CHARACTERIZATION OF ELEVATED TEMPERATURE FATIGUE CRACK GROWTH RATES

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Summary

The applicability of the fracture mechanics parameter K to characterizing elevated temperature fatigue crack growth data has been examined. The extent to which the testing conditions influence the degree of crack tip stress relaxation has been determined by measurement of the crack tip plastic zone size. The application of the stress intensity factor to both characterizing crack growth data and near crack tip deformation is considered.

Introduction

The concepts of linear elastic fracture mechanics have been extensively used to describe the distributions of stress and strain in the vicinity of crack tips. In particular, the stress intensity factor, K , may be used to characterize these distributions in terms of the applied load and the specimen and crack geometry. The use of K has been extended to encompass the concept of a driving force for crack extension and to relate the loading conditions which give rise to both unstable crack extension (1) and fatigue crack growth (2). In the latter case, the cyclic stress intensity ΔK , the difference between the maximum and minimum stress intensities encountered during the loading cycle, is used.

The use of K is strictly only valid when linear elastic conditions exist but its use is generally considered to extend to situations in which yielding of material at the crack tip takes place, providing the size of this plastic zone is small in comparison with the specimen dimensions. In this case small scale yielding is encountered and the size of the region over which the stress distribution may be adequately described by the stress intensity is large compared to the region determining the fracture process. Such situations are commonly encountered during ambient temperature fatigue and the crack growth rates may be adequately correlated with the cyclic stress intensity.

However, during crack growth at elevated temperature, it has been considered that time dependent deformation of material may result in stress redistribution in the crack tip region thus giving a corresponding increase in the crack tip plastic zone size. Under these conditions there are uncertainties in extrapolating the concepts of linear elastic fracture mechanics to the characterization of crack tip stresses.

Several approaches have recently been made to utilize elastic/plastic fracture parameters which encompass the effects of crack tip plasticity. During creep crack growth the use of rate dependent elastic/plastic fracture parameters has been investigated (3,4) whereas attempts have been made to correlate elevated temperature fatigue crack growth data in terms of elastic/plastic J integral concepts (5,6).

The aim of the present work has been to investigate the use and applicability of linear elastic fracture mechanics parameters to the characterization of crack growth in a series of nickel base superalloys. The influence of temperature and frequency on both the extent of crack tip plasticity and the correlation of crack growth data are considered.

Material and Experimental Techniques

Two nickel based superalloys were investigated in the present work, U.D.S. single crystal Mar M002 with a growth direction of [001] and polycrystalline H.I.P.'ed Nimonic AP1. The compositions are given in Table I.

Table I. Material Composition (wt.%)

Mar M002:	Co 10; Cr 8.8; Al 5.5; Ti 1.4; W 9.8; Ta 2.5; Hf 1.5; C 0.15; B 0.012; Zr 0.07; Ni balance
Nimonic AP1:	Co 16.9; Cr 14.8; Al 4.0; Ti 3.5; C 0.022; B 0.0002; Mo 5.0; Ni balance

The single crystal material was heat treated for 1 h. at 1100°C followed by 16 h. at 860°C. The resulting microstructure consisted of approximately 60 volume percent of cuboidal γ' of 0.05 μm edge dimension together with about 6 volume percent of γ - γ' eutectic and a number of script carbides.

The Nimonic AP1 was H.I.P.'ed for 2 h. at 1160°C and 103 MPa and solution treated at 1150°C for 2 h. developing a grain size of 40-50 μm diameter. To enable the effect of precipitate distribution to be examined the material was then given differing heat treatments. A coarse γ' precipitate of 0.1 μm diameter (microstructure C) was obtained by aging at 800°C for 24 h. A fine γ' of 0.05 μm diameter (microstructure F) was obtained by aging at 650°C for 24 h. and a commercial heat treatment was used to develop a duplex precipitate distribution (microstructure D) containing irregular cuboidal γ' precipitates of 0.12 μm edge together with a fine spherical γ' precipitate of 0.03-0.05 μm diameter.

Fatigue crack propagation tests were conducted on center cracked tension specimens having dimensions 30 mm x 105 mm x 2 mm. Single crystal specimens were oriented such that each face was close to 100°, testing was conducted in air with an R ratio of 0.1 at room temperature, 600°C and 850°C using frequencies of 10 Hz, 1 Hz and 0.1 Hz. Nimonic AP1 was tested at room temperature and 600°C at a frequency of 10 Hz. Crack extension was monitored using a D.C. potential drop technique capable of detecting changes in crack length of approximately 10 μm .

Crack propagation was carried out under conditions of constant applied ΔK in which a constant ΔK was maintained over large crack lengths. Crack growth rates per cycle, da/dN , were evaluated using a linear regression analysis of the recorded crack length and number of applied loading cycles. Crack initiation was at an intermediate ΔK after which the applied ΔK was progressively reduced in steps of 5-10%. The applied ΔK was then systematically increased and crack growth rates determined at ΔK values identical to those previously investigated.

The extent of crack tip plasticity was determined in interrupted specimens deformed under known conditions of temperature, frequency and stress intensity using selected area channelling patterns (SACPs). In each case, electropolished longitudinal mid-thickness sections through the crack tip were prepared and the position of the elastic/plastic interface determined by investigation of the SACP quality obtained from small volumes of material at points successively closer to the crack tip (7). A departure from lattice perfection results in a deterioration in the SACP quality which enables strains of between 1% and 0.5% to be accurately detected. The position at which a detectable deterioration in pattern quality occurred was taken as the plastic zone boundary in the single crystal material patterns were generated from material having a surface diameter of 2-3 μm ; in the H.I.P.'ed material patterns were obtained from material having a surface diameter of approximately 10 μm .

Experimental Results

Crack Growth. During crack extension values of crack length and number of cycles were recorded under constant applied ΔK conditions over crack increments originating from different initial crack lengths. An example of the data from single crystal Mar M002 at room temperature is given in Fig. 1.

Fig. 1 - Increment of crack length, da , vs. applied number of cycles at a constant ΔK for varying initial crack lengths in Mar M002 single crystal at room temperature.

Under all the conditions of applied ΔK and microstructure investigated at room temperature the data demonstrated linear regression coefficients for da/dN values of better than 0.99 with good agreement observed between the values of da/dN measured at identical applied ΔK but different absolute crack length. On increasing the temperature to 600°C , this behavior was maintained over the range of frequencies and microstructures investigated. Fig. 2 shows the data from Nimonic AP1 at 600°C . At the highest temperature of testing, 850°C , a slight change in behavior was observed. A small reduction in the correlation coefficient was observed with a slight increase in the scatter of da/dN values associated with identical applied ΔK found.

Fig. 2 - Increment of crack length, da , vs. applied number of cycles at a constant ΔK for varying initial crack lengths in Nimonic AP1 at 600°C .

Crack Tip Plasticity. The crack tip plastic zones developed in the single crystal material under similar values of ΔK at room temperature and the three frequencies at 600°C are represented in Fig. 3. It may be seen that there exists only a relatively small difference between the plastic zone size associated with room temperature deformation and that developed at 600°C and 10 Hz. However, on reducing the frequency at 600°C, progressive increases in the measured plastic zone size are seen.

The plastic zone sizes at 850°C are given in Fig. 4. Once again, it can be seen that decreases in the frequency from 1 Hz to 0.1 Hz give rise to an increase in the plastic zone size.

The extent of crack tip plasticity developed in the H.I.P.'ed polycrystalline Nimonic AP1 at differing temperatures but identical ΔK s are presented in figs. 5 to 8. It can be appreciated that under identical conditions of temperature, frequency and applied stress intensity the crack tip plastic zone sizes are considerably smaller than those developed in the single crystal material. It may also be noted that changes in either the microstructure or the temperature of testing give rise to only small variations in the measured plastic zone size.

Fig. 3 - Crack tip plastic zones in Mar M002 single crystal at room temperature and three test frequencies at 600°C.

Fig. 4 - Crack tip plastic zones in Mar M002 single crystal for 1 Hz and 0.1 Hz at 850°C, $\Delta K = 31.6 \text{ MPa}\sqrt{\text{m}}$.

Nimonic API (F)
Room Temperature $\nu = 10$ Hz
 $\Delta K = 21.6 \text{ MPa}\sqrt{\text{m}}$

Fig. 5. Crack tip plastic zone at Rm.T.

Nimonic API (D)
Room Temperature, $\nu = 10$ Hz
 $\Delta K = 21.6 \text{ MPa}\sqrt{\text{m}}$

Fig. 6. Crack tip plastic zone at Rm.T.

Nimonic API (F)
 $T = 600^\circ\text{C}$ $\nu = 10$ Hz
 $\Delta K = 21.6 \text{ MPa}\sqrt{\text{m}}$

Fig. 7. Crack tip plastic zone at 600°C

Nimonic API (C)
 $T = 600^\circ\text{C}$ $\nu = 10$ Hz
 $\Delta K = 21.6 \text{ MPa}\sqrt{\text{m}}$

Fig. 8. Crack tip plastic zone at 600°C

Discussion

It is apparent from the crack growth data that a good correlation exists between the experimentally determined values of da/dN and the applied cyclic stress intensity. The values of da/dN exhibit remarkable reproducibility over large crack lengths and for different initial crack lengths at various temperatures and frequencies. It is initially pertinent to consider this behavior in terms of the regions of plasticity at the crack tips.

In the present work, both the single crystal and the polycrystalline materials have been shown to contain discrete regions of plasticity at the crack tips. In the polycrystalline material the plastic zone sizes are significantly smaller than those of the single crystal material an effect which may be interpreted in terms of the incompatibility of deformation across grain boundaries. At room temperature the extent of crack tip plasticity in all the materials tested is observed to be small in

comparison to the overall crack length. Under these conditions, it is to be expected that the crack tip plastic zone size is small with respect to the size of the region of material in which the near crack tip elastic stress distributions are given in terms of linear elastic stress intensity factors. Small scale yielding at the crack tip then exists and characterization of the crack growth rates with the stress intensity factor is appropriate. This situation is reflected in the excellent agreement found in the crack growth rates when the cyclic stress intensity is used as a correlating parameter.

When the temperature of testing is raised to 600°C, the extent of crack tip plasticity is observed to be dependent on the frequency of testing (Fig. 3). At high frequencies calculations show that the crack tip plastic zone size may be simply related to that at room temperature. Consequently, it is to be expected that small scale yielding conditions still exist at the crack tip and crack growth data may thus be adequately related to the cyclic stress intensity factor. With decreasing frequency increases in the plastic zone size may, initially, be expected to result in a deviation from small scale yielding conditions. However, even though a one hundred fold decrease in the frequency effects an approximately four fold increase in the plastic zone size, the extent of this crack tip plasticity remains physically small in comparison to the overall crack length. The plastic zone size was always observed to be less than $a/15$ so that once again small scale yielding of the crack tip region may be considered to take place.

On increasing the temperature of testing to 850°C, discrete regions of plasticity at the crack tip were still observed. Once again, these regions are physically small in comparison with the region over which linear elasticity conditions may exist so that the characterization of crack growth data in terms of linear elastic parameters is maintained. Thus, even though high temperature and low frequency has been shown to give rise to an increasing amount of crack tip stress relaxation, it is considered that small scale yielding conditions at the crack tip are encountered in the present work.

However, although the stress intensity factor may be applicable to the characterization of crack growth data limitations may arise if its use is extended to the consideration of crack tip plasticity. Many dimensions of the plastic zone may be used to compare the extent of crack tip plasticity, it is convenient in the present case to consider the dimension of the plastic zone size directly ahead of the crack tip, r_p . This experimentally determined dimension is given in Table II for the variety of conditions investigated here.

In general, the monotonic plastic zone size may be related to the maximum stress intensity encountered during loading, K_{max} , and the material's yield stress σ_y , through equations of the form

$$r_p = \alpha \frac{K_{max}^2}{\sigma_y^2} \quad (1)$$

In the present study, a value of α , calculated from room temperature data, may be used to estimate the plastic zone sizes at specific elevated temperatures. These estimates are included in Table II.

Table II. Plastic Zone Sizes

K_{max} , MPa $\sqrt{m}$	Temp, °C Freq. Hz	Plastic Zone Size, μm			
		Measured		Calculated	
		Mar M002	Nimonic AP1	Mar M002	Nimonic AP1
24	RT, 10	158	66 (F)* 56		
26	600, 10	178		170	
	1	223			
	0.1	656			
24	600, 10		69 (F)* 72 (C)		82 78
34	850, 1	300		402	
	0.1	515			

*
Parenthesis refer to the precipitate distributions, F = fine, C = coarse, D = duplex.

From the data it may be appreciated that at 600°C and 10 Hz the calculated plastic zone sizes for both the single and polycrystalline material are close whereas significant deviations from this behavior take place at high temperatures and low frequencies. This latter observation has been discussed in terms of creep deformation at the crack tip (8). At 600°C and high frequencies little stress relaxation occurs and the crack tip plastic zone size is close to that predicted from room temperature data. With decreasing frequency an increasing amount of stress relaxation takes place and deviations from this behavior arise.

Under the conditions where creep deformation occurs limitations in the use of linear elastic parameters in characterizing the near tip region may arise. These limitations arise not through the violation of small scale yielding conditions but from an inability to take into consideration the changes that occur in the behavior of material both at the crack tip and ahead of it. At high frequencies instantaneous plastic deformation takes place and consequently linear elastically parameters may be used to characterize the crack tip plastic zone size. However, when time dependent deformation also takes place giving rise to either increased plastic zones or crack tip blunting this situation no longer arises. Thus, although small scale yielding conditions may still exist the stress intensity factor may no longer be appropriate to describe the near crack tip deformation behavior of the material.

Conclusions

From the fatigue crack growth tests conducted under conditions of constant ΔK it is apparent that a high degree of correlation exists between the fatigue crack growth rate and the values of ΔK . This behavior is maintained at high temperatures and low frequencies.

Discrete regions of plasticity have been observed at the crack tip of material deformed under various conditions of temperature and frequency. It would appear that under conditions where time dependent deformation mechanisms become important the applicability of linear elastic parameters to defining the near crack tip deformation behavior is limited. However, in all the conditions investigated the extent of crack tip plasticity is small and characterization of crack growth data by the stress intensity factor is adequate.

Nomenclature

a = half crack length of center cracked tension specimen
 da/dN = crack growth rate per cycle (mm/cycle)
 K = linear elastic stress intensity factor ($\text{MPa}\sqrt{\text{m}}$)
 K_{max} = maximum stress intensity factor ($\text{MPa}\sqrt{\text{m}}$)
 K_{min} = minimum stress intensity factor ($\text{MPa}\sqrt{\text{m}}$)
 r = plastic zone size directly ahead of crack tip (μm)
 R^p = $K_{\text{min}}/K_{\text{max}}$
 α = dimensionless constant relating r and $(K_{\text{max}}/\sigma_y)^2$
 ΔK = cyclic stress intensity = $K_{\text{max}} - K_{\text{min}}$ ($\text{MPa}\sqrt{\text{m}}$)
 σ_y = yield stress (MPa)

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