A study of low cycle fatigue life prediction method for 1Cr11Ni2W2MoV at 360℃

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Abstract. The high temperature low cycle fatigue tests of 1Cr11Ni2W2MoV are conducted under total axial strain control. The specimens are tested under fully reversed strain. The relationships of cyclic strain-life, stress-strain and stress-life are analyzed. Manson-Coffin method and a new method based on power transformation theory are evaluated by the low cycle fatigue data. The results showed that two methods can effectively predict low cycle fatigue life of 1Cr11Ni2W2MoV at 360℃. Prediction accuracy within ±1.65 times scatter band. The life prediction capability of new methods proves more effective and accurate than Manson-Coffin method. The new method has smaller standard deviation than Manson-Coffin method. Manson-Coffin method and new method have standard deviations of 0.32 and 0.18 respectively.

1. Introduction

1Cr11Ni2W2MoV is a martensitic stainless steel, mainly for the manufacture of load-bearing components which work in wet conditions at below 550℃. It can be used to manufacture rotor blade plate and other rotating components in aero engine compressor. Guo Xiaoguang et al. proposed that these components bear the complex alternating loads at high temperatures during the service, which may be the cause of early fatigue damage [1].

The high temperature low cycle fatigue (LCF) life prediction is an important basis for safety assessment on the project, and has long been concerned by domestic and foreign scholars [2, 3]. In order to accurately predict the high temperature LCF life prediction, various methods have been proposed over the years. Manson and Coffin established Manson-Coffin method [4]. This method is widely used in LCF life prediction. They noted that in some cases, relationship of plastic strain amplitude and failure reverse number presents linear relationship in the double logarithmic coordinates. Chen Lijie et al. proposed quadratic characters of plastic strain amplitude vs. failure reverse number presents linear relationship in the double logarithmic coordinates. Chen Hong and Jiang Hongde proposed the low cycle fatigue life prediction method which can...
consider the effect of average stress, strain ratio and crystal orientation on fatigue life. The method is validated using low cycle fatigue test data of DD3 and PWA1840 nickelbase single crystal superalloy, and the results show that the proposed method is acceptable [8]. Chen Ling et al. proposed the life prediction model for low cycle fatigue based on continuum damage mechanics. Results show that the predicted results which are obtained by the sampling data of different life periods are in good agreement with the experiment results [9].

In this paper, the high temperature LCF tests of 1Cr11Ni2W2MoV are conducted under total axial straincontrol. The specimens are tested under fully reversed strain. The relationships of cyclic strain-life, stress-strain and stress-life are analyzed. Manson-Coffin method and a new method based on power transformation theory are evaluated by the LCF data. Related research can provide reference for component design and life evaluation.

2. Experimental methods

2.1. Material
The testing material was 1Cr11Ni2W2MoV bar. The base material was given a normalizing treatment at 1000 to 1020 °C for 1 hour followed by oil quenching and subsequently tempering at 540 to 600 °C for 1.5 hour followed by air cooling, before machining the standard fatigue specimens. The chemical composition of 1Cr11Ni2W2MoV is presented in Table 1. The tensile properties for 1Cr11Ni2W2MoV at 20 °C and at 360 °C are shown in Table 2.

| Table 1. The chemical composition of 1Cr11Ni2W2MoV (weight, %) |
|------------------|------|------|------|-------|------|-----|-----|-----|
| C                | Cr   | Mn   | Si   | Ni    | W    | Mo  | P   | S    | Nb   |
| 0.10~0.16        | 10.50~12.00 | <0.60 | <0.60 | 1.40~1.80 | 0.35~0.50 | <0.030 | <0.020 | 0.75~1.25 |

| Table 2. The tensile property for 1Cr11Ni2W2MoV |
|------------------|------|------|------|------|------|------|------|------|------|
| Temperature T(°C) | Young’s modulus E (MPa) | Fracture limit σb (MPa) | Yield strength σ0.2 (MPa) | Elongation δ,%(weight) | Reduction of area ψ,%(weight) |
| 20 °C             | 206000 | 1183 | 993 | 8 | 68 |
| 360 °C            | 163000 | 989 | 825 | 14 | 71 |

2.2. Test conditions and methods
The LCF tests were conducted under total axial strain control at 360 °C. The specimens are tested under fully reversed strain. The temperature variation did not exceed ± 2 °C. The experimental frequency was 0.333HZ for all tests. Experimental waveform was a triangular waveform. Three specimens are tested under each amplitude. The average of similar data is taken as the experimental result.

3. Results and discussion

3.1. Low cycle fatigue test results and discussion of 1Cr11Ni2W2MoV
The linear relationship of $\Delta \varepsilon / 2 - 2N_f$, $\Delta \varepsilon_p / 2 - 2N_f$ and $\Delta \varepsilon / 2 - 2N_f$ in double logarithmic coordinates is presented figure 1. Fitting coefficient ($R^2$) of $\Delta \varepsilon / 2 - 2N_f$, $\Delta \varepsilon_p / 2 - 2N_f$ and $\Delta \varepsilon / 2 - 2N_f$ is 0.914, 0.9704 and 0.975 respectively. Regression equation (1) and equation (2) can be obtained by regression analysis.

$$\Delta \varepsilon_p / 2 = 6.9776(2N_f)^{-1.1448} \quad (1)$$
$$\Delta \varepsilon / 2 = 0.0076(2N_f)^{-0.0878} \quad (2)$$

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The curve of $\Delta \sigma / 2 — \Delta \varepsilon_p / 2$ is shown in figure 2. Regression equation (3) can be obtained by regression analysis.

$$\Delta \sigma / 2 = 1216.9 (\Delta \varepsilon_p / 2)^{0.0764}$$  \hspace{1cm} (3)

3.2. Fatigue life prediction

3.2.1. Life prediction by the Manson-Coffin method. Manson-Coffin method is widely used in LCF life prediction. For LCF test under total strain amplitude control, Manson-Coffin method predicts life using equation (4).

$$\frac{\Delta \varepsilon_t}{2} = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\sigma_f'}{E} (2N_f)^b + \varepsilon_f' (2N_f)^c$$  \hspace{1cm} (4)

where, $\frac{\Delta \varepsilon_t}{2}$ is total strain amplitude, $\frac{\Delta \varepsilon_e}{2}$ is elastic strain amplitude, $\frac{\Delta \varepsilon_p}{2}$ is plastic strain amplitude, $\sigma_f'$ is fatigue strength coefficient, $b$ is fatigue strength exponent, $\varepsilon_f'$ is fatigue ductility coefficient, $c$ is fatigue ductility exponent. The $\frac{\sigma_f'}{E}$, $b$, $\varepsilon_f'$ and $c$ values are obtained by regression analysis. Therefore, Manson-Coffin method predicts the low cycle fatigue life of 1Cr11Ni2W2MoV at 360°C thorough equation(5).

$$\frac{\Delta \varepsilon_t}{2} = 0.0076(2N_f)^{-0.0878} + 6.9776(2N_f)^{-1.1448}$$  \hspace{1cm} (5)

3.2.2. Life prediction based on the power transformation theory. According to LCF data analysis results, the relationship between plastic strain and failure reverse number presents nonlinear in the double logarithmic coordinates. It will lead to generating a prediction error using Manson-Coffin method. In order to solve the problem, a new method based on power transformation theory is proposed.

3.2.3. Power transformation theory. Box and Cox proposed the power transformation method as follows [10]:

$$T_p(x) = \begin{cases} \frac{x^p - 1}{p}, & p \neq 0 \\ \ln x, & p = 0 \end{cases}$$  \hspace{1cm} (6)

Order M_x and M_y are the median of the variable x, y respectively. Assuming the real model data as follows:
\[
\frac{y^p - 1}{p} - \frac{M_y^p - 1}{p} = K(x-M_x)
\]  

(7)

Order \(z = \frac{y^p - 1}{p}\), if \(p \neq 0\), there:

\[
M_y \approx (pM_z + 1)^{1/p}
\]  

(8)

Equation (9) is obtained by equation (6) variable substitution:

\[
z - M_z \approx K(x-M_x)
\]  

(9)

Where, \(M_z\) is the median of the variable \(z\), \(K\) is the model constants.

Make \((pz+1)\) as an independent variable, \(y = (pz+1)^{1/p}\) is expanded by second-order Taylor formulas in \((pM_z+1)\) point as follows:

\[
y \approx (pM_z + 1)^{1/p} + (pM_z + 1)^{(1/p-1)}(z - M_z) + \frac{1-p}{2}(pM_z + 1)^{(1/p-2)}(z - M_z)^2
\]  

(10)

The equation (8) and equation (9) is substituted into equation (10). Equation (11) is obtained.

\[
y \approx M_y + \frac{KM_y}{pM_z + 1}(x-M_x) + \frac{1-p}{2M_y} (\frac{KM_y}{pM_z + 1})^2(x-M_x)^2
\]  

(11)

Order \(C = \frac{KM_y}{pM_z + 1}\), the equation (11) is simplified to equation (12):

\[
y \approx M_y + C(x-M_x) + \frac{1-p}{2M_y} C^2(x-M_x)^2
\]  

(12)

Order \(L = y - M_y - C(x-M_x)\), \(F = \frac{C^2(x-M_x)^2}{2M_y}\), the equation (12) is simplified to equation (13):

\[
L = (1-p)F
\]  

(13)

Where, \(C\) is obtained by linear regression for equation \(y - M_y = C(x-M_x)\); \(p\) is obtained by linear regression for equation (13).

3.2.4. Life prediction model based on the power transformation theory. For metal material whose the plastic strain amplitude is less than the metal material 1, take \((-\ln \frac{\Delta \varepsilon_p}{2} )\) as intermediate variable. Equation (14) is obtained by transforming equation (6).

\[
(-\ln \frac{\Delta \varepsilon_p}{2})^p - 1 - \frac{M_y^p - 1}{p} = K_0[\ln(2N_f) - M_x]
\]  

(14)

Where, \(M_x\), \(M_y\) are the median of the variable \(2Nf\) and \((-\ln \frac{\Delta \varepsilon_p}{2} )\) respectively. \(K_0\) is the model constants.

Order \(C_0 = \frac{M_y}{p} - K_0M_x\), the equation (14) is simplified to equation (15):
\[ (-\ln \frac{\Delta \varepsilon_p}{2})^p = K_0 \ln (2N_f) + C_0 \]  

Figure 3 presents the linear relationship of \((-\ln \frac{\Delta \varepsilon_p}{2})^p\) and \(\ln (2N_f)\). Linear correlation has reached more than 0.99. \(C_0\) and \(K_0\) are obtained by linear regression for equation (15).

Equation (16) is obtained by transforming equation (15).

\[ \frac{\Delta \varepsilon_p}{2} = e^{-[C_0 + K_0 \ln (2N_f)]^{1/p}} \]  

Therefore, the life prediction method based on power transformation theory can be expressed as the equation (17):

\[ \frac{\Delta \varepsilon_p}{2} = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\sigma_f}{E} (2N_f)^b + e^{-[C_0 + K_0 \ln (2N_f)]^{1/p}} \]  

3.3. Quantitative evaluation of life prediction ability

Scatter band and standard deviation can be used to evaluate quantitatively the life prediction ability of model. Scatter band shows that the degree of deviation from the predicted life and experimental life [11, 12]. The scatter band \((S)\) can be expressed as equation (19).

\[ S = \max \left[ \frac{N_f^p}{N_f^m}, \frac{N_m^p}{N_f^m} \right] \]  

Figure 4 presents all of life prediction value fall within 1.65 times scatter band by Manson-Coffin method. Figure 5 presents all of life prediction value fall within 1.57 times scatter band by the new method.
The standard deviation is smaller; the life prediction ability of the model is better. The standard deviation(s) can be expressed as equation (20).

\[ s = \left( \sum_{i=1}^{n} \frac{(\lg N_{f}^p - \lg N_{f}^m)^2}{(n-1)} \right)^{1/2} \]  

(20)

Where, \( n \) is number of data points.

The fatigue life prediction for 1Cr11Ni2W2MoV by the Manson-Coffin method and new method had standard deviation of 0.32 and 0.18 respectively. The fatigue life prediction for 1Cr11Ni2W2MoV by the Manson-Coffin method and new method had Scatter bands of 1.65 and 1.57 respectively.

The evaluation of life prediction methods is shown in figure 6. The new method based on power transformation theory has smaller standard deviation and scatter band than Manson-Coffin method. Therefore, the life prediction capability of new methods proves more effective than Manson-Coffin method.

4. Conclusions

The LCF tests of 1Cr11Ni2W2MoV were carried out under total axial strain control at 360℃. The relationships of cyclic strain-life, stress-strain and stress-life are analyzed. Cyclic stress-strain and strain-life curves of the 1Cr11Ni2W2MoV were obtained. There was a nonlinear relationship between the plastic strain amplitude (\( \Delta \varepsilon_p / 2 \)) and reverse number (2N) in double logarithmic coordinates.

The LCF life prediction model of 1Cr11Ni2W2MoV at 360℃ is established by Manson-Coffin method and power transformation method.
Manson-Coffin method and new method can effective predict LCF life of 1Cr11Ni2W2MoV at 360 °C. Prediction accuracy within ±1.65 times scatter band.

The life prediction capability of new methods proves more accurate than Manson-Coffin method. The results of life prediction showed new method has smaller standard deviation and scatter band than Manson-Coffin method. The Manson-Coffin method and new method have scatter bands of 1.65 and 1.57 respectively and have standard deviations of 0.32 and 0.18 respectively.

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