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Invited keynote paper

Short cracks initiated in Al 6013-T6 with the focused ion beam (FIB)-technology

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Abstract

The fatigue crack growth behaviour of short corner cracks in the Aluminium alloy Al 6013-T6 was investigated. The aim was to determine the crack growth rates of small corner cracks at a stress ratio of $R = 0.1$, $R = 0.7$ and $R = 0.8$ and to find a possible way to predict these crack growth rates from fatigue crack growth curves determined for long cracks. Corner cracks were introduced into short crack specimens, similar to $M(T)$ – specimens, at one side of a hole (Ø = 4.8 mm) by cyclic compression ($R = 20$). The precracks were smaller than 100 μm (notch + precrack). A completely new method was used to cut very small notches (10–50 μm) into the specimens with a focussed ion beam. The results of the fatigue crack growth tests with short corner cracks were compared with the long fatigue crack growth test data. The short cracks grew at ΔK-values below the threshold for long cracks at the same stress ratio. They also grew faster than long cracks at the same ΔK-values and the same stress ratios. A model was created on the basis of constant K_{max}-tests with long cracks that gives a good and conservative estimation of the short crack growth rates.

Keywords: Fatigue crack growth; Long cracks; Short corner cracks; Focussed ion beam; Constant K_{max}-tests; Prediction model; Threshold; Aluminium alloys

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1. Introduction

The short fatigue crack growth phenomenon was first observed in commercial aluminium alloys by Pearson [1]. The differences compared to the behaviour of long fatigue cracks were studied by many researchers [2–12] and can be summarised in two points:

- Based on linear elastic fracture mechanics (LEFM) short cracks grow faster than long cracks at the same stress intensity factor range (ΔK) and the same stress ratio R.
- Short cracks grow below the threshold for crack propagation of long cracks (ΔK_{th}).

For many engineering applications it is necessary to have reliable and handy tools to predict the growth of short cracks. Fatigue crack growth curves (da/dN–ΔK) are such a tool for fatigue crack growth problems and are already widely accepted and used by engineers in the industry. The emphasis of this paper is to show that it is possible to predict short fatigue crack growth rates from long fatigue crack growth data using linear elastic fracture mechanics under certain circumstances, which frequently occur in industrial applications.

2. Experiments

All specimens were cut out by water jet cutting from Al 6013-T4 sheets (3,6 × 2100 × 5000 mm) delivered by Airbus. They were then heat treated to the T6 condition, in which the tensile properties were determined. The yield

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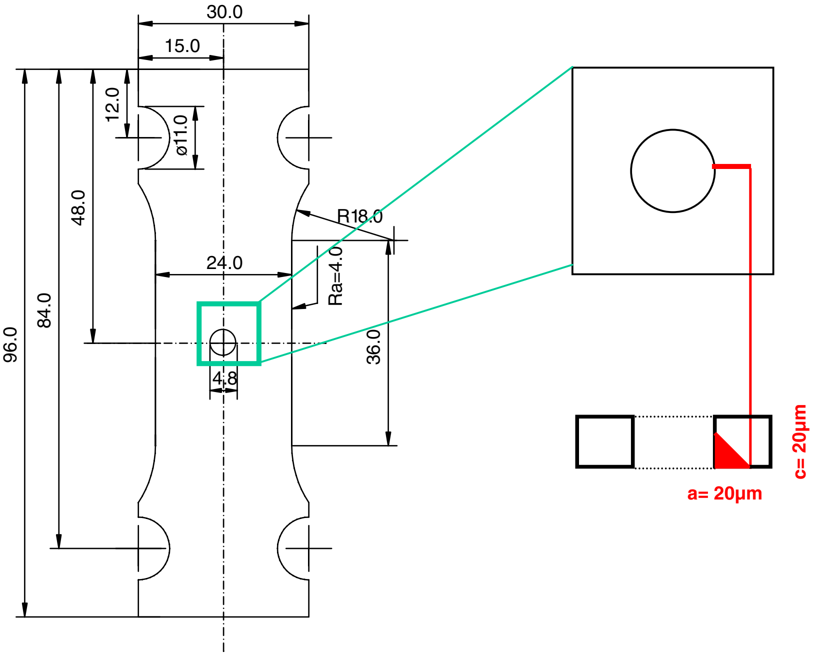

Fig. 1. Detailed geometry of the short crack specimen (FIB-specimen) with a starting corner notch of 20 µm in both, in surface and thickness direction.

stress ($R_{p0.2}$) was about 350 MPa and the ultimate tensile strength around 385 MPa. For the determination of the fatigue behaviour of long cracks standard middle tension ($M(T)$)-specimens with $W = 160$ mm, $L = 180$ mm, $B = 3.6$ mm and a starting crack length $2a_0 = 14$ mm were used. The short crack specimen geometry is shown in Fig. 1.

A hole (with a diameter of 4.6 mm) was drilled in the middle of the specimens. They were then reamed to the final diameter of 4.8 mm, which is a typical dimension for rivet holes in lap joints used in aircraft structures. The edges of the holes were polished at both sides, to reduce the risk of a crack initiation at another site than the artificial notch.

A completely new method was used to introduce the short cracks in the material. With a focussed ion beam (FIB) it is possible to remove material with an accuracy of 0.1 µm [13]. So the idea was to cut a notch in the edge of the hole of a $M(T)$-specimen, with lengths of only a few µm and even more important, with notch root radii of 1 µm or smaller (Fig. 2).

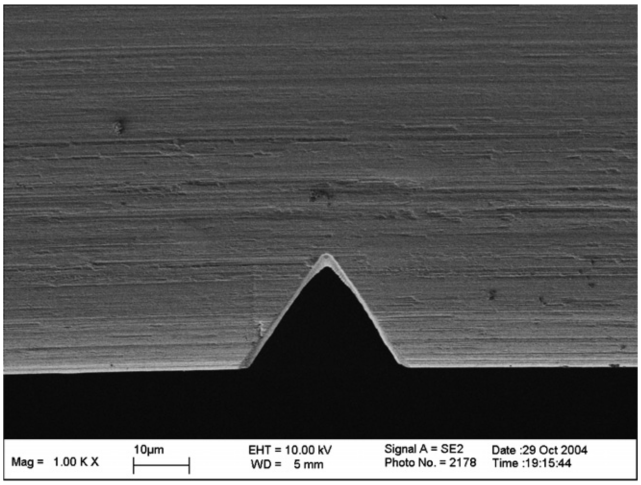

Fig. 2. Notch cut with a focussed ion beam (FIB) at the edge of a hole in a short crack specimen, similar to a $M(T)$-specimen. The picture was taken with the FIB directly after the cutting procedure.

3. Description of the focused ion beam (FIB)

The system is similar to that of a scanning electron microscope (SEM), the major difference being the use of a gallium ion (Ga^+) beam instead of an electron beam. The ion beam is generated in a liquid-metal ion source (LMIS), and the application of a strong electric field causes emission of positively charged ions from a liquid gallium cone, which is formed on the tip of a tungsten rod. Modern FIB systems involve the transmission of a parallel beam between two lenses. A set of apertures is used to select the beam current and hence the beam size and image resolution. The beam energy is typically 30 or 50 keV with a beam current in the range of 1–20 nA. The best image resolution that can be obtained is approximately 5–7 nm. The beam is scanned over the sample, which is mounted in a vacuum chamber at pressures of about 10^{-10} bar. When the beam strikes the sample, secondary electrons and secondary ions are emitted from its surface. The electron or ion intensity is monitored and used to generate an image of the surface. Secondary electrons are generated in much greater quantities than ions and provide images of better quality and resolution; consequently the secondary electron