Cyclic characteristic analysis of 9-12%Cr steel at high temperature: experiment and model

Yu Cao¹, Xin Cui², Chuan-huai Liu³, Wei-guo Pan¹, Dong-Mei Ji¹*

¹. College of Energy and Mechanical Engineering, Shanghai University of Electric Power, Shanghai200090, China
². NARI Technology Company Limited, NanJing 211106, China
³. Fengtai Power Generation Branch Company, Huai Zhe Coal Power Co. Ltd., Huainan Anhui Province, 232131, China
* Corrresponding Author: Dri Dong-Mei Ji, e-mail: jdm@shiep.edu.cn

Abstract. Strain controlled creep-fatigue experiments of P92 steel with various strain amplitudes and holding time were conducted under 600°C. The effect of strain amplitude on cyclic softening and stress relaxation behavior is negligible. However, the holding time has a greater impact on both. A new constitutive model within the framework of Chaboche model was developed by improving the nonlinear isotropic hardening law and kinematic hardening law with cyclic characteristic parameters. According to the experimental data, the constitutive model deduced above was applied on P92 steel, and the reliability of the model was also verified, in which the cycle characteristics of P92 steel under creep-fatigue was finely described.

1. Introduction
Due to good resistance to creep and fatigue damage, P92 steel is widely employed in high temperature components of ultra-supercritical power generation units. Long-term operating under the high pressure and temperature, the creep voids (caused by the high temperature and continuous stress) and fatigue cracks (caused by the alternating load) would promote or develop each other, forming creep-fatigue interaction. It would lead to a premature failure of the critical components and thus bring more challenges in high temperature strength design and structural integrity assessment[1]. The crucial matter is that the damage gradually accumulates inside the material, and failure always appears without obvious signs[2]. Therefore, it is of great significance from both scientific exploration and engineering applications to establish a damage constitutive model which can not only provide a basis for life prediction, but also meet the reference requirements of power plant maintenance work.

So far, many studies have been conducted on the organizational performance, failure mechanism of creep-fatigue and constitutive model of P92 steel[3-8], which provides important theoretical support for the safe operation of ultra-supercritical units, and plays a certain reference role for this article. It has been an effective method to apply constitutive models to simulate the creep-fatigue process of metal material and provide a basis for life prediction. In order to ensure the simulation precision, the choice of constitutive model also should be considered. During the past several decades, with the rapid development of the power industry, it is necessary to more accurately predict the deformation of
high-temperature structures.

Although many researches have been conducted on P92 steel constitutive model, no consensus has been reached. It is necessary to continue to develop a new material constitutive model, and constantly explore and improve the constitutive theory. A new constitutive model within the framework of Chaboche model was developed by improving the nonlinear isotropic hardening law and kinematic hardening law with cyclic characteristic parameters in this study. Strain-controlled creep-fatigue test of P92 steel at 600°C had been conducted to obtain the damage evolution law and analysis the cyclic characteristics and a new damage constitutive model of P92 steel coupled with creep-fatigue damage had been constructed based on the Chaboche model in this paper.

2. Experiments

The strain-controlled creep-fatigue tests are conducted at 600°C on the Hydraulic servo drive fatigue testing system MTS370.10. The strain rate (loading and unloading) of the tests is controlled at 0.001%/s. The specific test parameters are listed in Table 1.

| Group          | Sample number | Strain range (Δε_{fat}/%) | Holding time (T/min) |
|----------------|---------------|---------------------------|----------------------|
| Different      |               |                           |                      |
| holding time   |               |                           |                      |
| 1              | C01           | 0.5                       | 5                    |
|                | C02           | 0.5                       | 15                   |
|                | C03           | 0.6                       | 6                    |
|                | C04           | 0.6                       | 15                   |
| Different      |               |                           |                      |
| strain amplitude |              |                           |                      |
| 3              | C02           | 0.5                       | 15                   |
|                | C04           | 0.6                       | 15                   |

3. Creep-fatigue strain evolution law of P92 steel

In the strain-controlled creep-fatigue test, the cyclic response of P92 steel is expressed as the change of stress amplitude with cycle time, and then the cyclic hardening/softening behavior of P92 steel is determined. The stress amplitude can be expressed as follows:

\[ Δσ_i = σ_{max}^i - σ_{min}^i \]  

Where, \( σ_{max}^i \) is the maximum stress at the i-th cycle; \( σ_{min}^i \) is the minimum stress at the i-th cycle.

Fig. 1 shows the evolution of stress amplitude with different cycle number under strain control. It is not difficult to find that as the cycle number increases, the stress amplitude gradually decreases, and
P92 steel exhibits obvious cycle softening characteristics. Stress relaxation caused by creep strain during loading under the strain control is defined as the difference between the stress at the initial time of loading and the stress at the end of loading.

Fig. 2 (a) shows the evolution of stress relaxation of P92 steel under strain control conditions with different strain amplitudes. It is not difficult to find that the stress relaxation tends to be stable and the fluctuation is relatively stable after a certain number of cycles. However, it is difficult to judge the relationship between stress relaxation under different working conditions. Therefore, in order to observe and judge the factors which affect stress relaxation more intuitively, the average stress relaxation bar chart under different working conditions is shown in Fig2(b). Compared (A), (B) and (C), (D), it can be found that, the average stress relaxation grows with the increasing holding time at the same strain range; contrasting (A) and (D), it can be preliminarily considered that the average stress relaxation of larger strain range is slightly bigger than one of the small strain range during the same holding time.

Fig. 2 Evolution of stress relaxation under strain control (a) relaxed stress- normalized number of cycles and (b) mean relaxed stress with different working conditions

4. Viscoplastic constitutive model

4.1. Main control equations

The construction of cyclic viscoplastic constitutive model should include the following four basic elements: yield condition, strain decomposition, hardening criterion and plastic flow rule. The Von Mises yield criterion should be obeyed. In this paper, the creep strain is introduced into the original Chaboche constitutive model, and its evolution rate is shown as equation (5). The specific expression of the main control equation of the metal material is as follows:

$$\epsilon = \epsilon^p + \epsilon^c + \epsilon^\dot{c}$$  

(2)

Where, $\epsilon^p$ is the elastic strain; $\epsilon^c$ is the plastic strain; $\epsilon^\dot{c}$ is the creep strain.

$$\epsilon^c = \frac{1+v}{E} \sigma - \frac{v}{E} tr(\dot{\sigma}) I$$  

(3)

Where, $E$ is the material elastic modulus; $v$ is the Poisson's ratio; $I$ is the unit tensor. For a uniaxial stress state, the expression is:

$$\epsilon^c = \frac{\dot{\sigma}}{E(1-D)}$$  

(4)

The creep strain is defined as,
The plastic strain is defined as,
\[ \dot{\varepsilon}^p = \frac{3}{2\sigma} \left( \varepsilon^e : \varepsilon^e \right)^{\frac{1}{2}} \]
(5)

Where, \( \varepsilon^e = (\frac{3}{2} \varepsilon^e : \varepsilon^e)^{\frac{1}{2}} \); \( \sigma = (\frac{3}{2} \dot{\sigma} : \dot{\sigma})^{\frac{1}{2}} \); \( S \) is the deviator stress tensor, \( S = \dot{\sigma} - \frac{1}{3} \text{tr}(\dot{\sigma})I \).

For a uniaxial stress state, \( \varepsilon^e = \frac{3}{2} \left| \varepsilon^e \right| \), \( \sigma = \frac{3}{2} |\dot{\sigma}| \).

The plastic strain is defined as,
\[ \dot{\varepsilon}^p = \frac{3}{2n} \left\{ \frac{F_y}{K} \left[ S - \alpha \right] \right\} \]
(6)

Where, \( K \) and \( n \) are material parameters; \( \alpha \) is back stress tensor; \( F_y \) is viscoplastic overstress, the expression is:
\[ F_y = \frac{3}{2} \left( S - \alpha \right)^2 - Q \]
(7)

For a uniaxial stress state, the expression above can be simplified as:
\[ F_y = \frac{3}{2} \left( S - S \right)^2 - Q \]
(8)

4.2 Introduction of nonlinear hardening rule

The constitutive model in this paper adopts the nonlinear kinematic hardening rule. This rule is firstly proposed by Armstrong and Frederick, referred to as the A-F model\[^{[19]}\]. It considers the dynamic recovery effect of material hardening based on the linear hardening criterion, and adds a dynamic recovery term to connect with the gradually dissipated strain memory effect, which makes the motion hardening rule non-linear. Chaboche et al.\[^{[20]}\] decomposed the back stress in the A-F model, which can better simulate various hysteresis loops and the average stress relaxation phenomenon. In order to make the model more accurately describe the cycle characteristics, this paper adds the power function to the dynamic recovery term based on the Chaboche model. At the same time, in order to better regulate the role of the dynamic recovery term, the Heaviside function is introduced. The specific expression of the model is shown as follows:
\[ \alpha = \sum \alpha_i \quad (i = 1, 2, 3) \]
(9)

Where, \( \alpha_i \) is the i-th partial back stress tensor.

\[ \dot{\alpha}_i = \frac{2}{3} \zeta_i r_i \dot{\varepsilon}^p - \zeta_i \left( \frac{\| \alpha \|}{r_i} \right)^{m_i} \left[ \alpha \right] \dot{\varepsilon}^p \quad (i = 1, 2, \ldots, M) \]
(10)

Where, \( \dot{\varepsilon}^p \) is cumulative plastic strain rate; \( \zeta_i \), \( r_i \) and \( m_i \) are material parameter for kinematic hardening rate; \( H(u) \) is the Heaviside function \((u \leq 0, H(u) = 0; u > 0, \quad H(u) = 1); \| \alpha \| \) is the magnitude of the i-th partial back stress tensor, \( \| \alpha \| = \frac{2}{3} \alpha_i : \alpha_i \); \( f_i \) is the critical plane, \( f_i = \| \alpha \|^2 - r_i^2 = 0 \).

When \( \| \alpha \| \leq r_i \),
\[ \dot{\alpha}_i = \frac{2}{3} \zeta_i r_i \dot{\varepsilon}^p - \zeta_i \left( \frac{\| \alpha \|}{r_i} \right)^{m_i} \alpha \dot{\varepsilon}^p \quad (i = 1, 2, \ldots, M) \]
(11)
When $\|\alpha_i\| > r_i$,

$$\dot{\alpha}_i = \zeta_i \left[ \frac{2}{3} r_i \dot{\epsilon}^p - \left( \frac{\|\alpha_i\|}{r_i} \right)^n \alpha_i \langle \dot{\epsilon}^p : K_i \rangle \right] \quad (i = 1, 2, \ldots, M) \quad (12)$$

### 4.3. Modification of isotropic hardening rule

In the creep-fatigue test at 600°C, P92 steel performs obvious cyclic softening characteristics, however, the material parameter $r_i$ in the constitutive model cannot accurately and reasonably describe this characteristic. Therefore, the isotropic hardening rule needs to be introduced in the model to describe the material cyclic softening/hardening characteristics. At present, the nonlinear hardening rule proposed by Chaboche et al.\textsuperscript{[20]} is generally used in the viscoplastic unified constitutive model:

$$\dot{Q} = \gamma (Q_{sa} - Q) \dot{p} \quad (13)$$

Where, $\dot{p}$ is the cumulative plastic strain rate; $\gamma$ is the evolution rate of isotropic deformation resistance $Q$; $Q_0$ is the initial isotropic deformation resistance, $Q_0 = 0$; $Q_{sa}$ is the saturated isotropic deformation resistance.

In this paper, the original model is improved based on the above evolution rate, and then the cyclic softening behavior of P92 steel can be described reasonably.

### 5. Determination of material parameters

#### (1) Elastic parameters $E$ and $v$

The elastic modulus $E$ and Poisson's ratio $v$ can be obtained from the uniaxial tensile test curve of P92 steel. According to the uniaxial tensile test results in the literature\textsuperscript{[1, 22]}, the required uniaxial tensile test data at 600°C is obtained by interpolation.

#### (2) $K$ and $n$

The parameters $K$ and $n$ can be obtained from several uniaxial tensile curves with different strain rates. The data are same as above. Points (as $A(\varepsilon_\lambda, \sigma_\lambda, \dot{\varepsilon}_\lambda), B(\varepsilon_\mu, \sigma_\mu, \dot{\varepsilon}_\mu)$) on uniaxial tensile curves at different strain rates with the same strain are picked, as shown in Fig. 8. The cumulative plastic strain rate and stress of the above two points can be expressed as follows:

$$\Delta \sigma = \sigma_\mu - \sigma_\lambda \quad (14)$$

$$\Delta \sigma = K (\dot{\varepsilon}_\mu^{1/n} - \dot{\varepsilon}_\lambda^{1/n}) \quad (15)$$

In the uniaxial tensile test, the cumulative plastic strain rate is the plastic strain rate.

$$\dot{\varepsilon}^p = \dot{\varepsilon}^p \quad (16)$$

Where, the plastic strain rate $\dot{\varepsilon}^p$ can be obtained from the curve of $t - \varepsilon^p$. Finally, the least square method is used to obtain the values of $K$ and $n$. 
According to the Chaboche isotropic hardening rule, the relationship between the peak stress $\sigma_{\text{max}}$ and the cumulative plastic strain $\dot{\gamma}$ under the strain cycle is shown as follows:

$$\sigma_{\text{max}} = C + Q_{\text{sa}} \left[ 1 - \exp(-\gamma \dot{\gamma}) \right]$$  \hspace{1cm} (17)

Where, $C$ is constant. $Q_{\text{sa}}$ and $\gamma$ can be obtained from the fitting with least squares by the curve of $\sigma_{\text{max}} - \dot{\gamma}$ (as shown in Fig.4).

---

**Fig. 3 Stress-strain curves of P92 steel at different strain rates at 600℃**

(3) $Q_{\text{sa}}$ and $\gamma$  

According to the Chaboche isotropic hardening rule, the relationship between the peak stress $\sigma_{\text{max}}$ and the cumulative plastic strain $\dot{\gamma}$ under the strain cycle is shown as follows:

$$\sigma_{\text{max}} = C + Q_{\text{sa}} \left[ 1 - \exp(-\gamma \dot{\gamma}) \right]$$  \hspace{1cm} (17)

Where, $C$ is constant. $Q_{\text{sa}}$ and $\gamma$ can be obtained from the fitting with least squares by the curve of $\sigma_{\text{max}} - \dot{\gamma}$ (as shown in Fig.4).

---

**Fig. 4 Curve of $\sigma_{\text{max}} - \dot{\gamma}$**

(4) $\zeta^{(i)}$ and $r^{(i)}$  

$\zeta^{(i)}$, $r^{(i)}$ and $Q_{\text{sa}}$, $\gamma$ are the parameters describing the degree of hardening. $\zeta^{(i)}$ and $r^{(i)}$ can be determined from the uniaxial tensile curve obtained above. However, the effect of isotropic hardening must be removed first because of the feature that will make the obtained parameters inaccurate. The uniaxial tensile results can be corrected according to the actual evolution of cyclic hardening. The specific process is as follows:

Step1: Because the model assumes that the material cyclic softening behavior is completely
reflected by the evolution of the isotropic hardening parameters, this article performs fitting with the uniaxial strain cycle test result. In order to improve the fitting accuracy, the original power function is modified by the index function to get the relationship between the peak stress and cumulative plastic strain for each cycle:

\[
\sigma_{\text{max}} = \sigma_{\text{max}}^0 h(p)
\]

\[
h(p) = 1.2221 - 0.2234 e^{-2.2755p}
\]

Where, \( \sigma_{\text{max}}^0 \) is the maximum stress in the first cycle. \( p = \varepsilon^p \) in the uniaxial test. The \( \sigma^* - \varepsilon^p \) curve can be achieved by the equation \( \sigma^* = \sigma / h(\varepsilon^p) \) \[23\]. In the curve (as shown in Figure. 9), \( R^2 = 0.9909 \) which means the effects of isotropic hardening are basically eliminated.

![Fig. 5 Curves of \( \sigma - \varepsilon^p \) and \( \sigma^* - \varepsilon^p \)](image)

Step2: According to the obtained curve of \( \sigma^* - \varepsilon^p \), \( \zeta^{(i)} \) and \( \mu^{(i)} \) can be determined according to the following equation (20) and (21). Due to the use of piecewise linear hardening equations, in order to achieve the purpose of describing the nonlinearity of uniaxial tensile curves with multilinearity, multiple sets of hardening equations need to be superimposed. Considering the amount of calculation and the convenience of application, this paper takes \( M=8 \).

\[
\zeta^{(i)} = \frac{1}{\varepsilon^{p(i)}}, \quad i=1,2,\cdots M
\]

\[
\mu^{(i)} = \left( \frac{\sigma^{*(i)} - \sigma^{*(i-1)}}{\varepsilon^{p(i)} - \varepsilon^{p(i-1)}} - \frac{\sigma^{*(i+1)} - \sigma^{*(i)}}{\varepsilon^{p(i+1)} - \varepsilon^{p(i)}} \right) \varepsilon^{p(i)}, \quad i=1,2,\cdots M
\]

(5) Cyclic parameter \( m \)

\( m \) is a parameter related to the cyclic characteristics, which can cause the dynamic recovery term non-linear and make the hysteresis loop non-closed. The value of \( m \) can be obtained by the trial-error method with the strain-controlled creep-fatigue test data\[17\].

Through the above methods, the obtained model parameters are listed in Table 2.

| \( \sigma_s \) (MPa) | \( E_0 \) (GPa) | \( \nu \) | \( K \) (MPa) | \( n \) | \( Q_{\text{eq}} \) (MPa) | \( \gamma \) | \( m \) | \( S_0 \) (MPa) |
|-----------------|-------------|-----|-------|-----|----------------|------|-----|--------|
| 297             | 156         | 0.33| 236.2 | 9   | 51.38          | 2.28 | 9   | 20.52  |

\( \zeta^{(1-8)} = 2391.66, 1195.89, 607.53, 402.81, 279.32, 139.15, 96.88, 75.28, 73.17 \)

\( \mu^{(1-8)} = 9.499, 15.911, 26.036, 22.555, 10.088, 1.620, 6.466, 65.550 \) (MPa)
6. Verification of the proposed model

In order to verify the rationality of the model to describe the cycle characteristics of P92 steel under strain control, Fig. 6 shows the comparison between the test results and the simulation results under different test conditions. The comparative analysis can be observed from the stress-strain cycle curves of the first and second cycles in the figure. It can be found that the agreement between the test results and the simulation results is very high. Therefore, it can be considered that this model can better simulate the cycling characteristics of P92 steel under strain control.

Fig. 6 Stress-strain simulation curves under strain control, (a) $t_h = 5 \text{ min} , \Delta \varepsilon_{\text{in}} = 0.5\%$ and (b) $t_h = 15 \text{ min} , \Delta \varepsilon_{\text{in}} = 0.5\%$ and (c) $t_h = 5 \text{ min} , \Delta \varepsilon_{\text{in}} = 0.6\%$ and (d) $t_h = 6 \text{ min} , \Delta \varepsilon_{\text{in}} = 0.6\%$

7. Conclusion

Strain-controlled creep-fatigue tests with various strain amplitudes and holding time were conducted at 600°C. The plastic evolution law and cyclic characteristics of P92 steel were analyzed. With the experimental characteristics, a viscoplastic constitutive model of P92 steel coupled with creep-fatigue damage was established based on the framework of the classic Chaboche constitutive model. The main conclusions are as follows:

1. Under strain control, the plastic strain of P92 steel changes with cycle number which can be divided into two stages. In the first stage, the plastic strain decreases rapidly, and the strain rate changes rapidly. In the second stage, the plastic strain rate tends to stable and the plastic strain gradually stabilizes.
(2) As the cycle number increases, the stress amplitude gradually decreases, and P92 steel exhibits obvious cycle softening characteristics. Under strain control, P92 steel performs stress relaxation behavior, the effect of strain amplitude on cyclic softening and stress relaxation behavior is negligible, while the holding time has a greater impact on both.

(3) Compared with the experimental results, this model can well describe the cycling characteristics of P92 steel. When solving the model hardening degree parameters, the exponential function is used to replace the original power function to obtain a better fitting result.

Acknowledgement
The authors gratefully acknowledge the financial support from Shanghai Natural Science Foundation (No. 19ZR1420300), and Shanghai Science and technology project (No. 19020500900).

Reference
[1] Zhang S, Xuan F. Interaction of cyclic softening and stress relaxation of 9−12% Cr steel under strain-controlled fatigue-creep condition: Experimental and modeling[J]. International Journal of Plasticity, 2017.
[2] Zhang B, Cai P, Li K, et al. Finite Element Analysis of Creep Behavior of Dissimilar Steel Welded Joint[J]. China Mechanical Engineering, 2015,26(02):266-271.
[3] Ge S, Ren J. The organizations research of P92 high temperature and high pressure pipe extrusion[J]. China Metalforming Equipment & Manufacturing Technology, 2016,51(1):111-114.
[4] Peng Y, Cai L, Chen H, et al. A Theoretical Model for Predicting Uniaxial Stress−Strain Relations of Ductile Materials by Small Disk Experiments Based on Equivalent Energy Method[J]. Transactions of the Indian Institute of Metals, 2019,72(1):133-141.
[5] Xu L, Zhao L, Han Y, et al. Characterizing crack growth behavior and damage evolution in P92 steel under creep-fatigue conditions[J]. International Journal of Mechanical Sciences, 2017,134.
[6] Xu H, Yuan J, Ni Y. Primary Creep Process of P92 Steel Based on Norton-Bailey Model[J]. Journal of Materials Science & Engineering, 2013,31(04):568-571.
[7] Chang Y, Xu H, Lan X. Building and Validation of a Multiaxial Creep Constitutive Model for P92 Steel[J]. Materials for Mechanical Engineering, 2017,41(02):112-118.
[8] Wen X, Jiang Y, Guo X, et al. High-Temperature Tensile Characteristicsof P92 Steel at Different Temperatures and Strain Rate[J]. Materials for Mechanical Engineering, 2016,40(11):115-118.
[9] Frederick C O , Armstrong P J . A mathematical representation of the multiaxial Bauschinger effect[J]. High Temperature Technology, 2007, 24(1):1-26..
[10] Chaboche J L. A review of some plasticity and viscoplasticity constitutive theories[J]. International Journal of Plasticity, 2008,24(10).