THE HIGH TEMPERATURE FATIGUE OF A NICKEL-BASE SUPERALLOY : THE INFLUENCE OF WAVEFORM VARIABLES

D.M. Knowles* and D.K. Skelton*

*Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, UK, CB2 3QZ

ABSTRACT

The drive for improved understanding of turbine disc alloys at elevated temperatures has led to an increased interest in the contribution of time-dependent mechanisms to high temperature fatigue crack growth. A study has been conducted on a new powder disc alloy to investigate the contribution of these mechanisms when the applied waveform is varied in terms of ramp rates and hold periods. Variable waveform tests performed in air and vacuum at 725°C have indicated that the hold period at maximum load causes the greatest acceleration in growth rate. In air, the ramp up is slightly more damaging than the ramp down and it is suggested that this is due to a fatigue/environment interaction. In vacuum no difference between ramp up and ramp down is observed, but at low stress intensity, a hold at minimum load was observed to cause retardation in crack growth, which may be attributable to either a blunting or crack tip annealing process. An extension of the duration of the hold at maximum load was observed to cause an acceleration in crack growth but not to induce intergranular cracking. It is suggested that the effects may be attributed to the influence of creep on the crack growth process. The linear summation model was shown to accurately predict growth rates in air but to over predict in vacuum.

KEYWORDS

High temperature, fatigue crack growth, nickel superalloy, waveform, vacuum

INTRODUCTION

The drive for improved gas turbine engine performance has led to an increase in the required temperature capability of the turbine disc alloys namely the polycrystalline nickel-base superalloys. As operation temperatures increase, time-dependent mechanisms begin to contribute to the fatigue crack growth process and growth rates per cycle (da/dN) increase.

The environment is well known to have a significant effect on the growth rate of fatigue cracks through polycrystalline nickel base superalloys, especially at lower frequencies [1,2,3]. Frequency, and cycle waveform can have a profound effect on measured crack growth rates, their influence being functions of temperature, alloy composition, grain size and heat treatment. Often an increase in growth rate is associated with a transition in the crack path from transgranular to an intergranular mode as the crack follows embrittled grain boundaries [1,4,5,6]. A previous study [7] conducted by the authors has demonstrated the influence of frequency on crack growth behaviour of a nickel based superalloy manufactured via a powder metallurgy route and the ability of a simple linear summation in predicting the effect of frequency on crack growth rates. Predictions in air were generally good but an under prediction observed on reduction in frequency at a stress intensity of 17 MPam1/2 and R ratio of 0.5 was proposed to be due to an environmental/fatigue interaction occurring during the loading or unloading part of the cycle. Understanding of the influence of waveform on the FCG of nickel base superalloys is relatively limited. In particular there has been little research into the effect of strain rate on crack growth. The literature suggests the importance of the ramp up over the ramp down during loading [8] and a mechanism has been proposed previously by Clavel et al. [9] based on the planarity of slip that may explain the effect of frequency on FCG modes and rates. More literature exists to explain the influence of dwell time on FCG [5,10] . The addition of hold time at maximum load allows processes such as creep and environmental damage which are not only time dependent but also dependent on stress state at the crack tip to be enhanced. In the majority of cases, this leads to acceleration in crack growth rate. However, studies by Sadananda et al [11] on Inconel 718 show that time dependent mechanisms which cause a transition to intergranular growth which can lead to crack closure, branching or deflection, may result in a reduction in growth rate per cycle.

This paper presents results from a continuing investigation into high temperature fatigue of a new fine grained nickel based superalloy produced by a powder metallurgy route, specifically addressing the influence of waveform variables and comparing the experimental results with predictions made using a linear summation model.

EXPERIMENTAL PROCEDURE

The material used throughout the course of this work was produced via a powder route with a composition limit listed in table 1 and had been supplied in the forged and heat treated condition. This gave it a 0.2% proof stress of 1020MPa at 725°C. Optical microscopy was carried out following electrolytic etching with 10% phosphoric acid in distilled water. For fatigue crack propagation tests a single edge notch (SENB) specimen geometry was used throughout the programme. Testing was conducted using a computer controlled servo-hydraulic 150 kN 'Mand' machine. The direct current potential difference (dcpd) technique was used to monitor crack growth and throughout testing, temperature, cycle count, notch voltage, maximum and minimum load and elapsed time were monitored and logged by a computer control and data acquisition system. High temperature testing was conducted using a quartz lamp heating arrangement within a vacuum chamber capable of maintaining a pressure of 10^{-6} mbar at temperature.

TABLE 1
COMPOSITION RANGE OF DISC ALLOY

Element	Cr	Co	Mo	Al	Ti	Ta	Hf	Zr	C	B
Wt%	14.35 15.15	14 19	4.25 5.25	2.85 3.15	3.45 4.15	1.35 2.15	0 1.0	0.05 0.07	0.012 0.033	0.01 0.025

Constant stress intensity factor range (ΔK) tests at varying cycle period were conducted using a trapezoidal waveform, with an R-ratio of 0.5. This waveform consists of a cycle that contains a linear ramp up to maximum load, a hold period, a ramp down to minimum load and a hold time at the minimum level. The four stages of the load cycle were altered independently to investigate the influence of each of the waveform variables. Total cycle period of 12 and 21 seconds were employed in this process, the time period of all variables but one being held at 1 second and the variable of interest changed to either 9 or 18 seconds (depending on cycle period). The tests were conducted in air and vacuum at 725 °C at ΔK values of 30 and 17 $MPa^{1/2}$.

Fractography was performed on a Jeol 6340F SEM. Side profile micrographs were taken using the SEM at an angle of approximately 65° to the fracture surface and this enabled one to establish more clearly the prominent crack growth mode.

RESULTS

A typical optical micrograph of the material is illustrated in figure 1. It generally consists of a uniform fine grain size of 15 microns. Large primary γ' particles exist at the grain boundaries which have not been dissolved by the solution heat treatment. The total γ' volume fraction consisted of around 50% with a typical secondary size of 300-350nm [7]

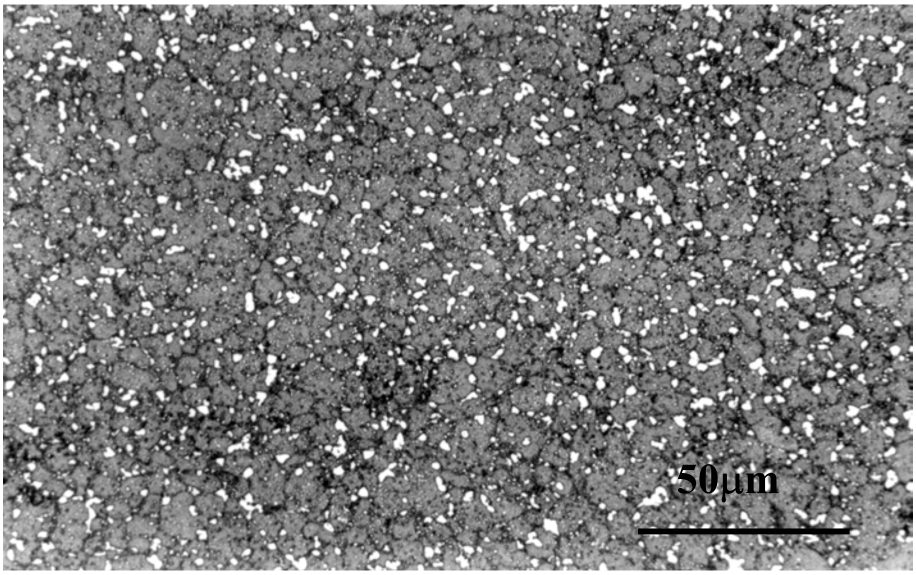

Figure 1: Optical micrograph of alloy

The results of the variable frequency constant ΔK=17&30 $MPam^{-1/2}$ tests conducted in air and under vacuum at 725°C and associated predictions are illustrated as a composite plot in figure 2. The data is arranged in sets corresponding to the environment, stress intensity range and cycle period conditions. Also included on this figure are predictions of growth rates using a simple linear summation model:

$$\frac{da}{dN} = \int_{t=0}^{t=1/\upsilon} \frac{da}{dt}(t)dt + \frac{da}{dN_{cyclic}} \tag{1}$$

In this model, static crack growth rates as a function of stress intensity factor K have been taken from a previous study on the material where they have been shown to follow the form:

$$\frac{da}{dt} = CK^n \tag{2}$$

in both air and vacuum. The values for the cyclic portion of the model have been taken as the measured growth rates at 20 Hz.

The fatigue crack growth results presented in figure 2 demonstrate that under any set of loading conditions the crack growth rates in vacuum are lower than those observed in air (in this figure A and V refer to air/vacuum, subsequent numbers relate to ΔK and the cycle period). At the lower ΔK this extends to over two orders of magnitude. Consideration of the effect of each waveform variable during this investigation demonstrates clearly that the application of a hold at maximum load caused the greatest acceleration in crack growth rate irrespective of the loading and environment conditions. Furthermore, in air, crack growth rates for the standard baseline 1-1-1-1 (0.25 Hz) cycle period data were significantly lower than that of the 12 and 21 second data, i.e. a hold at maximum or minimum load or a ramp up or down caused an increase in the crack growth rate per cycle when compared to the baseline. In vacuum this discrepancy was not so large and at ΔK=17 MPam$^{1/2}$ crack growth rates relating to the standard 0.25 Hz data were actually greater than those rates observed when a hold was applied at minimum load.

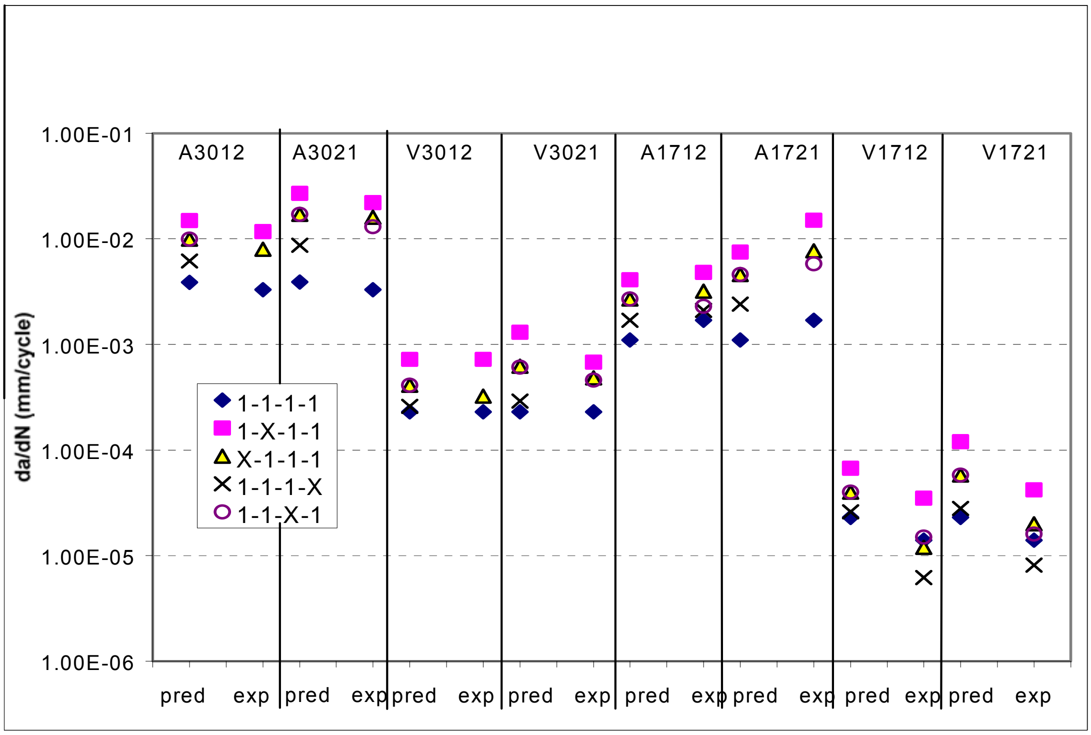

Figure 2: Results of variable waveform tests along with predictions from linear summation model as marked at the bottom of the columns. References at the top of the columns refer the air/vacuum, ΔK and total cycle period respectively.

The ramp to maximum load leads to a higher growth rate than the ramp down, when testing is conducted in air. This is most prominent for the lower ΔK test. In vacuum there is a negligible difference between growth rates for either ramp over all the tests undertaken within experimental error.

TABLE 2
SUMMARY OF THE CRACK MORPHOLOGY FOR EACH OF THE WAVEFORM VARIABLE CONDITIONS. I=INTERGRANULAR, M=MIXED MODE, T=TRANSGRANULAR.

	A3012	A3021	V3012	V3021	A1712	A1721	V1712	V1721
1-1-1-1	I	I	M	M	I	I	T	T
X-1-1-1	I	I	M	I	I	I	T	T
1-X-1-1	I	I	I	I	I	I	T	T
1-1-X-1	-	I	-	I	I	I	T	T
1-1-1-X	-	-	-	-	I	I	T	T

The crack growth modes in this material can be difficult to discern due to the fine nature of the microstructure, particularly in the regime of mixed mode. Detailed fractography on both surface and side profiles is summarised in table 2 as either predominantly transgranular (T), intergranular (I) or mixed mode (M). Intergranular has been defined when no definite areas of transgranular cracking have been observed. The table indicates that mixed mode cracking was visible in vacuum for the standard baseline test and where a 9 second ramp to maximum load was applied at ΔK=30 MPam$^{1/2}$. Apart from these instances the mode of failure could be clearly separated into the two distinct regimes of inter or transgranular crack growth. All the tests conducted in air displayed fully intergranular growth although this was associated with differing degrees of crack bifurcation, which was observed to increase as the hold time was extended. In contrast for the vacuum tests at ΔK=17MPa$^{1/2}$ all the observed fracture profiles were transgranular, despite the fact that there existed a discernible influence of hold time on growth rates.

DISCUSSION

At maximum load the crack tip opening displacement is at its greatest, maximising the extent of the strain field ahead of the crack tip. In air oxygen can sweep in along slip planes and the application of a hold allows deeper oxygen penetration. The longer the time available for the ingress of oxygen the more damage that can be accumulated in the form of internal oxidation and grain boundary embrittlement. This leads to intergranular cracking as has been observed in this study and an acceleration in the crack growth per cycle. As the extent of the hold is increased a larger amount of grain boundary embrittlement is able to occur throughout the strain field. This manifests itself as an increase in the degree of intergranular and secondary cracking, crack bifurcation and crack growth as observed in the current study. These observations support of the work by James [6] and Branco et al [10] where, following their logic it can be concluded that the tests have been conducted below the base cycle frequency sufficient to induce intergranular cracking. Although in air the hold time is the dominant parameter, which is no doubt an influence of both the high temperatures employed and the fine grain size of the material, a measurable difference in growth rate between ramping up and down was also observed in air. Although much shorter ramp times are employed and a high test temperature is used, these observations support the conclusions of Byrne et al [8] on Waspaloy although the differences measured are much less pronounced. Although it is difficult to draw definitive conclusions it is likely that oxygen is being swept in along slip planes during the ramping up section of the waveform that subsequently interacts with the fatigue process reducing the crack growth resistance [5]. Naturally the simple linear summation model does not pick up the influence of ramp rate. It assumes that transgranular and intergranular processes occur independently. The comparisons shown in figure 4 demonstrate that such a model is able to make a reasonably good approximation to experimental growth rates for all the variable waveform conditions. The model mirrored trends observed on alteration of the waveform and there is a reasonable close correlation between experimental and predicted growth rates, especially in regard to the typical levels of scatter associated with such testing. It is thought that this arises because time dependent mechanisms are dominating crack growth in air under these conditions [7].

Previous analysis using the linear summation model demonstrated that over prediction of growth rates in vacuum was a general observation [7]. This was attributed to the fact that in the sustain load crack growth tests initial transients were observed owing to a delay in rates reaching stable values on application of a load as would occur in the fatigue conditions experienced at the crack tip here. In effect the linear summation model assumes immediate stability of crack growth during the hold periods and it is this which leads to the over prediction. Figure 2 demonstrates that this was the case when attempting to predict the crack growth rates observed in vacuum for variable waveform conditions. The only exception appears to be at ΔK=30 MPam$^{-1/2}$ for the 9 second hold. This would appear to be an anomaly associated with scatter as it is not reflected in the longer hold where over prediction again occurs although a more accurate result would be expected from the longer hold time. Unlike air the vacuum data shows no definite trend in the crack growth rates for ramping up and down. This supports the view that environmental rather than creep processes must be influencing the ramping sections of the waveform in air. Crack growth rates increase with hold time and if time dependent growth mechanisms are in operation this often manifests itself in the form of intergranular regions, however all the fracture surfaces in this instance were transgranular. As discussed by Crompton and Martin [12] creep relaxation could increase the plastic zone size if there is sufficient time for creep processes to occur. Crack tip plasticity is associated with the yield stress and it is conceivable that under conditions where creep is able to occur, longer hold periods will lead to higher crack tip strain ranges. If this occurs an acceleration of crack growth rate per cycle would be observed for a transgranular growth mode. Interestingly a hold at minimum load at ΔK=17 MPam$^{1/2}$ led to a decrease in growth rates. The reasons for this again may well be associated with creep as postulated by Shahinian et al [13] leading to blunting during the minimum load hold, which serves to impede the progress of the crack. Alternatively one could consider that recovery processes could be operating which anneal out damage due to strain hardening. Crack growth during transgranular cracking is dependent on the reversibility of slip so an increase will reduce the crack growth resulting from cyclic deformation at the crack tip lowering growth rates. Pressure welding of asperities during the minimum hold is also a possibility die the high temperatures and low vacuums involved, but this is unlikely to be possible at such high R-ratios which would hold the crack tip faces apart.

CONCLUSIONS

Variable waveform tests performed on a powder disc alloy in air and vacuum at 725°C demonstrated that the hold at maximum load caused the greatest acceleration in growth rate. In air, the ramp up has been shown to be more damaging than the ramp down and it is suggested that this is due to a fatigue/environment interaction. In vacuum at low stress intensity, a hold at minimum load was observed to cause a retardation in crack growth which may be attributable to a blunting or crack tip annealing process. An extension of the duration of the hold at maximum ramp up or down was observed to cause an acceleration in crack growth but not to induce intergranular cracking. It was suggested that the affects were due to the influence of creep on the crack growth process. The linear summation model was shown to accurately predict growth rates in air but to over predict in vacuum.

ACKNOWLEDGEMENTS

The authors are grateful to EPSRC, Rolls Royce and DERA for financial support and supply of material.

REFERENCES

1. Pedron, J. P. and Pineau, A., (1982) *Mater. Sci. Engng,* 56, 143
2. Gayda, J., Gabb, T. P. and Miner, R. V., (1988), Low Cycle Fatigue, ASTM STP 942, Eds H D Sobran et al., ASTM, 293
3. Gabrielli, F. and Pelloux, R. M., (1982) *Met. Trans. A*, 13A , 1083
4. Andrieu, E., Molins, R., Ghonem, H. and Pineau, A., (1992) *Mater. Sci. Engng.*, A154, 21
5. Lynch, S. P., Radthe, T. C., Wicks, B. J., and Byrnes, R. T., (1994), *Fatigue Fract. Engng. Mater. Struct.*, 17, No 3, 297
6. James, L. A., (1986), *Engng Fract. Mech.*, 25, No 3, 305
7. Knowles, D.M. and Skelton, D.K., (2001), submitted to *Mater. Sci. Tech.*
8. Byrne, J., Hodkinson, V. and Tong, J., (1999), Fatigue '99, 2171, Wu, X.R. and Wang, Z.G. (Eds).,Higher Education press EMAS, Beijing.
9. Clavel, P and Pineau, A, (1978), *Met. Trans. A.,* 9A, 471
10. Monra Branco, C., Byrne, J and Hodkinson, V., (1996) Mechanical Behaviour of Materials at High Temperature, Ed. Monra Branco C. et al (Eds), NATO ASI Series, 93, Portugal
11. Sudananda, K. and Shahinian, P., (1981), *Metallurgical Society of AIME*, 86.
12. Crompton, J. S. and Martin, J. W., (1984), *Mater. Sci. and Engng.,* 64, 37.
13. Shahinian, P. and Sudananda, K., (1979), *Transactions of the ASME*, 101, 224.