EFFECT OF TEMPERATURE AND SECONDARY ORIENTATION ON NOTCH FATIGUE RESISTANCE OF CMSX4

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ABSTRACT

A turbine blade root contains notches that locate into a "fir-tree" root fixing in the turbine disc. Fatigue initiation in these stress concentrating features is of some concern. When a turbine blade is cast, the primary orientation along the blade is controlled (usually in the <001> direction) to within certain limits, however the secondary orientation (i.e. the orientation of any notches) is not generally controlled. The notch fatigue crack initiation and growth behaviour of CMSX-4 under low cycle fatigue conditions has been investigated at 650°C and 725°C. Two secondary orientations have been investigated and a separate oxidation study has been conducted. Heavy oxidation is observed in the notch root after a short amount of time at 650°C. At high temperatures, crack initiation occurs at subsurface pores.

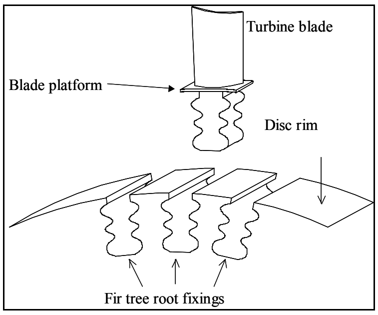

Figure 1 - 'Fir Tree' Notch Root fixing

INTRODUCTION

Turbine blades experience the toughest conditions within the modern aero engine. They are subjected to high temperature and direct stresses and also rapid changes in temperature at various points in the engine flight cycle. Hot gases present in the jet engine are highly oxidizing, and corrosive or erosive media, such as dust and sand can often find its way through the turbine. Nickel based superalloys and in particular, single crystal alloys such as CMSX-4 have been developed specifically to meet this variety of performance criteria.

Creep behaviour of CMSX-4 is well documented between 750°C-1000°C where it exhibits excellent creep resistance due to hardening by γ' precipitates. At high temperatures, and in particular, low stresses, rafting is observed. Multiple crack initiation is common in creep failure. Fatigue behaviour of CMSX-4 is less commonly investigated. The literature suggests that initiation is controlled by porosity and oxidation spikes. Oxidation is suggested to be a dominant factor in crack growth with oxidation induced closure effects retarding crack growth. Oxidation also causes crack tip blunting, this is more apparent at higher temperatures.

This paper discusses the effect of temperature (testing was conducted at 650°C and 725°C) and single crystal secondary orientation on fatigue crack initiation and early growth mechanisms.

TEST METHODOLOGY

Specimens 50mm by 8mm by 8mm were cut using electrical discharge machining. A notch diameter of 4mm was chosen in order to make it possible to polish the notch. Finite element analysis was carried out to determine the required depth of a 4mm diameter notch to achieve a stress concentration of 2 (typical of stress concentrations at the notch root fixing in service). Notches were then polished to a 1μm finish using a specially designed rig in order to remove oxide scale left over from machining process. Specimens were tested in 3 point bend using an Instron 8501 servo-hydraulic machine fitted with a high temperature chamber. Low frequency tests (0.25Hz) were conducted at an R ratio of 0.1 and a test temperature of 650˚C using a 1–1–1–1 trapezoidal waveform (where ramps up and down and dwells at maximum and minimum load were all of 1 second). Temperature was controlled to within 1˚C. A finite element model based on S-N data supplied by ALSTOM was used to identify a strain range in the notch root that would give around 10,000 cycles to failure (a typical service lifetime, and a test-time that would allow replication within reasonable testing timescales). The model used was an elasto-plastic 2D monotonic model using ANSYS finite element software and monotonic CMSX4 material properties supplied by ALSTOM. Results for air tests at 650°C and 725°C are discussed within the results and analysis section of this report. Scanning Electron Microscopy (SEM) of the fractured surfaces was used to identify crack initiation points and determine fracture modes. The SEM was also used to give topographical and compositional scans of the fracture surface. Energy dispersive x-ray (EDX) compositional mapping was conducted on sites of particular interest on the fracture surface using a Jeol JSM-6500F FEG SEM in conjunction with Oxford Inca 300 software.

Material left over from fatigue specimen machining was cut into ~8mm square samples. Plain polished samples and polished and etched samples were prepared and exposed at 650°C for 1, 2, 4, 8, 16, 32, 64, 128 and 256 hours. These were then available for examination by SEM after exposure in the furnace at 650°C.

RESULTS

Lifetimes for each test are shown in Table 1. There is no clear difference between orientation A and B over the range of temperatures tested within this limited test matrix.

Temp (°C)	Orientation	P_{max} (kN)	"Δ ε" (%)	Cycles to Failure
650	B	6.2	1.38	6500
650	A	6.2	1.38	25,500
725	A	6.2	1.38	5,271
725	B	6.2	1.38	13,717

Table 1 - Test lifetime data.

Crack initiation at high temperatures occurred at sub surface pores in all cases. Cracks in the surface oxide do penetrate the substrate but do not initiate the critical crack. All initiating sub surface pores were encircled by a halo (Figure 2). Subsurface pores were predominantly irregular shapes consistent with interdendritic spacing both in size and shape. The texture of the fracture surface within the halo differs from that seen in the surrounding area. This is better observed using backscattered electron imaging (Figure 3) to look at topographical features on the fracture surface. Using this method, several new crack initiation points were identified. A compositional scan also picked up differences within the halo region compared with the surrounding area.

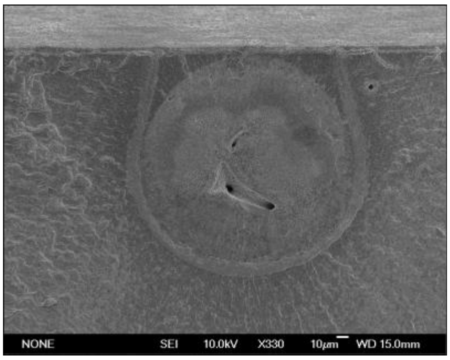

Figure 2 - Subsurface initiation point Orientation A, 725°C

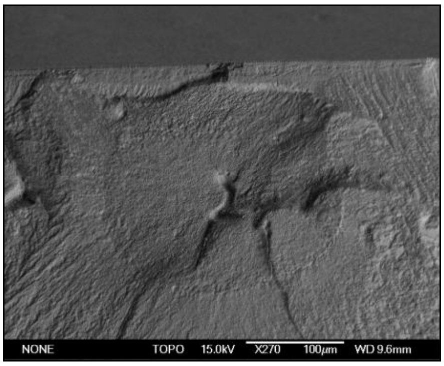

Figure 3 Subsurface initiation viewed using BEI (topographical)

Plain polished samples, and polished and etched samples were examined by SEM after exposure in the furnace at 650°C. To date, only the extreme cases (1 hour and 256 hours) have been examined for both polished and etched conditions. Heavy oxidation was observed on samples after just one hour. The γ matrix is clearly visible on a polished specimen (Figure 4). The etched sample also exhibited rapid oxidation, after one hour the γ matrix had become much thicker and less well defined (Figure 5a and 5b) show the matrix before and after heat treatment.

After 256 hours the polished sample had oxidised further, the oxidised γ matrix was clearly more prominent than after 1 hour exposure. Oxidation was not consistent across the surface of each specimen. Small blemishes and areas of lighter and heavier oxidation can be observed. Light areas of the same order as the dendrite spacing are visible on the etched sample after 256 hours.

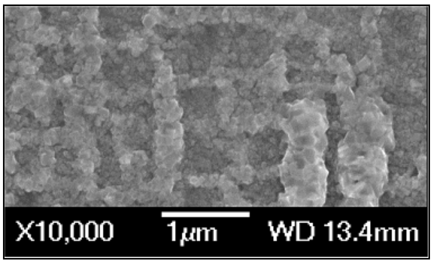

Figure 4 - Polished Sample after 1 hour at 650°C Gamma matrix is clearly visible

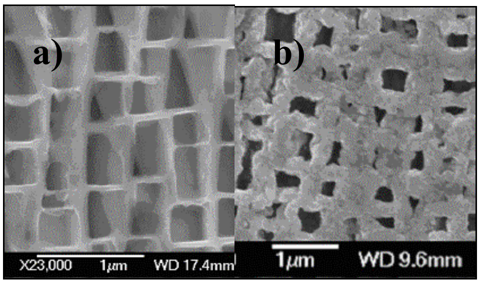

Figure 5 - Etched sample before (a) and after (b) heat treatment

DISCUSSION

Crack initiation in all but one high temperature test occurred at subsurface pores, this agrees with observations in the literature [i, ii, iii]. Such initiation is characterised by a halo around the pore where initial crack growth has occurred in vacuum. The proposed mechanism that causes this halo effect is due to the crack initiating and propagating in vacuum until it breaks the surface of the sample and is exposed to air. Initial crack propagation conditions are that of fatigue crack propagation in vacuum. Once air can enter the crack, the initial fatigue area within the halo undergoes oxidation, *after* failure has occurred. The boundary of the halo marks the point at which the crack continues to propagate, but now under combined fatigue and oxidation conditions. The two mechanisms described give rise to the change in texture and composition of the oxidised fatigue crack (Figure 2 & Figure 3). Similar halo effects have been seen in polycrystalline disk alloys [iv]. It is not yet fully understood why cracks do not initiate at the notch surface at higher temperatures. There may be sufficient oxidation of the surface pores to effectively plug them up therefore reducing the stress concentration induced by the pore - similar to oxide induced closure effects. The stress/strain fields below the notch surface may change/redistribute at higher temperatures thus making sub surface initiation more likely. Some initial analytical work has been done to understand the effects of sub surface pore geometry. A simple analysis of pore aspect ratio has been conducted using Scott and Thorpe's approximation for a semi-elliptical surface crack [v]. A pore area was selected that was representative of those observed to initiate cracks. The ratio of a/c was varied whilst keeping the area of the pore constant. A pore with high aspect ratio with major axis parallel to the notch surface gives the highest value of K_d (stress intensity at the maximum depth position). The secondary orientation of the single crystal will affect the direction in which interdendritic pores form and therefore could affect initiation behaviour if further analysis shows that the angle/orientation of the pore is important.

CONCLUSIONS

- Initiation of fatigue cracks is affected by critical pore size, angle, position and aspect ratio. The angle of the pores may be a direct effect of the secondary orientation of the specimen as pores are normally interdendritic.
- Coalescence of the fatigue cracks depends on initial distribution of initiating features (porosity). Pores have also been seen to cause temporary crack arrest which can add to the specimen lifetime.

FURTHER WORK

Further work relevant to this report consists of: sectioning and observation in SEM of some current test specimens and oxidation study specimens, a literature search for Oxidation of CMSX4. Also a further set of run out tests (650°C orientation A and B) on sub size CMSX-4 test specimens has been planned in order to generate S-N data and more porosity data from fracture surfaces.

ACKNOWLEDGEMENTS

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