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Direct high resolution in situ SEM observations of small fatigue crack opening profiles in the ultra-fine grain aluminium alloy

J.Z. Zhang[a,b,*], X.D. He[b], H. Tang[c], S.Y. Du[b]

[a] *School of Mechanical and Power Engineering, Harbin University of Science and Technology, Harbin 150080, China*
[b] *Composite Research and Structure Centre, Harbin Institute of Technology, Harbin 150001, China*
[c] *School of Material Science, Harbin University of Science and Technology, Harbin 150080, China*

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Abstract

A study of the fatigue crack opening displacements for a small contained fatigue crack in the ultra-fine grain size aluminium alloy (IN 9052) has been carried out using in situ SEM observation technique. It is found that the left hand crack tip opening displacement is significantly different from the right hand crack tip opening displacement. At peak applied stress the measured fatigue crack tip opening displacements are also significantly smaller than the calculated crack tip opening displacement based on Dugdale model. Significant micro-damage can also be observed around the two surface fatigue crack tips. When unloading to zero applied stress, fatigue crack tip has fully closed. These observations indicate that the fatigue crack tip opening displacement is strongly affected by the damage around the crack tip and are associated with the different stages of the fatigue crack propagation process.

Keywords: Small crack; Fatigue crack opening displacement; In situ SEM observations

1. Introduction

The introduction of the damage tolerance concept in engineering design, especially in modern aircraft design, has made the prediction of fatigue crack propagation lives become necessary. The study of fatigue crack growth mechanism is of fundamental importance to the successful prediction of fatigue crack growth rate. The fatigue crack tip opening displacement (CTOD) has long been recognized as an important parameter which is associated with both the fatigue crack propagation mechanism and the fatigue crack propagation rate [1–3].

The development of the high resolution in situ SEM technique has provided an effective tool for direct observation of fatigue crack growth process and the measurement of fatigue crack opening displacement. Fatigue crack propagation mechanisms have been directly observed for a wide range of metals and alloys [4–10], and fatigue crack opening displacements have been measured using the in situ SEM technology [7,8,11–15].

The well-known alternate shear band decohesion model has been verified by direct in situ SEM observations [4,5]. It also has been observed by in situ SEM technique that fatigue crack propagation could be a discontinuous process [6,7]. Recently in situ SEM observations have also shown that fatigue crack could propagate along a single shear band rather than two alternate shear band [8–10].

In the present study, the fatigue crack opening displacements of a small fatigue crack have been observed. The underlying mechanism of fatigue crack propagation in this alloys is discussed.

2. Material and experimental procedure

2.1. Material

The material used in this study was an IN 9052 aluminium alloy. The chemical composition of this alloy was (in wt.%): magnesium 4, carbon 1.1, oxygen 0.8, iron 0.2, silicon 0.05, aluminium balance. The material is intended for aerospace applications as a forging alloy. The high strength of this alloy is predominantly due to its fine grain size, which is of the order of 0.4 μm, and to the first and second order effects of the dispersoids

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[*] Corresponding author at: School of Mechanical and Power Engineering, Harbin University of Science and Technology, Harbin 150080, China.
Tel.: +86 451 86390570; fax: +86 451 86390500.
E-mail address: jzzhang8888@yahoo.co.uk (J.Z. Zhang).

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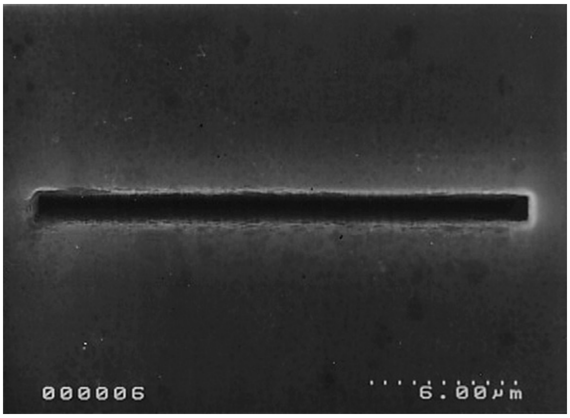

Fig. 1. The initial notch of the specimen.

present, Al_2O_3 and Al_3O_4, which comprise a volume fraction of 2–3%. The addition of magnesium promotes solid solution strengthening. Because of the material's ultra-fine grain size, this material is expected to have near isotropic mechanical properties. Tensile tests were performed and the mechanical properties are: elastic modulus, 70 GPa; 0.2% yield stress, 560 MPa; tensile strength 610 MPa [8]. The alloy was made available in the form of ∼100 mm diameter extruded billets. The billets were annealed at a temperature of 400 °C for one hour and furnace cooled prior to the machining of test specimens in the L–T orientation.

2.2. *Small fatigue crack specimen and test*

The small fatigue crack specimens had a circular cross section of diameter 2.5 mm and gauge length of 10 mm. The specimen was loaded through screw threads at each end. A flat section of approximately 1 mm in width was spark machined on the circular gross section of the specimen gauge length. The flat surface was then mechanically polished. A notch was cut into the flat surface of the specimen by laser machining after the specimen had been mechanically polished. This produced the type of notch shown in Fig. 1. The notch was ∼20 μm long by 1 μm wide and 2 μm deep and was formed by melting the material and ejecting it as vapour. Thus, defects were produced in the bottom of the notch from the rapid solidification of the molten material. The notch was machined with their axis perpendicular to the longitudinal axis of the test specimen.

The in situ SEM test was performed in a Hitachi-S4000 field emission scanning electron microscope. This microscope has a field emission gun which provides a high resolution capability for both metallic and ceramic materials. The high spatial resolution of 25 nm allows detailed examination of surface topography. This SEM also has a back scattered electron diffraction pattern analysis system which enables the crystallographic character of materials to be identified to a spatial resolution of 200 nm. Integral to the SEM facility is a loading stage capable of imposing monotonic and cyclic loads to a maximum of 10 kN. The stage is digitally controlled and the data is accessed through a microcomputer which provides load, strain and temperature control parameters.

The specimen was first cyclically loaded on an Instron 8501 fatigue test machine with a frequency of 0.5 Hz in air at room temperature under a constant applied load ratio $R = 0$, and then the specimen was transferred to the SEM loading chamber and was loaded and unloaded slowly in vacuum to study small part through thickness fatigue crack opening, closing and crack growth behaviours. The change of fatigue crack opening profiles were monitored on the SEM screen. Records of cracks were obtained using a video system and also photographically.

3. Results and discussion

Fig. 2 shows a small fatigue crack at an applied load of 2200 N which is the peak applied load of the load cycle. It can be seen that this small fatigue crack has been initiated from both the left and right sides of the notch, and the surface length of the fatigue crack is approximately 95 μm. It can also be seen that there is a very small fatigue crack initiated just above the right hand tip of the main 95 μm crack. This main fatigue crack path is relative straight observed at this magnification, this may be due to the ultra-fine grain structure of this material.

Fig. 3(a) and (b) shows the detailed near fatigue crack tip opening profiles and the damage around the fatigue crack tips. The right hand crack tip is relatively blunted but the left hand crack tip is relatively sharp. The change of the local fatigue crack propagation direction can be observed for both the left and right hand cracks. There are also severe damages around the two fatigue crack tips, particularly around the left fatigue crack tip.

Fig. 4 presents the measured near fatigue crack tip opening displacements for both left and right hand tips of this fatigue crack superimposed by the calculated crack tip opening displacement (CTOD) based on fracture mechanics definition. The fatigue crack opening displacement of the left hand crack is significantly smaller than the right hand crack within about 1 μm from the fatigue crack tips. The left and right hand crack opening displacements become closer when the displacements from the crack tips are greater than 1 μm. These results indicate that there exists a small but very close to the fatigue crack tips region where the fatigue crack opening displacements are strongly associated

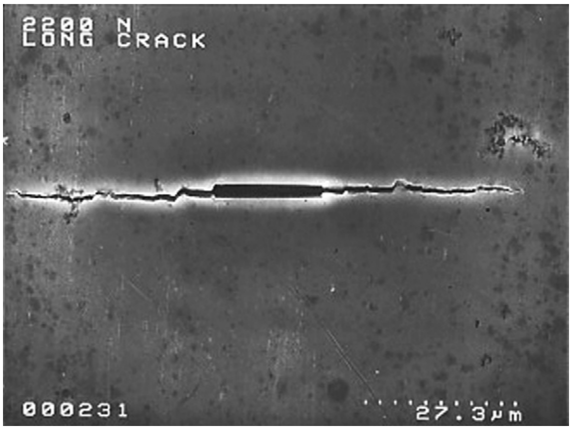

Fig. 2. The small fatigue crack at an applied load of 2200 N.