Materials Science and Engineering, 55 (1982) 63 - 67

Fatigue Crack Propagation Thresholds for Long and Short Cracks in René 95 Nickel-base Superalloy

J. F. McCARVER* and R. O. RITCHIE†

Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA (U.S.A.)

(Received November 7, 1981)

SUMMARY

A study was made of the near-threshold fatigue crack propagation behavior of a wrought nickel-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 (0.01 - 0.20 mm) cracks were found to be 60% smaller than the corresponding ΔK_0 values for long (about 25 mm) cracks. 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 nickel-base alloys. The large difference observed between the 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.

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 greater. 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 the microstructure, cracks which are of a length comparable with the scale of local plasticity and cracks which are simply physically small (*e.g.* less than 0.5 - 1 mm). Most investigations to date have focused 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,

---

*Present address: Schlumberger Well Services, Houston, TX 77002, U.S.A.

†Present address: Department of Materials Science and Mineral Engineering, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, U.S.A.

0025-5416/82/0000-0000/$02.75

TABLE 1

Chemical composition of René 95 superalloy

Element	Ni	Cr	Co	Nb	Mo	Al	W	Ti	Fe	C	Zr	Si	Ca
Amount (wt.%)	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

a comparison of corrosion fatigue behavior of long (about 25 mm) and physically short (less than 0.5 mm) cracks in AISI 4130 steel tested in aqueous NaCl solution revealed the short crack growth rates to be two orders of magnitude faster than the corresponding long crack rates at the same ΔK level, a result attributed to differing local crack tip environments [13].

The objective of the present paper 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 nickel-based superalloy, René 95. However, because of the complex nature of short crack testing, the initial studies described in this paper 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 for 16 h at 760 °C. The mechanical properties at ambient temperature are listed in Table 2. The microstructure of this alloy consisted of a "necklace" structure of warm-worked γ grains (average size, about 90 μm) surrounded by 10 - 20 μm recrystallized γ grains. A uniform distribution of small 0.5 μm γ' precipitates (Ni_3Al,Ti,Nb) was present in the warm-worked grains whereas larger 1 μm overaged γ' precipitates were present in the boundaries of the recrystallized grains. The interparticle spacings of these γ' precipitates were roughly 1 μm and 3 μm 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 (about 20 μm) MC carbides were seen both in the matrix and on grain boundaries.

TABLE 2

Ambient temperature mechanical properties of wrought René 95

Monotonic yield strength (MPa)	1400
Cyclic yield strength (MPa)	1200
Ultimate tensile strength (MPa)	1740
Reduction in area (%)	12
Elongation on 25 mm (%)	12
Fatigue transition life (cycles)	2×10^3

Long crack fatigue crack growth tests to determine the threshold ΔK_0 values were performed using compact test pieces 8 mm thick (in the transverse–longitudinal orientation) containing cracks about 25 mm long. The thresholds were determined in the usual manner by standard load-shedding procedures on electroservohydraulic 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 cantilever bend specimens 6.35 mm thick also tested at 25 Hz in ambient temperature air. The bend specimens were first notched with a spark cutter, and then a fatigue precrack was grown under cyclic compressive loads. In this manner the precrack advanced under residual tensile stresses to the edge of the maximum plastic zone [7, 15] to leave a crack of approximately 0.4 mm. The notch and most of the precrack 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 the final stress relief at 760 °C (1 h). Specimens were then loaded at $R = 0.1$ to various initial ΔK values and the number of cycles to failure was monitored.

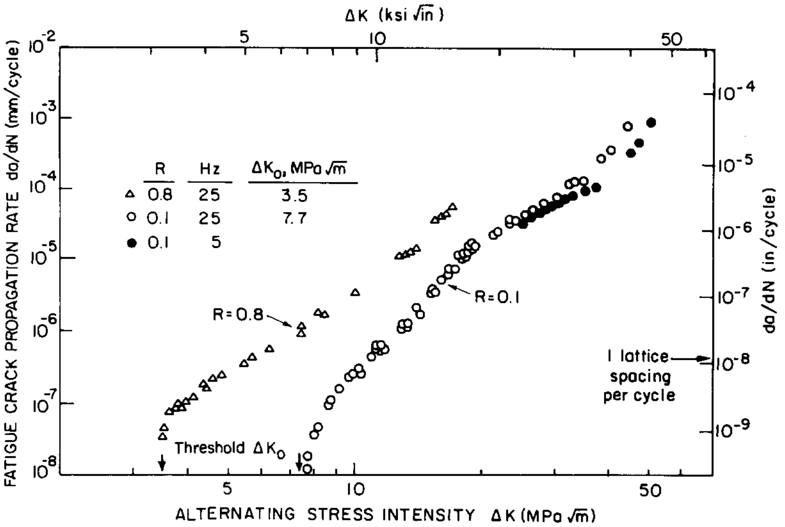

Fig. 1. Variation in fatigue crack propagation da/dN with the alternating stress intensity ΔK for long cracks in wrought René 95, showing the definition of threshold ΔK_0 for cracks about 25 mm long at R = 0.1 and R = 0.8 (environment: moist air, 30% relative humidity).

The 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 (about 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^{-1}) plotted as a function of the alternating stress intensity ΔK (= $K_{max} - K_{min}$). Similar to most metals [14], growth rates are a strong function of load ratio R, particularly at near-threshold levels below about 10^{-6} mm cycle^{-1}. 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^{-1} [14], were found to be 7.7 MPa m$^{1/2}$ at R = 0.1, and 3.5 MPa m$^{1/2}$ at R = 0.8. Such results compare closely with the elevated temperature fatigue data for this alloy, which have been determined by Gangloff [16].

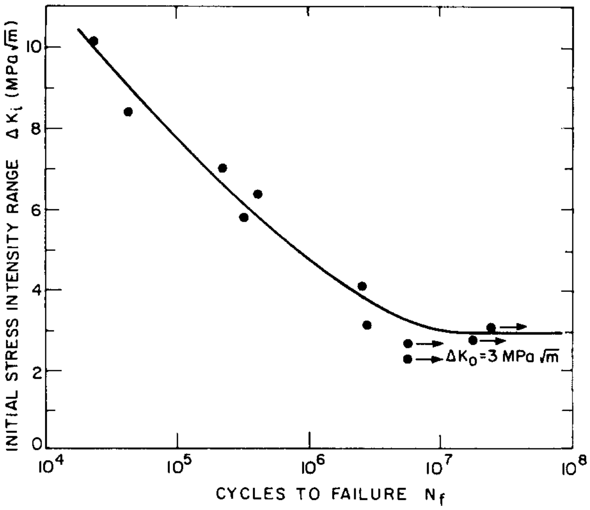

Fig. 2. Variation in the initial stress intensity ΔK_i with the number N_f of cycles to failure for physically short cracks in wrought René 95, showing the definition of threshold ΔK_0 for 0.01 - 0.2 mm cracks at R = 0.1 (environment: moist air, 30% relative humidity; frequency, 25 Hz).

The 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 N_f of cycles to failure. Using initial stress intensities ranging from 10.1 to 2.3 MPa m$^{1/2}$, 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 MPa m$^{1/2}$, over 60% smaller than the measured long crack threshold at the same nominal load ratio. Such ΔK_0 values and

TABLE 3

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

Crack size (mm)	*Load ratio* K_{min}/K_{max}	ΔK_0 (MPa $m^{1/2}$)	*Cyclic* r_y (μm)	*Maximum* r_y (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

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 between the threshold ΔK_0 values for long and short cracks in this superalloy, it appears to be 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 about one-fifteenth 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 a low mean stress (R = 0.1) compares closely with the value of the long crack threshold at a 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 ($\Delta K_{eff} = K_{max} - K_{cl}$ 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, the 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 plus mode II displacements (akin to the Forsyth 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 nickel-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.

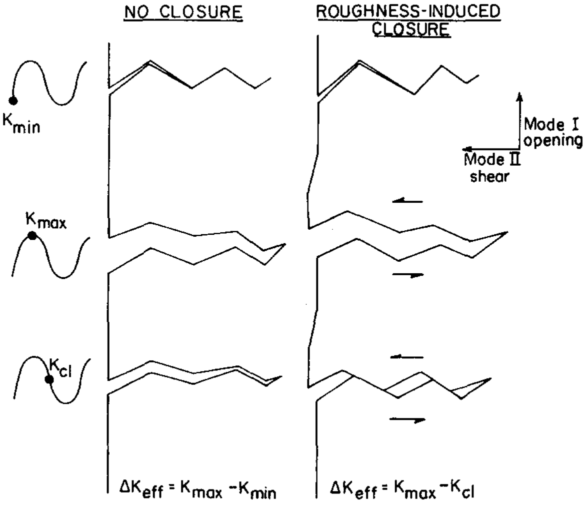

Fig. 3. Schematic diagram showing the fatigue crack closure originating from the fracture surface morphology or roughness. K_{cl} is the stress intensity to close the crack.

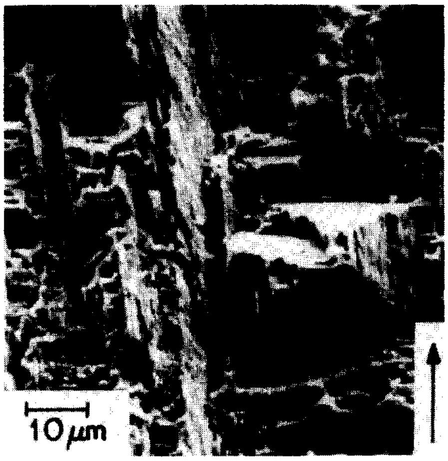

Fig. 4. Crystallographic fatigue crack propagation at near-threshold stress intensities ($\Delta K \approx 9$ MPa $m^{1/2}$ in the long crack $R = 0.1$ test), showing the faceted appearance of the fracture surface. The arrow indicates the general direction of crack growth.

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 indicate that the use of conventional (long crack) fatigue data (at low load ratios) for defect-tolerant lifetime predictions in components containing small defects should be severely questioned.

4. CONCLUSIONS

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

(1) Threshold ΔK_0 values for no detectable crack growth were found to be 7.7 MPa $m^{1/2}$ at $R = 0.1$ and 3.5 MPa $m^{1/2}$ 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 MPa $m^{1/2}$ at $R = 0.1$, over 60% lower than the long crack result at the same nominal load ratio.

(3) The marked discrepancy between the 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, appear to be non-conservative in this alloy for components containing small defects.

ACKNOWLEDGMENTS

The work was performed at the Massachusetts Institute of Technology, under a grant from the National Science Foundation administered through the Center for Materials Science and Engineering. Additional support was provided by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Science Division of the U.S. Department of Energy under Contract W-7405-ENG-48.

REFERENCES

1 S. Pearson, *Eng. Fract. Mech.*, *7* (1975) 235.
2 H. Kitagawa and S. Takahashi, *Proc. 2nd Int. Conf. on the Mechanical Behavior of Materials*, American Society for Metals, Metals Park, OH, 1976, p. 627.
3 R. A. Smith and K. J. Miller, *Int. J. Mech. Sci.*, *19* (1977) 11.
4 S. Taira, K. Tanaka and Y. Nakai, *Mech. Res. Commun.*, *5* (1978) 375.
5 C. Y. Kung and M. E. Fine, *Metall. Trans. A*, *10* (1979) 603.
6 N. E. Dowling, *ASTM Spec. Tech. Publ. 637*, 1978, p. 97.
7 S. Usami and S. Shida, *Fatigue Eng. Mater. Struct.*, *1* (1979) 471.
8 W. L. Morris, *Metall. Trans. A*, *11* (1980) 1117.
9 M. H. El Haddad, N. E. Dowling, T. H. Topper and K. N. Smith, *Int. J. Fract.*, *16* (1980) 16.
10 B. N. Leis and T. P. Forte, *Proc. 13th Natl. Symp. on Fracture Mechanics, 1980*, in *ASTM Spec. Tech. Publ. 743*, 1981.
11 T. S. Cook, J. Lankford and G. P. Sheldon, *Fatigue Eng. Mater. Struct.*, *3* (1981) 219.
12 S. J. Hudak, *J. Eng. Mater. Technol.*, *103* (1981) 26.
13 R. P. Gangloff, *Res. Mech. Lett.*, *1* (1981) 299.
14 R. O. Ritchie, *Int. Met. Rev.*, *20* (1979) 205.
15 C. N. Reid, K. Williams and R. Hermann, *Fatigue Eng. Mater. Struct.*, *1* (1979) 267.
16 R. P. Gangloff, Exxon Research, NJ, personal communication, 1980.
17 D. M. Tracy, *J. Eng. Mater. Technol.*, *98* (1976) 146.
18 R. A. Schmidt and P. C. Paris, *ASTM Spec. Tech. Publ. 536*, 1973, p. 79.
19 R. O. Ritchie, S. Suresh and C. M. Moss, *J. Eng. Mater. Technol.*, *102* (1980) 293.
20 K. Minakawa and A. J. McEvily, *Scr. Metall.*, *15* (1981) 633.
21 R. O. Ritchie and S. Suresh, *Metall. Trans. A*, *13* (1982) 937.