MICROMECHANISMS OF SHORT FATIGUE CRACK GROWTH IN NICKEL BASE ALLOY SINGLE CRYSTALS

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Long and short crack tests have been carried out in single crystal and polycrystalline Udimet 720 (U720). Single crystal crack growth rates are higher than those in the polycrystalline material because of the absence of grain boundaries to halt the crack. Single crystal behaviour appears to model the early stages of short crack behaviour of polycrystalline U720. In single crystals the presence of an initial defect results in Stage II type crack propagation rather than the highly faceted Stage I crack growth mechanism observed in initiation studies from smooth specimens. A Paris exponent, m-value of 2 is found for the highly crystallographic crack growth in single crystals.

INTRODUCTION

Attention has focussed on the fatigue and deformation behaviour of single crystal nickel-based superalloys, due to their use as blade materials in aeroengine gas turbines. In the single crystal form, the reduction of grain boundary sliding and intergranular cavitation results in a significant improvement in creep strength over the polycrystalline material. However a blade will also be subjected to fatigue loading over a range of temperatures within its service life, and thus the highly faceted fatigue crack growth mode has been of interest to previous researchers such as Crompton and Martin (1), and Howland and Brown (2).

It is generally accepted that *short cracks* (those which are of the same order as the grain size) propagate faster than long cracks in conventional test-pieces at the same nominal ΔK ranges, and that much of the fatigue life of turbine discs is taken up by the growth of these small defects (J.M. Kendall, J.E. King, P. Woollin and J.F. Knott (3), M.A. Hicks and C.W. Brown (4), and C.W. Brown, J.E. King and M.A. Hicks (5)). The understanding of short crack behaviour is complicated by the high level of scatter characteristic of growth rate data. It seems possible that crack growth in single crystals (where the whole specimen can be thought of as one grain) may offer some insights into short crack propagation behaviour in a system where cracks can be more easily observed. Fatigue crack growth in single crystals of U720 and in the polycrystalline form of the same alloy has been compared in this study.

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EXPERIMENTAL

Single crystal specimen preparation. A modified U720 alloy with reduced levels of grain boundary pinnning elements (C, B and Zr) was used in the single crystal production. Single crystals were produced by RAE Pyestock in the form of rods, 15mm in diameter, 130mm in length and with a drawing direction of <001>. Bend bar specimens were machined from the single crystals as shown in Figure 1, and angled slits employed to promote crack propagation down a specific {111} slip-plane. Standard polycrystalline U720 material was used to generate comparative data.

Heat treatments and microstructure. The polycrystalline U720 had a necklace grain structure (as seen in Figure 2) with a bimodal γ' distribution. To reduce the dendritic segregation the single crystals were soaked for 16 hrs at 1200°C. To simulate the bimodal γ' distribution in the polycrystalline material, the single crystals were then heat-treated at 1100°C for 4hrs, to form coarse γ', and cooled at 2-5°C per minute. By controlling the cooling rate a suitable distribution of fine γ' was obtained.

Mechanical testing and crack growth monitoring. The fatigue crack propagation tests were carried out on 50kN Mayes and 60kN Mand servohydraulic machines at an R-ratio of 0.1. Long and short crack growth tests were performed on the polycrystalline U720 bend bar specimens. The long crack specimens were tested under computer-controlled load shedding to reach threshold, and constant load growth to obtain the higher growth rate regime of the da/dN versus ΔK curve. Crack growth was monitored by the d.c. potential drop method. The polycrystalline short crack tests were carried out on smooth, polished bend bars, cycling was stopped every 10,000 cycles and acetate replicas taken of the specimen surface; from these replicas a record of a versus N was produced and the short crack growth rates over the relevant ΔK-range obtained. In the single crystal long crack case both d.c. potential drop and replication of the crack sides were used to monitor crack length in constant load and manual load shedding regimes. The single crystal short crack specimens were tested in the same manner as the polycrystalline ones. Fractography of the fracture surfaces was undertaken using a Camscan S4 SEM operated at 30kV.

RESULTS

The polycrystalline crack growth data are shown in Figure 3. The long crack growth data show a threshold ΔK of 10MPa√m. Facets were observed in this low growth rate regime (Figure 4), where the stress intensity was low enough for slip to be contained within individual grains at the crack tip, and sufficiently planar slip developed, such that the crack propagated down {111} slip planes. Such Stage I crack growth behaviour has also been seen in short crack initiation studies in similar materials [J.M. Kendall (6)]. The polycrystalline short crack growth behaviour can be seen to be in agreement with that observed by others (3,4,5) as the short crack growth rates are higher than the long crack growth rates at the same nominal ΔK ranges, and growth of short cracks occurs below the threshold value obtained for the long cracks. The sharp minimum in crack growth rate observed for one set of short crack data was related to crack arrest at a grain boundary.

The single crystal short and long crack results can also be seen in Figure 3. Previous workers had found highly faceted fatigue crack growth behaviour in nickel base single crystals (1,2), but in this work, crack propagation from the angled slits (intended to promote slip down a particular {111} plane) occurred in a non-crystallographic manner perpendicular to the maximum applied opening stress. A manual load-shedding operation was carried out, but no clearly angled faceted crack growth occurred, even at the lower ΔK ranges. The fracture surfaces of the specimens showed a little faceting down the sides of the specimen (plane stress) but fracture surfaces typical of those seen at high ΔK-ranges in polycrystalline specimens were observed throughout the rest of the specimen (Figures 5 and 6). An unnotched single crystal specimen was also tested and crack growth monitored by the replication technique. "Short" cracks developed along {111} type slip planes (Figure 7) and the specimen exhibited a highly faceted mode of crack growth. The non-crystallographic (long crack) single crystal data merge with the polycrystalline short and long crack growth data (Figure 3). The faceted single crystal crack growth (short crack data) shows the highest propagation rates (for the same nominal ΔK range) of all the tests. The scatter for the single crystal short crack data is small and a low Paris exponent, m-value, of 2 is seen in common with average lines through maximum growth rate points for polycrystalline short crack data, a much lower m-value than those observed for faceted polycrystalline long crack growth.

DISCUSSION

Polycrystalline short crack behaviour can be related to the schematic diagram shown in Figure 8. The scatter typically observed in short crack data is often due to grain boundary arrest. As a single crystal contains no grain boundaries the higher growth rates observed for single crystal crack propagation can be explained. Non-crystallographic (Stage II) single crystal crack growth, perpendicular to the tensile axis, occurs at similar growth rates to the polycrystalline alloy in the later stages of short crack growth, where structure-insensitive growth is begining to dominate and the long and short crack growth regimes merge. The anomalous non-crystallographic nature of the crack growth [c.f. (1,2)] appears to be due to the introduction of a notch. Stage I faceted behaviour is seen when cracks are initiated in slip-bands at a smooth surface and the resultant cyclic softening and hence increased planarity of slip give rise to crack propagation down {111} slip-planes. The results show this Stage I crack propagation gives rise to an m-value of 2. If an irreversible slip mechanism of crack advance is assumed, then on opening, the crack extends a distance x_1 along the slip-band by emission of dislocations from the crack-tip. In the unloading part of the cycle, the slip-band now only extends a distance x_2, so:

$$da/dN = x_1 - x_2 \tag{1}$$

and $(x_1 - x_2)$ is the sliding (mode II) CTOD range experienced by the crack-tip.

Since:

$$\delta \; \alpha \; K^2/\sigma_y E \tag{2}$$

it can readily be seen that:

$$da/dN = C\Delta K^2 \tag{3}$$

where C is a constant. The results were analysed in mode I (ΔK_I), but ΔK_{II} is likely to be controlling the irreversible slip mechanism. In this particular situation of constant crack orientation ΔK_{II} is proportional to ΔK_I and so the above reasoning still holds.

The single crystal short crack growth rates are higher than those in the same material in polycrystalline form when a faceted, crystallographic growth mechanism is operative in both cases. This can be interpreted as an extreme grain size effect.

SUMMARY

Single crystal crack growth rates are higher than polycrystalline crack growth rates due to the absence of grain boundaries which slow down and deflect the crack. The single crystal long crack (notched) specimens exhibited Stage II, non-crystallographic crack growth perpendicular to the tensile axis at rates which merged with maximum growth rate polycrystalline short crack data. The single crystal short crack tests produced highly faceted fracture surfaces and the highest crack growth rates, with an m-value of 2, in common with average lines through maximum growth rate points for polycrystalline short crack data. The m-values observed for faceted polycrystalline long crack growth (where closure effects are paramount) were much higher. The Stage I irreversible slip mechanism can be related to a CTOD dependence in mode II, and ΔK_{II} is directly proportional to ΔK_I which predicts an m-value of 2. The short crack behaviour of single crystals appears to model the short crack behaviour of polycrystalline material within individual grains as suggested by (4).

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following for research funding: the SERC and RAE Pyestock (PASR); British Gas and the Fellowship of Engineering (JEK); Rolls Royce for provision of polycrystalline U720 specimens and supply of modified U720; RAE Pyestock for casting and orienting the single crystals. Thanks are due to Professor D. Hull, F.R.S., F. Eng for the provision of research facilities.

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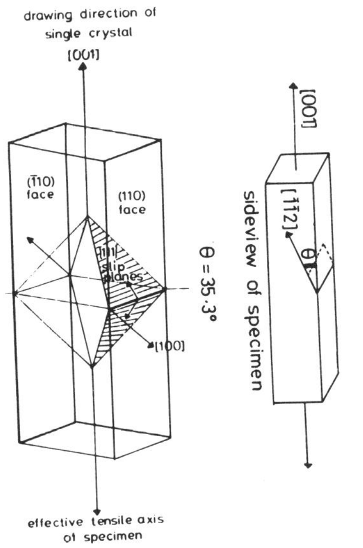

Fig.1 Orientation of single crystal specimens

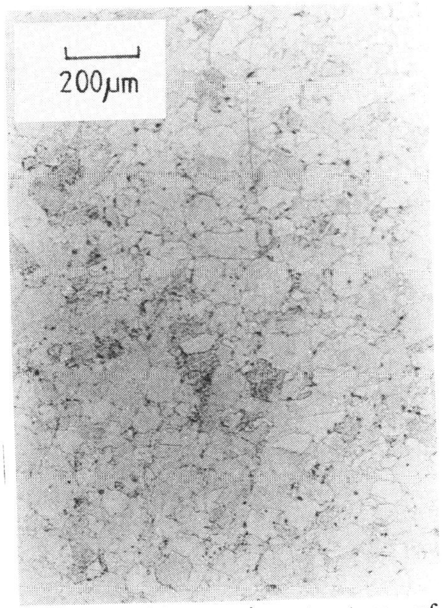

Fig.2 Necklace microstructure of polycrystalline U720

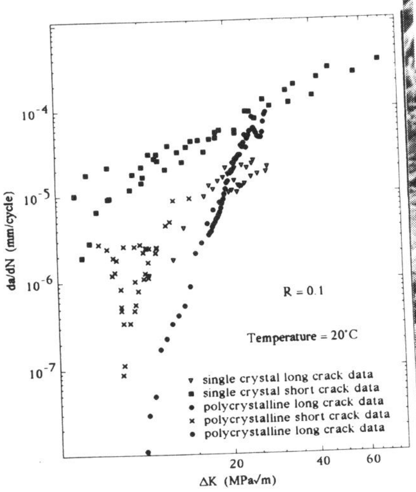

Fig.3 da/dN versus ΔK for long and short cracks in U720

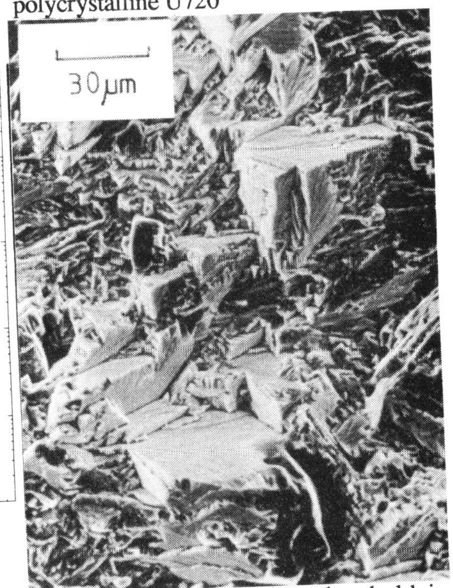

Fig.4 Facets observed at threshold in polycrystalline U720

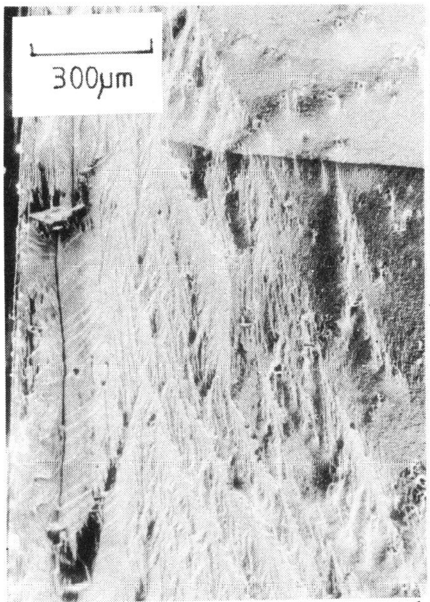

Fig.5 Side facets formed in single crystal long crack case

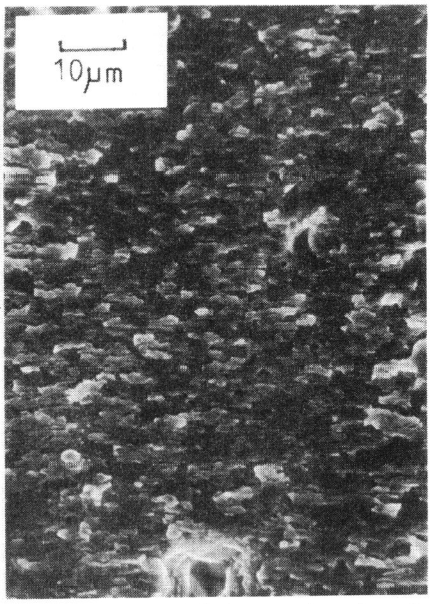

Fig.6 Non-faceted fatigue surface found in bulk of single crystal long crack case

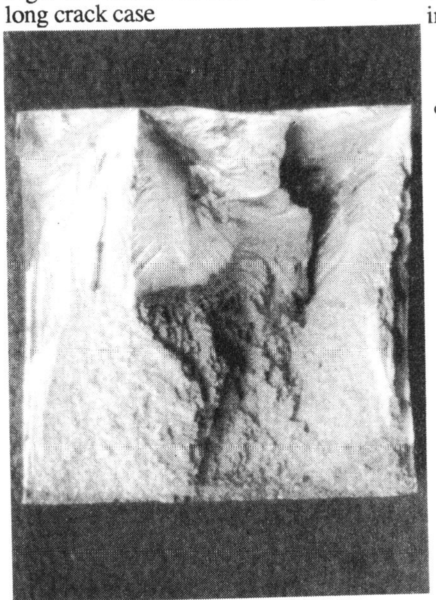

Fig.7 Crack propagation down {111} planes in single crystal short crack case

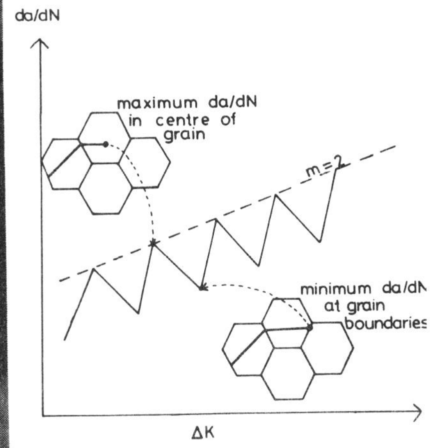

Fig.8 Schematic diagram showing typical scatter of polycrystalline short crack tests