INVESTIGATION ON LCF CRACK GROWTH RATE AT ELEVATED TEMPERATURE

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ABSTRACT

To simulate actual condition of crack growth in gas turbine disk, LCF crack growth rate of a superalloy was measured at 600°C by means of controlling deflection to a sloping line and the relation

$$da/dN = 1.26 \times 10^{-4}(\Delta J)^{1.96}$$

was obtained.

The equation about ΔJt and $\delta(a)$ in cyclic loading, determined by experiments, provided a convenient method for life prediction of gas turbine disks. SEM observation showed that owing to the fatigue and creep cumulative damage, the fracture morphology transfered from plastic blunting to intergranular mechanism.

INTRODUCTION

LCF failure frequently occurs in gas turbing components (e.g. disc and blade) owing to combined action of thermal stress and residual stress. It is difficult to analyse this sort of stress field in elastic-plastic fracture mechanics[1]. Under this condition crack growth behavior of a component is proved to be controlled by deflection[2]. Traditional simple load control or strain control can not measure the crack growth data due to appearing of plastic tearing. But by means of controlling deflection to a sloping line above difficulty may be avoided and stable LCF crack growth data have been obtained successfuly[3].

MATERIAL AND TEST PROCEDURE

The material tested is a superalloy. Its chemical composition is shown in Table 1.

Table 1 Chemical composition (%)

C	Si	Mn	Cr	Ni
0.34—0.4	0.3—0.8	2.5—9.5	11.5—19.5	7.0—9.0
No	Nb	Ti	V	
1.1—1.4	0.25—0.5	< 0.12	1.25—1.55	

For studying of residual life, the specimens were cut from disks after a certain flight time which represents the mean flight life. The CCT specimen was accepted in this test. Deflection $\delta(a)$, used for determining ΔJ, was measured over a specimen section where the train distributes uniformly.

All tests were carried out on ESH 100E testing machine with closed loop control system and crack length was monitored by electric potential method[4].

Fig. 1 demonstrates the principle of controlling deflection to a sloping line. The abscissa represents deflection and the ordinate-applied load. During testing the hysteresis loops are registered periodically with x-y recorder. The tops of these loops should fall on a predetermined sloping line S-D.

The variables are explained as follows:

ε_0— initial strain at test begining. It increases as crack grows f_0— initial loading frequency. It decreases with increasing of cyclic numbers. The purpose of decreasing frequency is to maintain a roughly constant rate of crack extension. P — load. It decreases with increasing of deflection.

Cyclic life of a specimen, i.e. slope of line S-D is affected by the above parameters. To simulate gas turbine mean cyclic life these parameters must be determined suitably, making failure cycle keep 10^3 or so. Table 2 shows these parameters:

Table 2 Experiment parameter

SPEC	S	D	ε_0	f (HZ)		Za/w		Nf
No:	(kg)	(mm)	(%)	initial	stop	initial	stop	
a	5162	0.154	0.6	0.17	0.03	0.43	0.9	623
B	6321	0.15	0.6	0.17	0.03	0.38	0.9	708

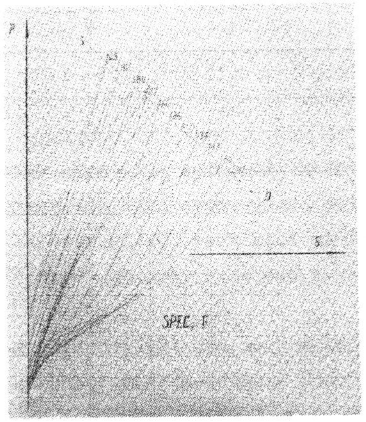


Fig.1 Principle of controlling deflection to a sloping line

PRINCIPLE AND DATE REDUCTION

Generally, in describing LCF crack growth rate at elevated temperature, J-integral may be used as mechanics parameter. According to J-definition:

$$J = \int_{\Gamma} Wdy - \vec{T}\frac{\partial u}{\partial x}ds$$

There are two equivalent expressions:

$$J = \int_0^{\delta} \left.\frac{\partial P}{\partial a}\right|_{\delta} d\delta \qquad \text{or} \qquad J = \int_0^{P} \left.\frac{\partial \delta}{\partial a}\right|_{P} dP \tag{1}$$

For CCT, δ_T expresses total displacement at calibration points, consisting

of two components

$$\delta_T = \delta_e + \delta_p \tag{2}$$

where δ_e—elastic portion of displacement. δ_p—plastic portion, it may be expressed by[5]

$$\delta_p = bf(\frac{P}{b}) \tag{3}$$

where b—ligament of specimen.

Note that :

$$b = w - a, \qquad \frac{\partial \delta_T}{\partial a} = \frac{\partial \delta_T}{\partial b}$$

$$J = J_e + \int_0^P [-\frac{\partial \delta_p}{\partial a}]\, dP \tag{4}$$

Form formula (3)

$$\frac{\partial \delta_p}{\partial b} = \frac{1}{b}[\delta_p - p\frac{\partial \delta_p}{\partial p}]$$

Substitute it into (4)

$$J = J_e + \frac{2}{b}\int_0^{\delta_p} Pd\delta_p - \frac{1}{b}P\delta_p \tag{5}$$

Transfer (5) into

$$J = J_e + \frac{2}{b}\int_0^{\delta_p} Pd\delta_p - \frac{1}{b}P\delta_p + \frac{2}{b}\int_0^{\delta_e} Pd\delta_e - \frac{2}{b}\int_0^{\delta_e} Pd\delta_e$$

$$= J_e + \frac{2}{b}[\int_0^{\delta} Pd\delta - \frac{1}{2}P\delta] \tag{6}$$

where

$$2\int_0^{\delta_e} Pd\delta_e = P\delta_e$$

The two terms in bracket of formula (6) are interprated as hysteresis loop area in each cycle[6].

In practice, considering effect of crack closure, the values are to be estimated with[7]

$$\Delta J = \frac{\Delta K_{eff}^2}{E} + \frac{\Delta U_{eff}}{2Bb} \tag{7}$$

where, ΔK_{eff}—effective stress intensity factor which is calculated with modified Fedderson formula[8].

$$\Delta K_{eff} = \frac{\Delta P_{eff}}{S_0} \sqrt{\pi a}\, f(\frac{a}{W})$$

$$f(a/W) = [1 - 0.025(a/W)^2 + 0.06(a/W)^4] \sqrt{\sec(\frac{\pi a}{2W})} \qquad (8)$$

ΔU_{eff} and ΔP_{eff} in formulas (7) and (8) are hysteresis loop area and load amplitude, respectively, corresponding to crack opening[9], as shown in Fig. 2.

Cyclic crack growth rate was determined for all tests based on a_i-N_i data by an incremental polynomial procedure[10].

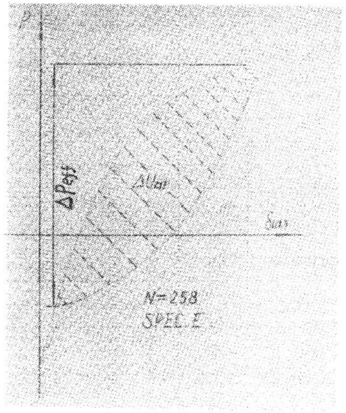


Fig.2 Estimation of ΔU_{eff} and ΔP_{eff}.

DISCUSSION AND SUMMARY

Fatigue crack growth rates are plotted versus ΔJ in Fig. 3 for elastic-plastic CCT specimen tested at 600°C in opening air.

1. From Fig.3 a simple power-law relationship can be regressed as follows:

$$da/dN = 1.26 \times 10^{-4} (\Delta J)^{1.96} \qquad (9)$$

Thus, J-integral concept was applied to describe LCF crack growth rate successfully at elevated temperature.

2. Fig. 4 demenstrates the relations between $\Delta J_t(\Delta J_e, \Delta J_p)$ vs. deflection. It is seen that ΔJ_t, corresponding to elastic-plastic cyclic loading, is directly proportional to δ and may be expressed as:

$$\Delta J_t = k\delta(a) + b \qquad (10)$$

The plastic portion of J-integral ΔJ_p monotonously increases with $\delta(a)$, following relation may be used to depict its variation:

$$\Delta J_p = C[\delta(a) - A]^m \qquad (11)$$

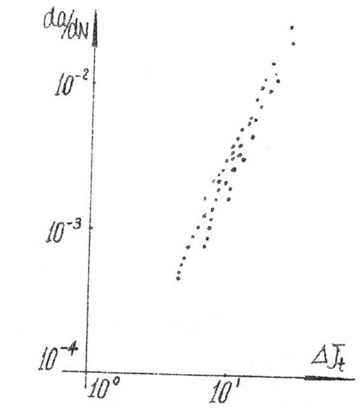


Fig. 3 da/dN versus ΔJ_t

For the elastic portion ΔJ_e in cyclic loading a peak value appears at about a/W=0.6.

It is difficult to find a suitable function to fit, but there is a restraint equation

$$\Delta J_t = \Delta J_e + \Delta J_p$$

so that

$$\Delta J_e = \Delta J_t - \Delta J_p = K\delta(a) + b - C[\delta(a) - A]^m \qquad (12)$$

In formulae (10) and (11) k, b, A, C and m are constants for a given set of testing parameters, e.g. for specimen A, they are

$k = 1.9$, $b = -5.9$, $A = 5.5$,

$C = 5.1 \times 10^{-2}$, $m = 2.3$

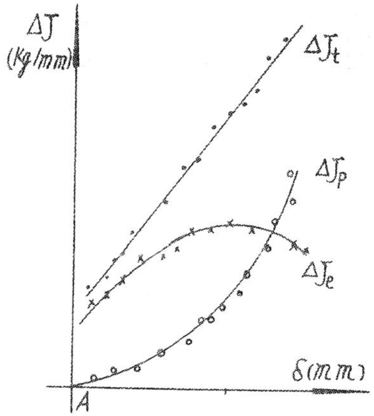


Fig. 4 Correlation of ΔJ_t (ΔJ_e, ΔJ_p) vs δ (a)

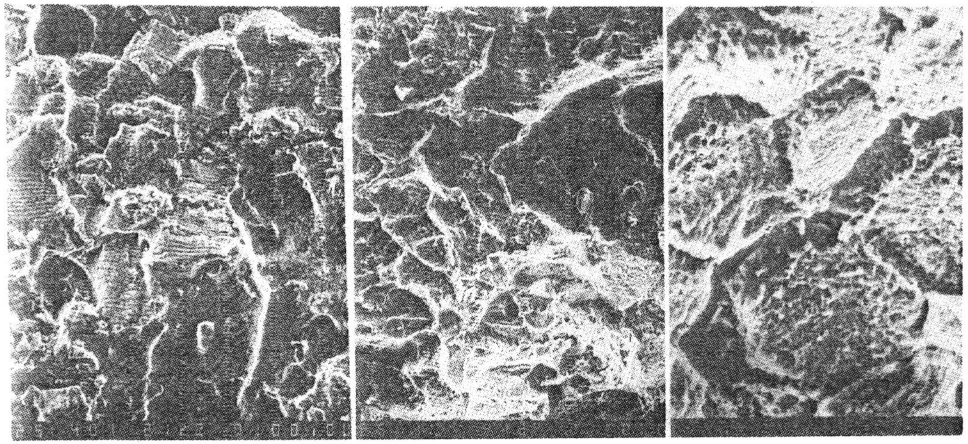
Above rules are similar to those obtained by the author at ambient temperature[11].

The most important formula is Eq. (10). Substitute it into (9) then

$$da/dN = 1.26 \times 10^{-4} [K\delta(a) - b]^{1.96} \qquad (13)$$

Expression (13) describes LCF crack growth rate with visual parameter $\delta(a)$. It's well known that although J-integral possesses strict theoretical basis, it is difficult to measure in engineering practice. On the other hand, though the physical meaning of $\delta(a)$ is not clear, it is easy to measure. Eq.(10), established by experiments, not only endows $\delta(a)$ an indirect theoretical basis, but also opens up a promising future for J-integral to be applied to life prediction, especially in elastic-plastic range.

3. SEM observation on fracture indicates that the morphology changes from fatigue striation to void coalescence, as shown in photo 1–3.



ph. 1 Fatigue striations ph.2 Mixed type ph. 3 Void coalescence

At the begining of test load frequency is higher than that of latter stage, waveform is possitive triangular and creep damage component is too small to consider. Fatigue crack growth mechanism is mainly plastic blunting[12]. Typical striations represent the character in this stage. As frequency decreases and deformation history elapses, creep damage becomes clearer and clearer. Photo 2 shows the morphology changing from plastic slip (lift-top) to void coalescence (right bottom). Photo 3 reflects intergranular fracture mechanism of the latter stage. By this time creep damage prevails and crack grows along grain boundaries.

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