

The application of Chaboche model in uniaxial ratcheting simulations

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Abstract

This article presents the application of Chaboche nonlinear kinematic hardening model in simulations of uniaxial ratcheting. First, the symmetrical strain-controlled cyclic tension/compression tests for PA6 aluminum samples were done. Using the experimental stress–strain curve, initial material hardening parameters were determined by the ABAQUS software. The experimental curve was compared with the numerical one. For better fitting of both curves, the optimization procedure based on the least-square method was applied. Using the determined hardening parameters, numerical simulations of the ratcheting were done by the finite element analysis software. Numerical results were then compared with the experimental data obtained in the stress-controlled cyclic loading test.

Keywords

cyclic plasticity, ratcheting, Chaboche model, nonlinear kinematic hardening, isotropic hardening

Nomenclature

b – material constant
 B – error norm
 c – material constant
 $d\varepsilon^p$ – the inelastic (plastic) strain increment
 dp – equivalent plastic strain increment
 dx – backstress increment
 dx_i – the kinematic hardening rule
 E – Young’s modulus
 ε_0^p – translation of the yield surface
 σ – stress
 σ_{appr} – approximated value of stress
 σ_{SAT} – saturation stress
 σ_γ – yield stress
 Q – material constant
 φ – true (logarithmic) strain
 p – equivalent plastic strain
 $r(p)$ – isotropic hardening function
 γ – material constant
 ν – Poisson’s ratio
 x – backstress

Bauschinger effect, cyclic hardening, relaxation, and ratcheting are the examples of phenomena related to the cyclic plasticity [2].

Among the cyclic plasticity phenomena, ratcheting can result in the additional damage of materials and the shortening of their fatigue life. Ratcheting is defined as a progressive strain accumulation in a material under the stress-controlled cycling loading with nonzero mean stress [3]. Correct prediction of the ratcheting can prevent the catastrophic failure of structures. Ratcheting has been extensively studied in both experimental and numerical researches in the recent years [4–8].

The appropriate constitutive models that can accurately describe the material behavior under cyclic loading are developed. Frederick–Armstrong, Chaboche model, which is the extension of Frederick–Armstrong model, is commonly used in modeling of uniaxial and multiaxial ratcheting. Even though a lot of research has been done in modeling of cyclic plasticity including ratcheting, none of the existing models is versatile and robust to simulate it accurately [9].

The precise identification of material hardening parameters is essential for the prediction of ratcheting. It was noted that kinematic hardening is considered as a main reason for ratcheting. On the other hand, this phenomenon is very sensitive to the isotropic hardening and depends on the isotropic hardening parameters values; thus, the gradual deceleration or even the blocking of ratcheting might occur [10].

1. Introduction

The cyclic plasticity concerns an elastoplastic stress–strain response of materials in closed and repeated loading paths [1].

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In this research, the Chaboche nonlinear kinematic model, with three nonlinear terms as well as the Voce isotropic one, is used to simulate the ratcheting for the PA6 aluminum. Hardening parameters for the Chaboche model are determined based on the experimental stress–strain curves obtained in strain-controlled cyclic tension/compression tests by the ABAQUS software. The numerical stress–strain curve was generated using initially determined hardening parameters. For better fitting of numerical and experimental curves, the optimization procedure with the use of the least-square method was applied. The computed set of hardening parameters is later on used in simulations of a uniaxial ratcheting. The numerical results are compared with the experimental curve for a stress-controlled nonsymmetrical cyclic loading test.

2. Constitutive model

Many constitutive models have been developed for the prediction of the material behavior subjected to the cyclic loading. In this research, the Chaboche nonlinear kinematic model, including the translation of the yield surface during plastic deformation in the stress plane, is applied. The kinematic hardening rule for Chaboche model is described in the following Eq (1).

$$dx_i = \frac{2}{3} c_i d\varepsilon^p - \gamma_i x_i dp \tag{1}$$

in which the superposition of some hardening rules is included (Eq. 2).

$$dx = \sum_{i=1}^N dx_i \tag{2}$$

Equation 1 consists of the linear purely kinematic term $\frac{2}{3} c_i d\varepsilon^p$ derived from Prager–Ziegler model and relaxation (recall) term $\gamma_i x_i dp$, which introduces the nonlinearity and includes the fading memory effect of the strain path [11].

Three decomposed hardening rules are recommended in simulations of stable hysteresis loop (Figure 1) [12]. The first rule (x_1) should start hardening with a very large modulus and stabilize quickly. The second rule (x_2) should simulate the transient nonlinear portion of the stable hysteresis curve. The third rule (x_3) should almost linear hardening rule ($\gamma_3 = 0$) to represent the subsequent linear part of a hysteresis curve at the high strain rate [13]. According to Bari and Hassan [9], the introduction of small nonlinearity ($\gamma_3 \neq 0$) might improve the simulation of ratcheting.

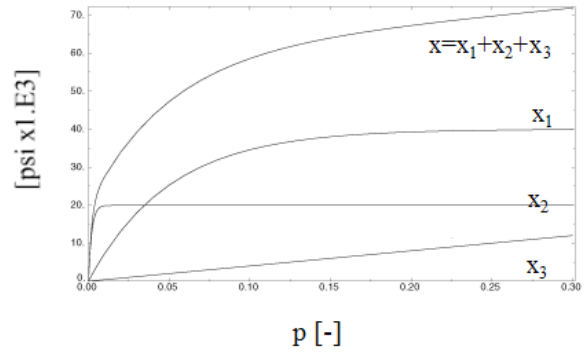


Figure 1. Kinematic hardening model with three backstresses.

For the evolution of the yield surface size in the stress space, the Voce isotropic hardening model was considered in this study (Eq. 3).

$$dr(p) = b(Q - r) dp \tag{3}$$

3. Experimental investigations

For the initial selection of hardening parameters for the PA6 aluminum, the strain-controlled symmetrical tension/compression test was carried out using the ZWICK/ROELL Z100 testing machine. The geometry of a specimen used in this study is shown in Figure 2. The deformation $\pm 2\%$ of the measuring base was applied. The experiment was carried out in triplicate, and the results were calculated as an average value from these series. The experimental true stress–true strain curve obtained is shown in Figure 3.

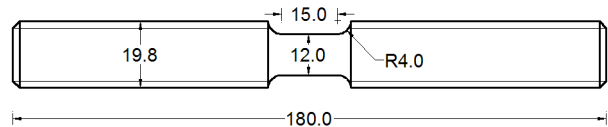


Figure 2. The geometry of specimens used in this research.

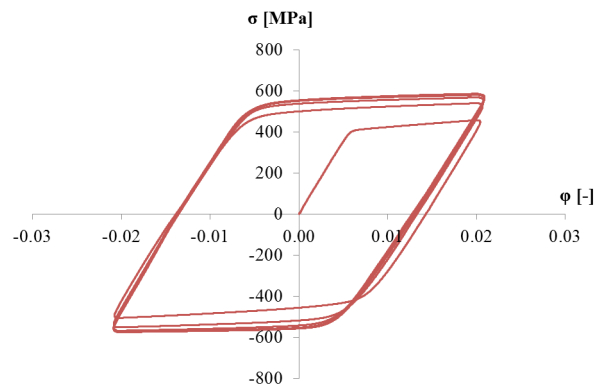


Figure 3. The experimental stress–strain curve for PA6 aluminum.

In this research, the unknown parameters were c_1 , c_2 , c_3 , γ_1 , γ_2 , and γ_3 (Chaboche model) as well as Q and b (Voce model). In Chaboche model, each c parameter is the initial kinematic hardening moduli, and each γ parameter defines the rate at which the kinematic hardening moduli decreases with the increase of the plastic deformation. For Voce model, parameter Q determines the saturation stress, and b parameter defines the rate in which the material saturates.

The Chaboche parameters were identified using automated calibration in ABAQUS program. Parameters C_i and γ_i were determined from the stabilized cycle test data. The constrained optimization problem was solved with $\sum_{i=1}^N \frac{c_i}{\gamma_i} = \sigma_{sat}$ equality and $\gamma_3 < 9$ inequality constraints [12]. Based on the experimental stress–strain data converted into true stress–plastic strain relation (Figure 4), ABAQUS automatically calibrates the parameters for Chaboche model. The yield stress was determined using the 0.2% offset method. The plastic strain was calculated using the additive decomposition of generalized strain (Eq. 4).

$$\varepsilon_i^p = \varepsilon_i - \frac{\sigma_i}{E} \quad (4)$$

The material hardening parameters for Chaboche selected by means of ABAQUS procedure are $Q = 150$ MPa, $c_1 = 4735$ MPa, $\gamma_1 = 299$, $c_2 = 1511$ MPa, $\gamma_2 = 291$, $c_3 = 1554$ MPa, $\gamma_3 = 22$, and $b = 11$. The numerical curve for such obtained parameters is shown in Figure 5.

It is clearly seen in Figure 5 that a relatively good correlation was obtained between the experimental and numerical curves. However, the stabilized cycle test data ensure the better selection of parameters for the last stabilized hysteresis loop than for the first one.

As a main part of this research, the nonsymmetrical stress-controlled cyclic tension-compression test for PA6 aluminum was carried out using the testing machine mentioned before. The registered hysteresis loops are shown in Figure 6.

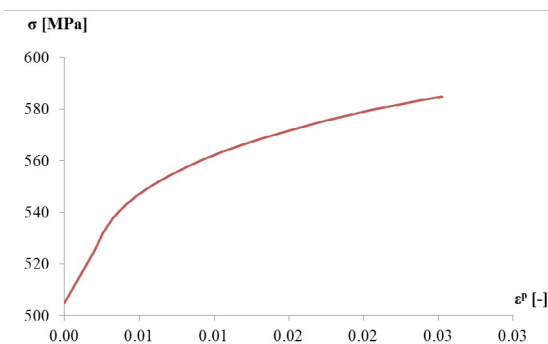


Figure 4. The calibration stress–plastic strain curve.

4. Approximation of hardening parameters

For better fitting of experimental and numerical curves, the optimization approach using the least-square method was applied. This procedure assumes that stress deviations from their approximate values (the error norm) are being minimized (Eq. 5). More information about this procedure is included in Wójcik and Skrzat [14].

$$B = \sqrt{\int_{\varepsilon} (\sigma_{exp} - \sigma_{appr})^2 d\varepsilon} \quad (5)$$

The minimum of Eq. (5) error norm (12%) was obtained for the following material's hardening parameters: $Q = 140$ MPa, $c_1 = 1544$ MPa, $\gamma_1 = 611$, $c_2 = 1028$ MPa, $\gamma_2 = 612$, $c_3 = 358$ MPa, $\gamma_3 = 20$, and $b = 18$. The comparison of experimental and numerical curves after the optimization procedure is shown in Figure 7.

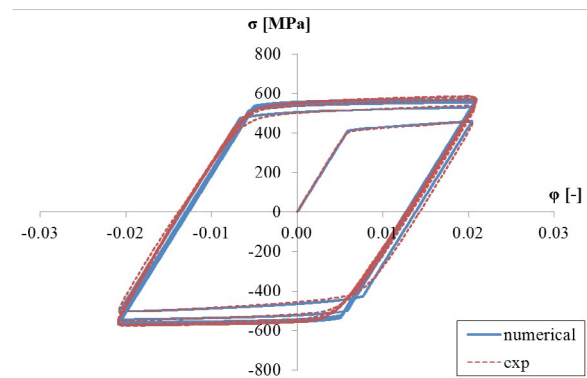


Figure 5. The comparison of experimental and numerical stress–strain curves for the Chaboche model obtained by ABAQUS program.

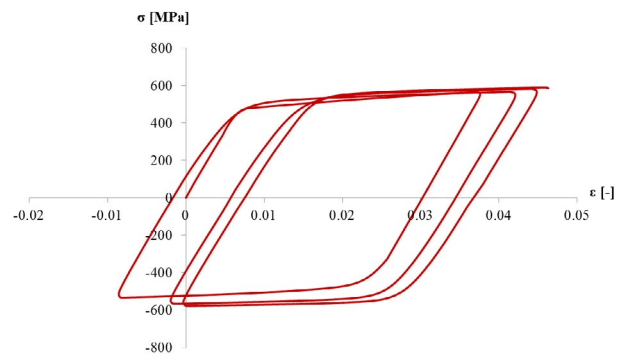


Figure 6. The stress–strain data for stress-controlled cyclic tension–compression test.

The kinematic and isotropic hardening parameters were then applied to create a model in ABAQUS for simulating of ratcheting in PA6 aluminum.

5. The modeling of the uniaxial ratcheting for PA6 aluminum

The ABAQUS software was applied in numerical simulations of nonsymmetrical stress-controlled cyclic tension/compression tests. The model is shown in Figure 8. Due to the axial symmetry of the specimen, the 2D axisymmetric analysis is made. The model was meshed by two-dimensional quadratic quadrilateral elements.

The following material data are used in analyses: $E = 70 \times 10^3$ MPa, $\nu = 0.33$, and $\sigma_y = 412$ MPa. The hardening parameters identified in the cyclic tension/compression test and optimized by means of the least-square method were applied in numerical calculations.

The specimen is constrained at the left end in the longitudinal direction, and a load is applied to the right end of the specimen. The load history applied is shown in Figure 9.

Figure 10 presents the results of the ratcheting simulation for stress-controlled hysteresis loop with the use of Chaboche model with three kinematic hardening rules. It is observed that the simulated hysteresis loop traces the experimental curve relatively close. The good agreement between both curves confirms the proper selection of the hardening parameters.

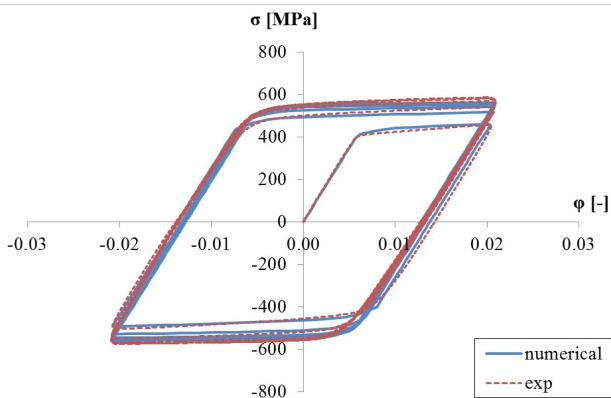


Figure 7. The comparison of experimental and numerical stress-strain curves for Chaboche model after the optimization by the least-square method.

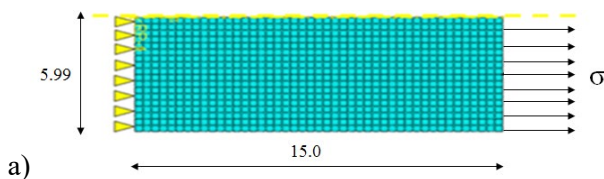


Figure 8. The sketch of the model.

6. Summary and conclusions

In this article, Chaboche model was used in numerical simulations of uniaxial ratcheting for the PA6 aluminum. The parameters for Chaboche model were determined from the stabilized cycle test data in ABAQUS program based on the experimental stress-strain curve. For better fitting of experimental and numerical curves, hardening parameters were enhanced using the least square method. The relatively good agreement between numerical and experimental curves was obtained for the Chaboche nonlinear kinematic hardening model with three decomposed rules.

The numerical simulation of the nonsymmetrical stress-controlled cyclic tension-compression test for the PA6 aluminum was done by the finite element method analysis. A relatively good agreement between experimental and numerical curves was noted for Chaboche nonlinear kinematic hardening model with three kinematic rules.

Further research will focus on the application of improved models, for example, Chaboche model with threshold on backstress or Chaboche model with fourth rule, in modeling of ratcheting. These models include the linear segment on the hysteresis curve within the threshold level, and therefore, the rate of ratcheting is reduced improving the simulations of the ratcheting.

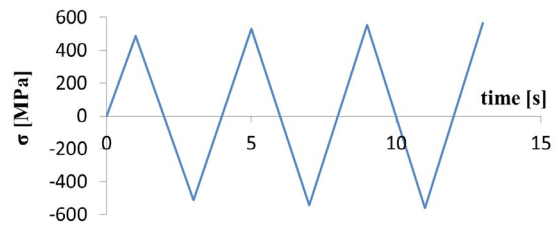


Figure 9. The load history used in numerical simulations.

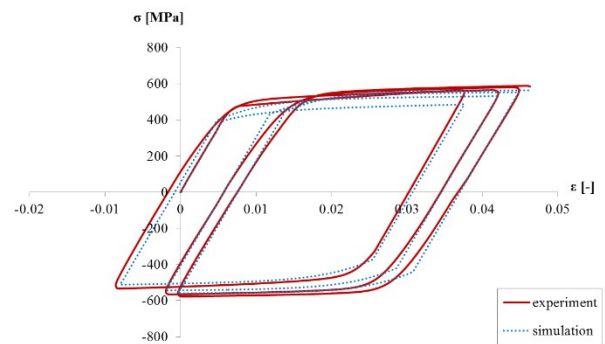


Figure 10. Numerical and experimental stress-strain curves for a nonsymmetrical stress-controlled loading test.

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