Experimental analysis for uniaxial ratcheting behavior of metals and simulation with Chaboche kinematic hardening model

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1. Introduction

Ratcheting is a material behavior of metals, in which the plastic strain accumulates under cyclic stress or thermal deformation. Since this behavior causes excessive strain even under a constant level of cyclic stress, mechanical parts subject to repeated loading condition should be designed with the ratcheting behavior in consideration, especially for fatigue life and initial structure integrity.

In this study, a set of uniaxial low cycle fatigue (LCF) tests is conducted with AISI 316L specimens for 100 cycles, and then the ratcheting response is analyzed according to alternative stress and mean stress. In addition, the uniaxial ratcheting behavior of AISI 52100 bearing steel, which is an actual engineering material, is simulated for 10 cycles by using Chaboche [1] kinematic hardening rule.

2. Uniaxial ratcheting analysis of AISI 316L

For AISI 316L (stainless steel), the uniaxial ratcheting experiments are performed. The round specimen is designed by considering the buckling resistance under compressive loading as shown in Fig. 1. The cyclic stress conditions are set to 5 cases by changing the alternative stress (σ_a) and mean stress (σ_m) by ±20 MPa on basis of (σ_m, σ_a) = (200, 400) MPa, respectively (Table 1). Fig. 2 shows the representative uniaxial ratcheting behavior under (σ_m, σ_a) = (200, 400) MPa. The tendency of ratcheting behavior according to the cyclic stress conditions is presented in Fig. 3. From this case study, it is demonstrated that the larger the alternative stress (σ_a) and mean stress (σ_m), the greater the ratcheting strain at each cycles.

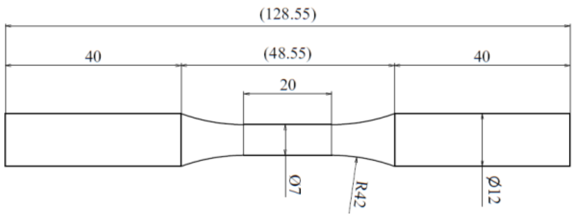

Fig. 1 Round specimen for uniaxial ratcheting test

Table 1 Cyclic stress conditions for LCF test

five conditions of (σ_m, σ_a) MPa				
200, 420	220, 400	200, 400	180, 400	200, 380

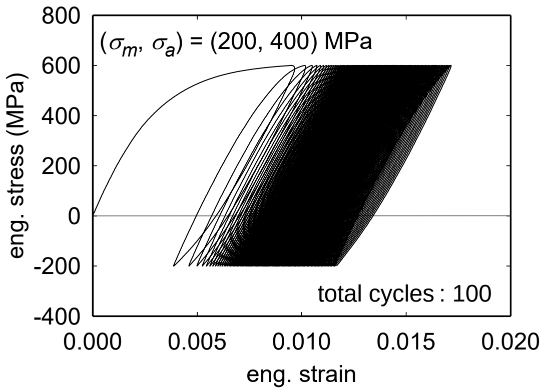

Fig. 2 Uniaxial ratcheting behavior of AISI 316L under (σ_m, σ_a) = (200, 400) MP

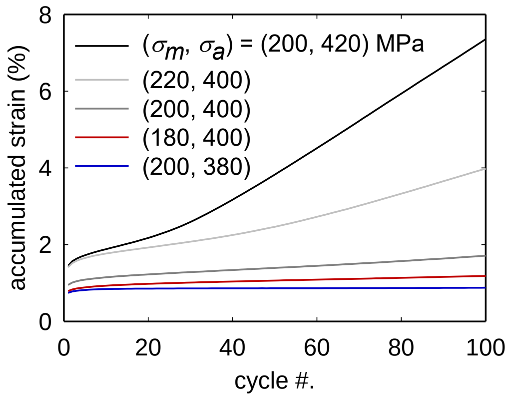

Fig. 3 Ratcheting strain with various cyclic stress conditions

3. Simulating uniaxial ratcheting of AISI 52100

For simulating uniaxial ratcheting behavior of AISI 52100 bearing steel, the Chaboche kinematic hardening model [1] is used with triple backstress. In a framework of this model, yield criterion, flow rule and hardening rule are as follows.

Von-Mises yield criterion

$$F(\mathbf{s}-\mathbf{a}) = \sqrt{\frac{3}{2}(\mathbf{s}-\mathbf{a}):(\mathbf{s}-\mathbf{a})} - \sigma_o = 0$$

Flow rule

$$d\boldsymbol{\varepsilon}^p = \sqrt{\frac{3}{2}}\, dp\,\mathbf{n}, \quad \mathbf{n} = \sqrt{\frac{3}{2}}\frac{(\mathbf{s}-\mathbf{a})}{\sigma_o}$$

Hardening rule

$$d\mathbf{a}_m = \frac{2}{3}C_m d\boldsymbol{\varepsilon}^p - \gamma_m \mathbf{a}_m dp, \quad \text{for } m = 1,2,3$$

The **s** and **a** are deviatoric parts of stress and backstress, respectively. The C_m and γ_m are model parameters which are determined by uniaxial cyclic loading tests. In this study, these parameters are optimized by using analytical solution in uniaxial condition. The analytical solution [Eq. (1)] and objective function [Eq. (2)] are given as follows.

$$\sigma^{\text{model}} = \sum_{i=1}^{M}\left[\left(\alpha_{i,\text{o}} - v\frac{C_i}{\gamma_i}\right)e^{-v\gamma_i\left(\varepsilon^{pl}-\varepsilon_{\text{o}}^{pl}\right)} + v\frac{C_i}{\gamma_i}\right] + v\sigma_{\text{o}} \quad (1)$$

$$F(\sigma_{\text{o}},\alpha_{i,\text{o}},C_i,\gamma_i) = \frac{w_1}{K_1}\sum_{i=1}^{K_1}\left[\frac{\sigma_{\text{mono},i}^{\text{exp}} - \sigma_{\text{mono},i}^{\text{model}}}{\sigma_{\text{mono},i}^{\text{exp}}}\right]^2 + \frac{w_2}{K_2}\sum_{i=1}^{K_2}\left[\frac{\sigma_{\text{peak},i}^{\text{exp}} - \sigma_{\text{peak},i}^{\text{model}}}{\sigma_{\text{peak},i}^{\text{exp}}}\right]^2 \quad (2)$$

Where the value of v is +1 and −1 for tension and compression, respectively. The K_1 and K_2 mean number of monotone and peak data (Fig. 4). The w_1 and w_2 mean each weighting factor.

The uniaxial ratcheting test with AISI 52100 steel is conducted in condition of $(\sigma_m, \sigma_a) = (300, 260)$ MPa. Fig. 5 shows the experimental result of the uniaxial ratcheting behavior of AISI 52100 for 10 cycles. The optimized parameters are listed in Table 2 and predicting results are shown in Fig. 6.

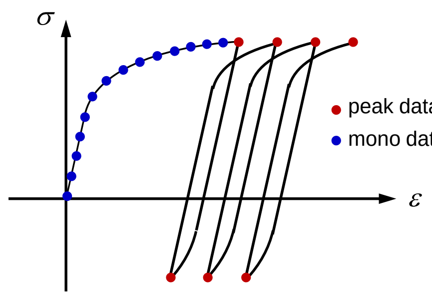

Fig. 4 Data selection scheme for optimization

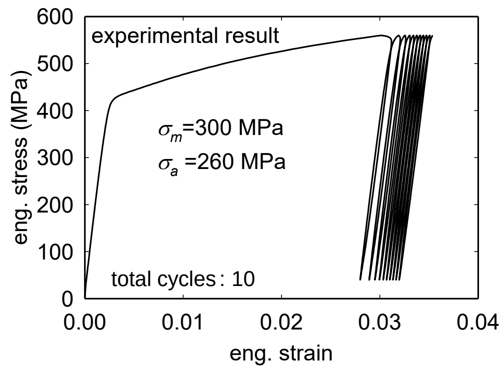

Fig. 5 Uniaxial ratcheting behavior of AISI 52100

Table 2 Optimized values of model parameters

σ_0 [MPa]	C_1 [MPa]	C_2	C_3	γ_1
214.8	103×10^4	5.4×10^3	17.7×10^3	19.8×10^3
γ_2	γ_3	$\alpha_{1,0}$ [MPa]	$\alpha_{2,0}$	$\alpha_{3,0}$
2.53	472	0	140	0

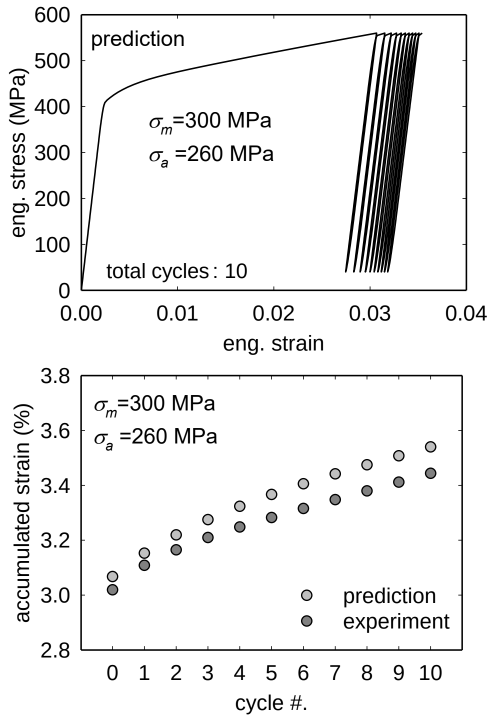

Fig. 6 Prediction results using Chaboche model with optimized parameters

4. Conclusion and discussion

From the uniaxial LCF test with AISI 316L, it is demonstrated that the larger the cyclic stress level, the greater the ratcheting strain increment, and the alternative stress has a greater effect. Since the Chaboche kinematic hardening model has the analytical solution under uniaxial condition, it is very effective in determining the parameters. By using this advantage, model parameters are simply optimized and the uniaxial ratcheting behavior of AISI 52100 for initial 10 cycles is well simulated. However, the used model has a limitation to overestimate the ratcheting behavior and cannot be used to multiaxial condition. Since most actual engineering parts are subject to multiaxial loads, a more sophisticated study should be conducted with multiaxially improved kinematic hardening model [2], which will be our future work.

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References

[1] J.L. Chaboche, Time-independent constitutive theories for cyclic plasticity, *International Journal of Plasticity*, 2 (1986) 149−188.

[2] S. Bari and T. Hassan, An advancement in cyclic plasticity modeling for multiaxial ratcheting simulation, *International Journal of Plasticity*, 18 (2002) 873−894.