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دورة الأجهاد المنخفضة للتنبؤ بعمر السبيكة الفائقة GH4133 تحت درجة حرارة 550°C استنادا إلى معادلة قوة الأس

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الخلاصـة

تم إجراء اختبارات دورة الأجهاد المنخفضة للسبيكة الفائقة GH4133 تحت استطالة محورية ودرجة حرارة 500°C، وتم تحليل العلاقة بين إجهاد واستطالة الدورة واستطالة العمر للسبيكة. وتمت معالجة انخفاض دورة للجهد بواسطة بيانات الاختبار لسبيكة الفائقة GH4133 باستخدام طريقة مانسون–كوفن. وعند معالجة البيانات التجريبية، تبين عدم وجود علاقة خطية بين استطالة البلاستيك وعدد الفشل العكسي في إحداثيات الوغاريتمي المزدوج. ولذلك، يجب أن يكون هناك بعض الخطأ في التنبؤ عند استخدام طريقة مانسون– كوفن. ولحل هذه المشكلة، تم تطوير طريقة جديدة استنادا إلى معادلة قوة الأس. وبالنظر إلى النتائج للتنبؤ بعمر السبيكة باستخدام طريقة جديدة في نفس الوقت. وأظهرت النتائج أن الطريقتين كانتا قادرتين على تقديم نتيجة معقولة للتنبؤ بعمر السبيكة الفائقة GH4133 مع دقة التنبؤ في حدود ± 1.5 مرة من حدود البيانات المبعثرة. من أجل التحقق من مدى انطباق طريقة جديدة، تم إجراء إختبارات دورة الإجهاد المنخفضة لسبع مواد مختلفة. وأظهرت نتائج التنبؤ بعمر السبيكة بأن طريقة جديدة أعطت أفضل النتائج مع أصغر الفرقة لبيانات المبعثرة والانحراف المعياري لطريقة مانسون– كوفن. وبالتالي فإن التنبؤ بعمر السبيكة بواسطة الطريقة المقترحة تبرهن على أنها أكثر فعالية ودقة من الأسلوب مانسون–كوفن.

Low cycle fatigue life prediction for GH4133 at 550°C based on power-exponent function

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ABSTRACT

The low cycle fatigue tests of GH4133 superalloy are carried out under total axial strain at 550°C. The relationships of cyclic stress-strain and strain-life are analyzed. The low cycle fatigue test data of GH4133 superalloy are processed by using the Manson-Coffin method. When experimental data is processed, the relationship between plastic strain and failure reverse number presents nonlinearity in the double logarithmic coordinates. Therefore, there must be some prediction error, when using the Manson-Coffin method. In order to solve the problem, a new method based on the power-exponent function is developed. The results of life prediction are given by using a new method at the same time. The results showed that the two methods chosen were able to provide a reasonable life prediction result for the GH4133 superalloy with prediction accuracy within ± 1.5 times the scatter band. In order to verify the applicability of the new method, the low cycle fatigue life of the seven materials is predicted. The results of life prediction showed new method gave better results with the smaller scatter band and standard deviation than Manson-Coffin method. Thus the life prediction capability of the proposed method proves to be more effective and accurate than the Manson-Coffin method.

Keywords: GH4133 superalloy; low cycle fatigue; life prediction; power-exponent function; scatter band.

NOMENCLATURE

E(MPa)	elastic modulus	$2N_f$	failure reverse number
σ_b(MPa)	fracture limit	β, C	material constants
$\sigma_{0.2}$(MPa)	yield strength	σ_f' (MPa)	fatigue strength coefficient
δ(%)	elongation	b	fatigue strength exponent
ψ(%)	reduction of area	ε_f'	fatigue ductility coefficient
$\Delta\varepsilon_e$ (%)	elastic strain	c	fatigue ductility exponent
$\Delta\varepsilon_p$ (%)	plastic strain	a, a_0, a_1	material constants
$\Delta\varepsilon_t$ (%)	total strain	s	standard deviation
$\Delta\sigma/2$ (MPa)	cyclic stress range	N_f^p	predicted life
$\Delta\varepsilon/2$ (%)	strain amplitude	N_f^m	experimental life
N_f	failure cycle number	n	number of data points

INTRODUCTION

GH4133 can be used in the manufacture of aircraft engine turbine disk because of its excellent high temperature mechanical properties, resistance to high temperature oxidation, and hot corrosion resistance. Wang *et al.* (2000) proposed that during the service, turbine disk is subject to complex alternating loads at high temperatures, which can be the cause of early low cycle fatigue damage.

Life prediction of high temperature low cycle fatigue has been a concern to the engineering and academic community. In order to effectively predict the high temperature low cycle fatigue life, various methods have been established over the years. Miner (1945) proposed the damage accumulation model. According to this model, damage caused by mechanical fatigue and creep is using linear superposition method. Coffin (1954) and Manson (1954) proposed Manson-Coffin method. The Manson-Coffin equation is widely used in life prediction. The Manson-Coffin method indicates that the relationship of plastic strain amplitude and failure reverse number, elastic strain amplitude, and failure reverse number exhibit a bilinear relationship in the double logarithmic coordinates. Coffin (1973) proposed the frequency correction relationship referred to as the Manson-Coffin equation. According to this method, frequency items are added to Manson-Coffin equation in order to correct the cycle frequency impact on the high temperature cycle response. For damage caused by different types of strain regardless of time-dependent and time, Halford *et al.* (1973) proposed the strain range partitioning method. Wang *et al.* (2006) proposed the simplified Walker strain model to predict the disk low cycle fatigue life for unsymmetrical loads and the main life regions. The effect of number of life critical regions in each disk was taken into account in the life prediction.

The Aeronautical Industrial Science & Technology Committee (1987) proposed that in many cases, the relationship of plastic strain amplitude versus the failure reverse number is a nonlinear relationship in the double logarithmic coordinates, but showing an upward convex curve. Ye *et al.* (2004) proposed that the relationship of plastic strain amplitude versus the failure reverse number exhibits a bilinear relationship in the double logarithmic coordinates. Taking a point as the cut-off point, Manson-Coffin equation can be applied to a linear fit by means of curve segments. Wang *et al.* (2001) proposed a new model based on damage fraction model. Chen *et al.* (2006) proposed a low cycle fatigue life prediction energy model. This energy model for low cycle fatigue life prediction was derived from the laws of entropy conservation and energy conservation. Chen *et al.* (2006) proposed a power-exponent function model. The study took two points into account, namely quadratic characters of plastic strain amplitude versus reversals to failure in log-log scale coordinates and the residual stabilization.

In this paper, low cycle fatigue behaviors of GH4133 superalloy at 550°C are studied under conditions of total strain control. The relationships of cyclic stress-strain and strain-life are analyzed. High temperature low cycle fatigue life of GH4133 superalloy is predicted by Manson-Coffin method and a new method based on the power-exponent function is proposed. When the relationship between plastic strain and failure reverse number presents nonlinearity in the double logarithmic coordinates, the new method can give better prediction results than the Manson-Coffin method. The low cycle fatigue life prediction result of the seven materials proves the applicability of the new method to be more effective and accurate than the Manson-Coffin method. Related research can provide reference for component design and life evaluation.

EXPERIMENTAL METHODS

MATERIAL

GH4133 superalloy was used as the testing material. The base material was given a normalizing treatment at 1080°C for 8 hours, followed by air cooling at 750°C for 16 hours, followed by air cooling, before machining the standard fatigue specimens. The chemical composition of GH4133 superalloy is shown in table 1. The tensile properties for GH4133 superalloy at 20°C and at 550°C are presented in table 2.

Table 1. The chemical composition of GH4133 superalloy (weight, %)

C	Cr	Al	Ti	Fe	Nb	Mn	Si	P
<0.07	19.0~22.0	0.70~1.20	2.50-3.00	<1.50	0.75~1.25	<0.35	<0.65	<0.015
S	**Cu**	**Bi**	**B**	**Ce**	**Sn**	**Ni**	**Mg**	**Zr**
<0.007	<0.007	<0.001	<0.01	<0.01	<0.0012	surplus	0.001~0.01	0.01~0.1

Table 2. The tensile property for GH4133 superalloy

Temperature (°C)	Elastic modulus E (MPa)	Fracture limit σ_b (MPa)	Yield strength $\sigma_{0.2}$ (MPa)	Elongation δ,%(weight)	Reduction of area ψ,%(weight)
20°C	215000	1202	791	26	29
550°C	163000	1031	720	23	35

Test conditions and methods

The low cycle fatigue tests were carried out under total axial strain at 550°C. The temperature variation along the gauge length of the specimen did not exceed ± 2°C. The cyclic strain rate was equal to 0.333Hz for all tests. Continuous cycling tests were performed using a triangular waveform. The strain ratio was equal to -1.

RESULTS AND DISCUSSION

Low cycle fatigue test results and discussion of GH4133 superalloy

Figure 1 presents the linear relationship of $\Delta\varepsilon_t/2—2N_f$, $\Delta\varepsilon_p/2—2N_f$ and $\Delta\varepsilon_e/2—2N_f$ in double logarithmic coordinates. The following regression equations can be obtained by regression analysis

$$\Delta\varepsilon_p/2 = 0.8299(2N_f)^{-0.9054} \tag{1}$$

$$\Delta\varepsilon_e/2 = 0.0082(2N_f)^{-0.1026} \tag{2}$$

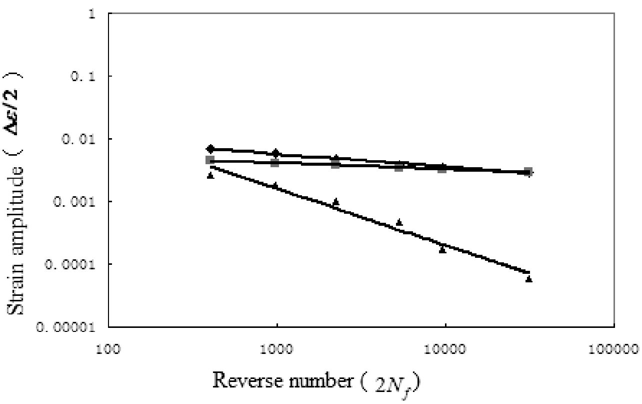

Fig. 1. Curve of $\Delta\varepsilon/2$—$2N_f$

Figure 2 shows the curve of $\Delta\sigma/2$—$\Delta\varepsilon_p/2$. Regression equation (3) can be obtained by regression analysis.

$$\Delta\sigma/2 = 1407.1(\Delta\varepsilon_p/2)^{0.1004} \tag{3}$$

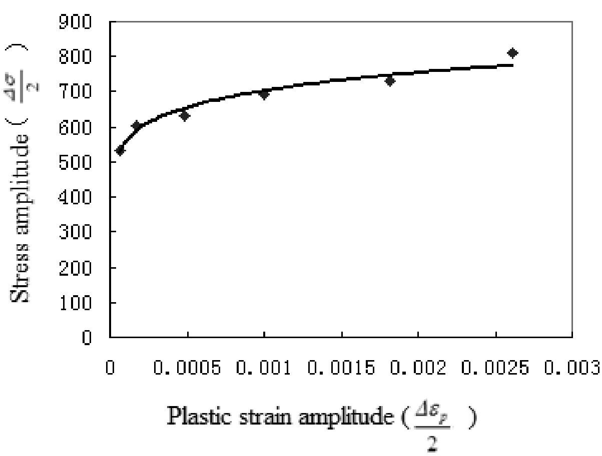

Fig. 2. Curve of $\Delta\sigma/2$—$\Delta\varepsilon_p/2$

Figure 3 shows the curve of $\Delta\sigma/2$—$2N_f$ in double logarithmic coordinates. Regression equation (4) can be obtained by exponentiation regression analysis.

$$\Delta\sigma/2 = 1419.2(2N_f)^{-0.0943} \tag{4}$$

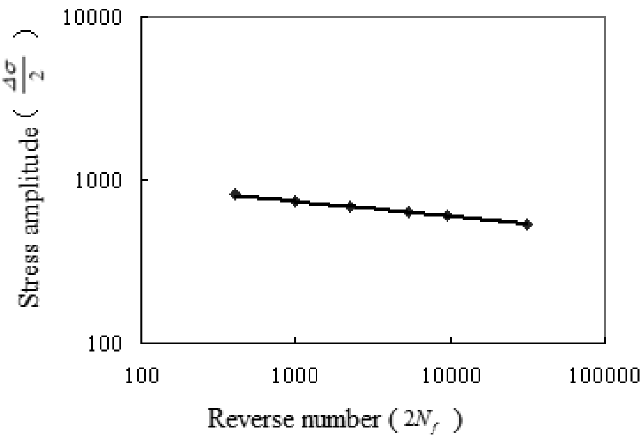

Fig. 3. Curve of $\Delta\sigma/2$—$2N_f$

FATIGUE LIFE PREDICTION

Currently, the Manson-Coffin method is widely used in low-cycle fatigue properties of the materials and life prediction. The Manson-Coffin method predicts life using the following equation

$$\Delta\varepsilon_p N_f^{\beta} = C_1 \tag{5}$$

where, β and C_1 are material constants.

For low cycle fatigue test under total strain amplitude control, the total strain amplitude ($\frac{\Delta\varepsilon_t}{2}$) is composed of plastic strain amplitude ($\frac{\Delta\varepsilon_p}{2}$) and elastic strain amplitude ($\frac{\Delta\varepsilon_e}{2}$). The terms $\frac{\Delta\varepsilon_p}{2}$ and $\frac{\Delta\varepsilon_e}{2}$ are written in the form of commonly used power functions. Hence, the Manson-Coffin method predicts life thorough following equation

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c \tag{6}$$

where $\sigma_f^{'}$ is the fatigue strength coefficient, b is the fatigue strength exponent $\varepsilon_f^{'}$ is the fatigue ductility coefficient, and c is the fatigue ductility exponent. The values of $\frac{\sigma_f^{'}}{E}$, b, $\varepsilon_f^{'}$ and c are obtained by regression analysis. The $\frac{\sigma_f^{'}}{E}$, b, $\varepsilon_f^{'}$ and c values are shown in table 3.

Table 3. Corresponding coefficient in equation (6)

$\frac{\sigma_f'}{E}$	**b**	ε_f'	**c**
0.0082	-0.1026	0.8299	-0.9054

Figure 4 presents the results predicted by Manson-Coffin method. According to figure 4, all of life prediction values fall within the 1.35 times scatter band.

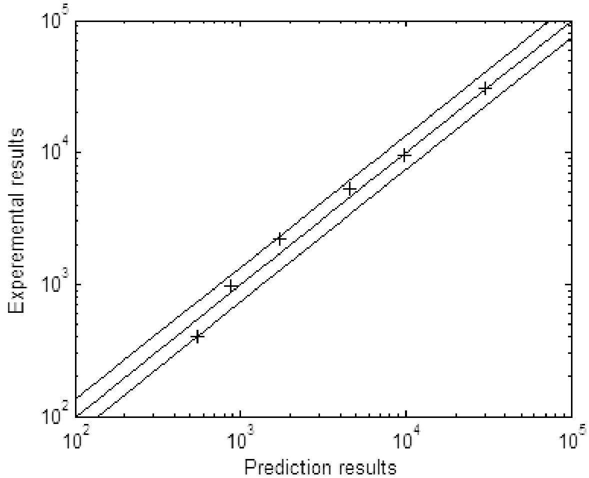

Fig. 4. Results predicted by Manson-Coffin method

Life prediction based on power-exponent function

According to high-temperature low cycle fatigue data analysis results, the relationship between plastic strain and failure reverse number presents nonlinearity in the double logarithmic coordinates. If the data is processed by using a linear relationship, it will result in a prediction error. In order to solve the problem, a new method based on power-exponent function method is proposed in this work. Assuming that a quadratic polynomial relationship exists between $(-\ln\frac{\Delta\varepsilon_p}{2})$ and $\ln(2N_f)$, the relationship can be expressed as follows

$$(-\ln\frac{\Delta\varepsilon_p}{2}) = a[\ln(2N_f)]^2 + a_0\ln(2N_f) + a_1 \quad (7)$$

Figure 5 presents the quadratic fit relationship of $(-\ln\frac{\Delta\varepsilon_p}{2})$ and $\ln(2N_f)$ where a, a_0 and a_1 are obtained by using the regression for equation (7).

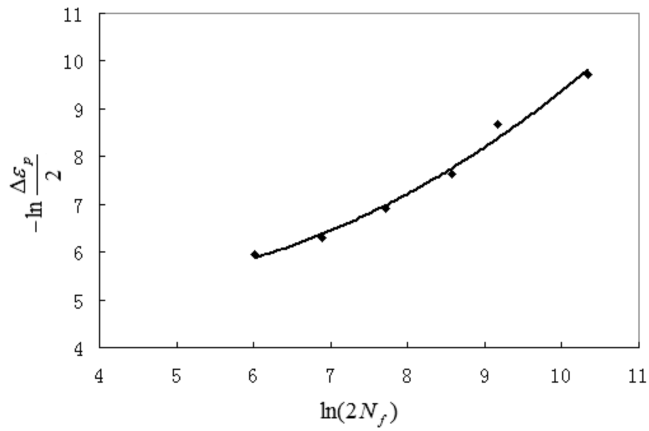

Fig. 5. Curve of $(-\ln\frac{\Delta\varepsilon_p}{2})$—$\ln(2N_f)$

Equation (8) is obtained by transforming (7) as follows

$$\frac{\Delta\varepsilon_p}{2} = e^{-a[\ln(2N_f)]^2 - a_0\ln(2N_f) - a_1} \tag{8}$$

Therefore, the life prediction method based on power transformation theory can be expressed as follows

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b + e^{-a[\ln(2N_f)]^2 - a_0\ln(2N_f) - a_1} \tag{9}$$

The $\frac{\sigma_f^{'}}{E}$, p, a, a_0 and a_1 values are shown in table 4. When a =1, Manson-Coffin equation is the first order Taylor's expansion approximation of power-exponent function model in the double logarithmic coordinates.

Table 4. Corresponding coefficient in equation (9)

$\frac{\sigma_f^{'}}{E}$	***b***	***a***	$\boldsymbol{a_0}$	$\boldsymbol{a_1}$
0.0082	-0.1026	0.0997	-0.7217	6.616

Figure 6 presents the prediction results by the new method. According to figure 6, all of life prediction value fall within 1.12 times scatter band.

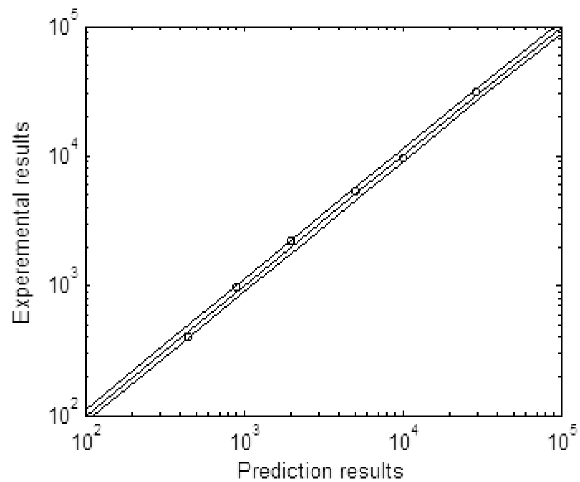

Fig. 6. Life prediction result by new method

QUANTITATIVE EVALUATION OF LIFE PREDICTION ABILITY

Scatter band and standard deviation are often used to evaluate quantitatively the life prediction ability of a model. Zhang *et al.* (2013) proposed that the scatter band is a statistical quantity with some deviation from the predicted life and experimental life. The standard deviation shows how tightly all the various examples are clustered around the mean in a set of data. Chen *et al.* (2006) proposed that the smaller the standard deviation, the better life prediction ability of the model. The standard deviation(s) can be expressed as follows

$$s = \left[\frac{\sum_1^n (\lg N_f^p - \lg N_f^m)^2}{(n-1)} \right]^{1/2} \tag{10}$$

where N_f^p is predicted life, N_f^m is experimental life, and n is number of data points.

Figure 7 presents the evaluation of life prediction methods. The fatigue life prediction for GH4133 superalloy by the Manson-Coffin method and new method had scatter bands of 1.35 and 1.12, respectively. The fatigue life prediction for GH4133 superalloy by the Manson-Coffin method and new method had standard deviations of 0.19 and 0.02, respectively. The new method based on power transformation theory gave better results with the smaller scatter band and standard deviation than Manson-Coffin method. Therefore, the life prediction capability of new methods proves more effective than Manson-Coffin method.

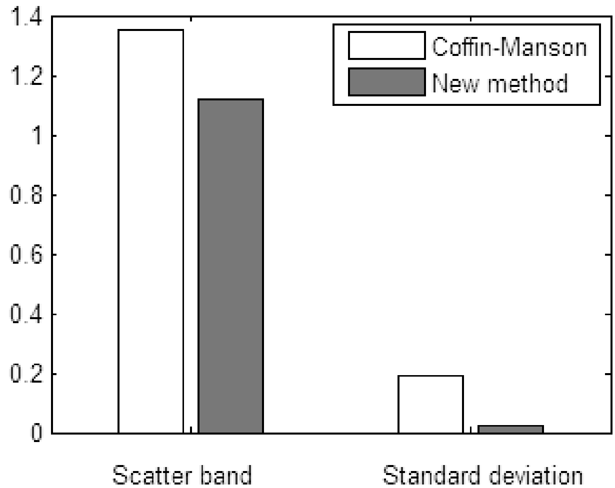

Fig.7. Evaluation of life prediction methods

POWER-EXPONENT FUNCTION MODEL VERIFICATION

Test conditions and methods

High temperature low cycle fatigue tests were implemented using a ± 100kN Mayes testing machine. The low cycle fatigue tests of various materials were carried out under total axial strain at different temperatures. The cyclic strain rate was equal to 0.333Hz for all tests. The Continuous cycling tests were performed using a triangular waveform. The strain ratio was equal to -1. All test data acquisition and processing is done by computer. Each test will be terminated until the sample breaks. (Xie, 1992).

RESULTS AND DISCUSSION

According to the low cycle fatigue data analysis of various materials, the results showed that the relationship of plastic strain amplitude vs. failure reverse number is a nonlinear relationship in the double logarithmic coordinates. Figure 8 presents the curve characteristics of $\Delta\varepsilon_p/2$—$2N_f$ for several materials in double logarithmic coordinates. Figure 9 presents the quadratic polynomial fit relationship of $(-\ln\frac{\Delta\varepsilon_p}{2})$ and $\ln(2N_f)$ for several materials. In order to verify applicability of the power-exponent function model, low-cycle fatigue data of several materials were analyzed (Xie, 1992). Table 5 presents a comparison of different model performances for different kinds of materials.

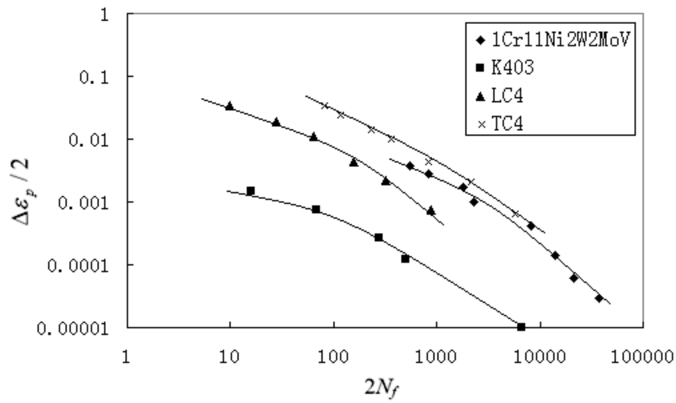

Fig.8. The curve characteristics of $\Delta\varepsilon_p/2$—$2N_f$ for several materials

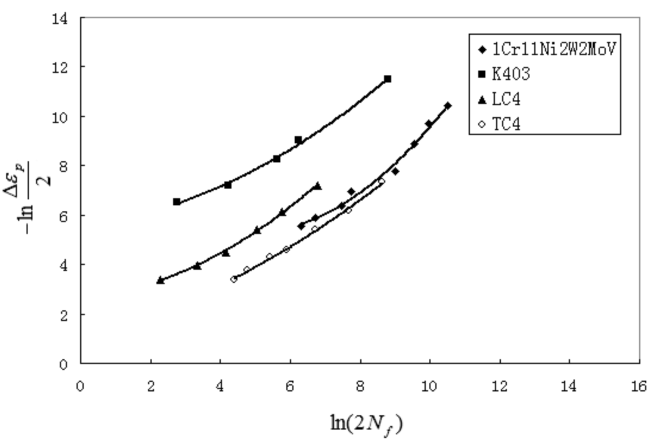

Fig.9. The quadratic fit relationship of $(-\ln\frac{\Delta\varepsilon_p}{2})$ and $\ln(2N_f)$ for several materials

Table 5. The contrast of different model performances for different kinds of materials

Material	Manson-Coffin method		Life prediction based on power-exponent function	
	Scatter band	Standard deviation	Scatter band	Standard deviation
GH4133 superalloy at 450°C	1.84	0.41	1.83	0.36
40CrMnSiMoVA steel at 20°C	1.43	0.28	1.24	0.07
300M steel at 20°C	1.54	0.29	1.17	0.02
1Cr11Ni2W2MoV steel at 400°C	1.65	0.32	1.59	0.18
LC4 aluminum at 20°C	1.36	0.17	1.16	0.03
K403 superalloy at 850°C	2.16	0.54	1.97	0.45
TC4 titanium at 350°C	1.53	0.20	1.39	0.05

The results of life prediction showed new method based on power-exponent function gave better results with the smaller scatter band and standard deviation than Manson-Coffin method. Prediction accuracy within ± 2 times scatter band for different kinds of materials. The life prediction capability of new methods proves more effective and accurate than Manson-Coffin method.

CONCLUSIONS

Low cycle fatigue tests were carried out in the present work in order to study the fatigue behavior of GH4133 superalloy at 550°C. The main conclusions are as follows.

There was a nonlinear relationship between the plastic strain amplitude ($\Delta\varepsilon_p / 2$) and reverse number ($2N_f$) in double logarithmic coordinates for GH4133 superalloy.

The new method based on power-exponent function predicts the low cycle fatigue life of GH4133 superalloy at 550°C thorough following equation.

$$\frac{\Delta\varepsilon_t}{2} = 0.0082(2N_f)^{-0.1026} + e^{-0.0997[\ln(2N_f)]^2 + 0.7217\ln(2N_f) - 6.616} \quad (11)$$

The Manson-Coffin method and the new method are able to give a reasonable life prediction result for GH4133 superalloy. The achieved prediction accuracy was within ± 1.5 times the scatter band method.

The life prediction capability of the new method for GH4133 superalloy and seven other materials proves to be more accurate and effective than Manson-Coffin method.

In fact, Manson-Coffin equation is the first order Taylor expansion approximation of power-exponent function model in the double logarithmic coordinates. It is the reason for a better precision of power-exponent function model in low cycle fatigue life prediction.

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