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Materials

A new model for the life prediction of GH4133 under TMF conditions

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Abstract: Thermal mechanical cyclic strain tests were carried out under in-phase and out-of-phase conditions on a Nickel-base Superalloy GH4133 in the temperature range of 571-823 ℃. Based on analyzing the present models of TMF (thermal mechanical fatigue) life prediction, a new model for predicting nickel-base superalloy TMF lifetime was proposed. TMF life of superalloy GH4133 was calculated accurately based on the new model. Experimental TMF life has been compared with the calculated results and all results fall in the scatter band of 1.5. The calculating results show that the new model is not only simple, but also precise. This model will play great roles in life prediction of the metal materials and the engineering components subjected to non-isothermal service conditions.

Key words: thermal mechanical fatigue; life production; Nickel-base superalloy; fatigue lifetime; prediction model; in-phase; out-of-phase

1 Introduction

In power generation, aerospace, mechanical engineering *etc*, service-operating conditions involve thermal transients as well as mechanical load at high temperature. A lot of components, such as turbine disk, are cyclically subject to thermal stress and mechanical stress at same time during their service, which is called thermal mechanical fatigue (TMF for short). During the last decade, great efforts have been paid for modeling material behavior under high operating temperature and severe TMF environments. One of the most problems is the formulating method to design and evaluate engineering system operating under TMF conditions. However, to design and evaluate the service life of such components accurately, the life prediction of materials and the test verification of fatigue life of simple specimens in laboratory are basic work. Without the simple specimen tests of low costs to improve life prediction method, it was impossible to carry out tests of full-scale components to evaluate fatigue life of engineering components [1]. Therefore, investigations on life prediction in turbine disk material GH4133 of aircraft engine under TMF are one of the basic works to estimate actual working life of turbine disk components. The purpose of the present paper is to evaluate and compare the prediction results of GH4133 TMF life by the present models at test condition. Then, a new TMF life prediction model can be established.

2 Experimental

The studied alloy is a nickel-base Superalloy GH4133, which is used for the turbine disk material of jet plane. The heat treatment conditions of the alloy are as follows: austenitization (8 h at 1080 ℃, air-cooled), tempering (16 h at 750 ℃, air-cooled). The chemical composition is given in **table 1**.

Table 1 Chemical composition of superalloy GH4133 (mass fraction) %

C	Mn	Si	P	S	Ni	Cr	Al	Ti	Nb	Fe
0.047	0.01	0.07	0.005	0.005	base	20.46	0.96	2.92	1.55	<0.02
Cu	Pb	Bi	As	Sb	Sn	B	Ce	Mg	Zr	
<0.05	<0.000 5	<0.001	<0.002 5	<0.002 5	<0.002 5	0.006	0.002	0.005	0.028	

The TMF and isothermal low-cycle fatigue experiment were conducted at servo-hydraulic MTS 809 testing system equipped with a PDP 11/23 PLUS computer and an induction heater. The tests were performed under axial total strain control with a triangular fully reversed waveshape, using an axial extensometer placed on the specimen. Numerous tests were carried out with various mechanical strain range of 0.45%-1.0%, for TMF in only one temperature range of 571-823 ℃ under in-phase and out-of-phase conditions, for isothermal low-cycle fatigue at temperature 571, 700 and 823 ℃ respectively.

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3 Results and discussion

3.1 Test results

The isothermal and thermal mechanical fatigue test life data are plotted in **figure 1** in the form of mechanical strain range against cycles to failure. The plotted data indicate that the lives of in-phase are less than that of out-of-phase for the same mechanical strain under TMF conditions. The lives of the isothermal low-cycle fatigue at 571, 700 and 823 ℃, respectively are also longer than that of TMF under in-phase condition.

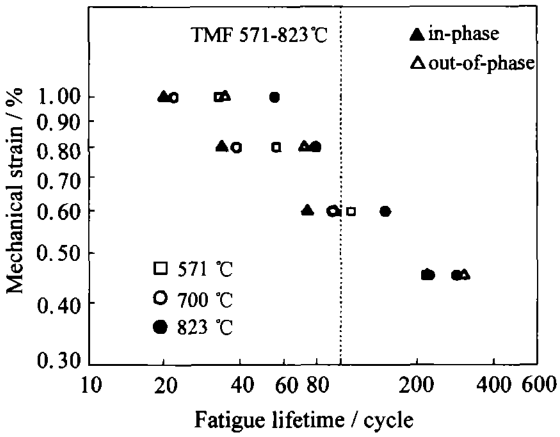

Figure 1 Curves of TMF and isothermal fatigue lifetime of superalloy GH4133.

3.2 Life predication by present models

As shown in figure 1, the number of cycles to fracture in TMF is lower than that in isothermal fatigue cycle at maximum temperature of TMF cycle, even lower than that at mean temperature of TMF cycle. It should be necessary for engineering technicians to do the TMF test to evaluate the lifetime of the components subjected to thermal and mechanical stress during their service. As the equipment of TMF is very complicated and the test is difficult to do, the engineers and researchers work for establishing model to predicte the TMF life of components without doing TMF test.

For early years, the life prediction of engineering materials and structures under TMF performances were calculated by analyzing the data of isothermal low cycle fatigue at the highest working temperature. It is approved that this method is unsafe to predict the component life working under TMF conditions. Thus, investigations of TMF performance and life prediction are much concerned by engineers and researchers. A lot of life prediction models and methods were proposed.

(1) Reforming Coffin-Manson model [2].

$$\frac{\Delta\sigma}{2}(N_f^{\mathrm{TMF}})^{\alpha}=K\cdot\exp\left(\frac{Q_1}{T_{\mathrm{mean}}}+\frac{Q_2}{T_{\max}}\right) \qquad (1)$$

where $\frac{\Delta\sigma}{2}$ is a half of stress amplitude; N_f^{TMF} is the number of cycles to fracture in TMF cycle; Q_1 and Q_2 are dislocation activation energy; T_{mean} and $T_{\max}$ are mean and maximum temperature in TMF cycle, respectively.

(2) Equivalent temperature and equivalent inelastic strain model [3].

$$\Delta\varepsilon_{\mathrm{ptm}}=\Delta\varepsilon_t-\left(\frac{\sigma}{E}\right)_{T_1}-\left(\frac{\sigma}{E}\right)_{T_2} \qquad (2)$$

where $\Delta\varepsilon_{\mathrm{ptm}}$ is the equivalent inelastic strain range in TMF cycle; $\Delta\varepsilon_t$ is the total strain range; $\left(\frac{\sigma}{E}\right)_{T_1}$ and $\left(\frac{\sigma}{E}\right)_{T_2}$ are elastic strain at temperature T_1 and T_2 in TMF cycle, respectively.

(3) Amplitude coefficient model [4].

$$N_f^{\mathrm{TMF}}=\frac{2(N_{f(T_1)}/N_{f(T_2)})^{1-\delta}}{1+N_{f(T_1)}/N_{f(T_2)}}\cdot N_{f(T_2)} \qquad (3)$$

where $\delta=\frac{2}{3}B$ is the material constant, B can be obtained from the Manson-Coffin equation; $N_{f(T_1)}$ and $N_{f(T_2)}$ are the number of cycles to fracture in isothermal fatigue at temperature T_1 and T_2, respectively.

(4) Damage fraction model [5].

$$\Delta\phi=\left(\frac{\Delta\phi_{T(\max)}}{2}+\frac{\Delta\phi_{T(\min)}}{2}\right)+\eta\left(\frac{\Delta\phi_{T(\max)}}{2}-\frac{\Delta\phi_{T(\min)}}{2}\right) \qquad (4)$$

where $\Delta\phi$ is the damage per cycle in TMF cycle; $\Delta\phi_{T(\max)}$ and $\Delta\phi_{T(\min)}$ are the damage per cycle in isothermal fatigue cycle at maximum and minimum temperature of TMF cycle; η is the damage factor and equals to 8 and 4 for in-phase and out-of-phase cycle, respectively.

However, TMF life prediction models, which were developed from life prediction equations of the isothermal low cycle fatigue, were much more simple and easy to use.

All above models were established by using limited test data and parameters on the basis of life prediction equations of low cycle fatigue at high temperature. Thus, the application fields are limited, and none of them has given satisfactory results for all TMF. In order to make up for the defaults of above models, some life prediction equations were proposed on the basis of combination of theories computation and tests analysis.

(5) Equivalent strain energy model [6].

$$\frac{1}{(N_f)_{\mathrm{TMF}}}=\Delta D_{\mathrm{TMF}}=\frac{1}{(N_f)_{T_0}}\sum\frac{\sigma_{T_i}\cdot\delta\Delta\varepsilon\cdot\lambda(T_i)}{(\Delta W_t)_{T_i}} \qquad (5)$$

where $\lambda(T_i)=(N_f)_{T_0}/(N_f)_{T_i}$ is the damage factor related with temperature, $(N_f)_{T_0}$ and $(N_f)_{T_i}$ are the isothermal fatigue life at reference temperature T_0 and given temperature T_i, respectively; ΔD_{TMF} is the damage per cycle in TMF cycle; $(\Delta W_t)_{T_i}$ is the incerement of strain energy of a given temperature T_i, $\delta\Delta\varepsilon$ is the increment of strain; σ_{T_i} is the stress at a given temperature T_i; $(N_f)_{TMF}$ is the number of cycles to fracture in TMF cycle.

In order to verify the prediction accuracy of TMF life of all kinds of models, TMF life of GH4133 superalloy at 571-823 ℃ was estimated by utilizing the former models. **Figures 2** and **3** show the comparison of experimental TMF life and predicted TMF life of GH4133 by using the equivalent temperature model, the amplitude coefficient model and the damage fraction model.

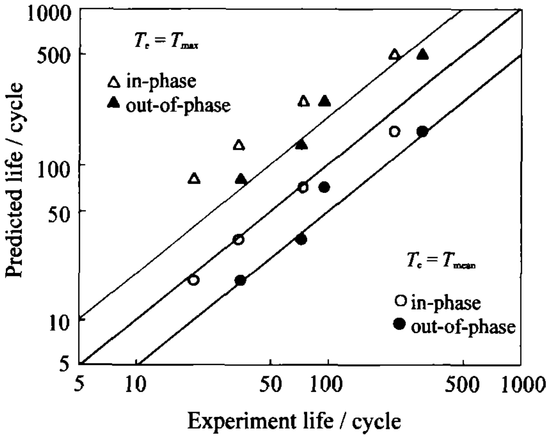

Figure 2 Comparison of experiment life and predicted life of equivalent temperature model.

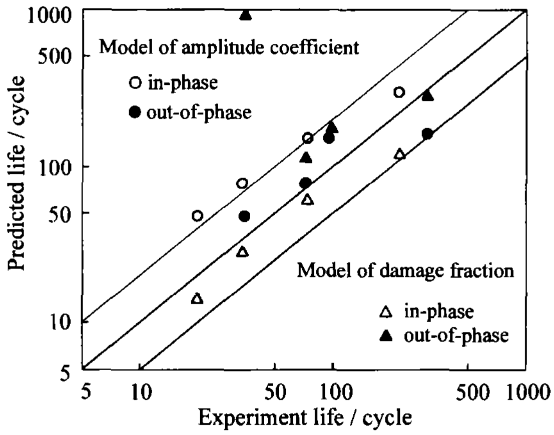

Figure 3 Comparison of predicted and TMF experiment life of amplitude coefficient model and damage fraction model.

It is shown that the rates of the predicted TMF life by all kinds of model and the experimental TMF life are bigger than 2. Thus, there are some differences by using directly above models to estimate TMF life of GH4133 superalloy in the temperature range of 571-823 ℃. When using equivalent temperature model, the selection of equivalent temperature T_e produces great differences to prediction life. As shown in figure 2, the estimated result of $T_e = T_{mean}$ is better than that of $T_e = T_{max}$, and predicted life of TMF is conservative. Thus, the selection of equivalent temperature can not be too sweeping for equivalent temperature model. It must be clear and definite to select $T_e = T_{mean}$ or $T_e = T_{max}$. Therefore, that the effect of cyclic mean temperature should be concerned, and the selection of equivalent temperature can be only determined by temperature range.

Thus it can be seen that the determination of parameter is the key of prediction life accuracy. However, the application fields of life prediction model are limited in some materials and certain conditions since it is established on the basis of limited test data.

All above models of TMF life prediction have common characterization. That is which basic parameters are to be determined by test data and performances of low cycle fatigue at high temperature. This is only the method to establish TMF life prediction model. Yet, each model has respectively characteristics.

Equivalent temperature model, equivalent plastic strain model, amplitude coefficient model and damage fraction model are more simple and easy to use. When these models are used, the relevant parameters of equations (2), (3) and (4) can be determined, and further TMF life can be calculated according to the data of isothermal fatigue at the highest and lowest cyclic temperature of TMF cycle. Equivalent temperature model and amplitude coefficient model neglect the effects of phase difference of temperature and strain on TMF life. Thus fatigue lives of in-phase and out-of-phase are equal when test conditions are the same. It is obvious that this is not corresponding to test results. The difference between the experimental and calculated TMF life based on damage fraction model is relatively small because this model considers the effect of phase difference.

Temperature T and dislocation activation energy Q determine the function of amended model of Coffin-Manson. However, Q value of most materials is unknown and its measurement is over-elaborated. Similarly, the model also neglects the effect of phase difference of temperature and strain on TMF life.

It is shown that the model of equivalent strain energy density is strict in theory. But the establishment of the model is on the basis of a lot of low cycle fatigue tests at high temperature. One needs to determine not only the variation regularity of cyclic stress and strain with temperature, but also variation curve of fatigue life and other physics parameters with temperature. Thus, a lot of tests must be done. At present, the model is considered to be the best one to predict TMF life in theory if the establishment of the model is on the basis of a lot of test data. According to Tomas principle [7], this model does not meet the principle of simple application and relates to so many test data. But there is not enough test data in practical application. Thus the application range of the model is also limited. There are greater errors in estimating TMF life especially for TMF of great difference of temperature.

In a word, although model of equivalent strain energy density is an ideal one among the present models of TMF life prediction, parameters of the model are difficult to determine. The damage fraction model is the most simple and practical one in the presented models in this paper.

3.3 A new prediction model

The cyclic variations of temperature have great effect on damage mechanism and fatigue life of materials under TMF condition. The main effect factors are amplitude of cyclic temperature, the highest temperature, frequency of temperature cycle, phase of temperature and stress or strain, sensitivity of materials on temperature variation, effect of temperature variation on phase transformation of materials and the interaction of several above factors *etc*. It can be seen that temperature is the main factor affecting TMF life. Thus the establishment of TMF life prediction model of GH4133 should include the effects of all above factors.

According to the available model of TMF life prediction, damage fraction model considers not only the effects of temperature range and the highest temperature on TMF damage, but also the effects of phase between temperature and stress or strain on TMF damage. Thus, the model is acceptable, simple and practical. Due to neglecting the effect of cyclic mean temperature, prediction results are not perfect for fatigue life of isothermal low cycle and cyclic temperature of GH4133. For this reason, a new model of damage fraction was proposed on the basis of damage fraction model. That is:

$$\Delta\phi = \frac{\Delta\phi_{\min}+2\Delta\phi_{\mathrm{mean}}+\Delta\phi_{\max}}{4} + \mu\cdot\left|\frac{\Delta\phi_{\min}-2\Delta\phi_{\mathrm{mean}}+\Delta\phi_{\max}}{4}\right| \tag{6}$$

Where

$\Delta\phi = 1/N_f^{\mathrm{TMF}}$, Damage of every cycle under TMF;

$\Delta\phi_{T(\max)} = 1/N_{f(T(\max))}$, Damage of every cycle under isothermal fatigue at $T_{\max}$ in TMF cycle;

$\Delta\phi_{T(\min)} = 1/N_{f(T(\min))}$, Damage of every cycle under isothermal fatigue at $T_{\min}$ in TMF cycle;

$\Delta\phi_{T(\mathrm{mean})} = 1/N_{f(T(\mathrm{mean}))}$, Damage of every cycle under isothermal fatigue at T_{mean} in TMF cycle;

μ, Factor of fatigue damage, a material constant.

In equation (6), the second item on the right is an additional damage. The meaning of the factor of damage μ is the same as η in equation (4). But the value of the factor of damage μ is different from coefficient η in equation (4) because μ is a constant relevant to materials. As the relationship between the isothermal low cycle fatigue life of GH4133 and temperature is not monotonic, the value of $(\Delta\phi_{\min}+2\Delta\phi_{\mathrm{mean}}+\Delta\phi_{\max})/4$ may be negative, or may be positive. Thus, it is an absolute value in this paper.

In order to determine damage factor μ, it is hypothesized that:

$$\delta(\Delta\phi) = \mu\cdot\frac{|\Delta\phi_{\min}-2\Delta\phi_{\mathrm{mean}}+\Delta\phi_{\max}|}{4} \tag{7}$$

where $\delta(\Delta\phi)$ is an additional damage corresponding to each strain of different phase, it can be obtained from equation (8):

$$\delta(\Delta\phi) = \Delta\phi - \frac{|\Delta\phi_{\min}+2\Delta\phi_{\mathrm{mean}}+\Delta\phi_{\max}|}{4} \tag{8}$$

The relation of additional damage $\delta(\Delta\phi)$ and $|\Delta\phi_{\min}-2\Delta\phi_{\mathrm{mean}}+\Delta\phi_{\max}|/4$ is shown in **figure 4**, and damage factor μ can be determined by combining with equation (7).

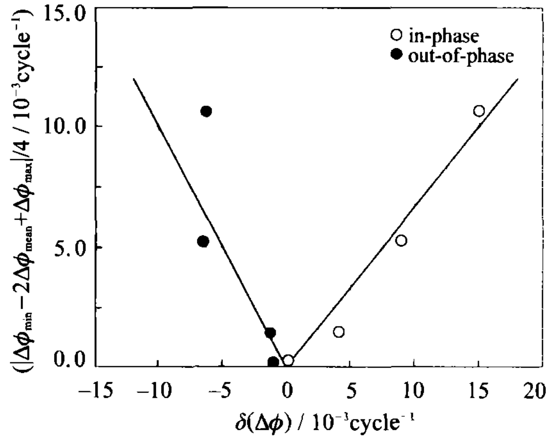

Figure 4 Relation of additional damage ($\delta(\Delta\phi)$) and ($|\Delta\phi_{\min}-2\Delta\phi_{\mathrm{mean}}+\Delta\phi_{\max}|/4$).

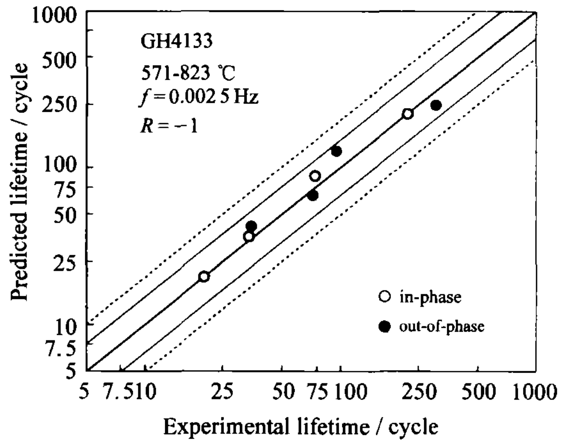

Figure 5 Comparison between predicted (by new method) and experimental lifetime under TMF.

$\mu = 1.5$, in-phase;

$\mu = -1$, out-of-phase.

By utilizing the new model of fraction damage, TMF life of GH4133 was calculated, and the relation of predicted life valve and experimental value was drawn in **figure 5**. As shown in figure 5, the predicted accuracy is higher, and all the predictive values fall in band of 1.5.

4 Conclusions

(1) The TMF lifetime of Nickel-base Superalloy GH4133 under in-phase condition in the temperature range of 571-823 ℃ is lower than that under out-of-phase condition in the same temperature range. The test results also show that the TMF lifetime under in-phase condition is lower than isothermal low cyclic fatigue life at 571, 700 and 823 ℃ respectively.

(2) Some present models had been used to calculate the thermal-mechanical fatigue life of superalloy GH4133. Unfortunately, all of them give poor life prediction.

(3) A new damage fraction model of TMF life prediction was established based on isothermal fatigue test data. It is shown that the new model of life prediction is simple, and has high predictive accuracy from predictive results of TMF of GH4133 in the temperature range of 571-823 ℃.

(4) As isothermal fatigue test is easy to do and the test data is easy to get and so rich in the literature, it is a realistic way to use data of the isothemal fatihue test to estimate thermal mechanical fatigue lifetime. The way will play great role in the life prediction of the metal materials and engineering components subjected to non-isothermal service conditions.

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