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High resolution X-ray tomography of short fatigue crack nucleation in austempered ductile cast iron

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Abstract

High-resolution X-ray tomography with synchrotron radiation has been used to obtain the first observations of the early stages of fatigue crack nucleation in an austempered ductile cast iron. The stable short cracks nucleated in the stress concentration of a pore and arrested due to the decreasing stress field of the pore. These observations demonstrate the potential for future applications of high-resolution tomography to fracture mechanisms research.

Introduction

Fracture mechanics can be used to model the relationship between the fatigue life and material defects. However, these models do not take full account of the heterogeneity of the microstructure, which can be of the same scale as the nucleating defect size. As a result, fatigue life models are least accurate for long lifetimes, since the early stages of short crack nucleation can occupy a significant fraction of the fatigue life. This can be particularly important for cracks nucleating and propagating in steep stress gradients, such as those produced by surface engineering, or adjacent to small stress-concentrating defects such as pores. Studies of short crack behaviour are generally restricted to the crack length at the surface, which provides no information about the development of the crack shape in the bulk. Serial metallographic sectioning can be used to reveal the crack shape at the end of a fatigue test. Similarly, interrupted testing and fracture can determine the typical development of crack shape. "Beach-marking" has also been used to record the development of individual cracks. These observations have revealed that physically short cracks which have a size greater than the microstructure scale may have an approximately semi circular shape. In some cases, however, a simple relationship between the crack surface length and depth cannot necessarily be assumed. Indeed, very little is known about the crack shape at the very early stage of growth when its size is comparable to that of the surrounding microstructure.

Computed X-ray tomography is a technique that can be used to visualise the internal structure of materials. In its classical form, this non-destructive technique uses two dimensional (2D) radiographic projections of a sample to reconstruct a three dimensional (3D) map of of the X-ray attenuation coefficient of the material. Thanks to the availability of new synchrotron X ray sources and of new detectors, reconstructed 3D images with a spatial resolution close to 1 µm can be obtained. Recent high-resolution applications include measurement of defect distributions and in-situ observation of microcracking in composites. Previous studies also demonstrated the feasibility of imaging short fatigue cracks with high resolution synchrotron X-ray tomography. These observations used small samples removed from larger test specimens, and contained short fatigue cracks whose 3D shapes could be studied in detail, as well as their interaction with the microstructure.

This paper reports the first observations of the early stages of nucleation and growth of short fatigue cracks nucleated at a stress-concentrating defect, obtained by in-situ high resolution X-ray tomography of miniature fatigue specimens. This work is part of a project developing techniques to characterise fatigue and stress corrosion crack behaviour in short-range residual stress fields.

Discussion

The results obtained are the first direct 3-D observations of the early life of a fatigue crack nucleus, obtained by in-situ measurements on beamline ID19 at the European Synchrotron Radiation Facility (ESRF) (Figure 1). Close to their initiation sites, all the cracks were inclined to the loading axis (Figure 2). Initiation on inclined planes is indicative of crystallographic stage I microstructure short crack initiation, which has been observed previously for this material. With increasing length, the overall crack plane became perpendicular to the loading axis with deviations, probably due to microstructure interaction. The observed sequence of cracking suggests that the stress concentration of a short crack may encourage initiation of subsequent cracks by sympathetic nucleation. The first ever quantitative measurements of crack velocity and the development of crack shape in 3D were made (Figure 3). Calculation of the crack tip stress intensity factor (ΔK) with increasing crack length in the decreasing stress field of the initiating pore (Figure 4) demonstrated that the stable crack length was controlled by the local notch geometry, not microstructure. The short crack nucleus therefore behaves as a *physically* short crack, rather than a *microstructurally* short crack.

Conclusions

High resolution X-ray tomography can be used to study short fatigue crack nucleation and propagation. The three-dimensional volume “replica” provides detailed information on the development of the crack shape and crack path, which cannot be obtained using conventional techniques. Future applications include in-situ observation of stress corrosion cracking and fatigue crack nucleation in the short-range stress fields of surface engineered components.

Although microstructure can control the stable *microstructure short crack* nucleus length in austempered ductile cast iron, this may not necessarily be the critical crack that controls the fatigue limit. The largest stable crack nucleus length can be a *physically short crack*, controlled by the local notch geometry of porosity. Microstructure, however, can increase the fatigue endurance limit by retarding the crack propagation.

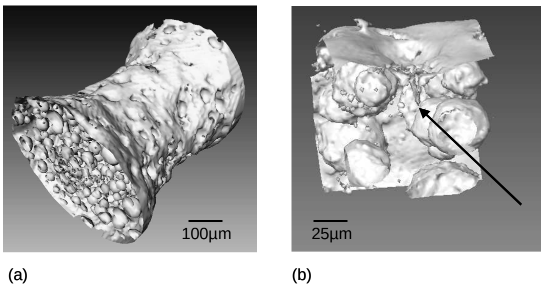

Figure 1: Short fatigue crack nucleus

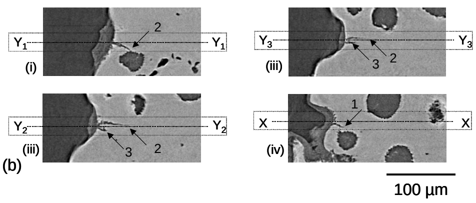

Figure 2: Tomographic sections of arrested short fatigue cracks, showing nucleation as stage I crystallographic cracks.

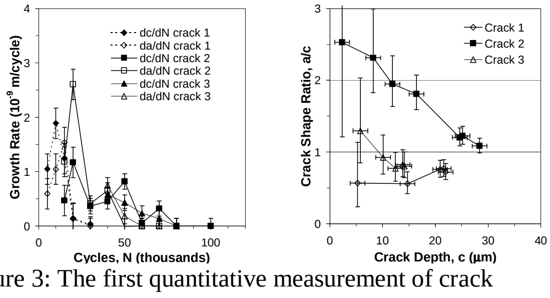

Figure 3: The first quantitative measurement of crack propagation rate and development of crack shape in 3D. Crack depth (c) crack surface length (2a)

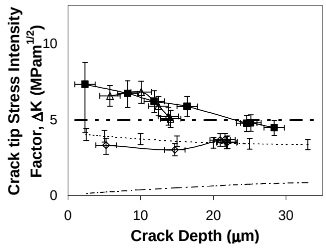

Figure 4: Calculation of crack tip stress intensity factor (ΔK) with increasing crack length in the decreasing stress field of the pore. Crack arrest occurs close to the closure free threshold for long cracks..