FATIGUE OF CAST NICKELBASE SUPERALLOYS AT 850^{o}C

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ABSTRACT

Some fatigue properties of the cast nickelbase superalloys IN 738 LC and IN 939 were studied at 850^{o}C using the fracture mechanics approach and smooth specimens. Fatigue crack growth rates $\Delta a/\Delta N$ were measured as function of the cyclic stress intensity range ΔK at various frequencies, mean stresses and in various environments. The results of fatigue crack propagation in vacuo could be used to estimate the fatigue strength measured with smooth specimens. Investigations of the fracture surfaces and the dislocation arrangement were performed with the scanning electron microscope and the transmission electron microscope.

KEYWORDS

Crack propagation; fatigue; high temperature properties; nickel alloys; fractography.

INTRODUCTION

During service, gas turbine blades are subjected to very complex mechanical loadings and aggressive enviroments at high temperature. Therefore blade materials are designed to combine high strength at high temperatures with high hot corrosion resistance. At present for stationary gas turbine applications these requirements are relatively well fullfilled by cast nickelbase superalloys. Especially the precipitation hardened alloys IN 738 and IN 939, showing better suphidation resistance, are commonly used for GT-blades. Typical mechanical loading conditions for blades are tensile stresses in the creep region due to centrifugal force, high alternating strains due to start up and shut down procedures and small alternating stresses with relatively high frequency due to blade-vibrations. The latter type of loading is mainly considered in the present investigation. The smooth specimen approach (S/N-curves) and the fracture mechanics approach ($\Delta a/\Delta N$-ΔK curves) have been used to investigate stages of fatigue crack initiation and fatigue crack propagation.

EXPERIMENTAL

Specimens of the cast nickelbase superalloys IN 738 and IN 939 have been used in the fully heat treated condition. The chemical composition and the heat treatment are indicated in table 1 for both alloys.

TABLE 1 Chemical compositions (weight %) and heat treatments (AC air cooling, FAC fast air cooling)

	C	Cr	Co	Mo	W	Ta	Nb	Al	Ti	Zr	Ni
IN 738:	0.17	16.0	8.5	1.7	2.6	1.7	0.9	3.4	3.4	0.10	Bal.
IN 939:	0.15	22.6	19.1	0.05	2.0	1.0	1.0	1.9	3.7	0.1	Bal.

Heat Treatment

IN 738: 2h/1120°C AC + 24h/845°C AC

IN 939: 4h/1160°C FAC + 6h/1000°C FAC + 24h/900°C AC + 16h/700°C AC

These precipitation hardening alloys consist of an austenitic γ -matrix with coherent fcc γ'-particles of the composition $Ni_3(Al, Ti)$ responsible for the hardening. Predominant additonal phases are primary carbides (Ti,Ta) C and the $(Cr, Co)_{23}C_6$-carbides at grain boundaries.
Fatigue crack propagation tests were performed with DCB-specimens in a hydraulic closed loop machine (MTS) with 5 ton capacity. Tests were performed in vacuum, air and in a service simulating sulphidizing atmosphere with and without chloride additions. A more detailed description of the testing equipment and the specimen geometry is given in literature (Hoffelner, Speidel, 1979). For the crack initiation tests conventional smooth specimens with a gauge length of 15 mm and a diameter of 4.5 mm were used. These tests were perfomred in a hydraulic closed loop machine with a frequency of 30 Hz and also in a resonant pulsator (Amsler Vibrophore) with a frequency of 170 Hz.

EXPERIMENTAL RESULTS AND DISCUSSION

Fatigue Crack Propagation

Fatigue crack propagation in vacuum: Fig. 1 shows the fatigue crack propagation rates $\Delta a/\Delta N$ as a function of the cyclic stress intensity range ΔK at 850°C in vacuum. Three stages of fatigue crack propagation can be seen. The region of the fatigue threshold, ΔK_o, the region where Paris law $\Delta a/\Delta N = C\ \Delta K^m$ is obeyed and the region of cyclic fracture toughness ΔK_C. In the linear part of the curve the values are slightly higher than expected according to the following relation proposed by Speidel (1974) $\Delta a/\Delta N = 1{,}7 \cdot 10^6\ (\frac{\Delta K}{E})^{3{,}5}\ |m/cycle|$. No significant differences in the fatigue crack propagation behaviour between IN 738 and IN 939 could be found in vacuum.
The threshold value ΔK_o decreases as the mean stress increases as shown in fig. 2. The fracture morphology near the threshold region changes from transgranular, at low mean stress to interdendritic at high mean stress. While the transgranular fracture propagates along crystallographic planes, the interdendritic fracture shows a ductile character.

Effect of environment on fatigue crack propagation. In a previous work (Hoffelner, Speidel, 1979) the influence of the environment on fatigue crack propagation rates of IN 738 and IN 939 has been investigated in the Paris law region at 850°C with 10-60 Hz. Only a small increase of about factor 2 of crack propagatione rates in air compared with that in vacuum could be found. The values in the sulphidizing atmosphere were on the upper side of the scatterband of the air values indicating

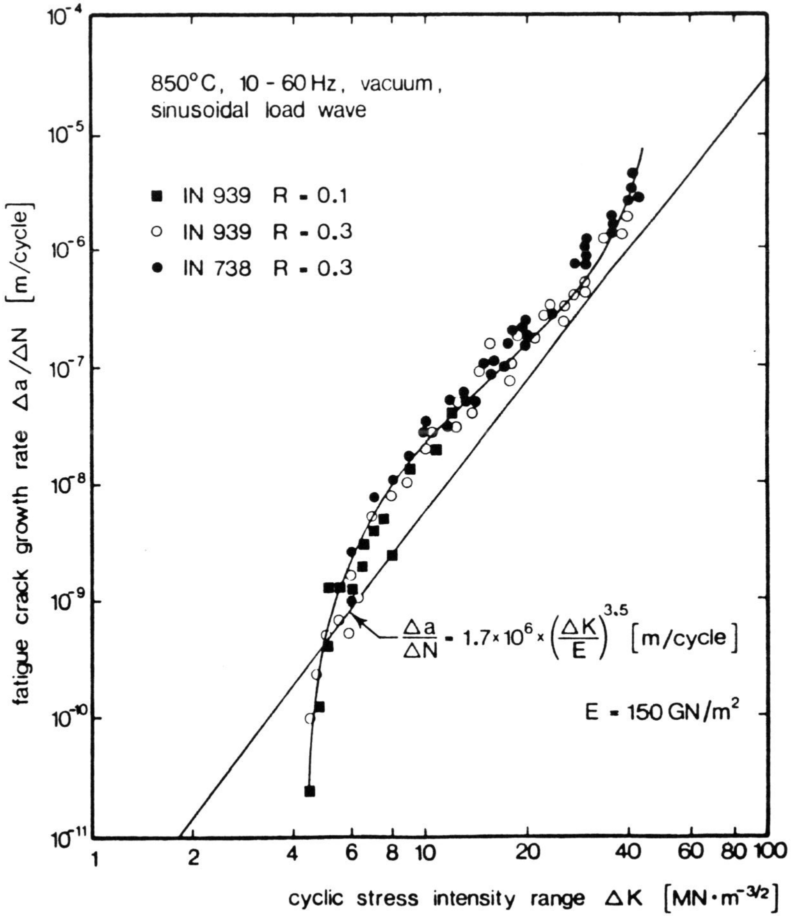

Fig. 1. Fatigue crack propagation rates of cast nickelbase superalloys as a function of the stress intensity range ΔK at 850°C in vacuo.

no significant effect of sulphidation on fatigue crack propagation under these conditions. Adding chloride changed the fracture path completely from transgranular to intergranular with heavily branched cracks, making an accurrate determination of crack propagation rates impossible. However, the situation changes completely in the threshold region where the ΔK_o-values could be found to be lower in vacuum than in air as shown in fig. 2. As discussed more in detail in (Hoffelner, Speidel, 1980) this effect of environment on the shape of the $\Delta a/\Delta N$ - ΔK curves can be understood as a superposition of crack accelerating effects as weakening of the material by γ'-dissolution at the crack tip in air and crack retarding effects as crack branching, which occurs in air and is completely absent in vacuo. A similar effect could be responsible for the results in sulphidizing atmosphere mentioned above where also crack acceleration could be compensated by more pronounced crack branching.

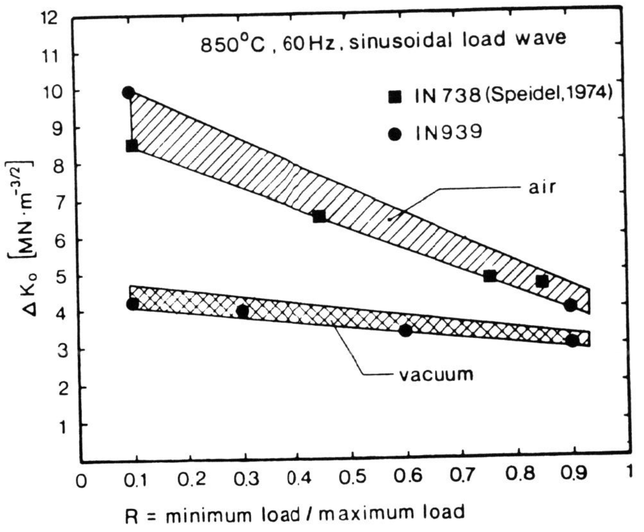

Fig. 2. The influence of environment and mean load on the fatigue threshold ΔK_o.

The influence of frequency on fatigue crack propagation. The influence of frequency on the fatigue crack propagation has been investigated only at high ΔK-values. A typical result is shown in fig. 3 at $\Delta K = 20\ MNm^{-3/2}$. As expected from literature (Solomon, Coffin, 1973, James 1978) an increase of crack propagation rates with decreasing frequency could be found. Both materials show this behaviour also in vacuo linking it to a superposition of fatigue- and creep crack growth. The amount of intercrystalline fracture increases also with decreasing frequency. In aggressive environments the effect of frequency on the crack propagation rates can be fairly seen, as in fig. 3, at the higher frequency end. At lower frequency the crack branching made an accurate determination of crack length difficult and hence a frequency effect could not be easily detected. This crack branching reduces the actual ΔK at the crack tip leading to a crack retardation effect. A general small increase of crack propagation rates of IN 738 over the frequency range in sulphidizing atmosphere would be agreement with the smaller sulphidation resistance of this alloy compared with IN 939.

Smooth specimen approach:

The stage of fatigue crack initiation has been investigated determining S/N-curves at various R-values. The fatigue limit for 10^7 number of cycles to failure is shown in fig. 4 in a Smith plot i.e. mean stress σ_m vs. mean stress ± alternating stress amplitude σ_a. The metallographic investigation of the broken samples showed that in all cases preexisting mainly internal casting defects e.g. pores, could be identified as origin of the fatigue fracture (fig. 5). The shape of the crack was as expected from the fracture mechanics specimens. Near the origin at low ΔK the fracture surfaces were smooth, with high amount of crystallographic fracture. With

increasing ΔK the ductile character increases and also striations could be found. From the spacing of the striations crack propagation rates $\Delta a/\Delta N \approx 10^{-6}$ m/cycle could be expected in this area. The residual fracture is mainly interdendritic.

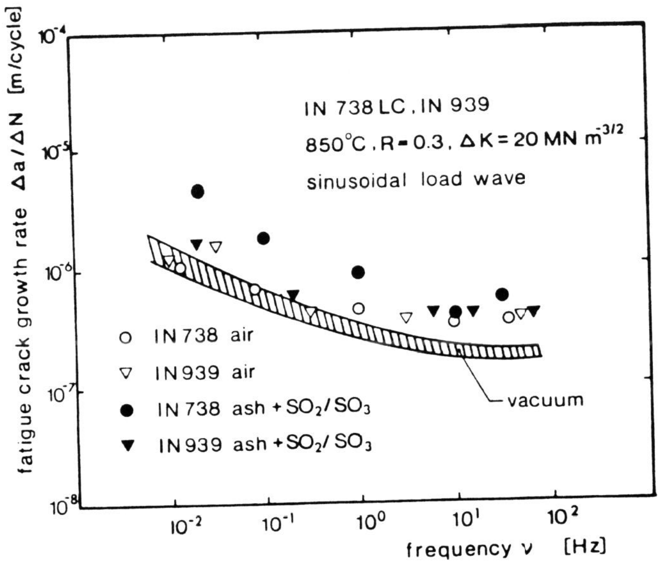

Fig. 3. The influence of environment and frequency on the fatigue crack propagation rates in IN 738 and IN 939.

By x-ray diffraction and TEM-investigations (Tschegg, Hoffelner, 1979) only little cyclic plastic deformation could be found in the gauge section of the specimens. A typical dislocation arrangement after fatigue deformation of IN 939 at 850°C can be seen in fig. 6. From these observations can be supposed that the fatigue strength is mainly determined by crack propagation from internal pores.
Therefore, the ΔK_o-values in vacuum have been used to explain the shape of the Smith diagram on the basis of the well known equation

$$\Delta K_o = 2\sigma_a \cdot \sqrt{\pi \cdot a} \cdot y$$

with following assumptions:

i) a ... mean/maximum pore diameter (150 μm/300 μm)
ii) $y \approx 1$
iii) For R = -1 only the positive stresses contributes to crack propagation.

These results are shown as shaded area in fig. 4. The agreement with the experimental data is rather good. This result strongly supports the assumption that the fatigue life of smooth specimens is mainly determined by the stage of fatigue crack propagation from preexisting flaws in this material. At R-values greater than 0.3 the situation becomes more complicated because of the high amount of creep due to the high mean stresses.

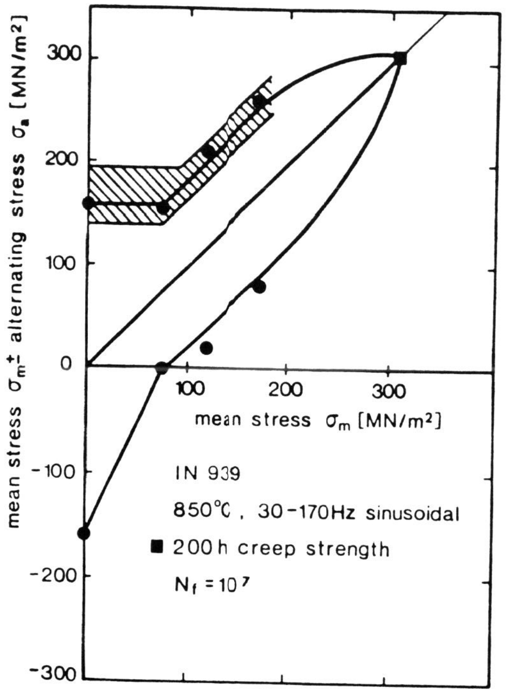

Fig. 4. Fatigue strength at $N = 10^7$ as function of mean stress for IN 939. The shaded area represents the values calculated from the threshold stress intensity ΔK_o.

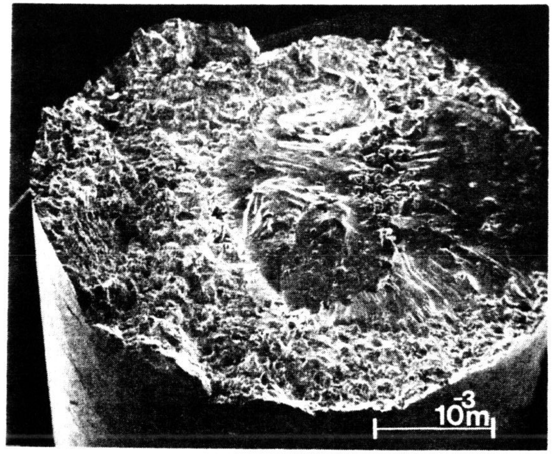

Fig. 5. Fracture surface of IN 939 after fatigue fracture at 850°C SEM-micrograph.

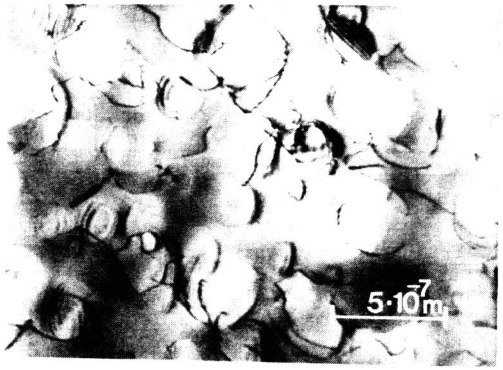

Fig. 6. Typical dislocation arrangement in IN 939 after fatigue deformation at 850°C (σ_a = 130 MN/m^2; R = 0,1; N_f = 3,9 · 10^6) TEM micrograph.

CONCLUSIONS

The fatigue behaviour at low alternating stresses has been investigated for the cast nickelbase superalloys IN 939 and IN 738 at 850°C using the fracture mechanics approach and the smooth specimen approach.
As most significant results could be found:

- The fatigue threshold value ΔK_o in vacuum is lower than in air which can be explained by crack branching effects.
- In the region of Paris law only little effect of environment on fatigue crack propagation rates could be detected.
- At high ΔK the fatigue crack propagation rates increase with decreasing frequency in vacuum, oxidizing and sulphidizing atmosphere.
- The fatigue limits for $N = 10^7$ can be estimated from the ΔK_o-values in vacuum showing the importance of crack propagation also in the smooth specimen approach.

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