THE EFFECTS OF MICROSTRUCTURE, TEMPERATURE AND R-RATIO ON FATIGUE CRACK PROPAGATION AND THRESHOLD BEHAVIOUR IN TWO Ni-BASE ALLOYS

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ABSTRACT

Fatigue crack propagation and threshold data for two Ni-base alloys, Astroloy and Nimonic 901, are reported. At room temperature the effect which altering the load ratio (R-ratio) has on fatigue behaviour is strongly dependent on grain size. In the coarse grained microstructures crack growth rates increase and threshold values decrease markedly as R rises from 0.1 to 0.8, whereas only small changes in behaviour occur in fine grained material. In Astroloy, when strength level and γ grain size are kept constant, there is very little effect of processing route and γ' distribution on room temperature threshold and crack propagation results. The dominant microstructural effect on this type of fatigue behaviour is the matrix (γ) grain size itself. Room temperature crack propagation in the near-threshold regime occurs in a transgranular faceted manner in both alloys, and comparison of the behaviour of the two materials suggests that surface roughness is a particularly important parameter in controlling crack growth rates.

Threshold values for the fine grained Astroloy are relatively insensitive to temperature in the range 20^{o}C to 600^{o}C whereas they fall with increasing temperature in coarse grained material. These results are also interpreted in terms of surface roughness effects, since there is no major change in crack propagation mechanism over the temperature range investigated.

KEYWORDS

Fatigue crack propagation; thresholds; microstructure; R-ratio; temperature; Astroloy; Nimonic 901.

INTRODUCTION

In recent years a considerable amount of effort has been put into the study of fatigue thresholds and near-threshold crack propagation in metals (Ritchie, 1979; Beevers, 1980). This has been due, to a large extent, to the fact that here is a fatigue regime in which relatively small metallurgical changes can bring about large increases in threshold values and dramatic reductions in crack propagation rates.

During this period a number of different theories have been advanced (Ritchie, 1979; Purushothaman and Tien, 1979; Davidson, 1981; Weiss and Lal, 1974; Walker and Beevers, 1979; Minakawa and McEvily, 1981; Ritchie, Suresh and Moss, 1980) to explain the observations made, but now a clearer picture seems to be emerging, in which much of the data concerning the effects of altering such parameters as load ratio (R-ratio), microstructure, orientation and environment can be simply explained in terms of fracture surface morphology (Walker and Beevers, 1979; Suresh and Ritchie, 1982; Mayes and Baker, 1981). This approach, which considers the way in which rough fracture surfaces or oxide debris can prop open the crack and thus affect the actual range of stress intensity experienced at the crack tip, is termed roughness-induced or oxide-induced closure (Suresh and Ritchie, 1982).

In this paper the effects of a wide range of experimental and micro-structural variables, on crack propagation in two nickel-base alloys, Astroloy and Nimonic 901 (N901), are presented and interpreted in terms of closure phenomena.

EXPERIMENTAL

Room temperature (20^{o}C) threshold tests were carried out at either 40 or 50 Hz on single edge notched specimens loaded in three point bend, in a laboratory air environment. Crack length was monitored continuously using a DC potential drop technique. A load shedding procedure was applied to obtain the threshold stress intensity value. Fuller details of these experimental techniques are reported elsewhere (Hicks and King, 1983; King, 1982; Venables, Hicks and King, 1984), as is the procedure followed for the elevated temperature tests (Hicks and King, 1983).

Closure measurements on N901 were made using a clip gauge mounted over the mouth of the crack (Venables, Hicks and King, 1984).

MATERIALS

Astroloy is a powder formed Ni-base alloy, of nominal composition (wt.%) 15.4Cr, 17.0Co, 5.2Mo, 4.0Al, 3.4Ti, 0.03C, 0.024B, 0.03Zr, balance Ni. A number of different microstructures were obtained by changing the hipping (hot isostatic pressing), forging and heat-treatment conditions, as described in Table 1, which also gives grain sizes and mechanical property data. Due to the large Ti and Al content, Astroloy contains a high volume fraction of γ'. In material solution treated above 1140^{o}C all the γ' goes back into solution and is present in the final microstructure as spherical particles, whereas partial solution treatment below this temperature results in the presence of coarse γ' (at grain boundaries, and in some cases as cuboidal particles in the matrix) in addition to the fine spherical particles in the fully heat-treated condition (King, 1982).

N901, of nominal composition (wt.%) 15Cr, 6Mo, 3Ti, 0.3Al, 0.1B, 0.04C, 40Ni + Co, balance Fe, is a conventionally cast and wrought alloy. In both conditions examined (Table 1) the γ' is present as fine, spherical particles, at a much lower volume fraction than in Astroloy (Venables, Hicks and King, 1984).

TABLE 1 Production Routes and Mechanical Properties

Astroloy

Condition	HIP temp. ^{o}C	Forging temp. ^{o}C	Solution treatment temp. ^{o}C	γ Grain size, μm	Yield stress at 20^{o}C, MPa
1	1100	1080	1104	11-13	1021
2	1200	1080	1104	5 & 35-40	942
3	1100	1080	1150	40-50	954
4	1200	no	1080	40-50	984
5	1200	forging	1130	40-50	1052

N901

Condition	γ Grain size, μm	Yield Stress at 20^{o}C, MPa
A	∿50	900
B	200-400	810

RESULTS

Astroloy

Fig. 1 shows plots of crack propagation rate (da/dN) versus applied stress intensity range (ΔK) at 20^{o}C and R = 0.1, for the different production routes listed in Table 1. By ΔK ∿ 30 MPa$\sqrt{m}$ all the curves have merged; however, at lower stress intensities, in the structure-sensitive regime, large differences in growth rates and threshold values can be seen. The fine grained condition, 1, shows the lowest threshold and fastest growth rates, whilst the results for the conditions with grain sizes in the range 40-50 μm (3, 4 and 5) all fall within the narrow scatter band encompassed by the two tests on condition 5, irrespective of production route. The mixed grain, or necklace microstructure, 2, with an intermediate grain size, shows intermediate crack growth rates.

In Fig. 2 da/dN versus ΔK is plotted for a coarse and a fine grained condition (1 and 3) at different R-ratios. The fine grained structure shows very little R-ratio dependence of threshold and near-threshold crack growth rate, with a roughly constant threshold value of 5.8 MPa$\sqrt{m}$, whereas for the coarse grain size the threshold falls markedly with increasing R-ratio, from 12.3 MPa$\sqrt{m}$ at R = 0.1, to 9.8 MPa$\sqrt{m}$ at R = 0.5 and to 6.7 MPa$\sqrt{m}$ at R = 0.8. Crack propagation data for the coarse grain size at R = 0.8 fall close to the data for the fine grained condition.

Table 2 lists the 20^{o}C, 200^{o}C and 600^{o}C tensile data and fatigue threshold values for Astroloy in coarse (40-50 μm) and fine grained conditions (5-12 μm) (Hicks and King, 1983). In both conditions the threshold values at high R fall with increasing temperature, but, whereas the R-ratio dependence of the coarse grained material is less marked at 600^{o}C than at 20^{o}C, a small R-ratio dependence has appeared for the fine grained material at 600^{o}C.

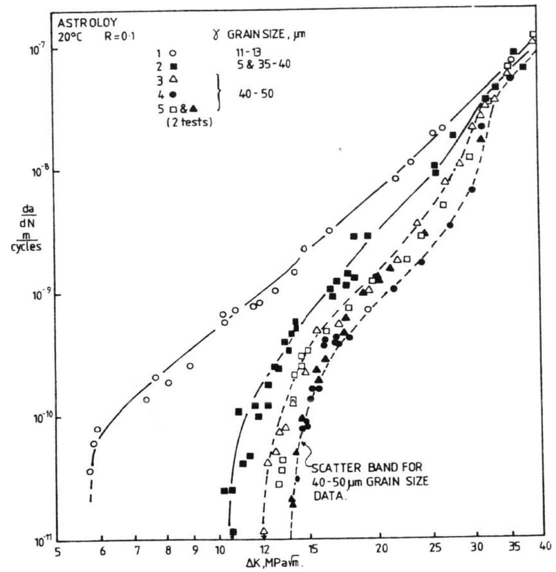

Fig. 1. da/dN vs. ΔK for Astroloy at R = 0.1 and 20°C.

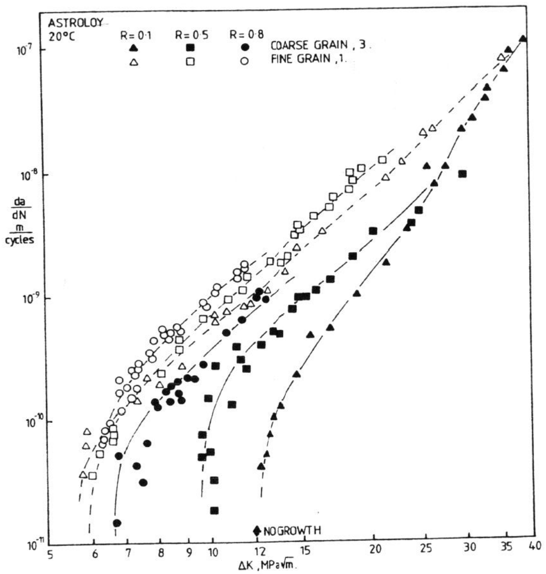

Fig. 2. Effect of R-ratio on da/dN vs. ΔK for Astroloy with coarse and fine grain sizes at 20°C.

Fig. 3. Near-threshold fracture surfaces, Astroloy.

Fine grain size: (a) 20°C (b) 200°C (c) 600°C.
Coarse grain size: (d) 20°C (e) 200°C (f) 600°C.

Table 2 Astroloy. Elevated Temperature Threshold Values

	20°C			200°C	600°C	
Yield Stress, MPa						
Coarse grain (40-50 μm)	954			890	900	
Fine grain (5-12 μm)	1021			930	930	
Threshold Values, MPa$\sqrt{m}$	R=0.1	R=0.5	R=0.8	R=0.1	R=0.1	R=0.5
Coarse grain	12.3	9.8	6.7	8.5	7.1-7.3	5.6
Fine grain	5.8	5.8	5.8	5.9-6.4	6.1	4.9
Young's Modulus, GPa						
	233			212	186	

For all the conditions investigated the fracture path was transgranular in the near-threshold regime. At 20°C angular, crystallographic facets are produced, whilst with increasing temperature the fracture surface gradually becomes flatter, but retains its faceted appearance. This is shown in Fig. 3.

N901

In N901, at 20°C, R-ratio has less effect on threshold than in Astroloy at a similar grain size: in condition A the threshold stress intensity (ΔK_{th}) falls from 7.8 MPa$\sqrt{m}$ at R = 0.1 to 5.1 MPa$\sqrt{m}$ at R = 0.8. In condition B, with a considerably larger grain size than A, the difference is somewhat greater: ΔK_{th} = 10.0 MPa$\sqrt{m}$ at R = 0.1 and ~6 MPa$\sqrt{m}$ at R = 0.8. At both R values ΔK_{th} is higher for condition B than for condition A. These results are plotted in Fig. 4.

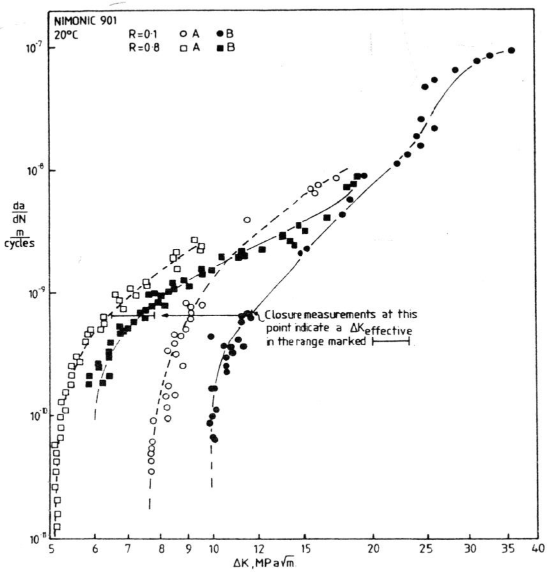

Fig. 4. da/dN vs. ΔK for N901 at R = 0.1, R = 0.8 and 20°C.

In condition B, at R = 0.1, compliance measurements, made with a clip gauge across the crack mouth, indicated that the actual range of stress intensity experienced at the crack tip ($\Delta K_{effective}$) was considerably less than the applied ΔK in the near-threshold regime. Plotted in terms of $\Delta K_{effective}$ the R = 0.1 data fall very close to those obtained at R = 0.8 (Fig. 4).

Crack propagation also occurred in a faceted manner in both conditions and at both R-ratios. However, unlike the coarse grained Astroloy, the near-threshold facets tend to be considerably smaller than the grain size, with a single grain failing along two or more sets of intersecting planes to give a distinctly "serrated" appearance (Fig. 5).

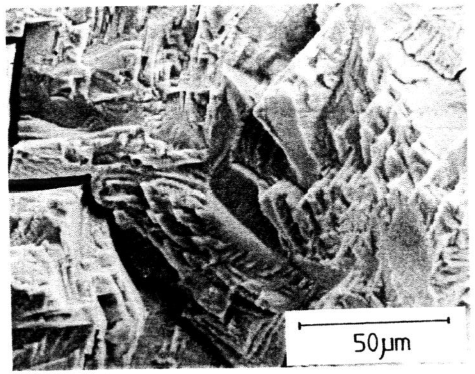

Fig. 5. Near threshold fracture surface in N901, condition B.

DISCUSSION

In Astroloy, at 20°C and R = 0.1 (Fig. 1), grain size is the dominant parameter controlling threshold behaviour. Planar facets, roughly equal in size to the grain size, are formed during structure-sensitive crack growth, producing rough fracture surfaces on which the scale of the roughness is directly related to the grain size. For coarse grain sizes, at low R-ratios, this results in a large surface-roughness induced closure contribution to the measured threshold value, which swamps any smaller effects which might occur due to changes in processing route and precipitate distribution. This also leads to a strong R-ratio dependence of threshold for the coarse grained material but a much reduced one for the fine grained structure, with its flatter fracture morphology, as shown by the experimental results in Fig. 2. At R = 0.8, where surface-roughness induced closure is only likely to have a small effect, the crack propagation behaviour for coarse and fine grained material is quite similar.

Fig. 6 shows fracture surface profiles for fine and coarse grained Astroloy at 20°C and 600°C. As temperature increases the fracture surface of the coarse grained material gradually becomes flatter (see also Fig. 3) and so the contribution of surface roughness induced closure to threshold values at low R is reduced with ΔK_{th} falling from 12.3 MPa$\sqrt{m}$ at 20°C to 8.5 MPa$\sqrt{m}$ at 200°C and 6.1 MPa$\sqrt{m}$ at 600°C. Over the temperature range 20-600°C the roughness of the fracture surfaces produced in the fine grained condition shows little change and similar threshold values are obtained at all three

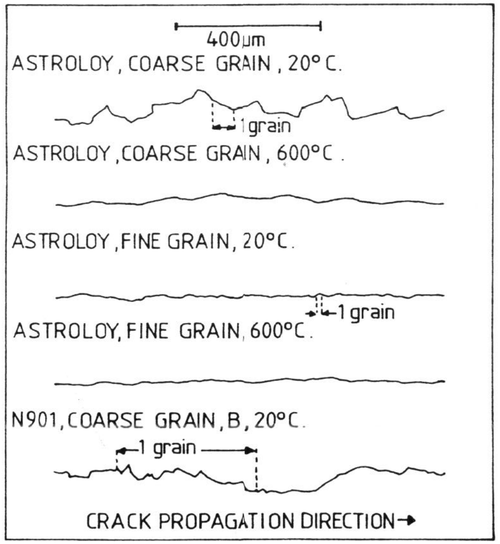

Fig. 6. Fracture surface profiles

temperatures (Table 2). The 16% drop in modulus between 20^{o}C and 600^{o}C could be expected to lead to a similar reduction in an intrinsic material threshold value (Weiss and Lal, 1974) and, if the intrinsic threshold is approximated by the measured value at high R, this is what is seen - from 5.8 to 4.9 MPa$\sqrt{m}$ in fine grained material and 6.7 to 5.6 MPa$\sqrt{m}$ for the coarse grain size. The R-ratio effect observed at 600^{o}C may be associated with oxide induced closure. The presence of oxide on the fracture surfaces at this temperature can be seen in Fig. 3.

It has been assumed that creep effects will be small when considering this type of high frequency testing of creep resistant alloys, and where the drop in yield stress over the temperature range involved is less than 10% (Table 2).

The closure measurements on N901 confirm that, when the closure contribution is removed, there is little effect of R-ratio on threshold values.

The surface roughness induced closure argument also provides an explanation for the small R-ratio dependence of threshold in N901 with a 50 μm grain size when compared with Astroloy at the same grain size; in N901 (condition A) ΔK_{th} falls by 2.7 MPa$\sqrt{m}$ as R increases from 0.1 to 0.8 whereas in Astroloy the difference is 5.3 MPa$\sqrt{m}$. The fracture profile for N901 in Fig. 6 shows that the serrated nature of the near-threshold facets leads to a fracture surface which is not as rough as that resulting from the planar facets produced in Astroloy. Thus, at the same grain size, roughness induced closure effects will be less significant in N901 than in Astroloy. The different nature of the facets in the two materials may be associated with the difference in γ' volume fractions (Venables, Hicks and King, 1981) or the high level of retained work present in N901 (Meetham, 1982).

SUMMARY

In the two Ni-base alloys, Astroloy and N901, a simple surface roughness induced closure argument provides an explanation for microstructural and R-ratio effects on room temperature threshold behaviour, and can also be used to explain temperature effects where there is no change in basic fracture mechanism (such as a transition from transgranular to intergranular crack propagation), and where creep effects do not play an important role.

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