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Fatigue and crack-growth behavior in a titanium alloy under constant-amplitude and spectrum loading

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ABSTRACT

A titanium alloy (Ti-6Al-4V STOA) plate material was provided by the University of Dayton Research Institute from a previous U.S. Air Force high-cycle fatigue study. Fatigue-crack-growth tests on compact, C(T), specimens have been previously performed at Mississippi State University on the same material over a wide range in rates from threshold to near fracture for several load ratios ($R = P_{min}/P_{max}$). These tests used the compression pre-cracking method to generate fatigue-crack-growth-rate data in the near-threshold regime. Current load-reduction procedures were found to give elevated thresholds compared to compression pre-cracking methods. A crack-closure model was then used to determine crack-front constraint and a plasticity-corrected effective stress-intensity-factor-range relation over a wide range in rates and load ratios. Some engineering estimates were made for extremely slow rates (small-crack behavior), below the commonly defined threshold rate. Newly-developed single-edge-notch-bend, SEN(B), fatigue specimens were machined from titanium alloy plates. These specimens were fatigue tested at two constant-amplitude load ratios ($R = 0.1$ and 0.5) and a modified Cold-Turbistan engine spectrum. All of the tests were conducted under laboratory air and room temperature conditions. Calculated fatigue lives from FASTRAN, a fatigue-life-prediction code, using small-crack theory with an equivalent-initial-flaw-size (semi-circular surface flaw) of 9-μm in radius at the center of the semi-circular edge notch fit the constant-amplitude test data fairly well, but under predicted the spectrum loading results by about a factor of 2–3. The reasons for the large under prediction were discussed. Life predictions made with linear-cumulative damage (LCD) calculations agreed fairly well with the spectrum tests.

1. Introduction

In 1961, the classic paper by Paris, Gomez and Anderson [1] on "A Rational Analytical Theory of Fatigue" was a major development in the study of fatigue, see Fig. 1. The newly emerging field of Fracture Mechanics, driven by the works of Griffith [2] and Irwin [3], began to help engineers characterize fracture of brittle materials; and to provide a crack-tip parameter, the stress-intensity factor (K), to correlate fatigue-crack-growth-rate data on metallic materials for different crack configurations, and provided a methodology to predict the failure of cracked structural components. By 1967, Paris, Irwin and others at Lehigh University began to hold conferences on fatigue and fracture behavior of materials, and these conferences lead to the birth of the Engineering Fracture Mechanics Journal.

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Nomenclature

a	crack depth in thickness direction, mm
a_i	initial crack depth in thickness direction, mm
B	specimen thickness, mm
c	crack length in width direction, mm
c_i	initial crack length in width direction, mm
D	edge-notch diameter, mm
da/dN	crack-growth rate in depth direction, m/cycle
dc/dN	crack-growth rate in width direction, m/cycle
E	modulus of elasticity, MPa
f	loading frequency, Hz
K	stress-intensity factor, MPa$\sqrt{m}$
K_{Ie}	elastic fracture toughness, MPa$\sqrt{m}$
K_{max}	maximum stress-intensity factor, MPa$\sqrt{m}$
K_T	elastic stress-concentration factor
N	number of cycles
N_f	number of cycles to failure
P	applied load, kN
P_{max}	maximum applied load, kN
P_{min}	minimum applied load, kN
P_o	crack-opening load, kN
R	load ratio (P_{min}/P_{max})
r	edge-notch radius, mm
S	applied remote stress, MPa
S_{max}	maximum applied stress, MPa
S_{min}	minimum applied stress, MPa
S_o	crack-opening stress, MPa
W	specimen width, mm
α	tensile constraint factor
β	compressive constraint factor
ΔK	stress-intensity factor range, MPa$\sqrt{m}$
ΔK_{eff}	effective stress-intensity factor range, MPa$\sqrt{m}$
ρ	plastic-zone size, mm
σ_o	flow stress (average of σ_{ys} and σ_u), MPa
σ_{ys}	yield stress (0.2 percent offset), MPa
σ_u	ultimate tensile strength, MPa
ω	cyclic plastic-zone size, mm

"Wild Bill" Anderson, as he was called, was very instrumental, at Boeing Airplane Company and, later, at the National Aeronautics and Space Administration (NASA) Langley Research Center, in promoting these new concepts to the next generation. The first author, at Langley, tried predicting fatigue in 1970 using crack propagation, but it could not be done with what was available at the time. Several things had to be developed before "fatigue" could be predicted using Fracture Mechanics: (1) Stress-intensity factors for small surface cracks [4–6], (2) Crack-closure theory [7–9], (3) Plasticity effects on crack-driving parameters [10,11], (4) Constraint effects on crack growth and closure [12,13] and (5) Small- and large-crack data in the "threshold" regime without load-history affects [14–16]. After several decades of research, these concepts began to merge together and the vision that Paris and Anderson had in 1961 could now be achieved on "engineered" materials. Materials that nucleated cracks at constituent particles, inclusions, grain boundaries, voids, and, also, manufacturing defects. In 1964–66, the first author was greatly influenced by Bill Anderson, during his short time at NASA Langley, in his quest to predict fatigue behavior of metallic materials using Fracture Mechanics concepts [17].

The current paper is another demonstration of using the principles of Fracture Mechanics to predict the fatigue behavior of notched specimens made of a titanium alloy. Fatigue-crack-growth-rate behavior in the threshold and near-threshold regimes is very important for the growth of small cracks for high-cycle propeller and engine components. However, the test procedures, which have been used to generate fatigue-crack-growth-rate data from laboratory specimens (American Society for Testing and Materials (ASTM) E-647 [18,19]) in the past, have produced "fanning" with the load ratio (R) in the low-rate regime, using bend-type specimens. (Fanning of the ΔK_{th} thresholds as a function of R is the phenomenon where the spread among the crack-growth-rate curves with R is significantly greater in the threshold region than in the mid-region.) During the past decade, it has been shown that data generated with the standard load-reduction test procedure exhibits configuration differences (results from tension and bend-type specimens differ), size effects (smaller specimens have produced lower thresholds and faster crack-growth rates than larger width specimens), and that environment plays a very important role in

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