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Relationship between unusual high-temperature fatigue crack growth threshold behavior in superalloys and sudden failure mode transitions

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A B S T R A C T

An investigation of high temperature cyclic fatigue crack growth (FCG) threshold behavior of two advanced nickel disk alloys was conducted. The focus of the study was the unusual crossover effect in the near-threshold region of these type of alloys where conditions which produce higher crack growth rates in the Paris regime, produce higher resistance to crack growth in the near threshold regime. It was shown that this crossover effect is associated with a sudden change in the fatigue failure mode from a predominant transgranular mode in the Paris regime to fully intergranular mode in the threshold fatigue crack growth region. This type of a sudden change in the fracture mechanisms has not been previously reported and is surprising considering that intergranular failure is typically associated with faster crack growth rates and not the slow FCG rates of the near-threshold regime. By characterizing this behavior as a function of test temperature, environment and cyclic frequency, it was determined that both the crossover effect and the onset of intergranular failure are caused by environmentally driven mechanisms which have not as yet been fully identified. A plausible explanation for the observed behavior is proposed.

1. Introduction

The use of damage tolerance methodology to meet engine certification requirements of nickel-based turbine rotating components requires extensive characterization and thorough understanding of the fatigue crack growth processes of turbine disk alloys. Of particular importance for achieving accurate damage tolerance life predictions is the threshold fatigue crack growth behavior under both cyclic and hold time conditions which consumes the bulk of the crack growth lives. While extensive work has been published in the literature over the years in regards to the high temperature FCG behavior of nickel-based superalloys in the Paris regime (i.e. at the intermediate and higher crack growth rates), relatively little research has appeared in publications on the near-threshold FCG behavior. However, the studies which have been published suggest that the high temperature cyclic FCG near-threshold behavior of superalloys may differ considerably from that observed in other classes of alloys [1–6].

It is well established that nickel-based superalloy mechanical properties are sensitive to environmental degradation as temperatures are increased, especially for test temperatures exceeding 538 °C (1000 °F) [7]. In terms of cyclic FCG behavior, an increase in temperature results in substantial increase in FCG rates. For instance, ME3 turbine disk alloy exhibits over an order of magnitude faster cyclic FCG rates at 704 °C in comparison to 204 °C [8]. The sensitivity of dwell FCG (DFCG) behavior to temperature is even more pronounced, with a number of disk alloys exhibiting a 10× increase in crack growth rates for every 56 °C (100 °F) increase in test temperature at temperatures exceeding 594 °C (1100 °F) [9].

The unusual high temperature superalloy FCG near-threshold behavior can be ascertained from data published on Alloy 718 (1), Astroloy (2), KM4 (3,4)) and Alloy 720Li (5). In most classes of metal alloys, higher Paris regime FCG rates are typically associated with either lower or similar threshold FCG stress intensities [10–12]. This is especially evident when FCG rates are plotted in terms of the applied minimum/maximum stress ratio (R) where the higher stress ratios produce considerably higher Paris regime FCG rates and lower thresholds [13]. However, the work on Alloy 718 (1) and Astroloy (2) demonstrated that while an increase in the test temperature significantly increased the Paris regime cyclic FCG rates, a crossover occurs in the near-threshold regime resulting in considerably higher FCG threshold stress intensities, $\Delta K_{th,}$ occurring at temperatures where environmental degradation is also known to occur. Yuen et al. [1] ascribed this effect in Alloy 718 to oxide induced crack closure significantly reducing the effective crack driving force, ΔK_{eff}. They postulated that oxide kinetics were important in increasing the oxide thickness at elevated temperatures to levels which affected the crack

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driving force. However, the crossover effect persisted even at high R ratios where the influence of oxide induced closure should have been significantly diminished. Shyam et al. [3] found that for KM4 disk alloy tested, not only test temperature but also test frequency has an effect on cyclic FCG thresholds, with lower frequencies increasing the threshold stress intensities. In a recent study of Alloy 720Li, Li et al. [5] demonstrated that thresholds for dwell FCG where intergranular failure mode is dominant, are higher than for cyclic FCG tests even though the crack growth rates in the Paris regime are an order of magnitude higher for the DFCG tests. They postulated that crack tip blunting, which occurs during prolong dwells, reduces the crack driving force which in turn is responsible for the higher threshold stress intensities.

Due to the importance of the near-threshold FCG behavior on life prediction as well as the lack of clear understanding of the mechanisms causing the unusual threshold behavior in superalloys, the current study re-examines this issue by focusing on the effect of temperature, frequency and the environment on near-threshold FCG behavior of two nickel-based powder metallurgy (P/M) disk alloys, ME3 and LSHR. Particular attention in the study has been paid to the governing failure modes and their relationship to the near-threshold FCG behavior.

2. Experimental

2.1. Materials and heat treatment

Blanks of forged LSHR and pancake forgings of ME3 disk alloys of compositions shown in Table 1, were heat treated and given a two-step aging treatment. LSHR blanks were solutioned for 2 h at 1171 °C and aged at 855 °C/4 h and 775 °C/8 h to achieve a supersolvus microstructure with an average grain size of approximately ASTM 8. ME3 forgings were solutioned at 1171 °C for 2 h and aged at 843 °C/4 h and 760 °C/8 h to achieve a supersolvus microstructure with an average grain size of approximately ASTM 7. Typical resulting microstructures are shown in Fig. 1.

2.2. Fatigue crack growth testing

All crack growth testing was performed using the surface flaw, Kb bar specimen geometry with crack lengths measured by a computerized direct current electrical potential (DCEP) drop system. All specimens were pre-cracked at room temperature. Most of the testing was performed at 704 °C in air with selected testing also done at 538 °C and 760 °C. To determine the effect of the environment, a small subset of tests was performed in a vacuum chamber at a 10^{-7} Torr pressure range. After room temperature pre-cracking, threshold testing was performed with the approximate initial stress intensity range (ΔK) of 24 MPa√m. Due to the geometry limitations imposed by the use of Kb bar specimens, a steep stress intensity shedding rate, C = − 0.8 mm^{-1}, was utilized for the threshold tests. For some of the specimens, once near-threshold FCG rates were achieved, the stress intensity was increased and the test was continued under an applied constant stress range. In order to obtain near-threshold FCG data without the use of a steep load shedding procedure, selected tests were pre-cracked to shorter crack lengths and the near-threshold data was acquired by conducting the test under constant stress range conditions which produced the more typical ΔK increasing FCG curves.

Table 1
Average alloy composition in weight percent.

Alloy	Cr	Co	Al	Ti	Nb	Mo	Ta	W	Zr	B	C	Ni
LSHR	12.5	20.4	3.5	3.5	1.5	2.7	1.5	4.3	0.05	0.03	0.045	Bal
ME3	13	21	3.4	3.8	0.8	3.7	2.4	2.1	0.05	0.02	0.05	Bal

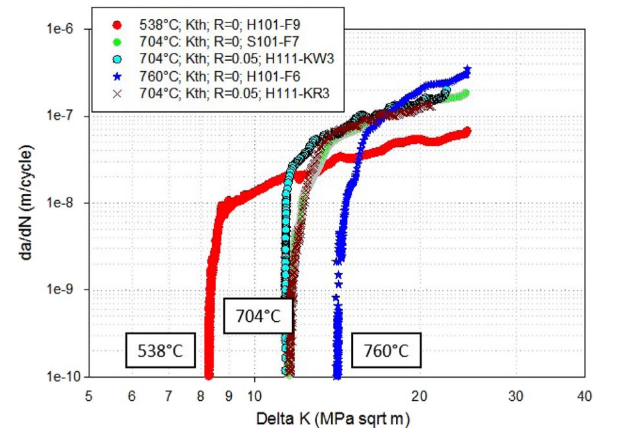

Fig. 2. Load shedding FCG test results for ME3 tested in air at 538 °C, 704 °C and 760 °C.

3. Results

3.1. Load shedding threshold FCG testing

The load shedding threshold FCG results for tests conducted in air at 538 °C, 704 °C and 760 °C for the ME3 alloy are shown in Fig. 2. The ME3 alloy exhibits the same FCG trends previously reported for Alloy 718 and Astroloy [1,2]. Thus in the Paris regime, the FCG rates increase as the temperatures rise, however in the threshold regime a crossover occurs resulting in an increase in the threshold stress intensity, ΔK_{th}, with an increase in test temperature. At 538 °C, the ΔK_{th} is approximately 8.2 MPa√m, 11.4 MPa√m at 704 °C and 14 MPa√m at 760 °C. The 704 °C load shedding threshold FCG results for the LSHR alloy are

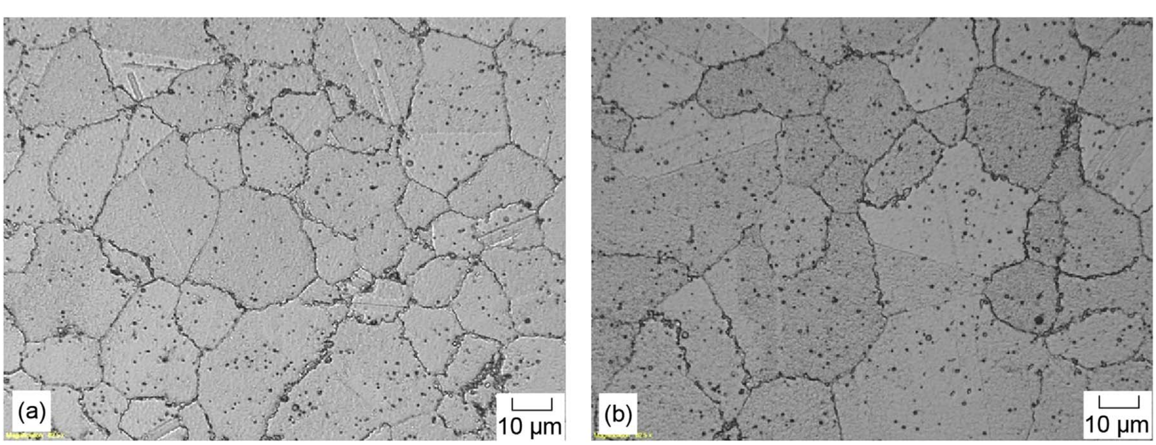

Fig. 1. Optical micrographs of a) LSHR and b) ME3 alloys.