SHORT FATIGUE CRACK PROPAGATION FROM NOTCHES IN N18 NI BASED SUPERALLOY

F. Sansoz *, B. Brethes **, A. Pineau *

Fatigue crack growth rates were measured on notched specimens with a tiny crack (≅ 0.1 mm deep) located at the minimum section. These tests were performed on a powder metallurgy Ni base superalloy, N18. The material was tested at 650°C under trapezoidal load cycles. Two experimental techniques were used to measure the length of small semi-elliptical cracks initiated from the EDM slot. The first technique which is the conventional potential drop method is shown to be inappropriate to measure crack lengths less than 400 µm in depth. On the other hand, the second technique based on high resolution optical observations proved to be efficient to detect crack growth increments as small as 10 µm from the EDM slot. These crack growth rates were correlated with ΔK calculated from 2D elasto-viscoplastic FEM calculations. Crack closure effects were also modelled using FEM node release scheme. It is shown that a proper account of these effects partly rationalizes the differences observed in growth rates between small and long cracks.

INTRODUCTION

N18 alloy is a powder metallurgy nickel based superalloy used by SNECMA for advanced turbine discs in aircraft engines. Due to the fabrication process, a small amount of inclusions is present in the material. The typical size of the biggest defects is 100 µm, but at stress gradients such as turbine blades fixatures, short elliptical cracks may initiate from these microstructural defects. Therefore our approach in this study is to investigate precisely the growth behaviour of short cracks located at notches simulating blades attachments. It is well-known that the growth behaviour of small cracks in a uniform stress field differs from long cracks with similar loadings, see eg. Pearson (1). A number of studies (2,3) have suggested that a reduction of crack closure associated with small fatigue cracks was responsible for these differences. However specific calculations must be made to account for closure effects associated with short cracks initiated from notches. This is one of the main objectives of the present study.

MATERIAL AND EXPERIMENTS

All tests were carried out on N18 alloy with a bulk microstructure. The details concerning

* Centre des Matériaux, Ecole des Mines de Paris, UMR CNRS 7633, Evry, France
** SNECMA- service YKOM- Etablissement de Villaroche, Moissy Cramayel, France

this material are given elsewhere (4-7). Its chemical composition is : Ni-11.5 Cr-15.7 Co-6.5 Mo-4.35 Al-4.35 Ti-0.5 Hf (weight %). N18 alloy, in the fully heat-treated condition, contains large primary γ' particles (≈ 5 μm) with a volume fraction of about 15%, used to control the grain size (≈ 15 μm) and smaller γ' precipitates ($V_f \approx 45\%$) with a mean size of about 150 nm. This leads to in a high strength alloy with good mechanical properties and excellent fatigue resistance at high temperature (650°C in service). The monotonic and cyclic yield stresses are close to σ_y = 1050 MPa and σ_y^c = 1150 MPa at 650°C, respectively.
Crack development in a non-uniform stress field was studied using a specifically designed double-edge U-notch (DEN) testpiece. The notch root radius was 2 mm and the reduced cross-section at the notch was 5 mm x 10 mm. The resulting elastic stress concentration factor, K_t, was 1.75 . The microstructural defects were simulated by a tiny semi-circular EDM slot (depth 100 μm) located at the center of the notch root on one side of the specimen. The program was carried out with trapezoidal loading cycles (10s-300s-10s) and with applied nominal stresses, S_{max}, between 700 MPa and 900 MPa. The load ratio, R = S_{min}/S_{max}, was kept at zero and the temperature was maintained at 650°C. Crack growth rates were measured over distances of the order of 1 mm.

CRACK GROWTH MEASUREMENTS AND ANALYSIS

Two techniques were developed to measure the growth of semi-elliptical crack in DEN specimens. First, data were obtained from a direct current Potential Drop (PD) system in which a 6 A current was applied. In order to make PD method sensitive enough, 0.1 mm-diameter probe wires were located across the EDM notch. Due to the small size of EDM defects, the probe wires were sufficiently keeped away from the machined defect to prevent cracks to be initiated from the welding points. Thus an equivalent crack length, R_{eq}, was calculated as R_{eq}^2 = a.c, where a and c are crack depth and surface crack length, respectively (see *figure 1*).
A high resolution optical system was also used to measure crack lengths. This technique proved to be efficient to detect *in situ* surface crack growth increments as small as 10 μm. The PD and optical results are shown for a typical experiment (S_{max} = 700 MPa) in *figure 1*. Typically, surface crack increments are observed during the first cycles with the optical system. But the first PD deviation occurs after about 4000 cycles which corresponds to more than one half of the test duration (≈ 6000 cycles). It is noticed that the surface crack length reaches approximitely 250 μm when the first PD deviation is observed. On the other hand a rather good agreement between both crack length measurement techniques is observed when the crack depth is larger than 500 μm. Small differences observed in this range of crack length may be due to the assumption concerning crack shape. In the following only the results obtained from optical measurements will be presented.

ΔK CALCULATIONS IN NOTCHED SPECIMENS

The stress intensity range, $\Delta K = K_{max} - K_{min}$, was calculated using the weight functions method introduced by Hand (8), which was established for semi-circular cracks at stress concentrations. The local stress-strain field near the notch was calculated by a Finite Element Method (FEM). ZéBuLoN FEM code developed by the Ecole des Mines de Paris was used for that purpose. A 2D mesh represented one quarter uncracked DEN specimen. Quadratic elements were used. Refined meshing (≈ 25 μm) was used in the vicinity of the notch root to model stress and strain gradients. The material behaviour was represented using an elasto-viscoplastic constitutive set of equations (Lemaitre and Chaboche (9)) :

- elastic constants: $E = 180\,000$ MPa ; $\nu = 0.3$
- Norton creep law $\dot{p} = \left\langle \frac{J_2(\sigma - X) - R}{K} \right\rangle^n$ $\qquad \dot{\varepsilon}_p = \frac{3}{2}\dot{p}\frac{\sigma' - X'}{J_2(\sigma - X)}$

  where σ' and X' represent deviatoric components
- isotropic hardening $R = R_0 + Q[1 - \exp(-b \cdot p)]$, p : cumulated plastic strain
- kinematic hardening $\dot{X} = \frac{2}{3} C \dot{\varepsilon}_p - D \cdot \dot{p} \cdot X$

In this study Q and b were maintained equal to zero. The remaining five coefficients (C, D, R_0, K, n) were identified using stabilized LCF tests. *Figure 2* shows typical results obtained on a specimen submitted to a nominal stress of 800 MPa. In this figure it is observed that the tensile stress ahead of the notch progressively decreases to reach a stabilized condition obtained after 50 cycles. In this figure significant compressive stresses are noticed when the specimen is unloaded. The stabilized behaviour is predominantly elastic since these calculations suggest that the plastic part of the strain range is of the order of 6.10^{-5} while the elastic part is equal to 8.10^{-3}. Similar calculations on the specimens submitted to S_{max} = 700 MPa showed that, besides of the plastic deformation occurring during initial loading, the cyclic loading remained elastic. In the specimen with S_{max} = 900 MPa, the plastic strain range was equal to 7.10^{-5} which is still much smaller than the elastic strain range. These calculations suggest therefore that an elastic approach in terms of ΔK should apply. Stress profiles similar to those shown in *figure 2* were approximated by a polynomial expression used in Hand's results to calculate ΔK.

FEM MODELLING OF CRACK CLOSURE EFFECTS

In order to compare results obtained on short cracks in the present study to results related to long cracks obtained previously (4), the effective stress intensity factor $\Delta K_{eff} = K_{max} - K_{op}$ was calculated. A number of factors play a key role in crack closure effect. In the present work only plasticity-induced crack closure effect was considered. A technique based on node release scheme similar to those used by other authors (see in particular (10-12)) was used. However in our specific case, viscoplasticity was taken into account since the tests were performed at elevated temperature. Crack closure calculations were made using 2D modelling. In our future work an attempt will be made to extend these calculations to 3D conditions. In the present study these calculations were made not only on notched bars but also on smooth specimens in order to analyse the effect of stress concentration. 8 nodes isoparametric meshes of 20 µm were used. This allowed us to simulate stepwise crack growth of 10 µm up to 1 mm in length from the notch tip. In these calculations plane strain conditions were applied. Node release method was conducted as follows : two trapezoidal cycles were simulated between two node releases. Such a scheme proved to be sufficient to model the plastic wake left behind the crack tip. The calculated opening ratios, S_{op}/S_{max}, are shown in *figure 3* for a test performed at S_{max} = 800 MPa with an initial crack length of 100 µm corresponding to the initial EDM slot depth. The numerical results obtained on smooth specimens are in good agreement with experimental measurements (4). The results given in *figure 3* indicate that the crack closure effect is more important for notched specimens than for smooth bars, at least for small crack lengths. This effect is likely related to the larger plasticity present in the notched specimens compared to smooth bars. In figure 3 it is also observed that K_{op} decreases for crack lengths larger than about 400 μm. A similar effect has already been noticed by other authors. In particular Fleck (13) numerically showed that the decrease in K_{op} with crack length was not observed under plane stress conditions. We reached similar conclusions. In the following, for simplicity sake, K_{op} will be assumed to be equal to the maximum calculated value, i.e. $K_{op} = 0.35\ K_{max}$.

SHORT CRACK GROWTH RATES ANALYSIS

The results of crack growth rates obtained at 650°C are shown in *figure 4*. In this figure we have included the results for long cracks obtained on conventional CT type specimens (4) and relatively long cracks obtained from tests on smooth KB bars (Clad (14)). In both cases K_{op} was assumed to be equal to 0.24 K_{max} which is the value obtained from the calculations (*figure 3*) and from experiments (4). The results obtained from notched specimens shown in *figure 4* indicate a perfect correspondance between short and long cracks when the nominal stress is equal to 700 MPa and when the comparison is made in terms of ΔK_{eff}. This clearly shows that, in the absence of large cyclic plasticity, the method adopted in the present study gives quite satisfactory results. It can be noticed that stresses of this order of magnitude ($S_{max}/\sigma_y^c \approx 0.6$) are quite representative of those existing in real components. On the other hand, *figure 3* shows that the crack growth rates measured from small cracks at notches are significantly larger when S_{max} is increased. This effect is all the more important than the applied stress is larger, but is observed only for small crack lengths (≤ 0.5 mm). Here it should be noticed that no significant variations with those shown in *figure 4* would be observed if the variation of K_{op} with crack length indicated in *figure 3* was taken into account. Further progress should be made to explain this behaviour observed at large nominal stresses including a proper account of significant cyclic plastic strains, 3D calculations, observations of the real crack front shape and, eventually more sophisticated constitutive equations. Similar calculations but using crack shapes different from semi-circular could be made using other weight functions, in particular Wang and Lambert's expressions (15) for semi-elliptical cracks.

CONCLUSIONS

(1) A technique based on high resolution optical measurement has been used to measure growth rates of very short cracks initiated from notches. The PD technique has proved to be inappropriate.

(2) Stress intensity factor and crack closure effect were modelled using F.E.M. calculations and simple elasto-viscoplastic constitutive equations. Crack closure effect was found to be more important in notched specimens than in smooth specimens, at least when the crack is located in the vicinity of the notch.

(3) There exists a good correspondance in terms of ΔK_{eff} between short cracks initiated from notches and long cracks when the applied load is moderate ($\approx 0.6\ \sigma_y^c$). At higher loads improvements must be made in the comparison between short cracks at notches and long cracks.

SYMBOLS USED

S = macroscopic applied tensile stress (MPa)

op = fully opened crack tip

max (min) = at maximum (minimum) value

ACKNOWLEDGEMENTS

The authors express their appreciation to SNECMA for its financial support. They are also grateful to Dr J. Besson from Ecole des Mines for his technical guidance on FEM calculations.

REFERENCES

(1) Pearson,S., Engng. Fract. Mech., 7, 1975, pp. 235-247

(2) Newman, J.C. Jr, AGARD Conference Proceedings n°328, 1982, pp. 6-1 to 6-26

(3) Bréat J.L., Mudry, F. and Pineau, A., Fat. Engng. Mater. Struct., 7, 4, 1984, pp.251-265

(4) Hochstetter, G., Ph.D thesis, Ecole des Mines de Paris, 1997

(5) Pineau, A., "Engineering against fatigue", conference proceeding at Sheffield, march 17-21, 1997

(6) Guédou, J.Y., Lautridou, J.C., Honnorat Y. in Proc. of the Minerals, Met. and Mater. Society. Conf. On Superalloys 92, Ed. by Antolovitch, S.D. and al., 1992, pp 267-276

(7) Pommier, P., Prioul C., Lautridou J.C., Bompard P., Fat. Fract. Engng Mater. Struct., 19, 9, 1996, pp. 1117-1128

(8) Hand R. J., Int. J. Fracture, 57, 1992, pp. 237-247

(9) Lemaitre, J., Chaboche, J.L. "Mécanique des matériaux solides", Dunod, Paris, 1985

(10) Newman, J.C. Jr, AIAA Paper n°74-366 AIAA/ASME/SAE, 1974

(11) Mc Clung, R. C., Sehitoglu, H., Engng. Fract. Mech., 33, n°2,1989, pp.237-272

(12) Ohji, K., Ogura, K. and Ohkubo, ., Int. J. Fracture, 10, 1974, pp. 123-124

(13) Fleck, N., Engng. Fract. Mech., 25, n°4, 1986, pp. 441-449

(14) Clad, T., Ph.D thesis, Ecole des Mines de Paris, 1997

(15) Wang, X., Lambert, S. B., Engng. Fract. Mech., 51, 1, 1997, pp. 13

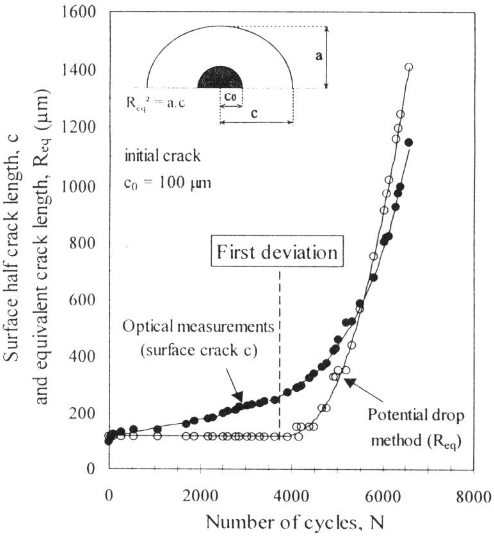

Figure 1 : optical and potential drop measurements of crack length for a same test

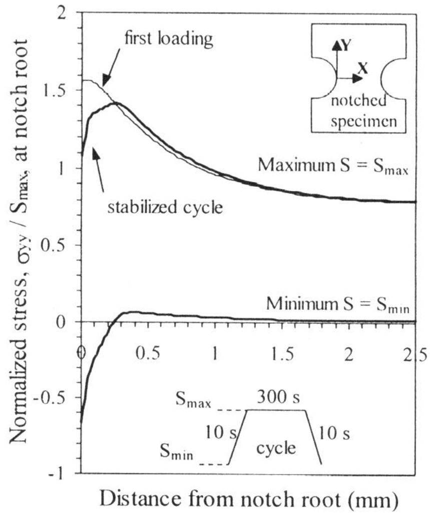

Figure 2 : stresses at minimum cross section by FEM elasto-viscoplastic modelling

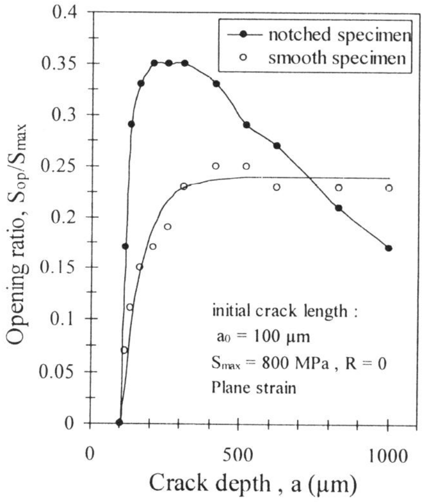

Figure 3 : crack opening ratios resulting from FEM modelling

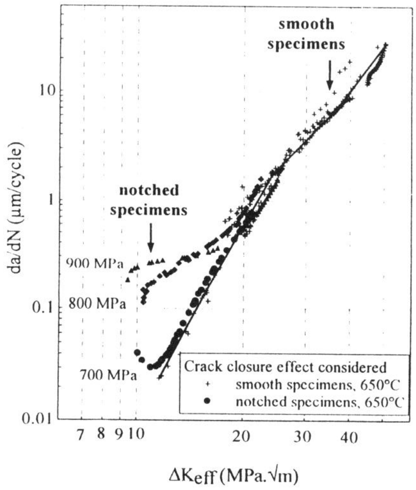

Figure 4 : fatigue crack growth rates, da/dN, versus effective stress intensity range, ΔK_{eff}