INFLUENCE OF STRESS RATIO AND TIME AT MAXIMUM LOAD ON THE FATIGUE CRACK GROWTH BEHAVIOUR OF IN718 AT 600°C

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The effects of dwell time at maximum load and stress ratio on the fatigue crack propagation rate of the nickel base superalloy IN718 at 600°C were analysed. The total applied cyclic frequencies ranged from 0.0015Hz to 15Hz and the stress ratios were 0.05, 0.5 and 0.8. Three regimes of FCG behaviour were observed: cycle dependent, time dependent and mixed.

The increase in stress ratio produced a significant increase in fatigue crack propagation rate in the time dependent regime. To a first approximation, transition frequencies from intergranular to transgranular failures were obtained at high stress ratios. The different failure mechanisms were identified by SEM observations on the fracture surfaces.

INTRODUCTION

In nickel base superalloys fatigue crack propagation at elevated temperatures is due to the effect of several rupture mechanisms such as cyclic plastic deformation at the crack tip, oxidation and creep. Depending on which these mechanisms is predominant three distinct crack propagation modes may occur: cycle dependent, time dependent or mixed. In the first, cyclic plastic shear at the crack tip is the leading factor and hence the failure mode is essentially transgranular.

However the crack growth rate increases also due to the presence of oxygen. The effects of oxygen are twofold: diffusion to the highly stressed region at the crack tip, with local embrittlement in the slip bands, and oxidation of the fracture surfaces which makes crack closure more difficult (1). Hence crack propagation and plastic

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deformation is enhanced by the presence of oxygen although cyclic plastic deformation remains the main failure mechanism.

In the time dependent regime the damage mechanisms are oxidation and creep which can act separate or simultaneously. Crack propagation is mainly intergranular since the grain boundaries are preferential paths for creep and oxidation (3,4). In the mixed regime there are contributions of the integranular and transgranular mechanisms refered to above.

When a dwell time is introduced at the maximum load, the frequency decreases and more time is available for creep and oxidation to occur. Besides, the reduction in frequency leads to a proportional reduction in the density of the slip bands and hence more heterogeneous cyclic deformation occurs (5). If the total cycle time is low cyclic plastic deformation increases and fatigue crack propagation is mainly transgranular. Therefore a dwell time t_D at maximum load, contributes towards time dependent mechanisms, with a resulting acceleration of fatigue crack growth as detected by Byrne and coworkers in IN718 and other Ni base superalloys (2).

The increase in stress ratio contributes to creep effects since the mean load increases and the creep threshold is exceeded. So, an increase of R favours time dependent propagation. Additionally when R increases less crack closure occurs and the ΔK effective at the crack tip also increases which increases the fatigue crack growth rate. The closure effect is more pronounced for time dependent propagation, where an oxide layer at the crack surfaces is formed and rough intergranular fractures occur specially in coarse grained materials (6).

For low R values, and mainly at high frequencies, fatigue crack growth is mainly cycle dependent (7). The effect of t_D and R is usually studied in da/dN against frequency diagrams. Usually when ΔK or K_{max} is reduced the transition frequencies also decrease and the transition frequency from transgranular to mixed fracture increases with R since an increase in R promotes intergranular crack propagation (8).

However, the transition behaviour and the crack propagation rates, also depend, perhaps to a lesser extent on other parameters such as wave shape, thickness, environment and temperature. For example, if the temperature is relatively low crack propagation can be always transgranular irrespective of the dwell time and R values.

In this paper a study is presented of the influence of dwell time at maximum load and stress ratio on fatigue crack growth rate in IN718 at 600^{o}C. A preliminary analysis of the transition frequency behaviour of this alloy is reported and the main failure mechanisms, as detected by SEM observations, are discussed.

EXPERIMENTAL PROCEDURE

The chemical composition (in % weight) of the IN718 alloy tested was: Ni-53.5; Fe-18.0; Cr-19.0; Nb-5.0; Mo-3.0; Al-0.6; Ti-0.9. The material was subjected to the conventional heat treatment: 1 hour annealing at 935°C followed by air cooling; ageing- 8h at 720°C and cooling until 620°C with a cooling rate of 38°C/h; finally an eight hour stage at 620°C followed by air cooling.

The specimens were of the corner cracked type (CC) with a 10x10 mm cross section (9). The initial notch depth was 0.25 mm and a fatigue precrack was started in air at room temperature before the test at 600°C. The Pickard solution was used for the computation of the stress intensity factor (10).

Crack length and depth during the fatigue tests were continuously monitored with a pulsed DCPD system directly linked to the testing machine. To check the crack lengths, calibration data was used obtained by crack marking and also by crack length measurements in the fracture surface after breaking the specimens. The fatigue tests were carried out in air at 600°C under load control (ΔK increasing) in a computer controlled servohydraulic testing machine. For the frequencies below 0.25 Hz a trapezoidal load wave was applied with 1 sec ramp up and ramp down and 1 sec dwell at minimum load. The dwell times at maximum load had the following values: 1; 10; 30; 60; 90; 120; 300 and 600 seconds. In the majority of specimens it was possible to run two tests with different dwell times consecutively. For the frequencies above 0.25Hz sinusoidal or triangular load waves were applied.

RESULTS AND DISCUSSION

The da/dN data was plotted against ΔK and K_{max} and Paris type correlations were obtained in region II of the diagram (9). Creep crack growth rate data was also obtained and this will be used to model the creep-fatigue growth behaviour.

The da/dN- against total frequency diagram, for the lower stress ratio of R=0.05, and for constant ΔK= 40MPa$\sqrt{m}$, is plotted in Fig. 1. It is seen that for frequencies below 0.01Hz (a t_D value close to 100s) fatigue crack propagation is time dependent ((da/dt= const.). For the frequencies above 1Hz crack propagation is cycle dependent, ((da/dN)= const.). The mixed regime is between 0.01Hz to 1Hz although its boundaries and shape need to be clarified with additional testing.

A review of the dwell effect on the fatigue crack growth behaviour of Ni base superalloys (2) has shown that, from the available data in the literature, the transition frequency, f_F, to totally transgranular fracture is above the frequency, f_c, of the ramp up and down of the loading cycle. In these tests, f_c=0.5 Hz, which is below the value of 1Hz found for the transition frequency (Figs. 1 and 2). In the time dependent regime, where the slope of the da/dN- frequency data, is (-1), Fig. 1, da/dt= Const. and the addition of a dwell time at maximum load to the base frequency does not change the fatigue crack growth rate per unit time.

The mixed regime is frequency dependent and the dwell time increases both with da/dN and da/dt (Fig. 2).

The influence of stress ratio in the da/dN- frequency diagram is depicted in Fig. 2. The increase of R from 0.05 to 0.5 and 0.8 leads to an increase of da/dN as expected. This increase is greater for the lower frequencies in the time dependent regime, since mainly intergranular fractures were obtained in this region. In the cyclic dependent regime the effect of the stress ratio on FCGR is comparatively minor, since in this regime oxidation and creep effects are absent.

There appears to be a trend of increase in the transition frequency from the intergranular to the mixed regime, as the stress ratio increases. However additional tests are required to stablish more definitive conclusions. The transition frequencies of the mixed to the cyclic dependent regime seems to be relatively independent of the stress ratio. For the higher stress ratio (0.8) the mixed regime tends to be very short (2) and this looks to be the trend of the data in Fig. 2.

Fig. 3 and 4 are two fracture surfaces obtained at the SEM. Fig. 3 shows the transition zone of the regions of the fatigue crack at R=0.05 and frequency of 10 Hz (on the right), and the crack with 10 sec. dwell at maximum load. In both regions, fatigue striations are visible in some grains. The rupture mode is totally transgranular in the 10Hz region. In the dwell crack there is an increase in surface roughness and a few intergranular cracks appear accompanied by some secondary cracking in between the fatigue striations. With 10 sec. dwell, although the predominant failure mechanism is still of transgranular type, there are contributions of intergranular failure (mixed mode).

Fig. 4 is a intergranular fracture obtained in a specimen tested at R=0.8 with 300 sec. dwell at maximum load. Large secondary cracks are visible in the contours of the grains. Note the oxidation products in the grain boundaries, which are absent in Fig. 3. At R=0.8 and 300 sec. dwell at maximum load oxidation effects are enhanced due to the combined actions of a high mean load and prolonged thermal exposure, which leads to a weakening of the grain boundaries. There is little evidence of creep deformation processes in Fig. 4, suggesting that oxidation effects are predominant over creep fracture even for this high value of stress ratio. Also crack closure is very minor since the amount of rubbing between crack surfaces is negligible (Fig. 4).

CONCLUSIONS

From the analysis of results obtained in IN718 at 600°C and for R=0.05, time dependent fatigue crack propagation behaviour was obtained for frequencies below 0.01 Hz corresponding to dwell times at maximum load above 100 seconds. Cycle dependent crack propagation behaviour was detected for frequencies above 1Hz. The fatigue crack growth rate (FCGR), in the cycle dependent regime was found not to depend on the loading frequency. For the three stress ratio values tested (0.05, 0.5 and 0.8), in the time dependent regime, FCGR, was inversely proportional to the frequency. Increases in the value of R from 0.05 to 0.5 and 0.8 led to an increase in the FCGR, which was, for the same dwell time, higher in the time dependent regime as compared with the cycle dependent one. Oxidation assisted cracking seems to be the predominant failure mechanisms in the intergranular time dependent regime.

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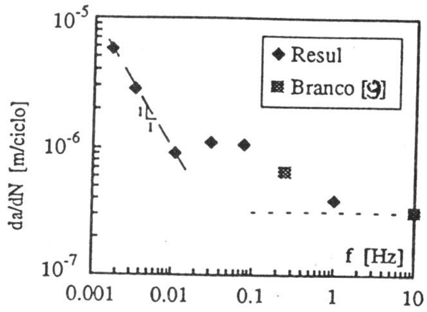


Fig. 1- da/dN against frequency for R=0.05.ΔK=40MPa√m. IN718. 600°C.

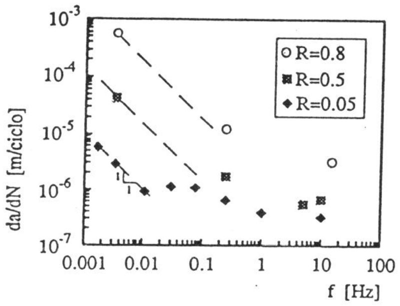
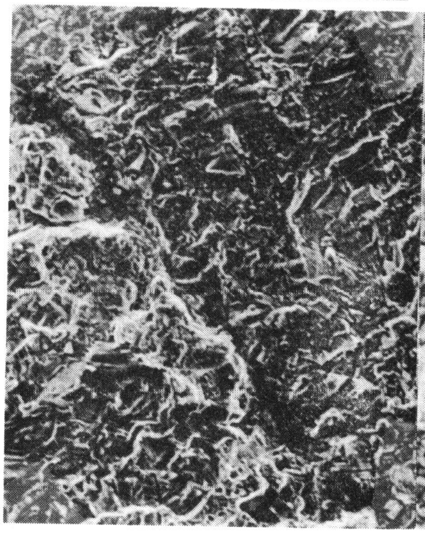


Fig. 2- da/dN against frequency for R=0.05,0.5 and 0.8. IN718. 600°C.



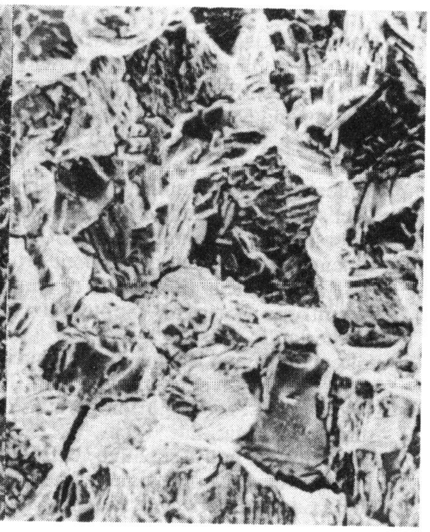


Fig. 3- Transition between f=10Hz crack and t_D=10 sec. 500x. IN718. 600°C.

Fig. 4- Fracture surface, R=0.8, t_D=300 sec.800x. IN718. 600°C.