International Journal of Fatigue 49 (2013) 73–80

Contents lists available at SciVerse ScienceDirect

International Journal of Fatigue

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

A new method for modelling the coalescence and growth of two coplanar short cracks of varying lengths in AA7050-T7451 aluminium alloy

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A R T I C L E I N F O

Article history:
Received 2 September 2012
Received in revised form 21 December 2012
Accepted 26 December 2012
Available online 5 January 2013

Keywords:
Multiple cracks
Short cracks
Fatigue crack growth
Experimental data
Life prediction

A B S T R A C T

The growth, interaction and coalescence of two coplanar short cracks of varying lengths in AA7050-T7451 aluminium alloy were studied under low amplitude cyclic loading. Fractographic studies showed that the way in which the fracture surfaces developed was dependent on the relative crack sizes, however interactions between the cracks did not significantly affect the crack growth rates before the tips of the cracks touch to form a single crack. Subsequently, the longitudinal growth rates of the crack were retarded for a period which appeared necessary for the newly coalesced crack to form a single semi-elliptical shape before resuming growth rates of a single crack. A new mathematical model was developed to account for this behaviour.

1. Introduction

Material defects induced by welding or machining and corrosion pits [1] are potential sites from which multiple 'short' cracks (i.e. crack length, $2c < 1$ mm) may initiate and grow under cyclic loading. The coalescence of these cracks may accelerate their growth thereby adversely affecting the structural integrity of aircraft components [2,3]. A number of methods have been introduced to deal with the way in which cracks grow and coalesce but most have been developed using data on the behaviour of 'long' cracks that are generally greater than 1 mm [4]. Although the propagation of cracks from microstructural defects make up a large percentage of the total fatigue life of a material [5,6], the way in which short cracks grow, interact and coalesce to form new cracks is still uncertain.

The importance of multiple crack coalescence was highlighted by the Aloha Airlines accident that was found to be caused by the linking of numerous small cracks at a number of fastener holes [7]. Multiple cracks may occur in structural components in shallow notches, in corroded areas [8], or as a result of multiple notches such as in fuselage lap joints, and they are inherently a stochastic phenomenon [3]. The presence of multiple cracks becomes a concern when the overall structural integrity of a component is adversely affected more than that expected from the growth of an individual crack under similar cyclic loading conditions [8]. Studies have shown that the interaction between multiple cracks influences the acceleration of crack growth caused by fatigue [9]. Jones et al. [10] reported that two interacting cracks promotes crack growth towards each other. Finite element evaluations by Kamaya et al. [11] found that the increase in the number of cracks accelerates crack propagation and shortens the use limit of a component. Research [2,9,12] also shows that the interaction between cracks is influenced not only by their relative positions but also by their relative lengths.

In this paper, the growth and coalescence of paired coplanar short cracks of varying sizes have been studied under constant amplitude cyclic loading. Quantitative fractographic methods were used to investigate the interaction of short cracks in close proximity to each other and to determine their influence on fatigue crack growth. The way in which fracture surfaces develop before, and after coalescence of short cracks were carefully examined and the relationships between paired crack length ratios on the crack growth rates were established. Based on experimental data, a new method was developed to predict the growth and coalescence of two coplanar short cracks and subsequent growth as a coalesced crack.

2. Experimental methods

Fatigue tests were performed to study the interaction of coplanar short cracks on their growth rates, coalescence and subsequent growth as a combined crack. Three specimens were prepared using an age hardenable aluminium alloy AA7050-T7451 (2.13% Cu, 2.26% Mg, 6.18% Zn, 0.13% Zr, less than 0.10% Fe + Si). Each specimen was 6 mm thick and shaped like a "dog bone" (Fig. 1a).

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0142-1123/$ - see front matter
http://dx.doi.org/10.1016/j.ijfatigue.2012.12.011

Nomenclature

a	crack depth of semi-elliptical crack
c	half surface length of semi-elliptical crack
C	material constant in equation for crack growth
d	separation distance between two inner crack tips
K	stress intensity factor
N	cycle number
σ	applied stress
α	numerical exponent in equation for crack growth
β	geometry correction factor
ΔK	stress intensity factor range (K_{max}–K_{min})
ΔK_{thr}	fatigue threshold
K_{Ic}	fracture toughness of material
m_f	factor associated with paired crack length ratio
R-ratio	stress ratio (= $\sigma_{min}/\sigma_{max}$)
r_{jumps}	shift associated with the centre of the recharacterized crack

Specimens were shot peened all around except for the area of interest (Fig. 1b) where it was metallographically polished thereby creating an area with relatively greater propensity for crack propagation (since shot peening [13] imparts compressive stresses at the surface). Polishing allowed clear observation of the propagation and coalescence of cracks on the specimen surface.

Initiating flaws were introduced to the polished area of the specimens using the Focus Ion Beam (FIB) milling technique [14]. These flaws were rectangular in shape (Fig. 3) with an initial depth of approximately 20 μm. The initial surface flaw lengths are denoted by c_1 and c_2, and d is the initial separation distance between the two flaws (d = 50 μm for all three specimens). Under cyclic loading, these initial rectangular shaped flaws grew into semi-elliptical shaped cracks and hence are referred to as ‘Crack 1’ and ‘Crack 2’. The orientation of the flaws for the specimens is shown in Fig. 1b and their dimensions are shown in Table 1.

Fatigue tests were performed using a digitally-controlled MTS 100kN force cyclic test machine. The specimens were tested under the same fatigue cyclic loading conditions (Table 2). Marker loading cycles were applied to facilitate quantitative fractography, and the marker loading pattern is shown in Fig. 2.

The surface crack length was measured periodically (every 1500 cycles) using a digital optical microscope after the cracks had begun propagating on the surface until coalescence of the cracks had been completed.

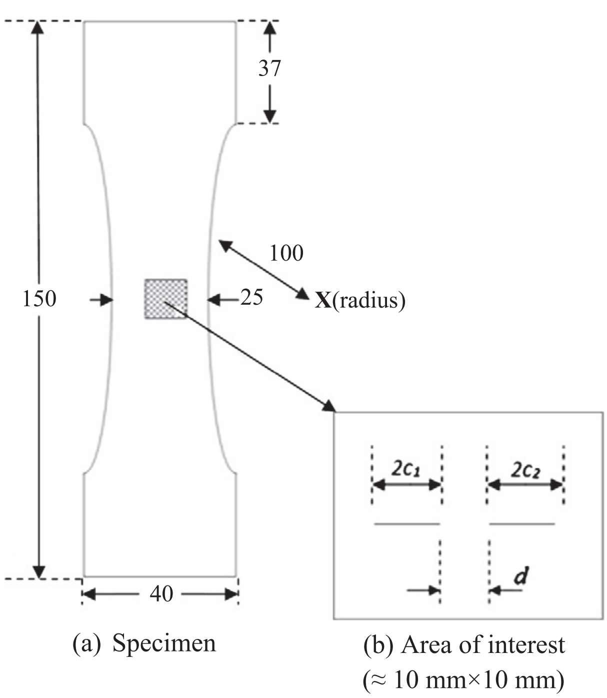

Fig. 1. Specimen geometry and crack orientations (units in mm) (a) specimen and (b) area of interest (≈ 10 mm × 10 mm).

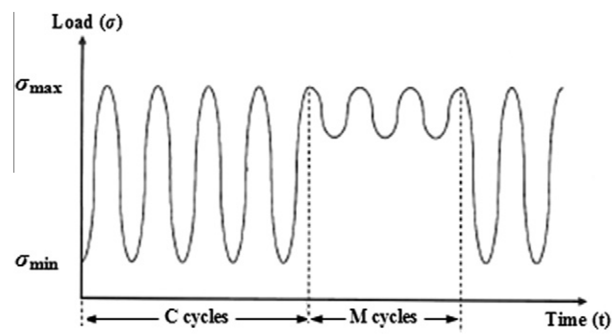

Fig. 2. Loading pattern with marker loads.

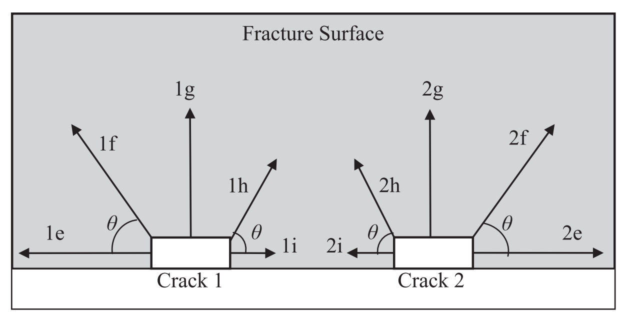

Fig. 3. Direction of measurements on fracture surface of fatigue specimens ($\theta \approx 45°$).

Postfailure crack growth measurements were further conducted using quantitative fractography [15] which involved locating marker bands on the fracture surface using a travelling optical-microscope. Marker loads are integrated in constant amplitude cyclic loading using the chosen R-ratio and number of cycles so that marker bands are readily visible. An optical microscope with high magnification and a high-precision stage was used to directly track and map the growth of cracks on the fracture surface. The position

Table 1
Specimens with different initial crack lengths.

Specimen ID	Initial crack length (μm)	
	Crack 1, $2c_1$	Crack 2, $2c_2$
Specimen B1	75	18.8
Specimen B2	75	38
Specimen B3	75	56.5