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Influence of closure on the 3D propagation of fatigue cracks in a nodular cast iron investigated by X-ray tomography and 3D volume correlation

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Abstract

Synchrotron X-ray tomography was performed during in situ fatigue crack propagation in two small-size specimens made of nodular graphite cast iron. While direct image analysis allows us to retrieve the successive positions of the crack front, and to detect local crack retardation, volume correlation allows for the measurement of displacement fields in the bulk of the specimen. The stress intensity factors (SIFs), which are extracted from the measured displacement fields and the corresponding local crack growth rate all along the front, are in good agreement with published results. In particular, it is possible to link the non-propagation of a crack with crack closure in the crack opening displacement maps or with a local value of the measured SIF range. It is shown that a non-uniform closure process along the crack front induces an asymmetric arrest/growth of the crack.

Keywords: Synchrotron X-ray microtomography; 3D digital image correlation; Crack propagation; Stress intensity factors; Nodular graphite cast iron

1. Introduction

Since the work of Paris and Erdogan [1] in the 1960s, the most generally accepted formalism for describing the growth of fatigue cracks is the so-called (empirical) Paris law that relates the fatigue crack growth rate (FCGR) per cycle (da/dN) to the stress intensity factor range (ΔK). While many, more or less sophisticated, methods have been used to obtain experimental values of da/dN in cyclically loaded samples or components (see for example a review in Refs. [2] or [3]), the number of experimental methods giving access to ΔK has remained very limited, especially in optically opaque materials such as metals and alloys. This is because any experimental method aiming at "measuring" ΔK should in principle probe the strain field at the tip of the crack.

In the last 10 years, however, important progress has been made in this field. Two different families of techniques have been used, namely synchrotron X-ray diffraction and displacement field measurement, either by digital image correlation (DIC) or tracking of individual markers. Synchrotron X-ray diffraction studies allow mapping the crack tip strain field [4–7]. This method is mainly applied to unloaded samples and it focuses on measurement of the residual strains in the wake and at the tip of a post-over-

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load fatigue crack with a rather coarse spatial resolution along the crack front where the strain is averaged through the sample thickness for 1 mm thick samples where plane stress should prevail [7] or sampled every 300 μm to understand the stronger crack retardation observed near the specimen edges [5]. Such diffraction studies bring valuable insights into the overload effect. For example, the post-overload residual strain was shown to persist after crack propagation with the overload response being "turned off" when loading above a critical load value [5]. However, no attempt was made to convert the measured strain maps into stress intensity factors (SIFs) as has already been done in DIC studies. DIC has been used by various authors to map crack tip displacement fields at the specimen surface. Displacement fields are measured between a pair of images of the same specimen at different loads. It is then possible to extract the corresponding SIF of a crack [8–12]. For example, Hamam et al. [8] and Lopez-Crespo et al. [10] use DIC to evaluate the effect of crack tip plasticity on crack closure and to measure the corresponding effective SIF range. However, if 2D measurements of the SIF for crack opening, K_{op}, are relevant for thin specimens where plane stress condition prevails, they are not representative of the bulk behaviour of thick samples [13].

The development of X-ray tomography has now made it possible to visualise cracks in optically opaque materials like metals and alloys. In some cases, the tomography images can be used to evaluate 3D displacement fields near the crack tip in a specimen under load. Toda et al. [14,15] used tracking of microstructural features, i.e. porosities, inside an Al alloy to map the 3D displacement field close to the crack tip in high-resolution tomographic images, i.e. obtained with a synchrotron source. The markers are first identified by their centre of mass, and then they are individually tracked between 3D images of the same specimen under different loads in order to compute the global displacement field inside the specimen. This allows for the variation of SIF along the crack front to be extracted while direct image analysis allows for the crack opening displacement (COD) to be retrieved [16]. Digital volume correlation (DVC) was also used to extract the COD maps in the cross-section of a pre-cracked specimen [17] while analysis of the measured 3D displacement field allowed for the SIFs to be computed [18]. It is to be emphasised that DVC, like the microstructural tracking method, can only be applied to materials with a suitable texture, i.e. materials that contain natural markers. Contrary to the 2D case, no "speckle pattern" can be introduced in the specimen except by adding artificial markers at the material processing step [19] but then the risk to influence the material properties is high.

Some studies combine characterisation of the crack-tip strain/displacement field with in situ observation of crack propagation. Korsunsky et al. [6] use synchrotron X-ray diffraction to gauge residual elastic strains through the thickness of unloaded samples. The comparison of the measured strain maps with finite element analysis was used to compute a residual stress intensity factor, K_{res}. An increased closure effect was observed after an overload. Then, the authors characterise crack opening during cyclic loading with 2D DIC. Several studies combined marker tracking to obtain the 3D displacement field in the vicinity of the crack tip with tomography to visualise 3D cracks [16,20] at different stages of crack propagation. Zhang et al. [16] studied 3D crack growth in an Al–Mg–Si alloy. Scans obtained at periodic intervals allowed them to follow crack shape, growth rate and opening in small-size specimens ($0.6 \times 0.6 \times 12\ mm^3$). Crack growth delay, which was observed in regions where crack segments overlap, could be correlated with crack tip opening displacement (CTOD) as a crack growth driving force. SIF measurements were also performed but larger values were unexpectedly correlated to smaller crack growth rate.

The material used in the present study was previously characterised using laboratory tomography during in situ static tensile loading of a cracked specimen [18]. This analysis allowed for the quantification of crack closure through the determination of the opening stress intensity factor, K_{op}. The present investigation goes further by investigating the effect of closure on crack propagation. 3D displacement fields, COD maps, and SIFs have been obtained in situ using DVC and synchrotron X-ray tomography at different stages of fatigue life. This complete 3D crack characterisation in combination with image analysis and post-failure topography measurements allows for an interpretation of the crack propagation/arrest. It is shown that a non-uniform closure level along the crack front induces asymmetric crack arrest/propagation of the crack.

2. Experimental methods

2.1. Material

The studied material is a nodular graphite cast iron (3.4 wt.% C, 2.6 wt.% Si, 0.05 wt.% Mg, 0.19 wt.% Mn, 0.005 wt.% S, and 0.01 wt.% P) with a fine dispersion of graphite nodules. Casting and appropriate heat treatments resulted in a ferritic matrix microstructure with a 14% volume fraction of graphite nodules with an average diameter of 45 μm. Young's modulus, yield stress and Poisson's ratio are equal to 175 GPa, 300 MPa, and 0.27 GPa, respectively. The difference in atomic numbers between carbon (nodules) and iron (matrix) results in a strong X-ray attenuation contrast so that the nodules, which are easily imaged by tomography, provide natural markers for volume correlation.

2.2. Pre-cracking in fatigue

To obtain small fatigue pre-cracked specimens, notched specimens with a $6 \times 4\ mm^2$ cross-section were machined from the heat-treated cast iron bar and loaded in fatigue at room temperature (load ratio = 0.1; frequency = 10 Hz). The specimen faces were mirror-polished prior to fatigue