Engineering Fracture Mechanics 202 (2018) 20–32

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Comparison of small and long fatigue crack growth behavior in AA 7050-T7451

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ARTICLE INFO

Keywords:
Fatigue crack propagation
7050-T7451 aluminum alloy
Threshold
Small crack
Short crack
Long crack
Crack closure
Microstructural barrier
Microstructure
Crack growth rate
Stress intensity factor

ABSTRACT

Fatigue crack growth behaviors of small and long cracks are compared in terms of crack closure, from near-threshold to final fracture, in over-aged aluminum alloy AA 7050-T7451. This is done experimentally to quantify inputs for crack propagation models such as the Navarro-Rios model. Growth rate of small cracks are determined as a function of stress intensity factor range using replicas taken from etched specimens loaded at high and low stress amplitudes. Similar data for long cracks are obtained using a compact tension C(T) specimen. Recrystallized grains are found to be the most significant microstructural barrier to propagation when cracks are small. In addition, small cracks typically appear to behave as closure-free long cracks. Transition from apparent closure-free to crack closure behavior is observed and characterized in terms of grain size. Finally, analysis of crack closure effects on C(T) specimens shows that long cracks propagating in the studied aluminum undergoes roughness- and oxide-induced closure.

1. Introduction

The fatigue lifetime of aluminum components is dominated by the propagation of cracks [1,2]. Cracks are qualified as small or long depending on their dimensions. Suresh [3] classified small cracks into three categories in a non-corrosive environment: microstructurally, mechanically, and physically small cracks. The dimensions of microstructurally small cracks are comparable with the dimensions of the microstructural features. The dimensions of mechanically small cracks are comparable with the plastic zone dimensions induced by the crack tip. The dimensions of physically small cracks are significantly longer than the dimensions of the microstructural features and the plastic zone, but are smaller than a couple millimeters. Finally, long cracks have dimensions higher than a couple millimeters. The growth of small cracks significantly differs from the long cracks. First, small cracks usually grow faster than long cracks at an identical nominal stress intensity factor [4,5]. Second, small cracks being of the size of the microstructure, usually interact with microstructural features resulting in fluctuations in small crack growth rates.

Upon initiation, a microstructurally small crack can brutally accelerates then decelerates as it approaches a microstructural barrier (*e.g.*, a precipitate, a grain boundary, twinned regions). If the stress at the crack tip is sufficiently large to overcome the microstructural barrier, the crack reaccelerates and propagates up to the next barrier. This acceleration-deceleration behavior persists until the crack's propagation becomes insensitive to the microstructure. The identification of the microstructural barrier decelerating crack growth is particularly important for microstructure-based crack propagation models such as the Navarro-Rios model [6], which predicts small and long crack propagation according to a unified framework. In the Navarro-Rios model, the acceleration-

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https://doi.org/10.1016/j.engfracmech.2018.09.009
Received 21 March 2018; Received in revised form 10 August 2018; Accepted 6 September 2018
Available online 12 September 2018

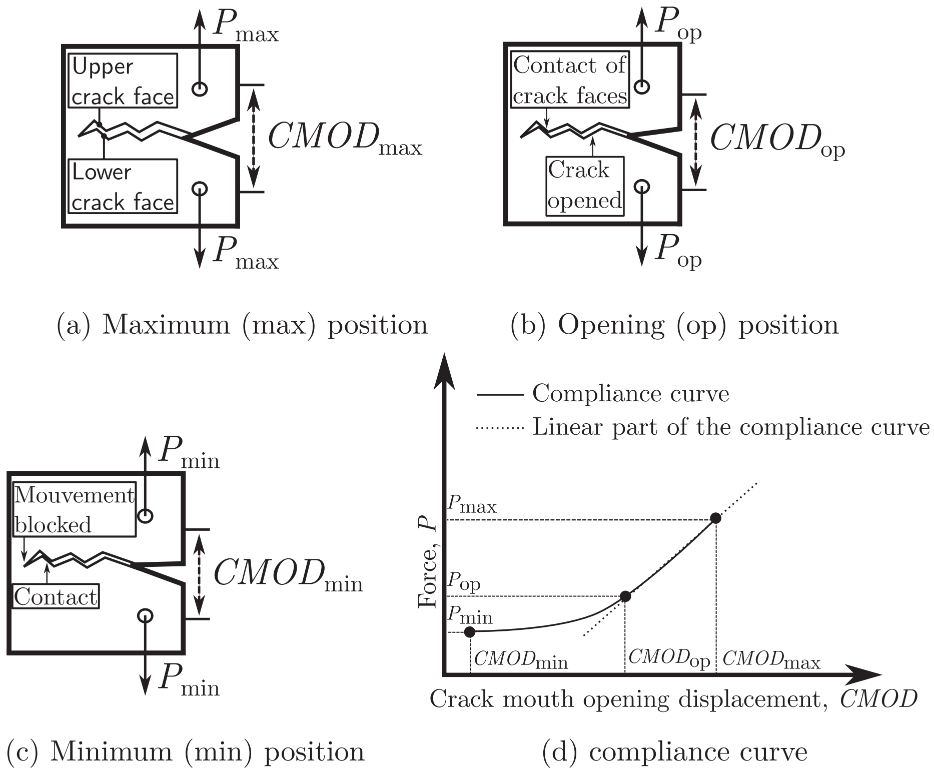

Fig. 1. Schematic representation of the roughness-induced crack closure phenomenon and its characterization. (a) At the maximum load, the crack is fully opened. (b) During unloading, a preliminary contact of the crack faces occurs. (c) When the nominal force decreases, the crack tip opening displacement remains constant. (d) Compliance curve (P versus CMOD) used to compute the opening force.

deceleration behavior is modeled and the distance between two peaks of deceleration (or acceleration) is defined by the spacing between two microstructural barriers. These barriers were experimentally identified as grain boundaries [7–9], interdendritic cells [10], or pearlites [11], depending on the material. Such a spacing has to be quantified experimentally for each studied material.

Moreover, in the Navarro-Rios model, the crack growth rate (da/dN) and the crack tip displacement are assumed to obey a power function for which the parameters are often chosen for a best fit to long crack behavior. Small and long crack growth rates are then compared to determine whether the best fit to long crack behavior is also applicable in the small crack regime. Finally, Vallellano et al. [12,13] improved the model to include the effect of crack closure, crack closure being significant for some materials.

Crack closure is caused by preliminary contact points between the crack faces. These contacts can be induced by plasticity, oxide, and/or roughness, and depend upon the sample geometry, environment, and microstructure [14]. Roughness-induced crack closure is schematically explained in Fig. 1. When the nominal force attains its maximum, the crack is fully opened and the nominal stress intensity factor (K) is at its maximum (K_{max}). When the nominal force reaches the closure force (P_{clos}), preliminary contacts between crack faces occur, limiting the crack tip displacement range. When the force decreases from P_{clos} to the minimal value (P_{min}), the nominal stress intensity factor range decreases to the minimum (K_{min}) and the crack tip position remains nearly constant. While the nominal stress intensity factor range is $\Delta K = K_{max} - K_{min}$, the stress intensity factor range characterizing the crack tip and the crack growth is better quantified by $K_{max} - K_{op}$, commonly called the effective stress intensity factor range (ΔK_{eff}). K_{op} is the operational stress intensity factor at the opening position. The value of P_{op} characterizing K_{op} can be obtained from a compliance curve where P_{op} is the nominal force at the beginning of the nonlinearity, as shown in Fig. 1d.

In over-aged AA 7xxx series compact tension specimens, crack closure is mainly induced by oxide and potentially by roughness, the degrees of which depend on the relative humidity and the grain size, respectively [15–18]. In particular, Carter et al. [17] studied the effects of grain size and relative humidity on crack growth in 7475 over-aged aluminum alloy. The authors observed that in vacuum, the crack growth rate in material with small grains (18 µm) was unaffected by crack closure, while the crack growth rate in material with bigger grains (80 µm) was affected by crack closure. In addition, in air, the crack growth rate of both microstructures was affected by crack closure. As a results, the crack growth rate depended on the grain size and the relative humidity through roughness and oxide-induced crack closure. Solanki et al. [18] modeled compact tension specimen using 2-D elastic-perfectly plastic finite element analyses under plane strain condition. The authors concluded that plasticity-induced crack closure was negligible for this case. This work corroborated the experimental results from Carter et al. that showed no crack closure for material with small grains (roughness-induced crack closure was ineffective) in vacuum (oxide-induced crack closure was ineffective).

Small and long crack growth rates were compared in the literature for steel and aluminum alloys. Bolingbroke & King [7] compared crack growth rates in AA 7010 exclusively at the crack propagation threshold, which is characterized by the ΔK value