Parameter Determination of the Chaboche Kinematic Hardening Models for 30CrMo Steel in Hydrogen Environment

Xin Wu, Yunrong Luo, Yanbing Guan, Yunbo Zhang

College of Mechanical Engineering, Sichuan University of Science & Engineering, Zigong 64300, Sichuan, China

Abstract

Steel is widely used in life, and fatigue failure is the most common failure mode. In this paper, based on Chaboche constitutive theory, the parameters of the 30CrMo steel kinematic hardening models were calibrated for different hydrogen charging durations and verified with ABAQUS finite element software. The results show that Chaboche kinematic hardening models can accurately simulate the half-life hysteresis curve of 30CrMo steel.

Keywords

30CrMo Steel; Numerical Simulation; Kinematic Hardening Models; Half-life Hysteresis Curve.

1. Introduction

The cyclic principal model of steel describes the stress-strain relationship of steel under cyclic loading [1]. At present, many scholars at home and abroad have studied the cyclic constitutive model of steel and obtained their respective calculation models [2-4]. The reliability of their constitutive models is verified by comparing and analyzing these models with the test results.

In order to obtain the Chaboche kinematic hardening model parameters of 30CrMo steel under different hydrogen charging time, equal amplitude tensile and compressive cyclic tests under were carried out and the stress-strain hysteresis curves under cyclic loading were obtained. Combined with the Chaboche kinematic hardening theory, the corresponding parameters were obtained and finally were verified using ABAQUS finite element software.

2. Experimental Design

In order to obtain the parameters of the Chaboche kinematic hardening model, push-pull strain-controlled fatigue tests under displacement control were then carried out with a strain ratio of -1 (ε_a =5.0%) in ambient air at room temperature. The experimental specimens were charged with hydrogen by electrochemistry for 1h and 4h before the fatigue test, respectively, at a current density of 2mA/cm2, and the fatigue tests were carried out immediately after the hydrogen charging.

3. Chaboche Kinematic Hardening Model

3.1 The Theory

Von Mises yield criterion was adopted in the Chaboche cyclic plastic constitutive model, and the material yield surface is defined in equation (1):

$$\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]=\sigma_y{}^2 \tag{1}$$

where: σ_1 , σ_2 and σ_3 are the principal stresses in the three directions respectively; σ_y is the yield stress of the material in monotonic tension.

A dynamic strengthening model can be used to describe the plastic deformation of the material under large strain cyclic load. The form of superposition of multilevel back stress components was used in the nonlinear kinematic hardening model to describe the kinematic hardening behavior of the material. The kinematic hardening model is shown in Eq. (2) and Eq. (3):

$$\alpha=\sum_{1}^{\mathrm{m}}\alpha_k \tag{2}$$

$$\alpha_{\mathrm{k}}=\frac{C_k}{\gamma_k}(1-e^{-\gamma_k\varepsilon^{pl}})+\alpha_{\mathrm{k},1}e^{-\gamma_k\varepsilon^{pl}} \tag{3}$$

where: α and α_{k} are the total backstress and the kth backstress component, respectively, m is the number of backstress levels, and in this paper m equals to 2; $\frac{C_{\mathrm{k}}}{\gamma_k}$ is the maximum change of backstress, and γ_{k} represents the rate of increase of backstress with plastic strain. The half-life stabilized hysteresis curve data pairs（α_{i}, ε_i^{pl}）are used in the kinematic hardening model to fit the parameters C_k and γ_{k} , the kinematic hardening models curve is shown in Fig. 1. Multiple data pairs（α_{i}, ε_i^{pl}）are obtained by processing the following Eq. (4) to (6).

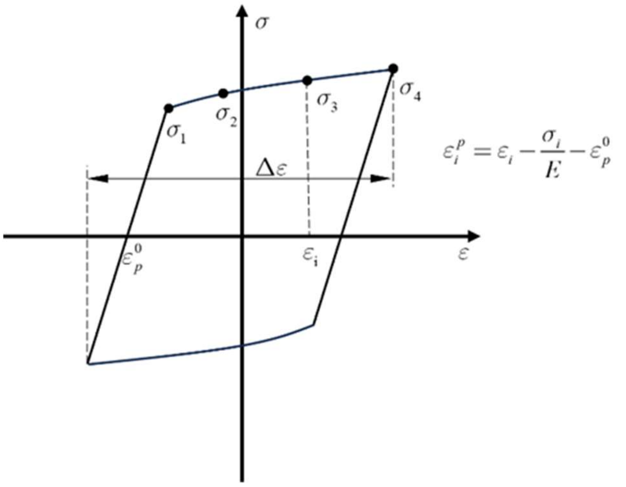

Fig. 1 The kinematic hardening models

$$\alpha_{\mathrm{i}}=\sigma_i-\sigma^s \tag{4}$$

$$\sigma^{\mathrm{s}}=\frac{\sigma_1+\sigma_n}{2} \tag{5}$$

$$\varepsilon_{\mathrm{i}}^{pl} = \varepsilon_i - \frac{\sigma_i}{E} - \varepsilon_p^0 \tag{6}$$

Where: α_{i}, σ_{i} and $\varepsilon_{\mathrm{i}}^{pl}$ are the total back stress, stress and plastic strain at data points i respectively; σ^{s} represents the average of the first data point σ_1 and the last data point σ_{n} of the hysteresis curve strengthening phase.

Based on the above equations, the kinematic hardening parameters of 30CrMo steel at a strain amplitude of 5.0% under different hydrogen charging durations were fitted. Multiple data pairs（α_{i}, ε_i^{pl}）were substituted into Eq. (2) and Eq. (3), and then iteratively solved by MATLAB software to obtain the material parameters C_k and γ_{k}, and the fitting results are shown in Table 1.

Table 1. Parameters of kinematic hardening

Hydrogen charging time/h	C_1/MPa	γ_1	C_2/MPa	γ_2
0	3601	309	5595	34.7
1	3975	367.9	6285	37
4	7391	432.8	9176	51

3.2 Finite Element Verification

In order to verify the accuracy and reliability of the kinematic hardening model, in this paper the 3D modeling software Solidworks was employed to establish a large model of the experimental specimen, and then the model was imported into the finite element software ABAQUS for calculation under cyclic loading. The mesh type used in the model is C3D8R, and the mesh division is shown in Fig. 2, with a total of 5920 meshes globally and an average aspect ratio of 1.82, which is of good mesh quality. In order to keep consistent with the experimental process, the boundary conditions are shown in Fig. 3, with fully fixed constraints applied at the lower end, displacement control at the upper end, and the type of load applied is sinusoidal. The ‘set’ set was created for the scalar segments of the specimen since only the scalar segments were required for data extraction.

Fig. 2 Finite element model **Fig.3** Boundary conditions

The parameters of the kinematic hardening model and the yield criterion in Table 1 are selected to define the material properties, and the model is subjected to finite element analysis to obtain the hysteresis curves under different hydrogen charging durations, which are compared with the experimental results as shown in the figure below, and it can be seen that the hysteresis curves obtained by the kinematic hardening model are basically in good agreement with those of the experimental hysteresis curves, which verifies the applicability of the model, and indicates that the parameters obtained by the calculation based on the kinematic hardening model can be used in the actual engineering.

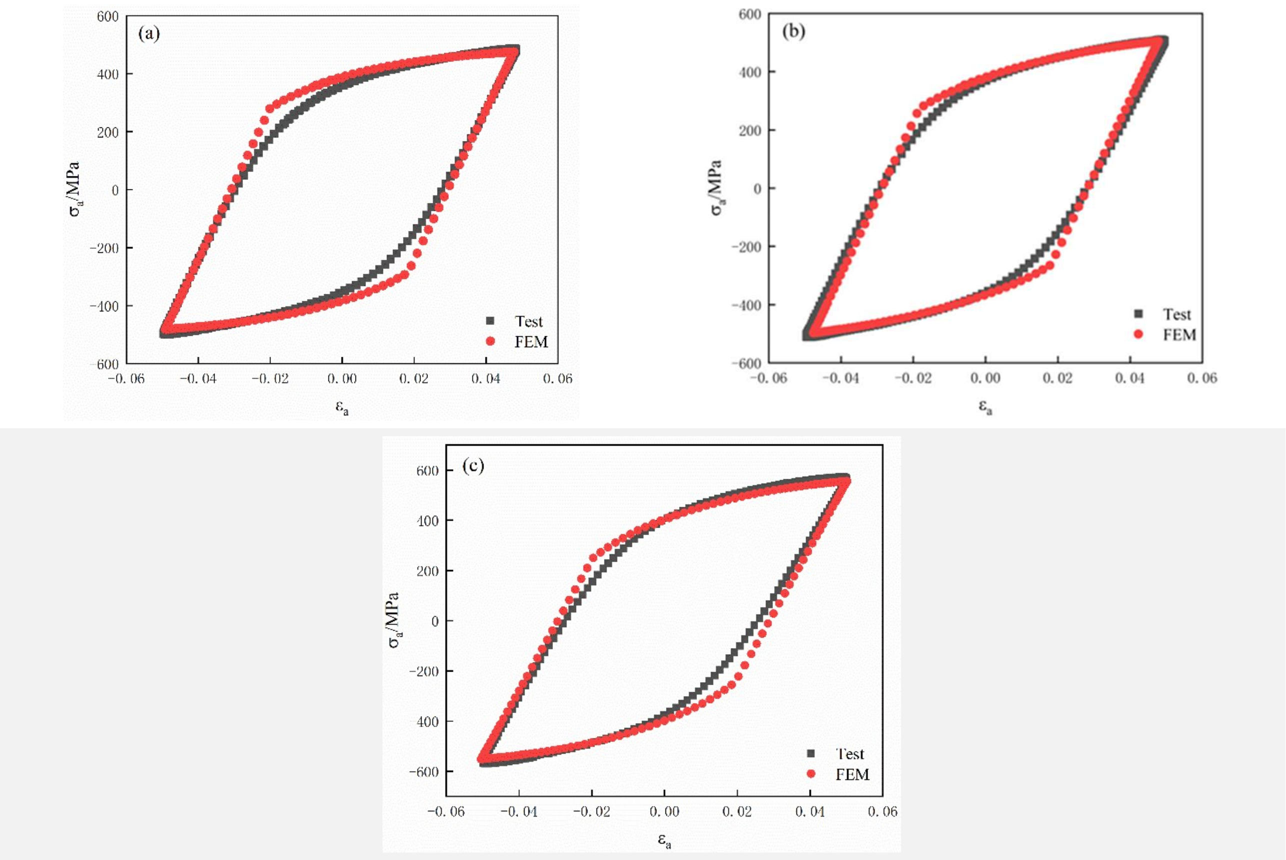

Fig. 4 Comparison of experimental and finite element results

4. Conclusion

(1) The ductility of 30CrMo steel material is better, the hysteresis curve is fuller under large strain cyclic loading, and the energy dissipation ability is better.

(2) By applying large strain cyclic loading to 30CrMo steel, the parameters of Chaboche kinematic hardening model were obtained under different hydrogen charging time, and based on the analysis of the finite element results, the cyclic intrinsic relationship of the material was able to be predicted by Chaboche kinematic hardening model well.

References

[1] WangJ J, Shi Y J, Wang Y Q, et al. Experimental study on low yield point steel LYP100 under cyclic loading[J]. Journal of Zhejiang University (Engineering Science),2015,49(8):1401-1409.

[2] Wang Y, Li G, Cui W, et al. Experimental investigation and modeling of cyclic behavior of high strength steel[J]. Journal of Construction Steel Research,2015,104:37-48.

[3] He Q, Chen Y, KE K, et al. Experiment and constitutive modeling on cyclic plasticity behavior of LYP100 under large strain range[J]. Construction and Building Materials,2019,202:507-521.

[4] Wang M, Fahnestock A L, Qian F, et al. Experimental cyclic behavior and constitutive modeling of low yield point steels[J]. Construction and Building Materials,2017,131:696-712.