ELEVATED TEMPERATURE FATIGUE CRACK GROWTH MODEL FOR DS-GTD-111

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ABSTRACT

The removal of grain boundaries normal to the principal loading direction with the introduction of directionally solidified (DS) grains has significantly improved creep strength, resistance to thermal fatigue, crack growth and oxidation. In this study, a model is developed for representing and predicting the high temperature fatigue crack growth behavior of directionally solidified Ni base alloy, DS GTD-111. A new physically-based model is proposed that accurately represents the influence of temperature on the fatigue crack growth behavior.

The test material was cast in the form of slabs that were approximately 254 mm long, 197 mm wide and 32 mm thick. Fatigue crack growth tests were carried out using 50.8 mm wide compact type specimens at 24, 649, 760 and 871°C in LT and TL orientations. The results showed that the dependence of the fatigue crack growth exponent, *m*, on the test temperature as well as the specimen orientation was weak. Hence, *m* was considered as constant in the temperature ranges considered in this study for both specimen orientations. The fatigue crack growth coefficient, *c*, was seen to increase with increasing temperature. A model based on thermal activation of dislocations is developed and shown to represent all the data.

1. INTRODUCTION

The performance of natural gas-fired turbines has steadily improved with the continuous development of advanced materials and design concepts for hot gas path components. The use of directionally solidified (DS) superalloy with adequate coatings has significantly improved the limitations inherent to equiaxed materials in the areas of oxidation and corrosion resistance, thermal and low cycle fatigue resistance, creep resistance and high cycle fatigue resistance. Since these materials are being pushed to the limits of their capability, accurate mathematical models are needed to predict the lives of hot-section components to prevent unscheduled outages due to sudden failures. There is also a need to develop realistic inspection intervals to further safe-guard against sudden failures, but these recommended inspection intervals cannot be too frequent to maintain economic viability. Therefore, the importance of accuracy in the models for predicting in-service performance cannot be over-emphasized. In this study, a model is developed for representing and predicting the high temperature fatigue crack growth behavior of directionally solidified Ni base alloy, DS GTD-111. A new physically-based model is proposed that accurately represents the influence of temperature on the fatigue crack growth behavior.

2. EXPERIMENTAL PROCEDURE

Rectangular test blocks of constant thickness from DS GTD-111 were specially cast because they are convenient in size and shape for machining large number of specimens. The test material was cast in the form of slabs that were approximately 254 mm (10 in) long, 197 mm wide (7.75 in) wide and 32 mm (1.75 in) thick. The grains were oriented along the length of the test blocks labeled “L”. The direction normal to L was labeled “T”. The nominal chemical composition of the alloy is given in Table 1. Standard compact type specimens, C(T), that were 50.8 mm wide and 12.7 mm thick were machined from the test block in the

LT and TL directions. In the LT specimens, the loading direction is in the longitudinal (L) direction and the crack growth direction is the T direction. In the TL orientation, T is the loading direction and L is the direction of crack growth.

Table 1 - Nominal chemical composition of DS GTD-111 alloy (wt %)

Ele.	Cr	Co	Al	Ti	W	Mo	Ta	C	Zr	B	Fe	Si	Mn	Cu	P	S	Ni
Min	13.7	9.0	2.8	4.7	3.5	1.4	2.5	.08	.005	.005	-	-	-	-	-	-	Bal.
Max	14.3	10.0	3.2	5.1	4.1	1.7	3.1	.12	.040	.020	.35	.30	.10	.10	.015	.005	Bal.

The microstructure of the test material consists of longitudinal grains that are approximately 150 mm in length and 5 mm wide. There are also small pores that are part of the microstructure that may also influence the mechanical properties. At a higher magnification, there appears to be γ' of two sizes, the cooling γ' that is approximately on the order of a micron in size and the aging γ' that is an order of magnitude smaller. Table 2 lists the 0.2 % yield strength and the other tensile properties in the longitudinal and transverse directions as a function of temperature. The strength in the longitudinal direction at each of the temperatures is higher than in the transverse direction. The yield strength in both directions seems to continuously decrease with temperature except for the anomalous region between 649 C (1200 F) and 760 C (1400 F) when the yield strength rises with increase in temperature.

Fatigue crack growth tests at different temperatures were performed according to the procedures specified in ASTM E647 with one exception. The specimens were side-grooved by 10% of the thickness on each side of the specimen surfaces for a total thickness reduction of 20% following fatigue crack growth. Side-groove prevents crack tunneling and helps in-plane crack growth during the crack growth testing at elevated temperature. Initial crack size to width ratio (*a/W*) was about 0.35. The DC electric potential technique was employed for crack length monitoring during fatigue crack growth tests at high temperature. Potential output data were collected automatically by TestStar II data acquisition system of the MTS servo-hydraulic tester. Since thermal voltage could not be measured by this system, it was measured manually after turning off the input current periodically. The measured thermal voltage was subtracted from the potential output.

Table 2- 0.2% Yield Strength for DS GTD –111 as a function of temperature

Temp	0.2% Yield Strength (MPa)		Tensile Strength (MPa)		Area Reduction (%)		Elongation (%)	
°C	L	T	L	T	L	T	L	T
21	977	817	1115	837	5.9	16.3	7.0	10.0
649	825	731	1110	876	7.8	15.0	7.0	9.8
760	903	776	1108	974	13.5	11.4	12.9	7.8
871	669	666	802	834	22.3	16.7	23.1	9.1

3. RESULTS AND DISCUSSION

Fatigue crack growth tests were conducted at loading frequency of 0.5 Hz using a triangular waveshape with equal time for loading and unloading. Duplicate tests were conducted for each test condition of eight different combinations of LT or TL direction and 24, 649, 760 or 871°C test temperatures for a total of sixteen tests. The da/dN versus ΔK test results are shown in Figs. 1 and 2 for LT and TL direction respectively. For both directions, it was clearly shown that the crack growth rate increases with test temperature. Fatigue crack growth rate is generally expressed as a function of ΔK by Paris' law as follows:

$$\frac{da}{dN} = c \cdot (\Delta K)^m \tag{1}$$

The coefficient, *c*, and exponent, *m*, were determined by linear regression of log(da/dN) and log(ΔK) data for each test condition using duplicate tests. The exponent, *m*, seems to be independent of the test temperature in both of LT and TL directions. And it was observed that the *m* value at 649°C values were smaller than the other cases. In order to determine the effect of specimen direction the LT and TL data at the same temperature were compared. At the temperatures of 649, 760 or 871°C the crack growth rates appear to be higher in the TL orientation even though the differences are marginal. This trend is reversed at the room temperature where the crack growth rate in the TL orientation was higher.

Figures 1 and 2 clearly show that the fatigue crack growth rate is increases with increasing temperature. Hence it has been generally accepted that the coefficient, *c*, in Eq (2) is a function of test temperature. For the directionally solidified GTD-111 alloy dependence of *c* and *m* on the temperature is not known. Thus, to begin with it can be assumed that both are temperature dependent. Yokobori et al [1-3]explained temperature dependence of fatigue crack growth based on dislocation dynamics theory. They postulated that crack tip stresses under cyclic loading are sufficiently high to produce instantaneous generation of dislocation loops and no thermal activation is required. However, once the dislocation movement occurs its velocity is a "thermally activated process". They further postulated that dislocation motion drives plastic crack extension and argued that the crack propagation is also expected to be thermally activated with activation energy being the same as that for dislocation movement [3]. Similar arguments are also found in other studies [4 – 9]. Thus, equation (1) is modified as follows:

$$\frac{da}{dN} = c_o \cdot \Delta K^{m_o} \cdot \exp\left(-\frac{Q_o - c_1 \cdot \log \Delta K}{RT}\right) = c_o \cdot \Delta K^{m_o + \frac{c_1}{RT}} \cdot \exp\left(-\frac{Q_o}{RT}\right) \tag{2}$$

Where, R is the gas constant which is 8.3143 J/mol·K, T is the absolute temperature in Kelvin, Q_o is the activation energy. c_o, c_1 and m_o are material constants independent of temperature. Perhaps *K_{max} might be a more appropriate parameter in representing thermal activation than ΔK.* In this study, the load ratio was chosen as 0.1 and the difference between using K_{max} versus ΔK are only marginal. These constants can be determined from several sets of fatigue crack growth data obtained at different temperatures.

The exponent, *m*, did not consistently increase or decrease with test temperature as seen in Table 3 and the dependence was weak. Thus, *m* was considered as a constant in the temperature ranges considered in this study. There was also no significant difference in *m* among LT and TL specimens. The mean value of *m* determined with all of the LT and TL specimens was 3.765. Therefore, for representing the temperature dependence of crack growth rate, the exponent, *m,* was fixed as the mean value while the crack growth coefficient, *c*, was considered as the only parameter changing as a function of temperature and orientation. The values of *c* corresponding to a value of *m* of 3.765 were recalculated and summarized in Table 4 and the regression lines with a fixed slope are shown in Fig 4. It is seen that the data are well represented by the regression equations using a common value of *m* at all temperatures in both orientations. The crack growth coefficient, *c*, was increased with temperature for both LT and TL specimens. If *m* in Eq (2) is not a function of temperature, the equation simplifies to:

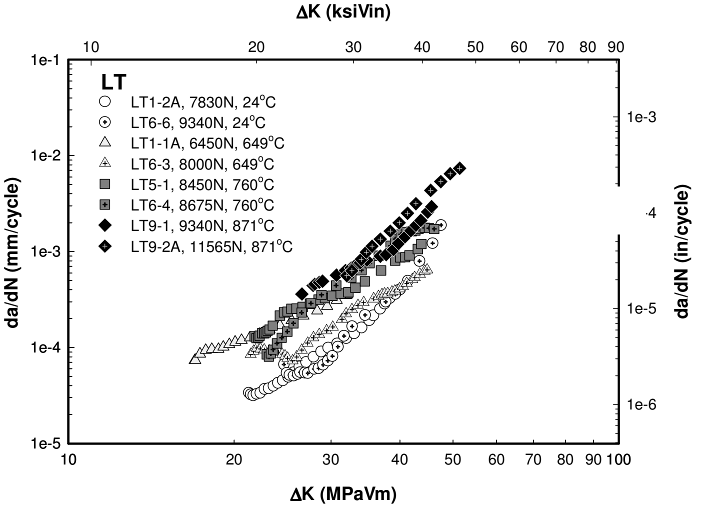

Fig. 1- Fatigue crack growth rate at different temperatures in the LT orientation

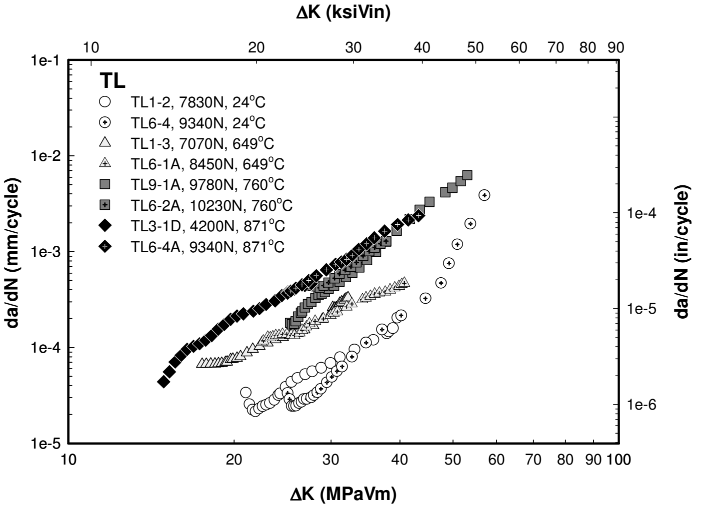

Fig. 2- Fatigue crack growth rate at different temperatures in the TL orientation

$$\frac{da}{dN} = c_o \cdot \exp\left(-\frac{Q_0}{RT}\right) \cdot \Delta K^{m_o} \tag{3}$$

and the value of *c* reduces to,

$$c = c_o \cdot e^{-\left(\frac{Q_o}{RT}\right)} \quad \text{or} \quad \ln c = \ln c_o - \frac{Q_o}{R} \cdot \frac{1}{T} \tag{4}$$

From regression analysis, Eqs (5) and (6) were determined representing the fatigue crack growth behavior of DS GTD-111 as a function of *ΔK* and temperature for the LT and TL orientation, respectively.

$$\frac{da}{dN} = 5.200\times10^{-8} \cdot e^{-\frac{486.7}{RT}} \left(\Delta K\right)^{3.765} \quad \text{for LT orientation} \tag{5}$$

$$\frac{da}{dN} = 1.714\times10^{-7} \cdot e^{-\frac{606.5}{RT}} \left(\Delta K\right)^{3.765} \quad \text{for TL orientation} \tag{6}$$

In these equations, da/dN is expressed in mm/cycle and ΔK in MPa√m. The activation energy in fatigue for DS GTD-111 alloy was 486 J/mol for LT and 606 J/mol for TL direction. Equations (5) and (6) were rewritten in the following form:

$$\frac{da}{dN} \cdot e^{\frac{Q_o}{RT}} = c_o \left(\Delta K\right)^{m_o} \tag{7}$$

In Fig. 3, we show the fits for the above equation to all the data clearly demonstrating that the model does an accurate job of representing the data at different temperatures over a very wide range.

4. CONCLUSIONS

5.

A mathematical model based on the physics of thermally activated dislocation motion is developed to represent the effects of temperature over a wide range for a DS GTD-111 Ni base alloy in the LT and TL orientations. The model predictions compare well with extensive amounts of fatigue crack growth data also developed as part of the study.

6. ACKNOWLEDGEMENTS

7.

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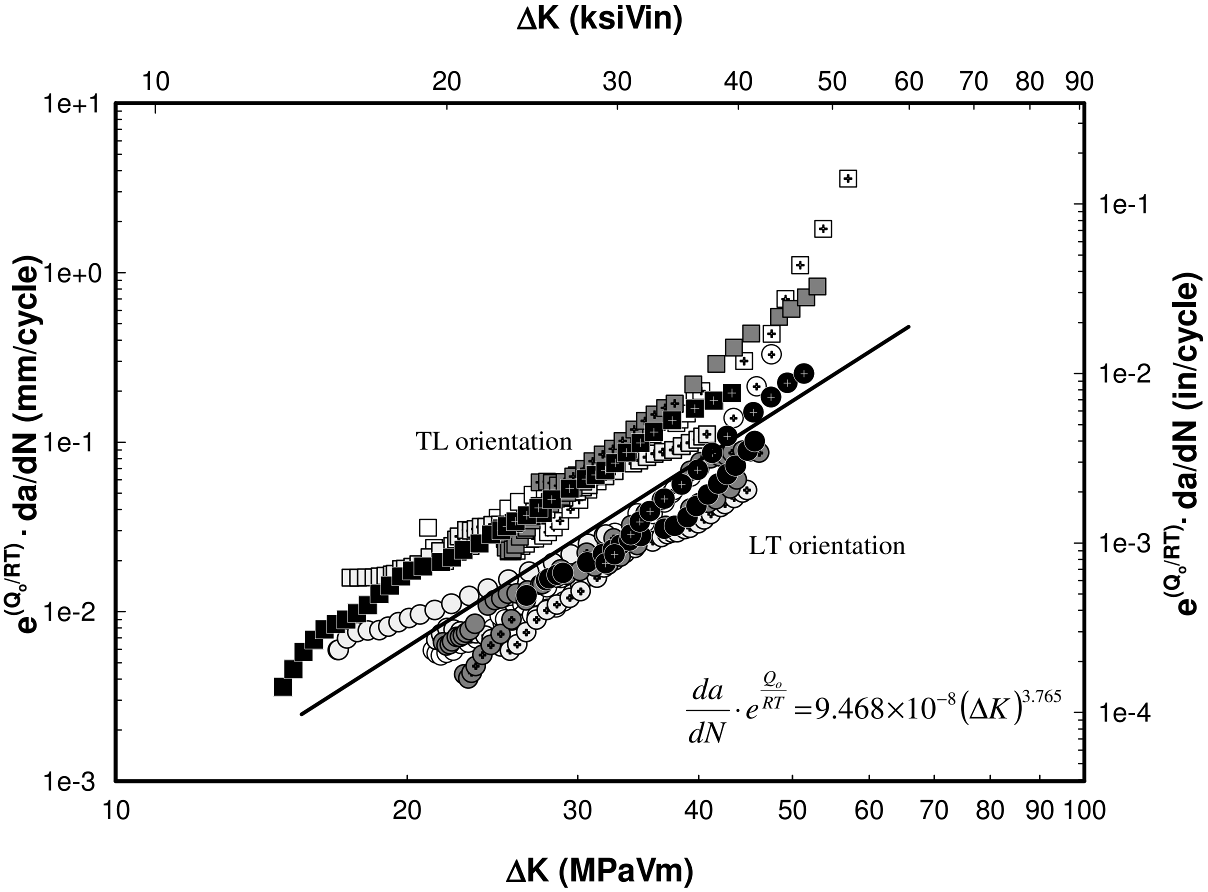

Fig. 3- Normalized *da/dN* vs Δ*K* curves for both of LT and TL specimens of DS GTD-111 alloy