MECHANISM MAP OF U720LI SUPERALLOY AT 650°C

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Effects of frequency on fatigue crack growth behaviour at elevated temperature have been studied in a pre-alloyed powder material U720Li at 650°C at frequencies ranging from 0.001 to 5 Hz. Tests were carried out under constant ΔK control with load ratio and temperature being held constant. A mechanism map was constructed where predominantly time dependent, mixed and cycle dependent crack growth behaviour were identified. Fully time dependent crack growth data were generated under static loads. The results were verified by SEM analysis. Data for other nickel based alloys from various sources in the literature compare well with that of U720Li alloy at a given stress intensity and temperature in the mixed regime. An analysis was developed to rationalise the observed effects of frequency on crack growth rates.

INTRODUCTION

The demands for improved aero engine efficiency and performance have resulted in the continued development of higher strength nickel based superalloys using advanced powder metallurgy techniques (1). Udimet 720 with low interstitials (U720Li) is such an alloy characteristic of the more recent products for gas turbine disc applications (2). Powder metallurgy techniques offer a means of producing highly alloyed compositions with a homogeneous microstructure, although the heat treatment route adopted may induce a high level of residual stresses which warrants critical assessment of crack growth behaviour under the influence of operational parameters.

Frequency has been identified as one of the key parameters governing the rate and micromechanism of crack growth at elevated temperature. The effect of cyclic frequency on crack growth behaviour has been the subject of many researches (3-10). The existence of cycle, time and mixed time/cycle dependent behaviour in frequency domain was first noted by Solomon (3) who composed what was described as a mechanism map for an iron

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based superalloy A286. Since then extensive research has been carried out in Inconel 718 for which mechanism maps are available (6). Effects of frequency on crack growth behaviour have also been studied in nickel based alloys including AP1 (5), René 95 (7) and Waspaloy (8-10), although few attempts have been made to generate the complete mechanism map. In general the change in crack growth rates reflects the characteristics of the material for a given testing condition and the transition from one regime to another is generally dictated by temperature, load as well as loading waveform.

This paper presents some preliminary results on the effect of frequency on crack growth behaviour of U720Li superalloy, as part of an ongoing collaborative research with Rolls Royce and the DERA.

EXPERIMENTAL DETAILS

U720Li alloy is a HIP and extruded powder material tested in the form of compact tension specimens. The chemical composition (wt%) was: 0.025 C, 0.2 Si, 0.15 Mn, 0.05 P, 0.05 S, 2.5 Al, 0.015 B, 15 Co, 16 Cr, 0.1 Cu, 0.5 Fe, 3 Mo, 5 Ti, 1.25 W and 0.03 Zr. The heat treatment route was: 4 hours at 1080°C to 1110°C, oil quench to 650°C; then 24 hours at 650°C and air-cooling; followed by 16 hours at 760°C and air cool to room temperature (2).

Fatigue tests at elevated temperature were conducted on a computer controlled Instron servo-hydraulic machine equipped with an electric resistance furnace. The temperature was controlled at 650°C±5°C. Crack lengths were monitored using the d.c. potential drop method and a pulsed d.c. current of 10 A was used to ensure data acquisition at peak loads. All specimens were precracked using a decreasing ΔK scheme (ASTM E647-95) at room temperature. Tests were carried out under constant ΔK control at a ΔK value of 30 $MPa\sqrt{m}$ and $R = 0.1$. Frequencies ranging from 0.001 to 5 Hz were selected. At each frequency a crack growth increment of approximately 1 mm was allowed and the crack length was recorded as a function of the number of cycles. Crack growth rates were then derived from a linear regression.

Room temperature tests were conducted to obtain the baseline fatigue crack growth rate data. A static test was also carried out at 650°C to obtain fully time dependent crack growth. Full experimental details are to be reported elsewhere (11).

RESULTS AND DISCUSSION

The adoption of a constant K approach was to obtain reliable crack growth rate data in the mid-power law region with a minimum number of specimens. The crack lengths were evaluated after tests and the discrepancies between the calibrated and measured crack length were found to be within 5% in all cases. Fig. 1 shows some typical crack growth data at three different frequencies where an excellent linearity was obtained in each case.

Crack growth at room temperature was taken as the lower bound representing the fully cycle dependent crack growth. A linear regression gives:

$$da / dN = 2.92 \times 10^{-13} \Delta K^{4} \quad \text{(m/cycle)} \tag{1}$$

This is considered reasonable due to the lack of crack growth data at high frequencies and the asymptotic nature of crack growth in such conditions (6). In general, the loading frequencies in this region were sufficiently high to outpace environmental damage such as oxidation, resulting in a transgranular type of crack growth.

Crack growth rates under static loads increased drastically (by approximately one order) compared with those under cyclic loads at the lowest frequency (0.001 Hz). Fractographic study shows entirely intergranular fracture mode with some scattered voids suggesting fracture/pullout of carbo-nitride inclusions. The crack growth rate may be expressed as:

$$da / dt = 1.44 \times 10^{-5} K_{max}^{3.3} \quad \text{(mm/hour)} \tag{2}$$

Virtually all fatigue data between test frequencies from 0.001 to 5 Hz at 650°C seem to fall in the mixed time/cycle dependent regime with a linear slope of -0.38 in the log-log plot of da/dN versus frequency, as shown in Fig. 2. SEM work revealed progressively increased amount of intergranular cracking as the frequency was reduced. Predominantly intergranular fracture surfaces were observed at low frequencies while predominantly transgranular features were found at high frequencies (photographs are omitted due to the limitation of space). The damage is believed to occur by an environmentally enhanced fatigue process (6), which appears to be consistent with the recent vacuum results on the same material (12). Equation (3) is proposed to address the mixed time/cycle dependent behaviour:

$$da / dN = 2.92 \times 10^{-13} \left(\frac{f_{mc}}{f} \right)^{0.38} \Delta K^{4} \quad \text{(m/cycle)} \tag{3}$$

Where f_{mc} is the transition frequency from cycle to mixed regime. And

$$f_{mc} = (2.55 \times 10^{7} \Delta K^{-4})^{0.92} \quad \text{(Hz)} \tag{4}$$

It is interesting to note that the slopes in the da/dN versus frequency plots for various superalloys compare well, as shown in Fig. 3, being traditional wrought alloys such as In718 (6) and Waspaloy (10) or powder materials U720Li and René 95 (7). This seems to suggest that the change of crack growth rates in the mixed regime is not sensitive to metallurgical details.

Fig. 4 shows a comparison of the experimental and predicted (using Equation (3)) results in the mixed regime. Good agreement has been achieved in the mid-power law region at frequencies from 0.0033 to 1 Hz. Full analysis is to be detailed elsewhere (11).

CONCLUSIONS

A mechanism map of U720Li alloy was generated at 650°C using a balanced triangular waveform. Mixed time/cycle dependent crack growth was found to be the dominant mcromechanism for crack growth at the frequencies studied.

A simple model is proposed to rationalise the effect of frequency in the mixed regime. Equations are also provided to describe the cycle and time dependent crack growth of U720Li alloy.

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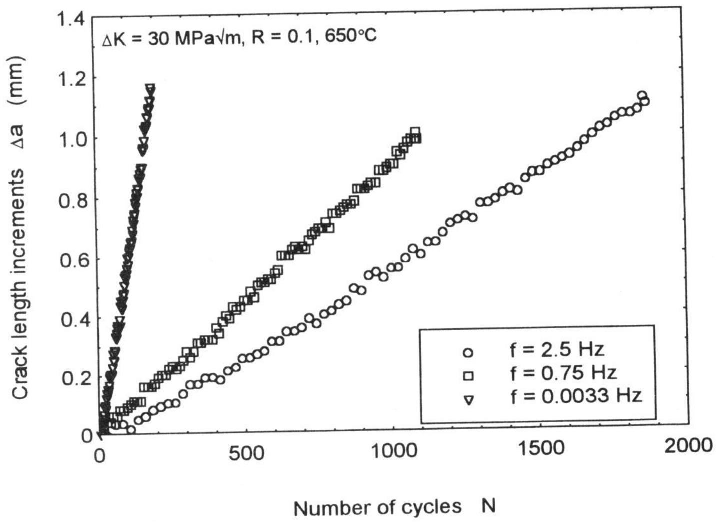

Figure 1. Crack growth behaviour under constant K control at selected frequencies

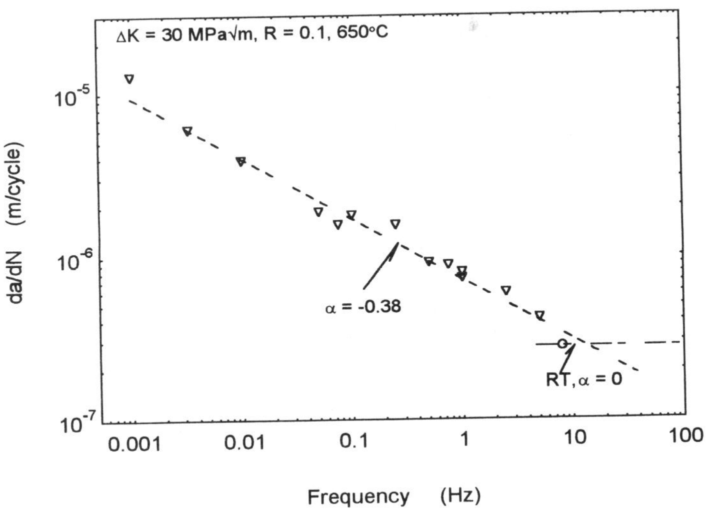

Figure 2. Crack growth rates of U720Li as a function of frequency at 650°C.

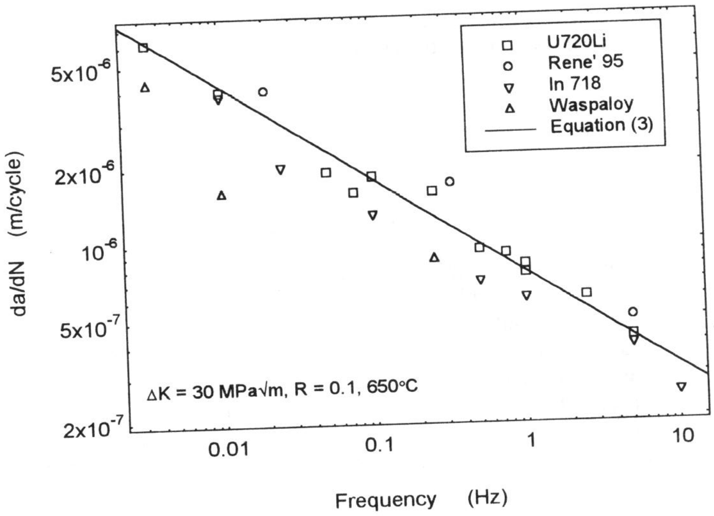

Figure 3. Crack growth in the mixed time/cycle dependent regime, results from various sources.

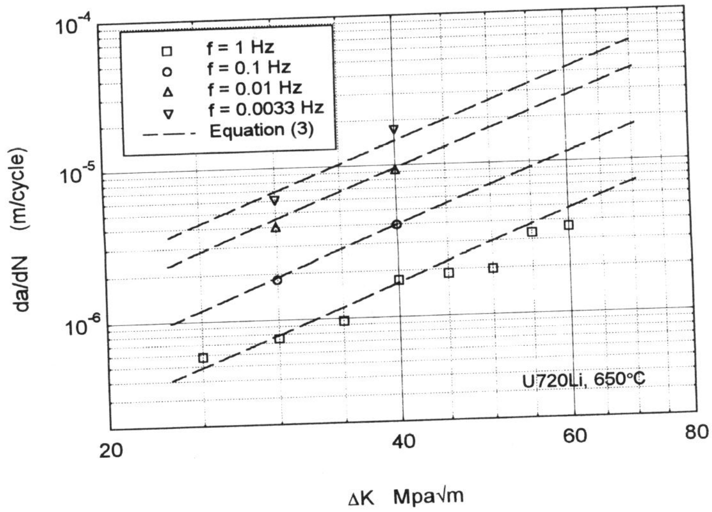

Figure 4. Comparison of experimental and predicted results at selected frequencies.