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by

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FATIGUE CRACK PROPAGATION THRESHOLDS FOR LONG AND
SHORT CRACKS IN RENÉ 95 NICKEL-BASE SUPERALLOY

J. F. McCarver¹ and R. O. Ritchie¹

SUMMARY

A study has been made of the near-threshold fatigue crack propagation behavior of a wrought Ni-base superalloy, René 95, with reference to the effect of crack size on the threshold stress intensity ΔK_0 for no detectable crack growth. Measured threshold ΔK_0 values at low load ratios ($R = 0.1$) for physically short cracks (0.01-0.20 mm) were found to be 60% smaller than the corresponding ΔK_0 values for long cracks (~ 25 mm). However, short crack threshold values at $R = 0.1$ were found to be similar to long crack thresholds at $R = 0.8$. Such behavior is rationalized in terms of fatigue crack closure, specifically involving the role of fracture surface roughness from crystallographic crack growth in Ni-base alloys. The large difference observed in threshold values for long and physically-short cracks serves to illustrate the potential problems in applying conventional (long crack) fatigue data to defect-tolerant lifetime predictions for structural components containing small flaws.

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1. INTRODUCTION

Defect-tolerant design to predict the fatigue life of structural components generally involves estimating the time or number of cycles required to propagate the largest undetected crack (determined from proof testing or non-destructive evaluation) to some critical size (defined by the fracture toughness, limit load or specific design criteria). Design codes at present attempt to predict such growth rates of in-service flaws on the basis of data collected in the laboratory with test specimens generally containing crack sizes of the order of 25 mm or more. Unfortunately many defects encountered in service, particularly in turbine disk and blade applications, are far smaller than this. In the relatively few cases where the behavior of such short cracks has been studied, it has been found, almost without exception, that at the same nominal driving force, the growth rates of short cracks are greater than (or equal to) the corresponding growth rates of long cracks [1-13]. This implies that the use of existing (long crack) fatigue crack propagation data for estimating the structural integrity of certain cyclically-stressed components with defect-tolerant design may in many cases be non-conservative. Accordingly, over the past few years, there has been a growing interest in fatigue research into the problem of the short crack.

There are several factors which constitute a definition of a short crack, namely cracks which are of a length comparable with the scale of microstructure, cracks which are of a length comparable with the scale of local plasticity, and cracks which are simply physically small (e.g., <0.5-1 mm). Most investigations to date have focussed on the first two factors [2-12] which represent, respectively, a continuum mechanics limitation and a linear elastic fracture mechanics (LEFM) limitation to

current analysis procedures. However, physically-short flaws, despite being considered long in terms of continuum mechanics and LEFM analyses, may also propagate at rates faster than conventional long cracks, once more resulting in non-conservative lifetime predictions. For example, a comparison of corrosion fatigue behavior of long (~ 25 mm) and physically short (< 0.5 mm) cracks in 4130 steel tested in aqueous NaCl solution revealed the short crack growth rates to be two orders of magnitude faster than corresponding long crack rates at the same ΔK level; a result attributed to differing local crack tip environments [13].

The objective of the present note is to describe preliminary results on the behavior of physically-short fatigue cracks in the absence of environmental factors, and in particular to examine how threshold stress intensities (ΔK_0), below which crack growth cannot be experimentally detected, vary for long and short flaws.

2. EXPERIMENTAL PROCEDURES

In view of the importance of the short crack problem to engine disk and blade applications, the material chosen for study was a high strength Ni-based superalloy, René 95. However, because of the complex nature of short crack testing, the initial studies described in this note were performed at ambient temperatures. Wrought René 95, of composition shown in Table 1, was supplied following vacuum induction primary melting, electroslag remelting, upset forging and hot-rolling before solution annealing at 1093°C and aging 16 hrs at 760°C . Ambient temperature mechanical properties are listed in Table 2. The microstructure of this alloy consisted of a necklace structure of warm-worked γ grains (average size ~ 90 μm) surrounded by 10-20 μm recrystallized γ grains. A uniform

distribution of small $0.5\ \mu\text{m}$ γ' precipitates ($\text{Ni}_3\text{Al}, \text{Ti}, \text{Nb}$) was present in the warm-worked grains whereas larger $1\ \mu\text{m}$ overaged γ' precipitates were present in boundaries of the recrystallized grains. Interparticle spacings of the γ' precipitates were roughly $1\ \mu\text{m}$ and $3\ \mu\text{m}$, respectively, with an overall volume fraction of approximately 0.47. MC, M_6C and M_{23}C_6 carbides were also observed; most notably large $\sim 20\ \mu\text{m}$ MC carbides were seen both in the matrix and on grain boundaries.

Long crack fatigue crack growth tests to determine threshold ΔK_0 values were performed using 8 mm thick 1-T compact test-pieces (T-L orientation) containing $\sim 25\ \text{mm}$ cracks. Thresholds were determined in the usual manner by standard load-shedding procedures on electro-servo-hydraulic testing machines using d.c. electrical potential methods for crack monitoring [14]. Tests were performed at 25 Hz (sine wave) at load ratios ($R = K_{\min}/K_{\max}$) of 0.1 and 0.8 in ambient temperature air (22°C , 30% relative humidity).

Short crack thresholds were determined using 6.35 mm thick cantilever bend specimens also tested at 25 Hz in ambient temperature air. The bend specimens were first notched with a spark cutter, and then a fatigue pre-crack was grown under cyclic compressive loads. In this manner the pre-crack advanced under residual tensile stresses to the edge of the maximum plastic zone [7,15] to leave approximately a 0.4 mm crack. The notch and most of the pre-crack were then carefully surface ground (using a low wheel speed and an oil-base grinding fluid) to leave a short crack of length between 0.01 and 0.2 mm, before final stress-relieving at 760°C (1 hr). Specimens were then loaded at $R = 0.1$ to various initial ΔK values and the number of cycles to failure monitored. Threshold ΔK_0 values were defined in terms of the initial ΔK value which did not cause

visible crack extension in 5×10^7 cycles, a procedure analogous to the determination of a fatigue limit for S/N curves. All specimens were subsequently examined fractographically in the optical and scanning electron microscope.

3. RESULTS AND DISCUSSION

The fatigue crack propagation behavior of long (~ 25 mm) cracks in René 95 is shown in Fig. 1 in terms of the crack growth rate da/dN (spanning six decades of growth from 10^{-8} to 10^{-3} mm/cycle) plotted as a function of the alternating stress intensity $\Delta K (= K_{\max} - K_{\min})$. Similar to most metals [14], growth rates are a strong function of load ratio R , particularly at near-threshold levels below $\sim 10^{-6}$ mm/cycle. Threshold ΔK_0 values, determined on the basis of the minimum stress intensity range to yield a maximum growth rate of 10^{-8} mm/cycle [14], were found to be $7.7 \text{ MPa}\sqrt{\text{m}}$ at $R = 0.1$, and $3.5 \text{ MPa}\sqrt{\text{m}}$ at $R = 0.8$. Such results compare closely with elevated temperature fatigue data for this alloy, determined elsewhere [16].

Corresponding threshold data for specimens containing short (0.01-0.20 mm) cracks are shown in Fig. 2 in terms of the initial stress intensity ΔK_i plotted as a function of the number of cycles to failure (N_f). Using initial stress intensities ranging from 10.1 to $2.3 \text{ MPa}\sqrt{\text{m}}$, a threshold ΔK_0 value for $R = 0.1$, defined as the maximum ΔK_i value which caused no visible crack growth in 5×10^7 cycles, was found to be a mere $3.0 \text{ MPa}\sqrt{\text{m}}$, over 60% smaller than the measured long crack threshold at the same nominal load ratio. Such ΔK_0 values and associated cyclic and maximum plastic zone sizes (r_y), computed using the standard small-scale yielding equation [17], are listed in Table 3. In view of the large

discrepancy in threshold ΔK_0 values for long and short cracks in this superalloy, it would appear inadvisable to base defect-tolerant lifetime calculations on conventional (long crack) fatigue data for René 95.

Explanations of this result must be viewed as speculative at this time but a number of points are worthy of note. First, in all cases maximum plastic zone sizes are less than $\sim 1/15$ of their respective crack lengths, indicating that the linear elastic, small-scale yielding characterization in terms of ΔK is valid. Thus the small defects utilized in this study must be considered as merely physically-short. Second, the value of the short crack threshold at low mean stress ($R = 0.1$) compares closely with the value of the long crack threshold at high mean stress ($R = 0.8$), with the long crack threshold at $R = 0.1$ being considerably larger. Such a result is plausible if viewed in terms of the concept of fatigue crack closure. Related studies on long crack near-threshold behavior in steels and aluminum alloys [18-21] have attributed the marked load ratio effect on ΔK_0 values to crack closure mechanisms, where, at low mean stresses, some physical contact occurs between mating crack surfaces above the minimum load. This effectively reduces the nominal stress intensity range ($\Delta K = K_{\max} - K_{\min}$) to some lower effective level ($\Delta K_{\text{eff}} = K_{\max} - K_{\text{cl}}$, where K_{cl} is the stress intensity to close the crack), thereby reducing the driving force for crack growth. At high mean stresses (high R) where the crack remains open for the entire loading cycle, crack closure effects are minimized and the full effect of the applied ΔK range is experienced at the crack tip. In the absence of significant environmental effects, a mechanism for such closure under plane strain conditions has been identified and experimentally verified in terms of the roughness or morphology of the fracture surface, so-called

roughness-induced closure [20,21]. Since at near-threshold levels where plastic zone sizes are generally less than the grain size, fatigue cracks propagate by a single shear mechanism with associated Mode I + Mode II displacements (akin the Forsyth's Stage I mechanism), the resulting faceted fracture surfaces can promote crack closure by wedging open the crack at discrete contact points along its length (Fig. 3). This is particularly relevant for Ni-base alloys where near-threshold fatigue fracture surfaces at low R values are significantly faceted and are usually referred to as crystallographic fatigue crack growth (Fig. 4). However, since a crack of zero length can have no fracture surface and hence no roughness-induced closure, it is likely that the extent of such closure is a function of crack length and that its effect on the very short crack will be minimal. Thus we would tentatively conclude that the physically-short crack threshold result, like the long crack threshold at $R = 0.8$, is less influenced by crack closure mechanisms and is therefore correspondingly smaller than the conventionally measured threshold for long cracks at $R = 0.1$.

Clearly this explanation lacks direct experimental verification at this time, but the result does highlight the large differences in near-threshold fatigue behavior that can arise between long and physically-short cracks, differences which severely question the use of conventional (long crack) fatigue data (at low load ratios) for defect-tolerant life-time predictions in components containing small defects.

4. CONCLUSIONS

Based on a study of the near-threshold fatigue behavior of long (~ 25 mm) and physically-short (0.01-0.20 mm) cracks in a wrought Ni-base superalloy, René 95, the following conclusions can be made:

- 1) Threshold ΔK_0 values for no detectable crack growth were found to be $7.7 \text{ MPa}\sqrt{\text{m}}$ at $R = 0.1$ and $3.5 \text{ MPa}\sqrt{\text{m}}$ at $R = 0.8$ for tests on long cracks.
- 2) The corresponding threshold ΔK_0 value for short cracks was found to be $3.0 \text{ MPa}\sqrt{\text{m}}$ at $R = 0.1$, over 60% lower than the long crack result at the same nominal load ratio.
- 3) The marked discrepancy between long and short crack threshold results is tentatively explained in terms of crack closure mechanisms, specifically involving the role of fracture surface roughness.
- 4) Defect-tolerant fatigue lifetime predictions, based on conventional long crack data for low load ratios, would appear to be non-conservative in this alloy for components containing small defects.

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TABLE 1

Chemical composition in wt.% of René 95 superalloy.

<u>Ni</u>	<u>Cr</u>	<u>Co</u>	<u>Nb</u>	<u>Mo</u>	<u>Al</u>	<u>W</u>	<u>Ti</u>	<u>Fe</u>	<u>C</u>	<u>Zn</u>	<u>Si</u>	<u>Ca</u>
balance	13.75	7.90	3.59	3.53	3.50	3.40	2.47	0.30	0.15	0.06	0.04	0.03

TABLE 2

Ambient temperature mechanical properties of wrought René 95.

<u>Yield Strength</u>				<u>Fatigue</u>	
<u>Monotonic</u>	<u>Cyclic</u>	<u>U.T.S.</u>	<u>Redn. in Area</u>	<u>Elong. on 25 mm</u>	<u>Transition Life</u>
(MPa)		(MPa)	(%)	(%)	(cycles)
1400	1200	1740	12	12	2×10^3

TABLE 3

Threshold data for wrought René 95 pertaining to long and short crack tests.

<u>Crack Size</u>	<u>Load Ratio</u>	<u>ΔK_o</u>	<u>Cyclic r_y</u>	<u>Max. r_y</u>
(mm)	(K_{min}/K_{max})	($MPa\sqrt{m}$)	(μm)	(μm)
~ 25	0.1	7.7	1.6	5.9
~ 25	0.8	3.5	0.3	24.9
0.01-0.20	0.1	3.0	0.2	0.8

LIST OF FIGURE CAPTIONS

- Fig. 1: Variation of fatigue crack propagation (da/dN) with the alternating stress intensity (ΔK) for long cracks in René 95, showing definition of threshold ΔK_0 for ~ 25 mm cracks at $R = 0.1$ and 0.8 .
- Fig. 2: Variation of initial stress intensity (ΔK_i) with number of cycles to failure (N_f) for physically-short cracks in René 95 showing definition of threshold ΔK_0 for 0.01 - 0.2 mm cracks at $R = 0.1$.
- Fig. 3: Schematic diagram showing fatigue crack closure originating from the fracture surface morphology or roughness. K_{c1} is the stress intensity to close the crack.
- Fig. 4: Crystallographic fatigue crack propagation at near-threshold stress intensities ($\Delta K \approx 9 \text{ MPa}\sqrt{\text{m}}$ in long crack $R = 0.1$ test) showing faceted appearance of the fracture surface. Arrow indicates general direction of crack growth.

Fig. 1: Variation of fatigue crack propagation (da/dN) with the alternating stress intensity (ΔK) for long cracks in René 95, showing definition of threshold ΔK_0 for ~ 25 mm cracks at $R = 0.1$ and 0.8 .

XBL 8110-6785

Fig. 2: Variation of initial stress intensity (ΔK_i) with number of cycles to failure (N_f) for physically-short cracks in René 95 showing definition of threshold ΔK_0 for 0.01-0.2 mm cracks at $R = 0.1$.

XBL 8110-6786

XBL8110-6787

Fig. 3: Schematic diagram showing fatigue crack closure originating from the fracture surface morphology or roughness. K_{cl} is the stress intensity to close the crack.

XBB 810 9960

Fig. 4. Crystallographic fatigue crack propagation at near-threshold stress intensities ($\Delta K \approx 9 \text{ MPa}\sqrt{\text{m}}$ in long crack $R = 0.1$ test) showing faceted appearance of the fracture surface. Arrow indicates general direction of crack growth.

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