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Life prediction for high temperature low cycle fatigue of two kinds of titanium alloys based on exponential function

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Abstract. The high temperature low cycle fatigue tests of TC4 titanium alloy and TC11 titanium alloy are carried out under strain controlled. The relationships between cyclic stress-life and strain-life are analyzed. The high temperature low cycle fatigue life prediction model of two kinds of titanium alloys is established by using Manson-Coffin method. The relationship between failure inverse number and plastic strain range presents nonlinear in the double logarithmic coordinates. Manson-Coffin method assumes that they have linear relation. Therefore, there is bound to be a certain prediction error by using the Manson-Coffin method. In order to solve this problem, a new method based on exponential function is proposed. The results show that the fatigue life of the two kinds of titanium alloys can be predicted accurately and effectively by using these two methods. Prediction accuracy is within ±1.83 times scatter zone. The life prediction capability of new methods based on exponential function proves more effective and accurate than Manson-Coffin method for two kinds of titanium alloys. The new method based on exponential function can give better fatigue life prediction results with the smaller standard deviation and scatter zone than Manson-Coffin method. The life prediction results of two methods for TC4 titanium alloy prove better than TC11 titanium alloy.

1. Introduction
Titanium alloy has been widely used in the manufacture of aircraft engine compressor discs, blades and casing because of its high specific strength, good corrosion resistance, good heat resistance and good mechanical properties [1]. When titanium alloy is used for aircraft manufacturing materials, metal materials bearing the main form of the force structure failure is fatigue fracture, a serious threat to flight safety. Therefore, it is very important to study on the fatigue behavior of titanium alloy.

The high temperature low cycle fatigue (HTLCF) life prediction has been a hot research topic for many researchers. In order to effectively predict the HTLCF life of materials, many methods have been proposed in the past years. Manson and Coffin [2, 3] proposed Manson-Coffin equation. Manson-Coffin equation is widely used in fatigue life prediction. They noted that there was a linear relationship between plastic strain range and failure inverse number in the double logarithmic coordinates. Manson [4] considered that the fatigue life of the material can be estimated by alternative
thermal fatigue test results when the thermal fatigue is superimposed by alternative mechanical loading. Halford and Manson [5] proposed the strain range partitioning method. They believe that high temperature and low cycle fatigue include fatigue damage and creep damage. The fatigue damage is mainly related to the deformation of the slip surface, and the creep damage is mainly related to the deformation of grain boundaries. Shengtian et al. [6] proposed a continuum damage mechanics method. They believed that with increment of damage the stress range decreases slowly and steady. This continuum damage stage is a main part of the whole life. The total continuum damage is not large. It means that the damage rate of TC4 titanium alloy is low but fatigue is sensitive to micro-crack damage. Yang et al. [7] proposed the fatigue life prediction method based on radial basis function neural network. Tisong et al. [8] proposed a life prediction model that describes the relation between damage energy density and fatigue life based on the formula of Three-Parameter Power Function. The results show that the proposed method is in good agreement with the experiment results. Weiping et al. [9] put forward a continuous miner method which combines stochastic load probability weighting, linear miner cumulative damage rule and fuzzy theory. The result shows that the improved fatigue prediction method is accurate within acceptable range. Ling et al. [10] proposed a new model for predicting low cycle fatigue life of magnesium alloy. The results show that the predicted results are in good agreement with the experimental results. Guodong et al. [11] proposed fatigue life prediction method based on power-exponent function. They considered that there was a power-exponent function relationship between the plastic strain range and inverse number in log-log scale coordinates. Although many models have been proposed for the HTLCF life prediction, each method has its limitations. Because the high temperature fatigue damage of materials is affected by creep-fatigue interaction and the other factors. It has been very difficult to accurately predict the high temperature fatigue life of the material. Yi et al. [12] considered that it is very difficult to analyze the behavior of fatigue creep interaction. So it becomes very important to study the high temperature fatigue life prediction model for specific materials.

In this paper, the HTLCF tests of TC4 titanium alloy and TC11 titanium alloy are carried out under total axial strain. The relationships of cyclic strain-life and stress-life are analyzed. The HTLCF life prediction models of two kinds of titanium alloys are established by Manson-Coffin method and new method based on exponential function. In addition, the fatigue life predictive ability of two methods was assessed. Related research can provide reference for component design and life evaluation.

2. Experimental methods

2.1. Materials

TC4 titanium alloy and TC11 titanium alloy are used as experimental materials. The Chemical composition of two kinds of titanium alloys are shown in table 1. The tensile property of two kinds of titanium alloys are shown in table 2 [13].

| Material | Al | C | Fe | Si | O  | H   | N   | Ti    |
|----------|----|---|----|----|----|-----|-----|-------|
| TC4      | 6.22 | 0.02 | 0.09 | 0.04 | 0.12 | 0.015 | 0.02 | surplus |
| TC11     | 5.8~7.0 | ≤0.10 | ≤0.25 | 0.20~0.35 | ≤0.15 | ≤0.012 | ≤0.05 | surplus |

Table 1. The chemical composition of two kinds of titanium alloys (wt%).

| Material | Young’s modulus E (GPa) | Fracture limit $\sigma_f$ (MPa) | Yield strength $\sigma_{0.2}$ (MPa) | Elongation $\delta$ (%) | Reduction of area $\psi$ (%) |
|----------|-------------------------|-------------------------------|---------------------------------|------------------------|-----------------------------|
| TC4      | 109                     | 969                           | 948                             | 16                     | 45.5                        |
| TC11     | 83                      | 806                           | 641                             | 20.8                   | 63.5                        |

Table 2. The tensile property of two kinds of titanium alloys.
2.2. Experimental conditions and methods
The HTLCF experimental conditions and methods of two kinds of titanium alloys are shown in table 3.

Table 3. The experimental conditions and methods of two kinds of titanium alloys.

| Experimental conditions and methods | TC4          | TC11          |
|------------------------------------|--------------|---------------|
| Experimental temperature           | 350°C        | 500°C         |
| Experimental control mode          | Axial strain control | Axial strain control |
| Material specifications            | d68 mm       | d18mm         |
| Loading Waves                      | Triangle wave | Triangle wave |
| Strain ratio                       | –1           | –1            |
| Loading frequency                  | 0.033–0.33 Hz| 0.167–0.333 Hz|
| Failure criterion                  | Crack        | Crack         |
| Heat treatment process             | 477°C, 4.5 h hardening, 121°C, 9h+177°C, 9h aging | 800°C, 1 h, air-cooled |

3. Results and discussion

3.1. Low cycle fatigue experimental results and discussion of TC4 titanium alloy
The HTLCF experimental results of TC4 titanium alloy are shown in table 4.

Table 4. The HTLCF experimental results of TC4 titanium alloy.

| Total strain range $\Delta \varepsilon / 2$ (%) | Elastic strain range $\Delta \varepsilon_e / 2$ (%) | Plastic strain range $\Delta \varepsilon_p / 2$ (%) | Stress range $\Delta \sigma / 2$ (MPa) | Fatigue inverse number $2N_f$ |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------|-----------------------------|
| 4.160                                         | 0.816                                         | 3.344                                         | 759                                | 81                          |
| 3.198                                         | 0.827                                         | 2.371                                         | 769                                | 118                         |
| 2.237                                         | 0.843                                         | 1.394                                         | 781                                | 229                         |
| 1.831                                         | 0.824                                         | 1.007                                         | 766                                | 363                         |
| 1.221                                         | 0.777                                         | 0.444                                         | 722                                | 830                         |
| 0.902                                         | 0.696                                         | 0.206                                         | 647                                | 2176                        |
| 0.682                                         | 0.617                                         | 0.065                                         | 574                                | 5681                        |

The linear relationship of $\Delta \varepsilon / 2$ $-2N_f$, $\Delta \varepsilon_p / 2$ $-2N_f$ and $\Delta \varepsilon / 2$ $-2N_f$ in log-log coordinate is shown in figure 1. Regression formula (1) and formula (2) can be obtained by regression analysis:

$$\Delta \varepsilon / 2 = 1.8919 (2N_f)^{0.9052}$$

$$\Delta \varepsilon / 2 = 0.0117 (2N_f)^{0.0681}$$

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

$$\Delta \sigma / 2 = 1043.7 (\Delta \varepsilon_p / 2)^{0.0765}$$

3.2. The HTLCF experimental results and discussion of TC11 titanium alloy
The linear relationship curve of $\Delta \varepsilon / 2$ $-2N_f$, $\Delta \varepsilon_p / 2$ $-2N_f$ and $\Delta \varepsilon / 2$ $-2N_f$ in log-log coordinate are shown in figure 3. Regression formula (4) and formula (5) can be obtained by regression analysis:

$$\Delta \varepsilon_p / 2 = 4.8798 (2N_f)^{0.9994}$$

$$\Delta \varepsilon / 2 = 0.0151 (2N_f)^{0.1293}$$
The relationship curve of \( \Delta \varepsilon / 2 \) \( - \) \( 2N_f \) is shown in Figure 1. Regression formula (6) can be obtained by regression analysis:

\[
\Delta \sigma / 2 = 1204.7(\Delta \varepsilon_p / 2)^{0.1275}
\]

Figure 1. The relationship curve of \( \Delta \varepsilon / 2 \) \( - \) \( 2N_f \)

Figure 2. The relationship curve of \( \Delta \sigma / 2 \) \( - \) \( \Delta \varepsilon_p / 2 \).

Figure 3. The linear relationship curve of \( \Delta \varepsilon / 2 \) \( - \) \( 2N_f \).

Figure 4. The relationship curve of \( \Delta \sigma / 2 \) \( - \) \( \Delta \varepsilon_p / 2 \).

4. Fatigue life prediction

4.1. Life prediction by the Manson-Coffin method

Manson-Coffin method is widely used in HTLCF life prediction. For HTLCF test under total strain ranges control, Manson-Coffin method predicts life using formula (7).

\[
\frac{\Delta \varepsilon}{2} = \frac{\Delta \varepsilon}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon_f (2N_f)^c
\]

where, \( \frac{\Delta \varepsilon}{2} \) is total strain ranges, \( \frac{\Delta \varepsilon}{2} \) is elastic strain range, \( \frac{\Delta \varepsilon_p}{2} \) is plastic strain range, \( \sigma_f \) 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 can are obtained by regression analysis.

The \( \frac{\sigma_f}{E} \), \( b \), \( \varepsilon_f \) and \( c \) values are shown in table 5.
Table 5. Corresponding coefficients in formula (7) of two kinds of titanium alloys.

| Material | $\frac{\sigma_f}{E}$ | b     | $\varepsilon'_f$ | c     |
|----------|---------------------|-------|------------------|-------|
| TC4      | 0.0117              | -0.0681 | 1.8919           | -0.9052 |
| TC11     | 0.0151              | -0.1293 | 4.8798           | -0.9994 |

4.2. Life prediction method based on exponential function

According to the HTLCF data analysis results, the relationship between plastic strain and failure inverse number presents nonlinear in log-log coordinate. It will lead to generating a prediction error using Manson-Coffin method. In order to solve this problem, a new method based on exponential function is proposed. Assuming a exponential relationship exists between $\left(-\ln\frac{\Delta\varepsilon_p}{2}\right)$ and $\ln(2N_f)$, the relationship can be expressed as formula (8):

$$(-\ln\frac{\Delta\varepsilon_p}{2}) = a_1 e^{a_2 \ln(2N_f)}$$  \hspace{1cm} (8)

Figure 5. Curve of TC4 titanium alloy $\left(-\ln\frac{\Delta\varepsilon_p}{2}\right)$-ln$(2N_f)$.

Figure 6. Curve of TC11 titanium alloy $\left(-\ln\frac{\Delta\varepsilon_p}{2}\right)$-ln$(2N_f)$.

Figure 5 and figure 6 present the exponent fit relationship of $\left(-\ln\frac{\Delta\varepsilon_p}{2}\right)$ and ln$(2N_f)$. $a_1$ and $a_2$ are obtained by regression for formula (8).

Formula (9) is obtained by transforming formula (8):

$$\frac{\Delta\varepsilon_p}{2} = e^{a_1 e^{a_2 \ln(2N_f)}}$$  \hspace{1cm} (9)

Therefore, the life prediction method based on exponential function can be expressed as the formula (10):

$$\frac{\Delta\varepsilon_f}{2} = \frac{\Delta\varepsilon_c}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma'_f}{E} \left(2N_f\right)^b + e^{a_1 e^{a_2 \ln(2N_f)}} \left(2N_f\right)^b$$  \hspace{1cm} (10)

The $\frac{\sigma'_f}{E}$, $b$, $a_1$ and $a_2$ values are shown in table 6.

Table 6. Corresponding coefficients in formula (10).

| Material | $\frac{\sigma'_f}{E}$ | b     | a1    | a2    |
|----------|---------------------|-------|-------|-------|
| TC4      | 0.0117              | -0.0681 | 1.6041 | 0.1772 |
| TC11     | 0.0151              | -0.1293 | 2.038  | 0.1407 |
5. Evaluation of life prediction ability
Shichao et al. [14] and Lijia et al. [15] believed that the life prediction ability of model can be quantitatively evaluated by scatter zone and standard deviation. The deviation degree between the experimental life and predicted life can be analyzed by scatter zone. The scatter zone ($x_{\text{max}}$) can be expressed as formula (11):

$$x_{\text{max}} = \max \left[ \frac{N_f^p}{N_f^s}, \frac{N_f^e}{N_f^s} \right]$$  \hspace{1cm} (11)

where, $N_f^p$ is predicted life, $N_f^e$ is experimental life.

The standard deviation is smaller; the life prediction ability of the model is better. The standard deviation(S) can be expressed as formula (12):

$$S = \left[ \frac{\sum (\log N_f^p - \log N_f^s)^2}{(n-1)} \right]^{1/2}$$  \hspace{1cm} (12)

where, $n$ is total number of experimental samples.

Scatter zone and standard deviation of two life prediction models are shown in table 7. As seen from the table 7 that the life prediction for TC4 titanium alloy by the Manson-Coffin method and exponential function method had standard deviation of 0.20 and 0.12 respectively. The life prediction for TC11 titanium alloy by the Manson-Coffin method and exponential function had standard deviation of 0.43 and 0.36 respectively.

| Material | Prediction method | Scatter zone | Standard |
|----------|-------------------|--------------|----------|
| TC4      | Manson-Coffin     | 1.54         | 0.20     |
|          | New method        | 1.28         | 0.12     |
| TC11     | Manson-Coffin     | 1.83         | 0.43     |
|          | New method        | 1.62         | 0.36     |

6. Conclusions
In order to study the HTLCF behaviour of TC4 titanium alloy and TC11 titanium alloy, the HTLCF tests were carried out under total axial strain control. The relationships of cyclic strain-stress and strain-life are analyzed. Cyclic strain-stress and strain-life relationship curves of the two kinds of titanium alloys were obtained. According to analysis results, there was an exponential relationship between $\Delta \varepsilon_p/2$ and $2N_f$ in log-log coordinate.

The high temperature LCF life prediction models of two kinds of titanium alloys are established by Manson-Coffin method and new method based on exponential function.

Manson-Coffin method and exponential function method can effectively predict the HTLCF life of TC4 titanium alloy and TC11 titanium alloy. Prediction accuracy within $\pm 1.83$ times scatter zone.

The fatigue life prediction results of two kinds of titanium alloys by two prediction models showed new method based on exponential function proved more accurate and effective than Manson-Coffin method. The new method can give better life prediction results with the smaller scatter zone and standard deviation.

Manson-Coffin method and new method based on exponential function can effectively predict the HTLCF life of TC4 titanium alloy. The fatigue life prediction for TC4 titanium alloy by the Manson-Coffin method and new method based on exponential function has scatter zone of 1.54 and 1.28 respectively and standard deviations of 0.20 and 0.12 respectively.

The life prediction capability of Manson-Coffin method and new method for TC4 titanium alloy prove more accurate than TC11 titanium alloy. Two methods can give better fatigue life prediction results for TC4 titanium alloy with the smaller standard deviation and scatter zone than TC11 titanium alloy.
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