06	435.85	156.83	1.0
b	2.96	3.57	5.25	0.1
C_1 (MPa)	10,594.61	9,742.56	5,437.75	2,817.11
γ_1	291.03	595.32	57.45	6.24
C_2 (MPa)	–	79,050.83	–	91,502.47
γ_2	–	5,557.51	–	831.33
C_3 (MPa)	–	903.93	–	1,000
γ_3	–	60.08	–	6.31

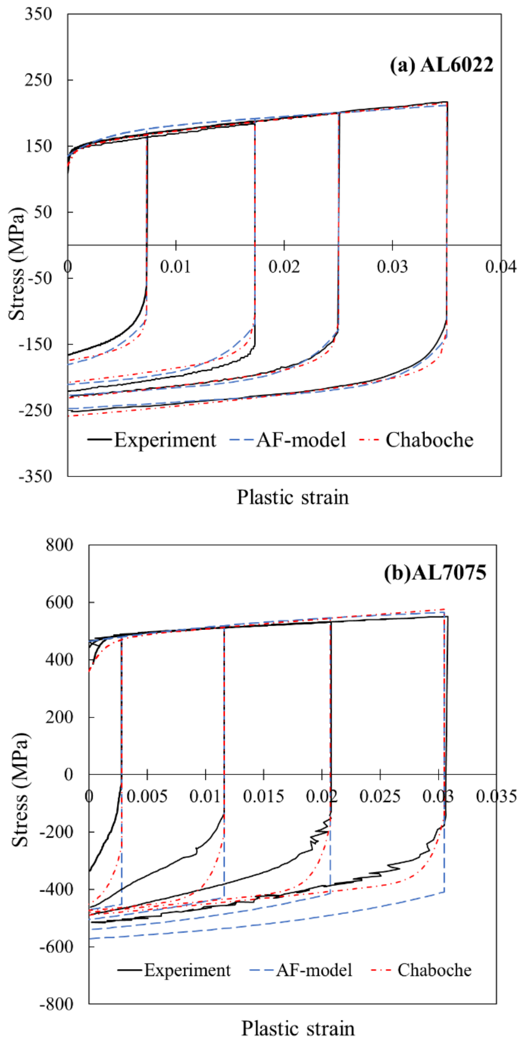


Fig. 5: Comparison between the experimental stress–strain curves obtained from the TC tests and models' predictions.

sion in the outer surface and compression in the inner surface). Meanwhile, the latter generates cyclic loads acting on the forming areas. This study conducted both testing methods for AA7075-T76 sheets to investigate experimentally the springback behavior. Details on the boundary conditions and geometries of each test can be found in another work of the first author [20].

(a) V-bending specimen.

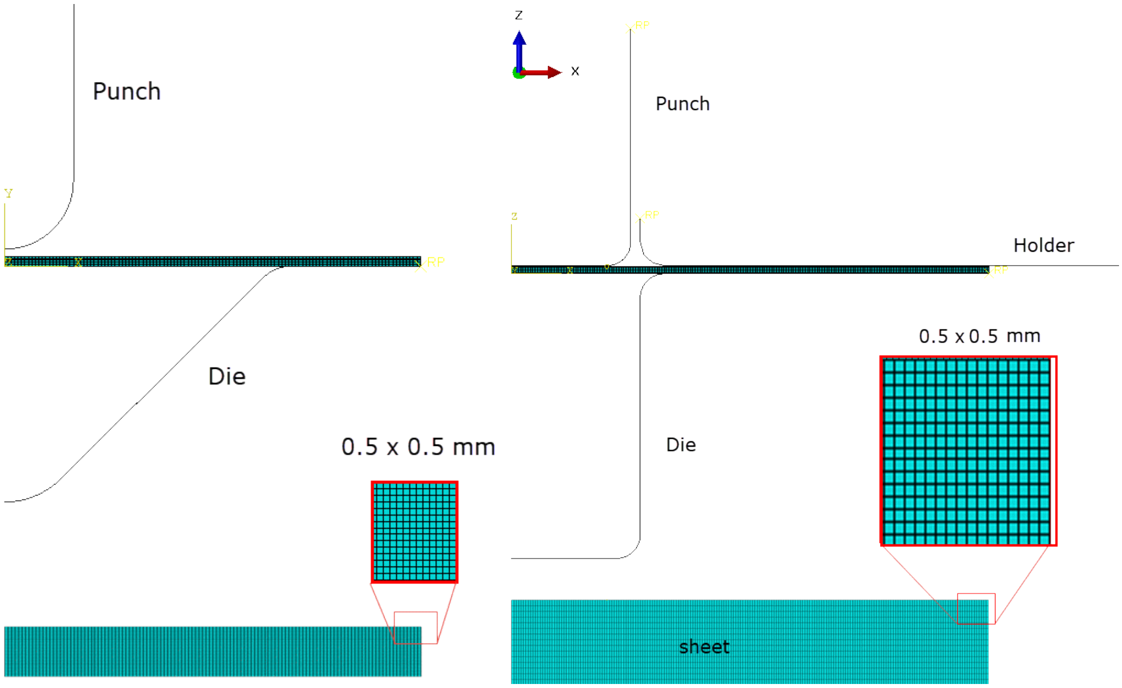
(b) U-bending specimen.

Fig. 6: Deformed specimens obtained from the springback tests for AA7075-T76 sheets [20].

Fig. 6 shows deformed specimens obtained from these tests. For the V-bending specimen, springback is characterized by the angle, φ between two sidewalls. In addition, the two angles θ_1 and θ_2 are used to evaluate the springback behavior of the U-bending specimen.

5.2. Comparisons

Finite element models are developed in Abaqus software to simulate the designed V-bending and U-bending tests, which are shown in Fig. 7. The geometry of the blank sheets used in both tests is 70 × 15 mm. Only a half of the model is simulated due to the asymmetry. In these simulations, solid elements C3D8R were used to model the sheet; and rigid body elements R3D4 were adopted to describe the forming tools. A fine mesh of 0.5 × 0.5 mm was generated on the specimens. The Coulomb friction law with a constant coefficient of 0.17 is applied to model the contacts between the blank sheet and tools.



(a) V-bending simulation. **(b)** U-bending simulation.

Fig. 7: FE models used to simulate the springback tests for AA7075-T76 sheets.

Table 3 reports the experimentally measured springback angles along with the predictions based on two material models. The difference between the measurement and predictions is estimated by the equation:

$$\delta = \frac{\left|\omega^{exp} - \omega^{pre}\right|}{\omega^{exp}} \times 100\% \qquad (7)$$

where ω^{exp} and ω^{pre} denote the measured and predicted springback angles, respectively. Compared to the experimental data, the Chaboche model provides better results of all springback angles than those obtained from the AF model. The comparison confirms the effectiveness of the DE algorithm in identifying parameters of the Chaboche model.

Tab. 3: Comparison between measured and predicted springback angles.

Springback angle	Exp. [20]	AF		Chaboche	
		Pre.	δ (%)	Pre.	δ (%)
φ	105.6°	106.6°	0.95	106.4°	0.76
θ_1	112.5°	109.6°	2.58	110.5°	1.78
θ_2	87.5°	92.2°	5.37	88.9°	1.37

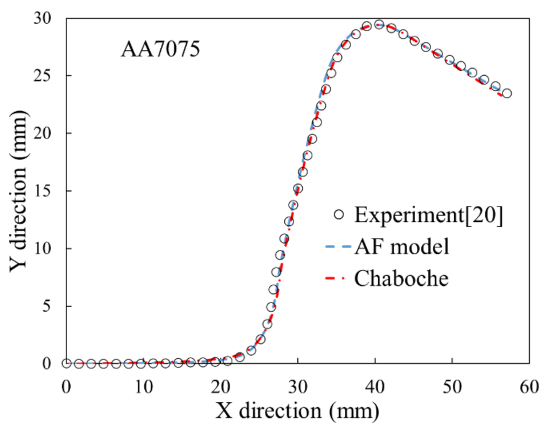


Fig. 8: Comparison between the measured and simulated geometries obtained from the U-bending test for AA7075-T76 sheets.

Furthermore, Fig. 8 compares the measured and simulated geometries obtained from the U-bending test for AA7075-T76 sheets. It is seen that the results of the two models are in good agreement with experimental data. However, the prediction of the Chaboche model captures the measured data better than the AF model, especially at the transition region from the side-wall to the flange area.

6. Conclusions

This work presents an application of the DE algorithm to identify parameters of the kinematic hardening model. Several experimental tests have been conducted for AA6022-T6 and AA7075-T6 to achieve sufficient data to characterize material behavior subjected to reversal loads. Parameters of AF models were calibrated by a common curve fitting method using these experimental data. Moreover, the presented DE algorithm was adopted to identify parameters of the Chaboche model for both aluminum sheets. Compared to experimental data, the calibrated Chaboche model provides better predictions for the Bauschinger's effect observed during TC tests.

The calibrated AF and Chaboche models were applied to simulate V-bending and U-bending tests for AA7075-T76 sheets. The simulated results were compared with the measured data for springback angles. The comparison reveals that the use of the Chaboche model provides better prediction for springback angles observed in the tests. That verifies the effectiveness of the DE algorithm in calibrating parameters of Chaboche kinematic hardening law. The algorithm can be used to identify parameters of different material models.

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