ELASTIC PLASTIC ANALYSIS AND EXPERIMENT ON STRAIN CONTROL LCF LIFE AND STRESS RUPTURE LIFE OF PRECRACKED SUPERALLOY

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ABSTRACT

Experiments on strain control LCF life and stress rupture life of smooth and precracked superalloy specimens show that small pre-existing crack seriously reduces the LCF life and stress rupture life of superalloy specimens. The results were interpreted by elastic plastic fracture mechanics using J integral parameter. Formulas for estimating the crack growth rate and life of precracked specimens and components under strain control LCF and stress rupture conditions were proposed.

INTRODUCTION

LCF is an essential limiting factor for design life of engine components. Coffin-Manson formulas are widely used to predict the LCF life of smooth specimens or components under strain control condition, but the prediction is usually conservative since it ignores the propagation life. Also, Coffin -Manson Formula is inapplicable for specimens with small pre-existing crack which may sometimes be present or form by hot corrosion in engine components. This paper introduces an analytical model based on elastic plastic fracture mechanics for predicting the crack growth rate and LCF life of precracked specimen under strain control fatigue condition. Experimental verification of the model on superalloy is given. Furthermore, similar experiment and analysis on creep crack growth and stress rupture life of precracked superalloy specimen are briefly demonstrated. This analysis is especially suitable and needed for superalloy because pre-existing cracks may be inavoidable and their interactions, say, with grain boundary cavitations under creep and combined creep-fatigue loading condition can be deleterious.

EXPERIMENTAL RESULTS AND DISCUSSION

LCF life experiments with controlled total strain range were conducted on an Instron testing machine for an engine disk superalloy Ni-20%Cr-2.5%Ti-0.7%Al-1.5%Nb, treated by 1080°C, 8 hrs. solutioning and 750°C, 16 hrs. aging. Smooth specimens and precracked specimens of 10mm diameter with small initial cracks of two given depth (a_i=0.22±0.005mm and a_i=0.67±0.005mm) were used. The lives N_f of forming a final crack depth a_f=2mm as detected by a given change (about 4%) of tension compliance versus compression one were measured. Coffin-Manson plot for smooth specimens yields the formula

$$\frac{\Delta\varepsilon_t}{2} = 0.18N_f^{-0.80}+0.8\times10^{-2}N_f^{-0.063}$$

for the superalloy which can be used for design purpose. However, in Coffin-Manson formula, the coefficients should change at the presence of an initial crack and the functional relationship of them versus a_i cannot be expressed explicitly as can be done by using lg $\int\sigma d\varepsilon$ -lgN_f plot based on the following results of elastic plastic fracture mechanical analysis proposed independently by Dowling and by authors of the present paper(1,2) i.e.

$$N_f\left(\int\sigma d\varepsilon\right)^r = (a_i^{1-r} - a_f^{1-r})/C(r-1)(2\pi Q^2)^r \quad (1)$$

This formula can be obtained by integrating the following crack growth rate formula under fully reversed strain fatigue condition (2)

$$\frac{da}{dN} = CJ^r = C(2\pi Q^2 a \int\sigma d\varepsilon)^r \qquad (2)$$

where $J=2\pi Q^2 a\int\sigma d\varepsilon$ and $\int\sigma d\varepsilon$ are corresponding maximal J integral value and maximal work density absorbed by the material during the uploading stage that makes the crack to open and propagate, Q^2 is the shape factor of the crack and had been experimentally calibrated for various crack geometry(3). The measured $\lg\int\sigma d\varepsilon - \lg N_f$ curves for precracked specimens with a_i=0.22mm and a_i=0.67mm are parallel straight lines (Fig.1) as predicted by formula (1) with r=1.8 and C=3.03 (with J integral in MN/m or MJ/m^2 and crack length in mm).

For smooth specimens, the equivalent initial crack depth calculated from measured N_f, $\int\sigma d\varepsilon$, a_f=2mm and r=1.8, C=3.03 is a_i=40μm, which is a little smaller than the mean grain size (70μm), suggesting that a given number of cycles is required for the crack nucleation along the persistent slip band in the grain.

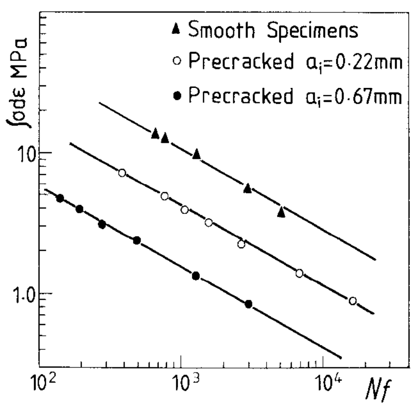

Fig.1. $\int\sigma d\varepsilon - N_f$ plot of smooth and precracked superalloy specimens.

It is difficult to follow and measure accurately the crack growth rate of very small crack (<1mm) in small strain control LCF specimens. Thus, in order to give direct experimental verification of the proposed crack growth rate formula (2) under fully reversed strain fatigue condition, the calculated da/dN using equation (2) for various crack depth and strain range (or $\int \sigma d\varepsilon$) with r=1.8 and C=3.03 were compared with the mean striation spacings measured at corresponding crack depth in SEM photographs (Fig.2), the result shows that, with some difference of macroscopic (or mean) and microscopic crack growth directions in mind, the agreement is satisfactory for intermediate and large crack growth rate region where each strain cycle produces a striation or crack extension step. However, for very small crack growth rate (<0.2μm/cycle), the measured striation spacings are apparently larger than calculated da/dN. This is understandable since at early stage of fatigue crack propagation, each strain cycle does not necessarily produce a striation at the whole crack front, but some redundant cycles may be required before sufficient damage accumulates to cause a crack extension step in some grains. Thus, at very small crack growth rate stage, the striation spacing is only loosely relate to the macroscopic crack growth rate da/dN and the theoretical formula (2) can only be verified indirectly by comparison of the derived life formula (1) with the strain control LCF life experiments as illustrated in Fig.1.

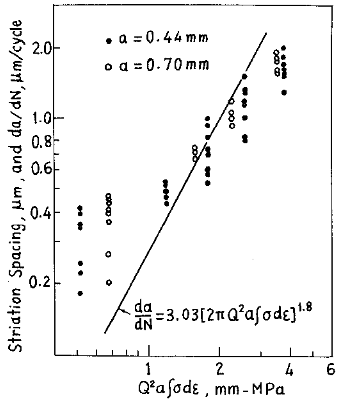

Fig.2. Comparison of measured striation spacing with calculated crack growth rate.

Owing to the difficulty of accurate experimental determination of crack growth rate and the parameters r and C in equation (2) under strain control LCF condition, we had proposed an indirect method of estimating r and C by using fatigue crack propagation data measured by conventional specimen under small scale yielding condition, i.e.

$$\frac{da}{dN} = A\,\Delta K^n \qquad (3)$$

Based on the idendity of crack tip singularity under the equality of $\Delta K^2/E$ for small scale yielding to J integral for general yielding, we may suppose equal crack growth rate in the two yielding cases, i.e. $CJ^r = A\Delta K^n$ when $J=\Delta K^2/E'$, from these two equations we can derive $r = n/2$, $C=A(E/1-v^2)^{n/2}$. Thus, for the superalloy $E=2.23\times10^5$MPa and $\nu=0.36$, using the results of Fig.3, i.e. $n=3.6$ and $A=4.48\times10^{-10}$ we have an estimation $r=n/2=1.8$ and $C=A(E/1-v^2)^{n/2}=2.45$ which are in good agreement with $r=1.8$ and $C=3.03$ derived from LCF life results in Fig.1.

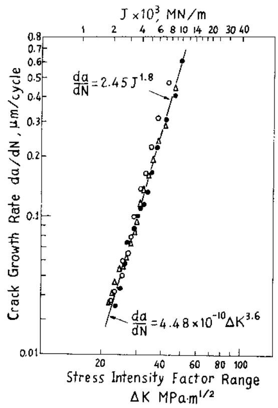

Fig.3. Fatigue crack growth rate as function of ΔK and J for the superalloy.

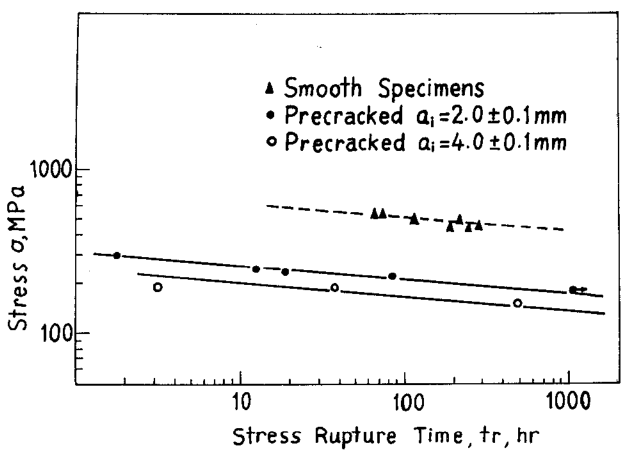

Fig.4. Stress rupture life of smooth and precracked specimens of the superalloy at 700°C.

Some preliminary experiments on stress rupture life of smooth and precracked specimens were conducted on the same superalloy at 700°C. Side crack tension plates of 3mm thickness and 20mm width with initial crack length $a_i=2.0\pm0.1$mm and $a_i=4.0\pm0.1$mm made by fatigue precracking were used for precracked specimens. The results are illustrated in Fig.4. Evidently, the presence of small crack of only 2mm length seriously reduces the rupture strength and the stress rupture life of the superalloy.

Based on the experimentally verified creep crack growth rate formula $da/dN \sim \dot{J}^{m/m+1}$ that can be derived through micromechanical analysis of cavity growth by power law creep and coalescence along grain boundaries within the crack tip stress field, and by using the F.E. results on J integral estimations of power law creep material given by Hutchinson(4), i.e. $\dot{J} \sim a\sigma_{net}^m$ the following approximate formula for crack growth rate under creep condition was proposed:

$$\frac{da}{dt} = Ba\,\sigma_{net}^m \tag{4}$$

for plate of width b and crack length a under nominal stress σ, the net section stress $\sigma_{net}=\sigma(b/b-a)$ after inserting into equation (4) and integrating, the following stress rupture life formula for precracked tension plate specimens is obtained:

$$B\sigma^m t_r = \int_{a_i}^{a_f} \frac{1}{a}(1-\frac{a}{b})^m da \tag{5}$$

The parameters m and B for the superalloy at 700°C were found to be m=10 and $B=0.7\times10^{-26}$ to fit the experimental results of precracked specimens as shown by the two lower solid lines in Fig.4. In principle, the above result can be used to predict the rupture life of an engineering component with a small pre-existing crack of depth a_i, since in this case, $a/b \to 0$ and equation (5) becomes

$$0.7\times10^{-26}\,\sigma^{10} t_r = \ln\frac{a_f}{a_i}$$

CONCLUSION

Small pre-existing crack seriously reduces the strain control LCF life and stress rupture life of superalloy specimens. Methods based on elastic plastic fracture mechanics for analysing crack growth rate and life of precracked specimens under strain control LCF and stress rupture condition were proposed and verified by experiments. The result shows that the J integral (and creep J integral) appears to be a promise approach not only for crack growth under cyclic strain condition where general yielding prevails, but also for crack growth under stress rupture condition, where either ligament creeping or general creeping may happens.

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