ON THE MECHANISMS OF THRESHOLD BEHAVIOUR

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ABSTRACT

The rate of fatigue crack propagation was determined as a function of the stress intensity amplitude ΔK in a cast nickel base superalloy MarM004 with a R ratio of 0.1, at room temperature on compact tension specimens. This alloy was found to exhibit a threshold behaviour with a departure from Paris' equation for ΔK lower than about 20 MPa$\sqrt{m}$, which corresponds to the onset of extensive crystallographic cracking along {111} planes. The large grain size of this alloy allowed **the determination** the orientation of each grain and that of the crystallographic fracture facets through X-ray diffraction and scanning electron microscopy. It was shown that Paris' law can apply even in the low crack growth rate regime provided the nominal ΔK is replaced by an effective Δk_I relative to the operating facets.

KEYWORDS

Fatigue crack propagation, threshold behaviour, nickel base superalloy, crystallographic cracking, crack tip stress field.

INTRODUCTION

The prediction of total life of components under service conditions has made considerable progress with the development of crack propagation tests using the concepts of linear elastic fracture mechanics (Paris, 1964). Paris found that the crack growth rate, da/dN, can be conveniently expressed as a function of the stress intensity range ΔK which often has the basic form :

$$da/dN = A\,\Delta K^m, \tag{1}$$

where A and m are two constants. Log-log coordinates are generally used which give a linear relation. However a progressive departure from Paris' equation (1) is often observed at low ΔK values, with an increase of the exponent m until the crack growth becomes nearly insignificant for a critical value, the stress intensity threshold ΔK_{th}.

Numerous explanations were proposed for this threshold behaviour but convincing rationales are still lacking. Further such rationales have to account for the importance of metallurgical factors since in the low crack growth range the plastic zone size becomes of the order of the grain size (Hornbogen and Zum Gahr, 1976; Beevers, 1977), the intensity of deformation becomes very low at the crack tip (Sadananda and Shahinian, 1977; Clavel, 1979) and the fracture mechanisms operating in the range of Paris' law are replaced by new mechanisms such as crystallographic cracking or intergranular failure (Beevers, 1977). Therefore it is highly desirable to get experimental information on the behaviour of individual crystals, which can be obtained using a coarse grained material.

Therefore the present work was undertaken along these lines using a cast nickel base superalloy with a centimetric grain size, which exhibits crystallographic cracking in low crack growth rate range at room temperature as many nickel, aluminium and titanium alloys (Beevers, 1977). Preliminary results are given here taking into account the orientation of each individual crystal and which allow to give a tentative rationale of the threshold behaviour in the presence of crystallographic cracking.

EXPERIMENTAL

The alloy studied is a nickel base superalloy MarM004 which contains in wt pct 0.057C, 11.4Cr, 6.15Al, 4.4Mo, 4.4Nb+Ta and 1.5Hf. Its room temperature yield and tensile strength are 760 and 940 MPa respectively.

Compact tension specimens where used with a dimension W = 40 mm and a thickness t = 10 mm. Due to the specific solidification conditions used the individual grains have an average width about 1 cm with their longest dimension more or less perpendicular to the surface of the specimens as illustrated in Fig. 1. Accordingly in the mid-plane of the specimen, i.e. the average crack plane, the grain boundaries are roughly parallel and normal to the specimen surface. Therefore in most cases the crack grows successively into single grains except in the vicinity of grain boundaries.

Fatigue testing was carried out at room temperature on an electrohydraulic machine under laboratory air. A controlled sinusoidal loading cycle was used with a test frequency in the range 20 to 80 Hz and a R ratio (K_{min}/K_{max}) of 0.1. The crack length was monitored continuously throughout the test using an electric potential measurement.

Fracture surfaces of tested specimens were observed on a scanning electron microscope. In addition the crystallographic facets which appear in the low crack growth rate regime were systematically used for determining the orientation of individual grains with a eucentric goniometer stage, according to a procedure explained in the results. This crystallographic orientation was confirmed by the more classical Laue back reflexion X-ray technique.

RESULTS

Precracking of CT specimens was carried out in such a way to end at a crack growth rate about 10^{-8} m per cycle. The range of lower and higher crack growth rates was investigated by decreasing and increasing the ΔK level respectively. The crack propagation data were so determined over four orders of magnitude from 10^{-10} to 10^{-6}m/cycle as illustrated in Fig. 2, using two different specimens. There is some experimental scatter as for fine grained wrought alloys, may be slightly higher as mentioned by Scarlin for other cast alloys (1975). Within this scatter the usual linear behaviour is observed for a stress intensity range 20 to 60 MPa $\sqrt{m}$ corresponding to an exponent m = 4.5 in Eq. (1). The low crack growth rates on the

contrary depart from Eq. (1) for ΔK values lower than 20 MPa $\sqrt{m}$. This behaviour typical of a threshold is similar to that observed in wrought superalloys of much smaller grains sizes 0.05 to 0.1 mm with crystallographic cracking which is rather gradual as also the threshold level about 14 MPa $\sqrt{m}$ (Clavel and Pineau, 1978).

However returning to the scatter just mentioned above it is worth noting that it is comparable to that observed in fine-grained materials except in the range of crack propagation rates 2 10^{-9} to 2 10^{-8} m/cycle. Nevertheless this scatter must be realized not to be due to a specimen to specimen variation but to the fact that for the same specimen the crack growth rate measured after increasing ΔK from the threshold value (say corresponding to rates about a few 10^{-10} m/cycle) is smaller in this range than the rate observed just before reaching the threshold (by decreasing ΔK).

As shown by scanning electron microscopy the fracture surfaces exhibit a fairly brittle aspect with a more or less interdendritic path in the range of validity of Paris' equation as previously noted in similar alloys (Scarlin, 1975). For rates below about 10^{-8} m/cycle quasi-cleavage facets are observed as for wrought superalloys (Clavel and Pineau, 1978), with steps and river lines as shown in Fig. 3, which can reach fairly large dimensions of the order of one millimeter. However it must be emphasized that there is a transition range where the proportion of facets

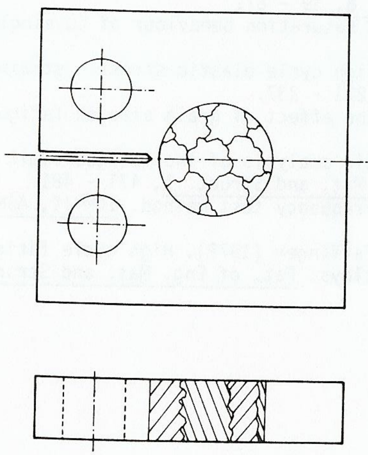

Fig. 1. Schematic drawing of the approximate orientation of grain boundaries with respect to the compact tension specimens.

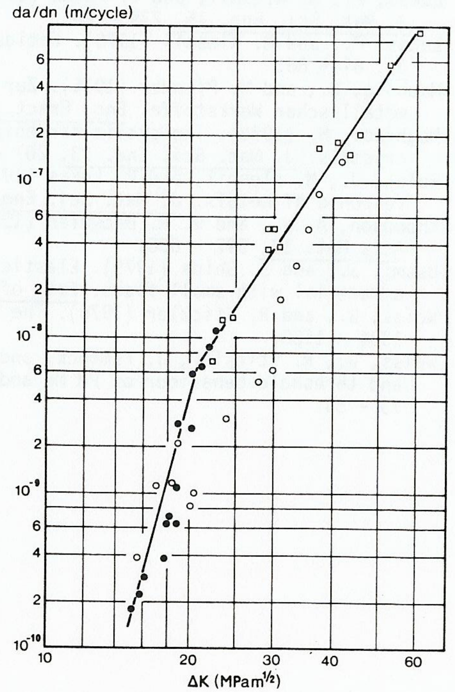

Fig. 2. Variation of the crack growth rate da/dN with the stress intensity amplitude ΔK. Open and closed symbols refer to increasing and decreasing ΔK levels.

increases with decreasing da/dN. The fracture surface becomes quite completely covered with crystallographic facets when the growth rate is decreased below $2\ 10^{-9}$ m/cycle. However when now ΔK is reincreased the fracture remains almost completely crystallographic for higher rates, up to $2\ 10^{-8}$ m/cycle.

In each grain there is not a single facet but always several types of facets, though their size can be fairly large. In some areas they are often three or even four types of crystallographic facets. Such an area is illustrated in Fig. 3. Using the goniometer stage of the scanning electron microscope, every crystallographic facet can be put edge on. Therefore one obtains the direction orthogonal to the slip plane and one can construct a stereographic projection for the grain considered in a reference system of the CT specimen. With three facets the orientation of each grain can be unambiguously determined. This procedure was systematically applied to the grains which contain facets. An angle of 70 degrees was always found between the facets of one grain which is consistent with {111} planes (It is worth noting the appearance of a Thompson's tetrahedron given by the interaction of three facets visible in Fig. 3 with the fourth one which is just delimited by its trace). This was confirmed by the Laue X-ray diffraction technique, and grain orientations obtained by both techniques were found to be in good agreement.

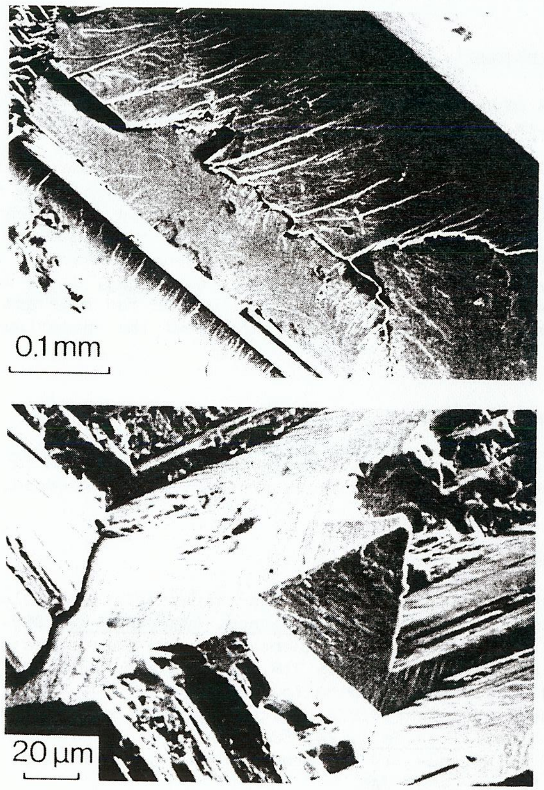

Fig. 3. (top) Crystallographic facet at low crack rates. Note the quasi-cleavage features such as the river lines. (bottom) representative area used for crystallographic orientation.

DISCUSSION

The most striking feature of the threshold behaviour and also the less understood is the departure from Paris' equation. The present results can be used to get some insight with respect to this fundamental problem in the case of a threshold behaviour associated with the occurrence of crystallographic cracking.

As a matter of fact the onset of crystallographic cracking does correspond to a local deviation of the fatigue crack from its original plane. Accordingly the stress intensity factor K_I calculated for a plane crack in the opening mode is no longer relevant and must be replaced by an effective stress intensity factor. Unfortunately the relevant stress intensity factors for a branch crack are not available. However an approximate solution can be obtained for a short length of deviated crack as compared to the original crack, using the elastic stress field of the original crack (Lawn and Wilshaw, 1975). More complete calculations for branch cracks have shown that this approximation was valid for short deviated lengths (Vitek, 1977).

Therefore we applied this method in order to estimate the effective stress intensity k_I normal to the facets. But since pure nickel and nickel base alloys are somewhat anisotropic, we further assumed that a good approximation can be obtained from isotropic elasticity (using a Poisson's ratio ν of 0.3). Assuming that the original crack grows in a direction x_1 in a plane normal to x_2 and with x_3 orthogonal to the surface, the elastic stress tensor σ_{ij} near the crack tip is given by the classical equations :

$$\sigma_{ij} = K_I/(2\pi r)^{1/2}\ f_{ij}(\theta), \tag{2}$$

where r, θ are polar coordinates in the x_1x_2 plane and f_{ij} are functions of θ with $f_{23} = f_{31} = 0$ and $f_{33} = \nu(f_{11}+f_{22})$ under plane strain conditions.

The components of the stress tensor σ_{ij} applied on a facet the normal of which has director cosines n_i, are given by $\sum_j \sigma_{ij}\ n_j$ and σ_n the stress normal to the facet is :

$$\sigma_n = \sum_{ij} \sigma_{ij}\ n_i\ n_j, \tag{3}$$

On the other hand the effective stress intensity factor k_I corresponding to an opening mode normal to the facet is such as :

$$\sigma_n = k_I/(2\pi r)^{1/2}, \tag{4}$$

After substitution of the proper terms in equations (2) to (4), one may write the effective stress intensity amplitude normal to the facets Δk_I as a function of the nominal stress intensity amplitude ΔK_I :

$$\Delta k_I = \Delta K_I\ f_n(\theta) \tag{5}$$

$$\text{with} \quad f_n(\theta) = \sum_{ij} f_{ij}(\theta)\ n_i\ n_j$$

The computation can be carried out numerically however an analytical expression can be obtained for $f_n(\theta)$ by expressing θ as a function of the first two direction cosines n_1 and n_2, which is :

$$r_n = \left[2\nu+(n_1^2+n_2^2)\ (1/2-2\nu+n_2(n_1^2+n_2^2)^{-1/2}/2)\right] \cdot 1/2 \left[1+n_2\cdot(n_1^2+n_2^2)^{-1/2}\right] \quad (6)$$

This calculation was applied to our crack propagation data of Fig. 2. As for the grains encountered more than one facet were present, an average value of f_n was then used which was a quadratic mean based on an energy rate G averaging. As illustrated in Fig. 4, the plot of crack growth rate data corresponding to crystallographic cracking as a function of the effective stress intensity Δk_I instead of ΔK levels off the "threshold behaviour" i.e. the sigmoidal shape of the crack propagation curve. Further within the experimental accuracy, Paris' equation with an exponent of 4.5 defined for growth rates above 10^{-8} m/cycle applies now down to 10^{-10} m/cycle.

In addition it must be remembered that an anomalous scatter was observed in the range of crack growth rates 2 10^{-9} to 2 10^{-8} m/cycle between values obtained at decreasing ΔK and those at increasing ΔK. This scatter is associated with the fact

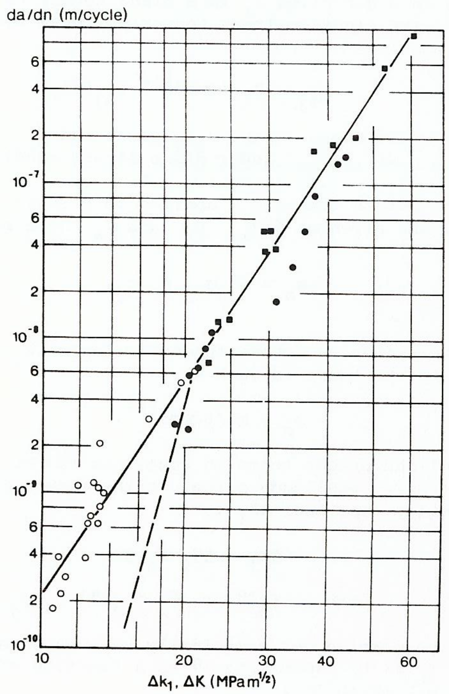

Fig. 4. Variation of the crack growth rate with the effective stress intensity amplitude (solid curve): the applied ΔK in absence of crystallographic cracking (closed symbols) and the effective Δk_I when it occurs (open symbols). The dotted curve refer to the uncorrected initial curve.

that facets remain to higher values of crack growth rates with increasing ΔK, and it can be checked that this scatter disappear when results are plotted as a function of the effective stress intensity amplitude Δk_I.

Thus the present results provide a tentative rationale for the departure from Paris' equation which is characteristic of the threshold behaviour, when the fracture mechanism is crystallographic. This points to purely mechanical effects though they are due to metallurgical factors. In this sense the effective stress intensity factor used here has some similarity with that obtained from application of the crack closure concept, which was recently shown to account for the threshold of some steels (Ohta and coworkers, 1978). In both cases within the accuracy of the data, the low crack growth rates were shown to be consistent as the higher rates with a single Paris' equation. However it must be noted that both effects may act in specific cases. Further the mechanism proposed in our work accounts for the threshold behaviour in presence of crystallographic cracking but this cannot provide of course any reason for the occurrence of this mode of cracking which might be sought in the decreasing strain at the crack tip with decreasing ΔK and in metallurgical factors such as the slip character i.e. the tendency of an alloy to give rise to heterogeneous planar deformation.

CONCLUSIONS

The fatigue crack propagation rate was determined in a cast nickel base superalloy at room temperature with a R ratio of 0.1. A threshold behaviour was observed which gives rise to a deviation from the Paris equation for K values lower than 20 MPa $\sqrt{m}$, which corresponds on the fracture surface to the onset of crystallographic cracking. The large grain size of this alloy (about one centimeter) was used to determine the location of grain boundaries and the orientation of each grain and of the operating crystallographic facets through X-ray diffraction and extensive scanning electron microscopy. The threshold behaviour was analyzed in terms of local crack deviations from its original plane. Using an estimation of the effective opening stress intensity amplitude on the relevant facets it was concluded that Paris' law can in fact apply throughout the investigated range of crack growth rates.

ACKNOWLEDGEMENTS

This study is part of a cooperative research with the Turbomeca Company, for which financial support of the DRET Agency is gratefully acknowledged.

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