INFLUENCE OF ENVIRONMENT ON THE CRACK PATH IN A SUPERALLOY AT LOW FATIGUE CRACK GROWTH RATES

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ABSTRACT

Fatigue crack growth rate tests in a cast nickel base superalloy, MAR-M004, were carried out in the rate range 10^{-10} to 10^{-6} m/cycle at 600°C in air and in vacuum using compact tension specimens with a load ratio of 0.1. The large grain size of the cast material (almost one centimetre) enabled a detailed study to be made of the crystallographic cracking occurring at low crack growth rates in the threshold regime. The threshold value in air was found to be twice that in vacuum. Pseudocleavage features were observed in each environment : either with a smooth {001} fracture surface or with numerous { 111 } facets in vacuum, as previously shown at 20°C, with a fairly smooth near { 001 } fracture surface with pronounced branching or a smooth {001} surface in air. The influence of temperature and environment on cracking mechanisms is then briefly discussed.

KEYWORDS

Fatigue crack propagation, nickel base alloy, turbine disc alloy, high temperature fatigue, microstructure, pseudo-cleavage, crystallography, threshold stress intensity.

INTRODUCTION

The low crack growth rate regime of the fatigue crack growth law, da/dN - ΔK, has been the object of numerous studies. In particular the departure from Paris' equation when decreasing the amplitude of the stress intensity factor, ΔK, which is typical of a threshold behaviour, is generally associated with the occurrence of cracking modes different from those observed at higher rates. In particular, crystallographic cracking is the most widely reported mode of cracking in the threshold regime (see for example, the review by Beevers, 1977). In the case of face centred cubic (fcc) materials this has been mainly studied in aluminium based engineering alloys (Garrett and Knott, 1975; Nageswararao and Gerold, 1976), to a lesser degree in nickel based engineering alloys (Gell and Leverant, 1968). In the case of nickel base superalloys only { 111 } facet plane was evidenced by X-ray diffraction. Some results actually suggest the occurrence of { 001} facets (Sadananda and Shahinian, 1981). In order to obtain the whole information about the cracking mechanisms in the threshold regime, it is highly desirable to have a grain size large enough to obtain the individual orientation of every grain on the fracture surface of fatigue specimens.

Therefore, a crystallographic study of the low crack growth rate behaviour of a cast nickel base superalloy, MAR-M004, was conducted at 20 and 600°C, which was reported previously (Vincent and Rémy, 1982a). The casting conditions produce large grain sizes almost one centimetre in diameter. Therefore, the fatigue crack in a thin compact tension specimen can grow from one single grain into another single grain, which enables a study to be made of the influence of orientation of every grain and of individual grain boundaries. Combined scanning electron microscopy (SEM) and Laue X-ray diffraction technique have actually shown that {111} facets are observed at 20°C and {001} facets occur at 600°C. However the mechanisms responsible for this change of crystallographic planes could not be identified. Therefore the present investigation was intended to clarify the influence of temperature on crystallographic cracking in the low fatigue crack growth rate (FCGR) regime. So tests were conducted in air and in vacuum. Results are reported together with metallographic examinations combined with X-ray diffraction. The influence of environment and temperature on the cracking mechanisms in the threshold regime is thus clarified and tentatively rationalized.

EXPERIMENTAL PROCEDURE

The studied alloy is the nickel base superalloy MAR-M004 which contains in wt pct 0.057C, 11.4Cr, 6.15Al, 4.4Mo, 1.9Nb + Ta and 1.5 Hf. Besides a few secondary phases, primary carbides and γ-γ' eutectics, it is mainly constituted of a fcc matrix which is hardened by a high volume fraction (around 50%) of γ' Ni_3 (Al, Nb+Ta) precipitates. These precipitates have a cubic shape with faces along cubic {001} matrix planes, their average size is about 1 μm. The yield and tensile strengths are 700 and 900 MPa respectively at 600°C.

Compact tension specimens where used with a dimension W = 40 mm and a thickness t = 10 mm for specimen number 1 to 3 and t = 8 mm for number 4 to 7. Due to the specific solidification conditions used, the grains with a width about 1 cm have their longest dimension more or less perpendicular to the surface of specimens. As previously illustrated (Vincent and Rémy, 1981), in the mid plane of the specimen 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 on an electrohydraulic machine at 600°C. Specimens were heated by a radiation furnace. Tests under vacuum were carried out in chamber in which a pressure less than 10^{-5} mbar was maintained throughout the test. A controlled sinusoidal loading cycle was used with a test frequency in the range 20 Hz to 40 Hz and a load ratio R = 0.1. The crack length was monitored continuously throughout the test using a direct current potential drop technique including a thermocoupling effect correction and calibrated by optical measurements.

After completion of the experiment, specimens were longitudinally cut by spark-machining to get a mid plane section. Then they have been broken at room temperature to enable SEM observations of the fracture surface to be

made. Further details on metallographic observations and on testing conditions in the low FCGR regime are given by Vincent and Rémy, (1982a).

RESULTS

Fatigue Crack Growth Rate

Precracking of CT specimens was carried out in such a way to produce a final crack growth rate of about 10^{-8} m/cycle. In Fig. 1 are reported the data from four specimens tested under laboratory air conditions. The first one was conducted with increasing ΔK and three others with decreasing ΔK to low ΔK values initially followed by increasing ΔK. Experimental results in the FCGR range 4.10^{-9} m/cycle to 10^{-6} m/cycle, are fitted by a single curve within a factor of 2.5 on the FCGR. This curve corresponds to an exponent m in Paris' equation ($da/dN = C\Delta K^m$, Paris, 1964) of 3.5, which is in good agreement with results obtained on Ni based superalloys (Clavel and Pineau, 1978; Sadananda and Shahinian, 1981; Hicks and King 1983). When the applied ΔK is decreased below 10 MPa.m½ the value of the slope m becomes very large defining a ΔK threshold between 9 and 10 MPa.m½ for a FCGR equal to 10^{-10} m/cycle. This threshold behaviour was observed with three specimens with a noticeable accuracy.

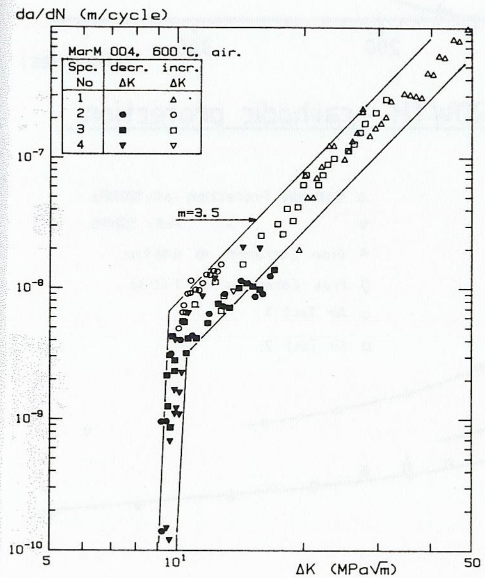

Fig. 1 - Variation of the fatigue crack growth rate with the amplitude of stress intensity factor for MAR-M004 CT specimens at 600°C under laboratory air conditions and R = 0.1.

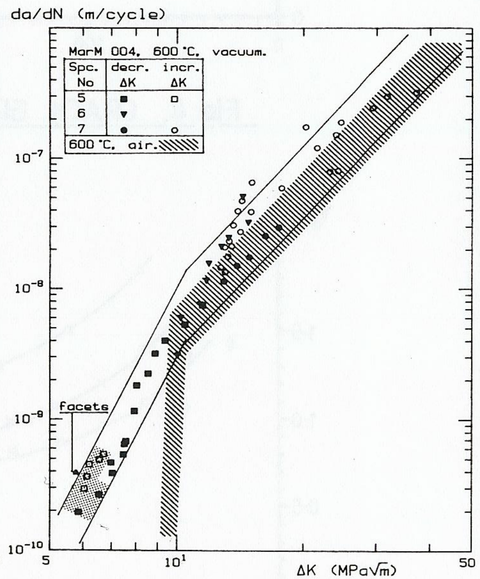

Fig. 2 - Variation of the fatigue crack growth rate with the amplitude of stress intensity factor for MAR-M004 CT specimens at 600°C under vacuum and R = 0.1, comparison with tests at 600°C under air.

Tests under vacuum conditions were first precracked at 600°C in air in order to reach a FCGR of about 10^{-8} m/cycle. Then vacuum was made; two tests were conducted at decreasing ΔK and one test was conducted at increasing ΔK. Results are plotted in Fig. 2 in log-log coordinates, they exhibit more scatter than in air, but they are included in a single scatter band within a factor 3.5 on FCGR, (this is to be compared to the scatter band in air represented by a dashed line area). The slope of this scatter band is close to the value m = 3.5 found in air and one can conclude that results are not very different in air and in vacuum. But now, when ΔK is decreased below 10 MPa.m½, the FCGR does not decrease so quickly as in air but gradually departs from the previous slope to give a threshold value equal about 5.5 MPa.m½ for a FCGR equal to 10^{-10} m/cycle. These two different near threshold behaviours should be discussed with observation of the crack growth path.

Metallographic observations

Fig. 3 shows SEM micrographs of the CT specimen number 4 which is one of three specimens corresponding to low FCGR testing in air. Fractographies of another specimen were previously shown (Vincent and Rémy, 1982a) under the same test conditions, and looked like the present ones. The fracture surface is rather flat with occasional kinks when crossing a grain boundary. Furthermore river lines are laying more or less along the crack growth direction.

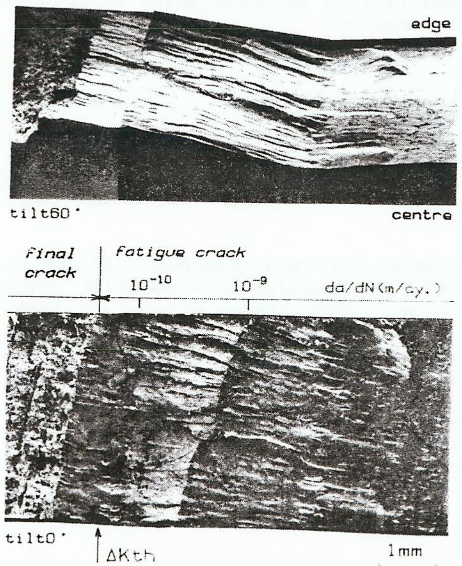

Fig. 3 - Fracture surface of half the CT specimen number 4 tested at low FCGR at 600°C under laboratory air.

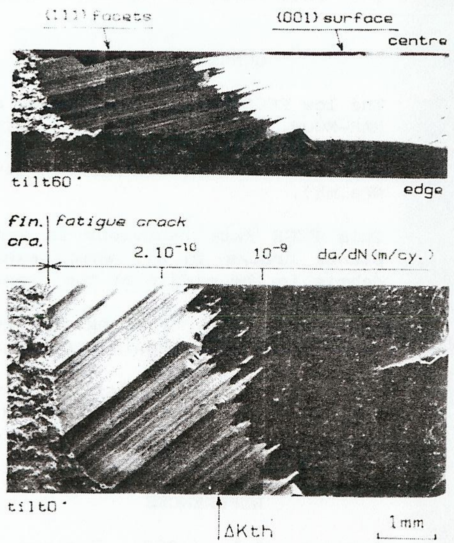

Fig. 4 - Fracture surface of half the CT specimen number 5 tested at low FCGR at 600°C under vacuum.

Fig. 4 shows SEM micrographs of the CT specimen number 5 which was tested under vacuum. As in Fig. 3 the near threshold area of the test is shown. Noticeable differences appear between the two types of fracture surfaces. First in the smooth part of the fracture surface which is a quasi plane, riverlines have completely disappeared. Secondly in the last part of the fracture surface (on the left of the picture), fairly well defined facets are observed. These are {111} fcc crystallographic facets as shown from Laue X-ray diffraction technique. This mode of crystallographic cracking is observed in the threshold regime at room temperature in the same alloy (Vincent and Rémy, 1981). When the FCGR is reported on the fractography picture, one can determine where the crystallographic crack growth starts. In this case, one can observe the shape of the crack front is approximately the same as that of the boundary between smooth and faceted areas. The result is shown in Fig. 2 and one can see on this specimen {111} crystallographic crack growth appears at very low values of crack growth rate, and is still present at the end of the test even if the FCGR is higher. This fact has already been noticed for room temperature tests (Vincent and Rémy, 1981). The larger part of the near threshold results

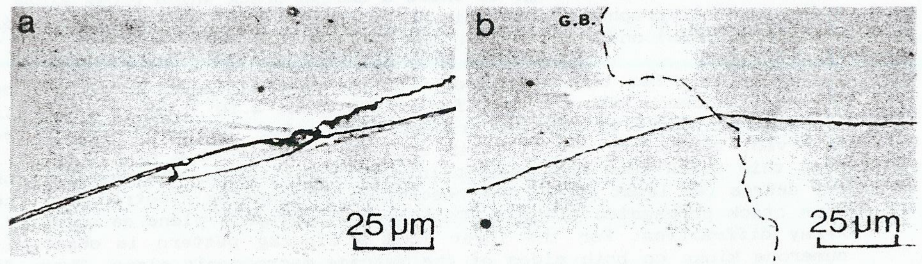

Fig. 5 - Longitudinal section of the CT specimen number 4 tested at 600°C, air (Crack grows from left to right.) :
a) decreasing ΔK area, da/dN = 10^{-9} m/cycle;
b) ΔK threshold area, da/dN = 10^{-10} m/cycle.

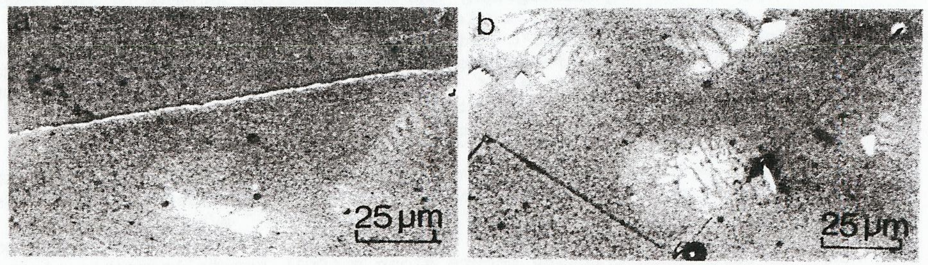

Fig. 6 - Longitudinal section of the CT specimen number 5 tested at 600°C under vacuum (Crack grows from left to right.) :
a) decreasing ΔK area, da/dN = 4.10^{-10} m/cycle;
b) ΔK threshold area, da/dN = 2.10^{-10} m/cycle.

reported on Fig. 2 is obtained on a smooth surface which is a {001} plane as in air. So both conditions may be compared directly without accounting for the faceted surface and one can conclude there is a higher threshold in air than in vacuum even if fracture surfaces are rather similar.

Longitudinal sections were cut to observe the crack path in the mid-plane of the CT specimens. Fig. 5 shows representative micrographs of the crack path in air in the low FCGR range. Fig. 5a is typical of FCGR in the range 10^{-9} -5.10^{-9} m/cycle. At numerous locations the main crack segments into closely adjacent cracks. Individual cracks are nearly but not strictly planar. These partial fronts are readily seen on the fracture surface (Fig. 3); this gives rise to the uneven aspect of the surface with a coarse step pattern. This is somewhat different from the fine classical river pattern observed at room temperature in this material (on {111} facets, Vincent and Rémy, 1981). In addition Fig. 5a indicates that the main crack is actually divided into two parallel cracks with a sliver of material a few µm in thickness in between. This sliver is often fragmented into debris which should enhance crack closure.

This step pattern and these debris disappeared at lower FCGR in the range 1 to a few 10^{-10} m/cycle. Fig. 5b shows a unique crack which grows along a {001} fcc crystallographic plane. This has been previously demonstrated (Vincent and Rémy, 1982a) and confirmed in the present work.

This behaviour has to be compared with the case of vacuum tests as shown in Fig. 6. The crack path is shown for a FCGR about 4.10^{-10} m/cycle and 2.10^{-10} m/cycle in Fig. 6a and 6b respectively. For the particular specimen observed, the higher crack growth rate corresponds to a single crack (Fig. 6a); this crack does not segment into parallel cracks and does not contain any debris (at least within the resolution of scanning electron microscopy). This crack propagates along a {001} crystallographic plane as shown by Laue X-ray diffraction. For the lower FCGR a zig-zag pattern is observed with numerous kinks on both sides of the average macroscopic plane. These facets occur along {111} crystallographic planes as those observed at room temperature (Vincent and Rémy, 1981).

DISCUSSION

This study of the crystallography and morphological aspects of the fracture surfaces in the threshold regime of MAR-M004 superalloy has shown the following results : at 600°C under vacuum {111} crystallographic cracking occurs in the threshold regime as at room temperature under air. This gives rise to a kinked appearance of the fatigue fracture path in both cases; however at 600°C {001} crystallographic cracking may occur and the occurrence of {111} facets seems to be restricted to lower FCGR at the higher temperature (at a few 10^{-10} m/cycle instead of a few 10^{-9} m/cycle but this should be confirmed by further experiments). On the contrary at 600°C in air {111} crystallographic cracking is no longer observed. Cracks near {001} planes are observed in the range 10^{-9} -5.10^{-9} m/cycle with debris and segmentation into parallel cracks which should be very effective in reducing FCGR. At lower FCGR cracking occurs along a {001} crystallographic plane.

Thus the comparison of results in air at 20 and 600°C and in vacuum at 600°C clearly suggests there is not a unique reason for the suppression of {111} cracking at 600°C in air. Some understanding of this behaviour can be achieved from the study of persistent slip bands in this material. Smooth fatigue specimens, were cycled at room temperature and some results were

recently reported (Vincent and Rémy, 1982). Measurements of the areas covered by persistent slip bands showed that these bands carried out an average plastic shear strain of $2.2.10^{-2}$ (half strain amplitude). Similar observations were carried out at 600°C under vacuum. Slip bands were found to occur along {111} planes as at 20°C and for a given strain range they were more numerous than at 20°C. Quantitative measurements give an average shear strain about one order of magnitude lower than at 20°C. Therefore temperature has a strong influence on the slip characteristics under cyclic conditions since the shear deformation is much less localized at 600°C than at 20°C. Accordingly classical formulae of dislocation theory for a pile up under stress (see for instance Hirth and Lothe, 1982) suggest that the size of {111} slip bands will be much shorter at 600°C than at 20°C for the same loading path.

This may explain that the activation of {111} facets at 600°C under vacuum is more difficult than at 20°C and requires lower FCGR. The slip distance which is much larger than the cuboidal precipitate size (about 1 µm) at 20°C may become commensurate with the precipitate size and interparticle spacing (about 1.2 µm) at 600°C. Therefore {111} cracking is less favored than at 20°C and {001} cracking can be observed. The absence of {111} cracking in air requires nevertheless an environmental effect which superimposes to the simple effect of temperature on slip mechanisms. Oxygen of the atmosphere can diffuse from the crack tip into the material. At such a low temperature oxygen is likely diffusing along dislocations; oxygen can thus pin dislocations and further reduce their slip distance. Eventually this effect can be enhanced by the possible role of interfacial dislocations at γ-γ' interfaces as diffusion short circuits.

CONCLUSIONS

The low FCGR regime was studied at 600°C in a coarse grained cast superalloy MAR-M004, in air and under vacuum. FCGR while similar in the Paris' law range, are different in the threshold regime and testing under vacuum results in a lower threshold value (about 5.5 $\mathrm{MPa.m^{1/2}}$) than in air (about 9.5 $\mathrm{MPa.m^{1/2}}$).

This FCGR rate behaviour is associated with the occurrence of nearly {001} planar cracks in air which exhibits segmentation into parallel cracks and debris in the middle of the cracks, and {001} cracks at very low FCGR.

In vacuum {001} cracking can occur, but without segmentation nor debris, as {111} crystallographic cracking as at 20°C.

These features are attributed to a decrease of slip distance along {111} planes at 600°C as compared to 20°C together with an interaction between oxygen and dislocations emitted at the crack tip.

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