Journal of Engg. Research **Vol. 3 No. (1) Mar 2015** pp. 113-126

دراسة اجهاد الدوران المنخفض بدرجة حرارة عالية لتنبؤ لاستمرارية السبائك الفائقة

،**قوه دونغ غاو ، *شو لين دوان و وينسياه زانغ**

* كلية الهندسة البحرية، جامعة داليان البحرية، داليان، الصين

**الكلية البحرية والهندسة البحرية، جامعة محيط داليان ، داليان، الصين

*** كلية الهندسة الميكانيكية، جامعة محيط داليان ، داليان، الصين

الخلاصـة

البحث يقدم نتائج اختبارات أجهاد الدوران المنخفض بدرجة حرارة عالية للسبائك الفائقة DZ22 وK403 تحت ضغوط مسيطرة عليها. يعرض بيانات اختبار اجهاد الدوران المنخفض لسبيكة فائقة DZ22 عند 850°C وسبيكة فائقة K403 سبيكة فائقة عند 750°C بطريقة التابوت– مانسون. عند معالجة البيانات التجريبية، غالبا ما تظهر القيم السلبية أو صغيرة للضغط ونتائج التنبؤ لاستمرارية وتفشل في تلبية احتياجات المصمم. لأجل حل المشكلة، تم تطوير طريقة جديدة تقوم على الإجهاد وطريقة التابوت–مانسون، وتعطى نتائج التنبؤ لاستمرارية باستخدام طريقة جديدة في نفس الوقت. وأظهرت النتائج أن الطريقة الجديدة هي أكثر دقة من طريقة التابوت–مانسون. والقدرة على التنبؤ للاستمرارية الطريقتين لسبيكة فائقة DZ22 ثبت أنها أكثر فعالية من السبيكة الفائقة K403.

A study of high temperature low cycle fatigue life prediction for two superalloys

Guodong Gao*,**, Shulin Duan* and Wenxiao Zhang***

**Marine Engineering College, Dalian Maritime University, 1 Linghai Road. Dalian, 116026, China, gaoguodong1979@hotmail.com*

***Nautical and Marine Engineering College, Dalian Ocean University, 52 Heishijiao Street. Dalian, 116023, China*

****Mechanical Engineering College, Dalian Ocean University, 52 Heishijiao Street. Dalian, 116023, China*

ABSTRACT

The high temperature low cycle fatigue tests of DZ22 superalloy and K403 superalloy are carried out under strain controlled. The low cycle fatigue test data of DZ22 superalloy at 850°C and K403 superalloy at 750°C are processed by Coffin-Manson method. When experimental data is processed, negative or small plastic strain values often appear and the results of life prediction fail to meet the needs of the designer. In order to solve the problem, a new method based on stress fatigue and Coffin-Manson method is developed, the results of life prediction are given by using new method at the same time. The results showed that new method is more accurate than the Coffin-Manson method. The life prediction capability of two methods for DZ22 superalloy proves more effective than K403 superalloy.

Keywords: High temperature; life prediction; low cycle fatigue; stress; superalloy

NOMENCLATURE

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

INTRODUCTION

Nickel-base superalloy can be widely used in the manufacture of aircraft engine components because of its excellent high temperature mechanical properties, resistance to high temperature oxidation and hot corrosion resistance. Guo Xiaoguang *et al*. (2007) considered that during the service, these components bear the start-stop transient load cycle at high temperatures, which may be the cause of early fatigue fracture.

High temperature low cycle fatigue behaviors of nickel-based superalloys have been studied by many scholars. Sun Jihong *et al*. (2010) analyzed the low cycle fatigue behaviors of K435 superalloy at 900℃. Fitted formula was calculated according to the tests, the plastic strain energy formula and power exponent function formula were modified. Zhang Guodong *et al*. (2004) analyzed the low cycle fatigue behaviors of K403 superalloy under strain controlled, at temperature 700℃. Experimental data were processed by Manson-Coffin method and results of life prediction were given. Wang Chunsheng and Li Qingchun (1995) analyzed the complex fatigue properties of DZ22 superalloy on the conditions of different test temperature, different low cycle stress.

Life prediction of the high temperature low cycle fatigue has been a concern to the engineering and academic comparison. In order to predict the high temperature conditions engineering material fatigue damage total life, various methods have been established over the years. Chen Ling *et al*. (2006) proposed low cycle fatigue life prediction energy models. Chen Lijie *et al*. (2006) proposed low cycle fatigue life prediction method based on power-exponent function model. Miner (1945) proposed damage accumulation model. Coffin (1973) proposed the frequency correction coffin-Manson equation. Halford *et al*. (1973) proposed the strain range partitioning method. Coffin (1974), Tomkins and Wareing (1977), and Batte (1983) made a comprehensive review on the suitability of various life prediction models. However, at high temperatures, material fatigue damage exclude the effect of creep-fatigue interaction. Young II Kwon and Byeong Soo Lim (2011) considered that the behavior of creep-fatigue interaction is not clear. Therefore, it is still difficult to predict the fatigue life of high temperature components.

In this paper, high temperature fatigue behaviors of two superalloys were studied under conditions of total strain control. High temperature fatigue life of two superalloys was predicted by Coffin-Manson method and the life prediction method based on stress fatigue and Coffin-Manson (SCM) method. In addition, the predictive ability of two life prediction models was assessed.

EXPERIMENTAL METHODS

Material

DZ22 superalloy and K403 superalloy are used as the testing material. Aeronautical Materials Handbook Edit Committee (2002) presents the chemical composition of DZ22 superalloy and K403 superalloy. The tensile property for DZ22 superalloy at 20°C and 850°C are shown in Table 1. The tensile property for K403 superalloy at 750°C are also shown in Table 1 (Xie Jizhou, 1992).

Table 1. The tensile property for two superalloys

Material	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)
DZ22	20°C	132000	1181	995	8	10
	850°C	88500	1051	800	11	13
K403	750°C	165000	950	—	9.5	14.6

Test conditions and methods

The low cycle fatigue test condition and method of DZ22 superalloy at temperature 850 °C are presented in Table 2. The low cycle fatigue test condition and method of K403 superalloy at temperature 750 °C are also presented in Table 2 (Xie Jizhou, 1992).

Table 2. The fatigue test condition and method of two superalloys

Test condition and method	Material	
	DZ22	K403
Experimental temperature	850°C	750°C
Control Method	Axial strain	Axial strain
Sample size	d6.35mm	d6.35mm
Loading Waveform	Triangle waveform	Triangle waveform
Strain ratio	-1	-1
Experimental frequency	0.167～0.830Hz	0.083～0.830Hz
Failure criteria	Fracture	Fracture
Heat treatment	1210°C, 2h, air-cooled+870°C, 32h, air-cooled	1210°C, 4h, air-cooled

RESULTS AND DISCUSSION

Low cycle fatigue test results and discussion of DZ22 superalloy

Low cycle fatigue tests of DZ22 superalloy at 850 °C are carried out. Test data is processed in accordance with the Manson-Coffin method. The elastic strain ($\Delta\varepsilon_e$) and plastic strain ($\Delta\varepsilon_p$) are obtained. The results are shown in table 3 (Xie Jizhou, 1992).

Table 3. Low cycle fatigue test results of DZ22 superalloy at 850 °C

Total strain amplitude $\Delta\varepsilon_t/2$ (%)	Elastic strain amplitude $\Delta\varepsilon_e/2$ (%)	Plastic strain amplitude $\Delta\varepsilon_p/2$ (%)	Stress amplitude $\Delta\sigma/2$ (MPa)	Failure reverse number $2N_f$
1.208	1.034	0.174	1009	22
1.002	0. 939	0.063	915	280
0.797	0. 0773	0.0024	763	1378
0.701	0. 687	0.014	668	5910
0.601	0. 593	0.008	578	26406
0.509	0. 505	0.004	492	169680

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. Regression equation 1 and equation 2 can be obtained by regression analysis.

$$\Delta\varepsilon_p/2 = 0.0063(2N_f)^{-0.4281} \tag{1}$$

$$\Delta\varepsilon_e/2 = 0.0141(2N_f)^{-0.08384} \tag{2}$$

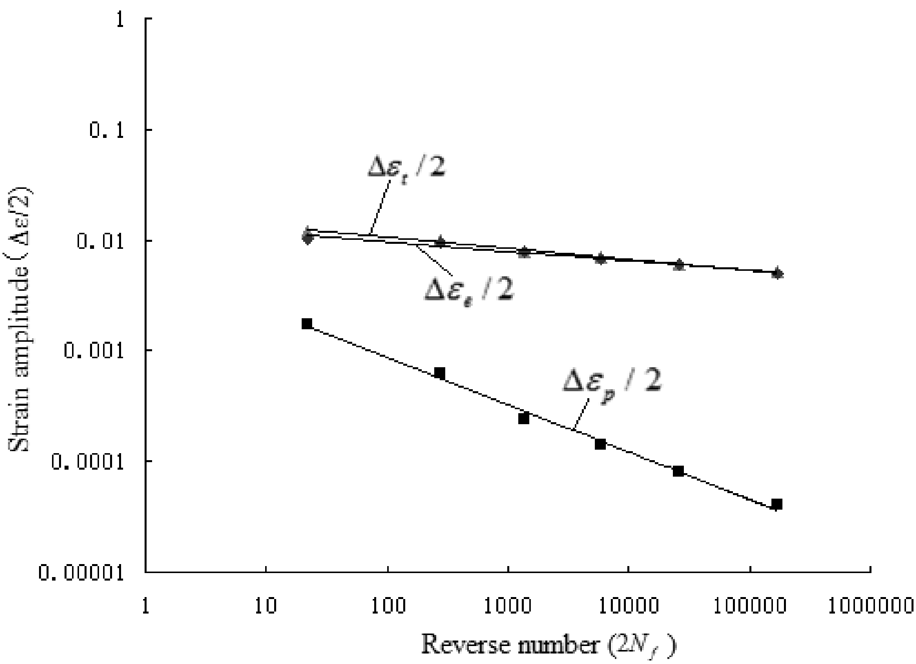

Fig. 1. Curve of $\Delta\varepsilon/2$ —$2N_f$

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

$$\Delta\sigma/2 = 3701.3(\Delta\varepsilon_p/2)^{0.1953} \tag{3}$$

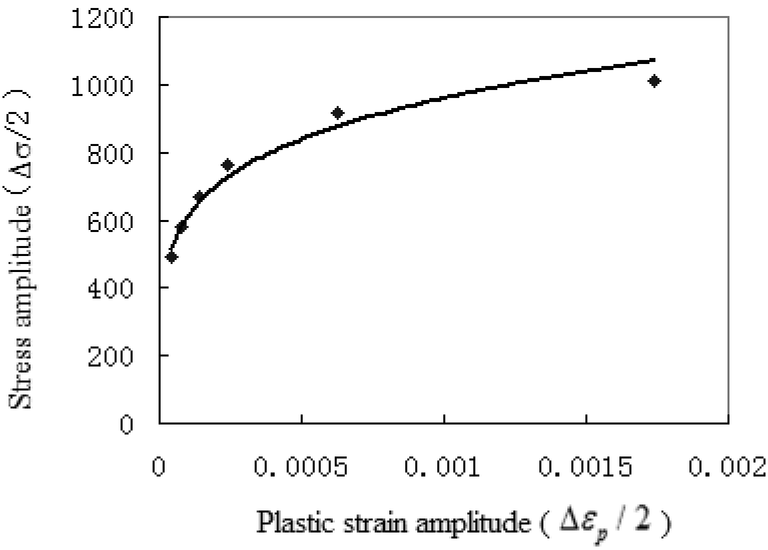

Fig. 2. Curve of $\Delta\sigma/2 — \Delta\varepsilon_p/2$

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

$$\Delta\sigma/2 = 13804(2N_f)^{-0.0842} \tag{4}$$

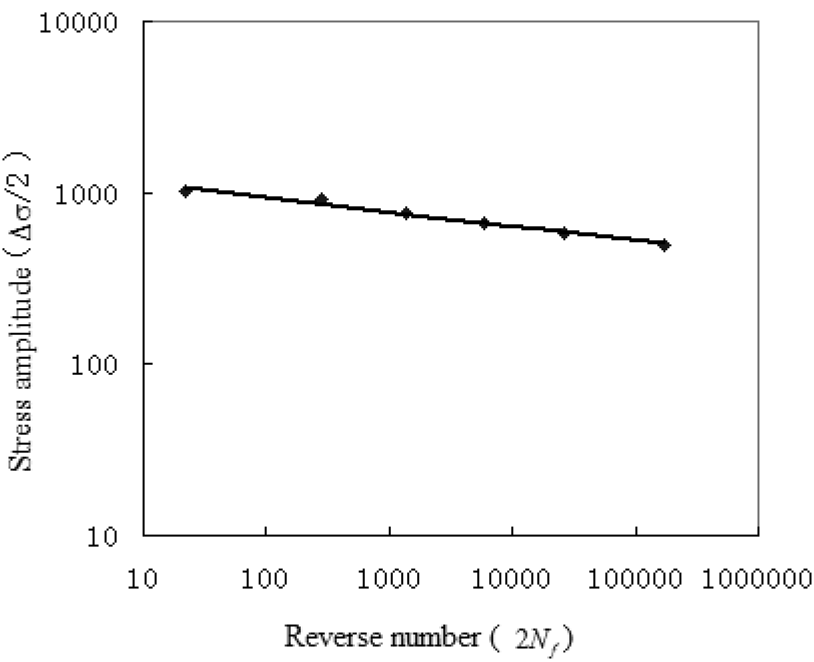

Fig. 3. Curve of $\Delta\sigma/2—2N_f$

Low cycle fatigue test results and discussion of K403 superalloy

Low cycle fatigue tests of K403 superalloy at 750 °C are carried out. Test data is processed in accordance with the Manson-Coffin method. The elastic strain ($\Delta\varepsilon_e$) and plastic strain ($\Delta\varepsilon_p$) are obtained. The results are shown in table 4.

Table 4. Low cycle fatigue test results of K403 superalloy at 750 °C

Total strain amplitude $\Delta\varepsilon_t/2$ (%)	Elastic strain amplitude $\Delta\varepsilon_e/2$ (%)	Plastic strain amplitude $\Delta\varepsilon_p/2$ (%)	Stress amplitude $\Delta\sigma/2$ (MPa)	Failure reverse Number $2N_f$
0.794	0.525	0.269	892	10
0.697	0.511	0.186	864	18
0.598	0.496	0.102	838	34
0.510	0.484	0.026	848	182
0.404	0.402	0.002	650	1514
0.293	0.300	-0.007	481	8410
0.246	0.256	-0.01	418	43894

Figure 4 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. Regression equation 5 and equation 6 can be obtained by regression analysis.

$$\Delta\varepsilon_p/2 = 0.0304(2N_f)^{-0.9744} \tag{5}$$

$$\Delta\varepsilon_e/2 = 0.0068(2N_f)^{-0.0856} \tag{6}$$

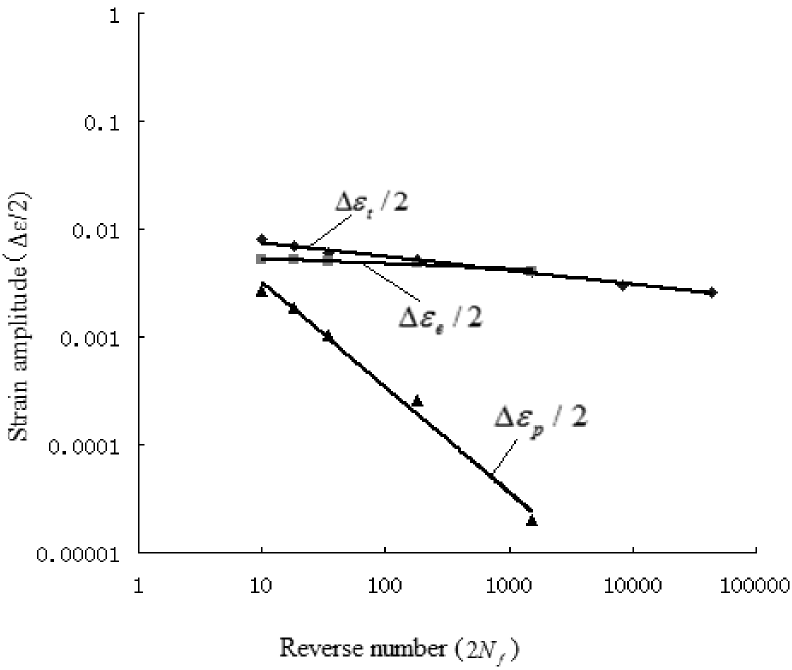

Fig. 4. Curve of $\Delta\varepsilon/2$ —$2N_f$

Figure 5 presents the curve of $\Delta\sigma/2$—$\Delta\varepsilon_p/2$. Regression equation 7 can be obtained by regression analysis.

$$\Delta\sigma/2 = 1285.5(\Delta\varepsilon_p/2)^{0.06} \tag{7}$$

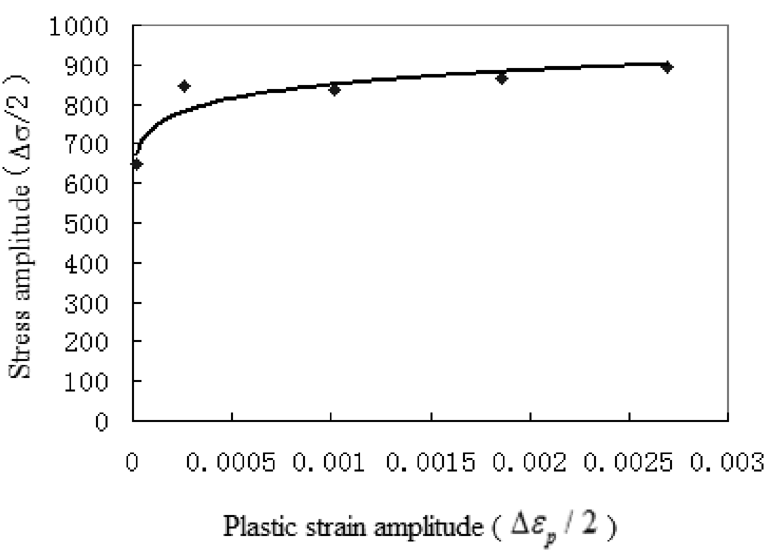

Fig. 5. Curve of $\Delta\sigma/2$ —$\Delta\varepsilon_p/2$

Figure 6 presents the curve of $\Delta\sigma/2$—$2N_f$ in double logarithmic coordinates. Regression equation 8 can be obtained by regression analysis.

$$\Delta\sigma/2 = 1179.7(2N_f)^{-0.0926} \tag{8}$$

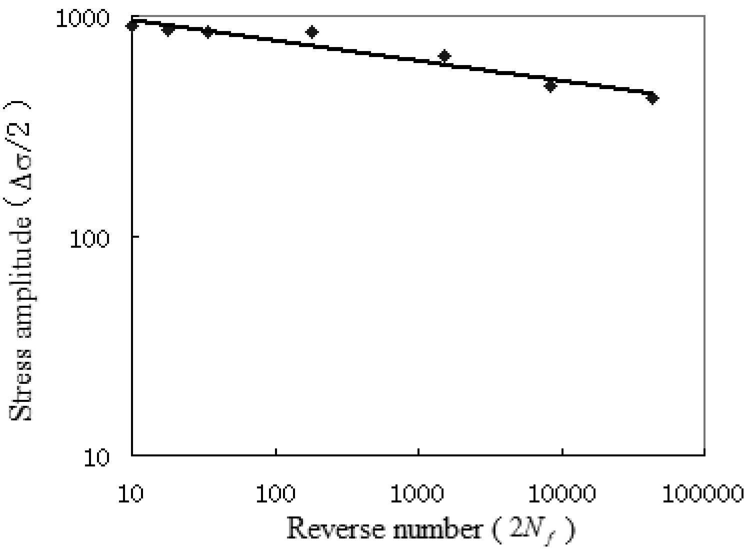

Fig. 6. Curve of $\Delta\sigma/2$—$2N_f$

FATIGUE LIFE PREDICTION

Life prediction by the Coffin-Manson method

Currently, there are a lot of low cycle fatigue life prediction methods. Coffin-Manson method is widely used in low-cycle fatigue properties of the material and life prediction (Reuchet, J. and Remy, L, 1983). Coffin-Manson method predicts life using equation 9 (Coffin, L. F, 1954; Manson, S.S, 1954).

$$\Delta\varepsilon_p N_f^{\beta} = C \tag{9}$$

where, β and C are material constants.

For low cycle fatigue test under total strain amplitude control, total strain amplitude ($\frac{\Delta\varepsilon_t}{2}$) is composed of plastic strain amplitude ($\frac{\Delta\varepsilon_p}{2}$) and elastic strain amplitude ($\frac{\Delta\varepsilon_e}{2}$). $\frac{\Delta\varepsilon_p}{2}$ and $\frac{\Delta\varepsilon_e}{2}$ are written in the form of commonly used power function. Coffin-Manson method predicts life by following equation 10.

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f^{'}}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c \quad (10)$$

where, $\sigma_f^{'}$ 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. The $\frac{\sigma_f^{'}}{E}$, b, $\varepsilon_f^{'}$ and c values are shown in table 5.

Table 5. Corresponding coefficient in equation 10 of two superalloys

Material	$\frac{\sigma_f^{'}}{E}$	**b**	$\varepsilon_f^{'}$	**c**
DZ22	0.0141	-0.0838	0.0063	-0.4281
K403	0.0068	-0.0856	0.0304	-0.9744

Life prediction method based on stress fatigue and Coffin-Manson (SCM) method

When the Coffin-Manson method to deal with low cycle fatigue test data are used, plastic strain values are often very small value or negative value. Such plastic strain point is shown as invalid data point.

To solve this problem, a new method SCM is developed. Based on to assumption that there is an exponential relationship between the distribution of stress ($\Delta\sigma$) and low cycle fatigue life (N_f), the relationship can be expressed as equation 11.

$$\frac{\Delta\sigma}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} = a(2N_f)^d \quad (11)$$

Where, $\sigma_{\max}$ is the maximum stress, $\sigma_{\min}$ is the minimum stress respectively, a and d are material constants.

The elastic strain ($\Delta\varepsilon_e$) and plastic strain ($\Delta\varepsilon_p$) can be expressed as equation 12 and equation 13.

$$\Delta\varepsilon_e = \frac{\Delta\sigma}{E} \quad (12)$$

$$\Delta\varepsilon_p = \left(\frac{\Delta\sigma}{K}\right)^{(1/n^{'})} \quad (13)$$

Where, $n^{'}$ is cyclic hardening exponent.

According to the equation 5, equation 12 and equation 13, $\frac{\Delta\varepsilon_e}{2}$ and $\frac{\Delta\varepsilon_p}{2}$ can be expressed as equation 14, equation 15 and equation 16.

$$\frac{\Delta\varepsilon_e}{2} = \frac{\Delta\sigma}{2E} = \frac{a}{E}(2N_f)^d \quad (14)$$

$$\frac{\Delta\varepsilon_p}{2} = (\frac{\Delta\sigma}{2K^{'}})^{(1/n^{'})} = [\frac{a}{K^{'}}(2N_f)^d]^{(1/n^{'})} \tag{15}$$

$$\frac{\Delta\varepsilon_t}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{a}{E}(2N_f)^d + [\frac{a}{K^{'}}(2N_f)^d]^{(1/n^{'})} \tag{16}$$

Where, $K^{'}$ is cyclic hardening coefficient. The a, d, $K^{'}$ and $n^{'}$ values are obtained by regression analysis. The a, d, $K^{'}$ and $n^{'}$ values are shown in table 6.

Table 6. Corresponding coefficient in equation 16 of two superalloys

Material	a	d	$K^{'}$	$n^{'}$
DZ22	1380	-0.0942	3701.3	0.1953
K403	1179.7	-0.0926	1285.5	0.06

QUANTITATIVE EVALUATION OF LIFE PREDICTION ABILITY

Standard deviation is often used to evaluate quantitatively the life prediction ability of model. The standard deviation is a statistic that shows how tightly all the various examples are clustered around the mean in a set of data. Chen Lijia *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 equation 17.

$$s = \left[\frac{\sum_1^n (\lg N_f^p - \lg N_f^m)^2}{(n-1)}\right]^{1/2} \tag{17}$$

Where, N_f^p is predicted life, N_f^m is experimental life, n is number of data points. While the fatigue life prediction for DZ22 superalloy and K403 superalloy by the Coffin-Manson method has standard deviations of 0.1463 and 0.3509 respectively; the SCM method has only 0.1447 and 0.3376 respectively. The standard deviation of SCM method is smaller than that of the Coffin-Manson methods. Therefore, SCM method to predict the life proves more effective than the Coffin-Manson method.

CONCLUSIONS

The high temperature low cycle fatigue tests were carried out in the present work in order to study the effect of cyclic loadings on the fatigue behavior of DZ22 superalloy and K403 superalloy. Cyclic stress-strain curves of the two superalloys were obtained. According to experimental data analysis, there was a linear relationship between the strain amplitude ($\Delta\varepsilon/2$) and reverse number ($2N_f$) in double logarithmic coordinates.

The low cycle fatigue life of DZ22 superalloy at 850°C and K403 superalloy at 750°C were predicted by Coffin-Manson method and SCM method. After conducting fatigue life prediction by Coffin-Manson method and SCM method, the results were compared and the following conclusions were obtained within the scope of this study.

As a fatigue life prediction method, SCM method is a method in which experimental data can be used as much as possible. What is more, this method proves more effective in testing the fatigue life prediction of two superalloys.

Coffin-Manson method and SCM method can accurately predict low cycle fatigue life of DZ22 superalloy at 850°C. The fatigue life prediction for DZ22 superalloy by the Coffin-Manson method and SCM method have standard deviations of 0.1463 and 0.1447 respectively.

The life prediction capability of two methods for DZ22 superalloy proves more effective than K403 superalloy.

ACKNOWLEDGEMENTS

This work was financially supported by scientific research projects from the education department of Liaoning Province (L2013281).

REFERENCES

Batte, A.D. 1983. Creep-fatigue life prediction. In: Skelton, R.P. (Ed.). Fatigue at high temperature. Pp, 365-401. Elsevier Applied Science, London.

Chen Lijia, Wu Wei & P.K.Liaw. 2006. Creep-fatigue interaction behaviors and life predictions for three superalloys. Acta Metallurgica Sinica **42(9)**: 952–958.

Chen Lijie, Gang Tieqiang & Xie Liyang. 2006. Low cycle fatigue life prediction method based on power-exponent function model. Journal of Mechanical Strength **28(5):** 761-765

Chen Ling, Jiang Jialing, Fan Zhichao, Chen Xuedong & Yang Tiecheng. 2006. Discussion of energy models for low cycle fatigue life prediction. Acta Metallurgica Sinica **42(2):** 195-200.

China Aeronautical Materials Handbook Edit Committee. 2002. China Aeronautical Materials Handbook. China Standard Press, Beijing.

Coffin, L.F. 1954. A study of the effects of cyclic thermal stresses on a ductile metal. Transactions of the American Society of Mechanical engineers **76:** 931–950.

Coffin, L. F. 1973. Fatigue at high temperature. In: Fatigue at Elevated Temperature, Special Technical Publication, Pp5-36. American Society for Testing and Materials, Philadelphia.

Coffin, L.F. 1974. Fatigue at high temperature-prediction and interpretation. Proceedings of the Institution of Mechanical engineers **188:** 109–127.

Guo Xiaoguang, Guo Jianting, Zhou Lanzhang & Yang Hongcai. 2007. Rotational bending fatigue behavior of ni-based casting superalloy K435 at room temperature. Journal of Northeastern University **28:** 357-360.

Halford, G.R., Hirschberg, M.H. & Manson, S.S. 1973. Temperature effects on the strain range partitioning approach for creep-fatigue analysis. In: Fatigue at Elevated Temperatures, Special Technical Publication, Pp 658-667. American Society for Testing and Materials, Philadelphia.

Manson, S.S. 1954. Behavior of materials under conditions of thermal stress. National Advisory Commission on Aeronautics. Report 1170. Lewis Flight Propulsion Laboratory, Cleveland.

Miner, M.A. 1945. Cumulative damage in fatigue. Journal of Applied Mechanics **12:** 159-164

Reuchet, J. & Remy, L. 1983. Fatigue oxidation interaction in a superalloy application to life prediction in high temperature low cycle fatigue. Metallurgical Transactions A **14:** 141-149.

Sun Jihong, Yang Zichun & Chen Guobing. 2010. Low cycle fatigue life prediction of nickle-based superalloy K435 at high temperature. Proceedings of the CSEE **30:** 106-109.

Tomkins, B. & Wareing, J. 1977. Elevated temperature fatigue interaction in engineering materials. Metal Science **11:** 414–424.

Wang Chunsheng & Li Qingchun. 1995. Study on complex fatigue properties of directionally solidified high temperature DZ-22 alloy. Physical testing **2:** 1-6.

Xie Jizhou. 1992. Handbook of Low-cycle Fatigue. Beijing Institute of Materials Publications, Beijing.

Young II Kwon & Byeong Soo Lim. 2011. A Study of Creep-Fatigue Life Prediction Using an Artificial Neural Network. Metal and Materials International **4:** 311–317.

Zhang Guodong, Su Bin, Wang Hong, He Yuhuai & Xu Chao. 2004. Method of life prediction for low cycle fatigue in superalloy K403. Journal of Mechanical Strength **26:** 263-266.

Submitted: 03-08-2014

Revised: 26-10-2014

Accepted: 15-12-2014