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Characterisation and modelling of the three dimensional propagation of short fatigue cracks

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Abstract. This paper reports recent results on the characterisation and modelling of the three dimensional (3D) propagation of small fatigue cracks using high resolution synchrotron X ray micro-tomography. Three dimensional images of the growth of small fatigue cracks initiated in two Al alloys on natural or artificial defects are shown. Because of the small size of the investigated samples (millimetric size), fatigue cracks grown in conventional Al alloys with a grain size around 100 micrometers can be considered as microstructurally short cracks. A strong interaction of these cracks with the grain boundaries in the bulk of the material is shown, resulting in a tortuous crack path. In ultra fine grain alloys, the crack shapes tend to be more regular and the observed cracks tend to grow like "microstructurally long cracks" despite having a small physical size. Finite Element meshes of the cracks can be generated from the reconstructed tomographic 3D images. Local values of the stress intensity factor K along the experimental crack fronts are computed using the Extended Finite Element method and correlated with the crack growth rate.

Introduction

In the last twenty years, a lot of experimental and theoretical efforts have been devoted to the characterisation and modelling of small fatigue crack propagation [1], Despite of this intense activity, the growth rate *predictions* for this kind of defects are far from being completely satisfactory for the moment.

Small fatigue cracks have a complex 3D shape and their propagation at the surface of a fatigue sample, where they are readily observed, is not necessarily representative of the bulk behaviour unlike long cracks (typically more than several millimetres in length). Although this problem has been recognised for at least twenty years [2] it has hardly been taken into consideration in practice. From a characterisation point of view, the resolution of experimental techniques such as beach marking or heat tinting conventionally used to visualise the 3D shape of long cracks is not sufficient for small cracks. Thus, up to now, experimental characterisation has remained quite limited.

For such a characterisation, X-ray micro-tomography is a very attractive technique which enables the visualisation of internal features in opaque samples. Being a non destructive technique, it also enables, in principle, in situ visualisation of damage during loading and hence the chronology of damage initiation and growth. In the last ten years, significant progress has

been made in terms of resolution with both the availability of new third generation synchrotron X-ray sources and new detectors [3]. A spatial resolution close to that of an optical microscope can now be achieved in 3D which opens (or re-opens) wide areas of research.

This paper presents some recent experiments which show the 3D development of fatigue cracks inside two aluminium alloys with very different grain sizes. The crack morphologies are studied in relation to the microstructure along the crack front. Examples of the use of 3D growth data for modelling the propagation of fatigue cracks are given.

Experiments and methods

Materials Two aluminium alloys have been studied. One is a model AS7G03 cast Al alloy (Al-7Si-0.3Mg, in wt%) containing artificial pores introduced during the casting process. This was used in the T6 conditions (yield stress 200 MPa). The pores located at the surface or just below it act as stress raisers in this material and promote local cyclic plasticity which leads to crack initiation. Because of the casting process, the size of the grains is large ($\sim 300 \mu\text{m}$) and their 3D shape is irregular. This can be visualised by X ray tomography via a Gallium infiltration technique. Although this method is destructive (Gallium renders the material extremely brittle) it can be used at the end of a fatigue test to reveal the shape of the grains surrounding a fatigue crack. The 3D shape of a crack can therefore be studied as a function of the grain boundaries encountered locally by the crack front [4]. More detailed descriptions of the microstructure and fatigue deformation mechanisms of this model material and of the infiltration technique can be found elsewhere [5], [6].

The second material studied is a powder metallurgy Al-Li alloy based on AA5091 alloy (Al-1.2Li-4.0Mg-1.0C-0.5O in wt%). The material was selected because of its grain size which is of the order of $1 \mu\text{m}$. The ultrafine grains promote homogeneous deformation and prevent crystallographic cracking so that the crack shape appears very regular with the spatial resolution of the 3D imaging technique employed in this study ($\sim 1 \mu\text{m}$). The material was produced from powders using a mechanical alloying process, followed by hot isostatic pressing (hipping) and forging. It was used in the as-forged (T1) condition (Yield stress 450 MPa) [7].

Micro-tomography All the experiments described in this paper have been performed at the European Radiation Synchrotron Facility (ESRF) in Grenoble (France) on beam line ID19. The details of the tomography experimental set up of ID19 can be found in reference [6], In the following paragraphs, only the main experimental features are presented. Obtaining a tomographic image consists, firstly, of recording a series of radiographs (called scans) of a sample which is rotated around one axis. These radiographs are further used by a reconstruction algorithm to obtain a 3D numerical image of the sample which is, in its classical form, a 3D map of the attenuation coefficient in the sample. The two dimensional (2D) radiographs are recorded on a Charge Coupled Device (CCD) camera with a square array of 2048×2048 elements. This detector is coupled with a fluorescent screen via optical lenses. The white beam coming from the synchrotron ring is rendered monochromatic by a multilayer monochromator. The energy of the beam is set to 20 keV. The monochromatic beam is parallel so no geometric enlargement is possible, instead, the voxel size is a result of the camera optics used. The size of the isotropic voxels in the reconstructed images is $0.7 \mu\text{m}$, a value which gave a good compromise between the specimen size and the spatial resolution. The specimen section to be imaged is hence restricted to $1 \times 1 \text{mm}^2$.

In situ fatigue tests A dedicated fatigue machine with a reduced size and a low vibration level has been designed in order to monitor crack development *in situ*. The machine was directly installed on the rotation stage of the micro-tomography setup. The samples have been cycled in air with a constant stress amplitude ($R=0.1$). Crack initiation was first monitored by radiography. Once a crack was initiated, full 3D tomographic scans of the crack were recorded at regular intervals during the (interrupted) fatigue test which was stopped before the final fracture of the sample. During image acquisition the sample was maintained under maximum load to improve crack detection. The cyclic conditions were different for the two materials.

For the cast alloy a maximum cyclic frequency of 5Hz was attainable. Therefore a maximum stress of 180 MPa was used in order to make the fatigue life "fit" within a 24 hour experiment. This rather high value somewhat restricts the probability of observing crack arrests, which are typical of the short crack regime below the macroscopic crack propagation threshold.

For the Al-Li alloy a cyclic frequency of 40 Hz could be achieved by changing the loading system from pneumatic to mechanical. The maximum load value was set at 220 MPa.

Similar hour glass specimens were used for both materials (section $1 \times 1 \text{ mm}^2$) but in the case of Al-Li a thin ($2 \mu\text{m}$) rectangular notch, $100 \mu\text{m}$ wide and $20 \mu\text{m}$ deep, was produced in the sample using Focused Ion Beam (FIB) machining. This notch was located at the centre of one of the specimen faces and acted as a crack initiation site [7]

Results and analysis Cast alloy

The development of a fatigue crack initiated on a sub-surface pore in the corner of a sample of the cast material is illustrated in Fig.1. This figure shows that, for the experimental conditions investigated, the front of a microstructurally short crack was not smooth but exhibited protruding and retreating parts (see arrows labeled 1, 2 and 3 on the figure). Although the crack propagation plane was on average perpendicular to the uniaxial fatigue stress, local deviations from this plane did occur. These appear as shadows on the image. The examination of several similar images revealed that these deviations were usually more pronounced in the interior of the specimen than at the surface where the crack remained, on average, more planar and perpendicular to the stress direction. Using the Gallium infiltration technique, it was possible to image the 3D shape of the grains surrounding the crack. The results of this analysis revealed that the irregularities observed on the crack front were always correlated with the presence of a grain boundary. Hence, in spite of the rather high stress level used for the tests, the local crystallography appeared to either promote or impede the crack propagation.

It has been suggested [8] that this effect of local crystallography could in fact be balanced by a local modification of the stress intensity factor K along the crack front: a protruding part of the front leading to an increase in K and vice versa. In order to check this assumption, K calculations along the experimental crack fronts have been performed using the eXtended Finite Elements Method (XFEM). The authors are well aware that for such short fatigue cracks the use of the K parameter is probably not valid. However the calculation was performed to estimate, as a first approximation, the magnitude of variation of K along an experimental crack front compared with a crack of similar shape but showing a regular crack front. To perform the calculation the 3D crack shape was first obtained by thresholding the grey level tomographic images. The crack was then transformed into a 3D FE mesh.

The results of the calculation are shown in Fig. 2. They confirm that in the parts of the crack front which are propagating faster (*eg* for the part of the crack front comprised between

the letters A and B on Fig. 2, a decrease in K is observed³ with respect to the crack with a regular shape. More precisely, the largest variations in K are induced by small values of the local radius of curvature (m_1 and m_2 on Fig. 2). The K values calculated at the surface of the sample ($\theta = 0$ degrees and $\theta = 90$ degrees) were higher than those calculated for a crack with a regular shape indicating that sub-surface irregularities along the crack front (invisible from the surface) do affect the values of the stress intensity factor at the sample surface.

Al-Li alloy

In the Al-Li material a crack initiated from the notch after 2000 cycles. Its propagation was monitored every 1000 cycles up to 24000 cycles. The observed crack shapes are shown in Fig. 3 for three different numbers of fatigue cycles. The crack fronts were very smooth and the plane of propagation was almost perfectly perpendicular to the cyclic stress direction. This is a direct consequence of the small grain size encountered in this material. The crack aspect ratio a/c (see definitions of a and c on Fig. 3) remained larger than 1 throughout the propagation, indicating a higher crack growth rate in the bulk.

Calculation of the K_I values along the crack front was carried out using the same thresholding/meshing method described previously for the cast alloy. Fig. 4 shows examples of the calculated K_I values. At the sample surface the K_I values were obtained by extrapolating the values obtained immediately below the surface. As expected from the crack aspect ratio the K_I values were found to be lower in the bulk of the sample. It is worth mentioning out that analytical values obtained with the classical Newman & Raju [9] formulas were in very good agreement with the FE values (see Fig. 4).

From the $K=f(\theta)$ curves, and the experimental values of the crack size at different number of cycles, $da/dN=f(\Delta K)$ and $dc/dN=f(\Delta K)$ curves could be obtained. They confirm that the crack growth rate is higher in the bulk of the material than at the surface, for a given ΔK value. The measured surface crack growth rate was very similar (for ΔK larger than $3.5 \text{ MPa}\cdot\text{m}^{1/2}$) to that measured on macroscopic CT samples.

The 3D propagation of the crack was simulated using the C and m parameters of the Paris law determined from the experimental $da/dN=f(\Delta K)$ curve. This curve was chosen rather than the dc/dN curve because the calculation of K_I values was assumed to be less problematic in the bulk (no extrapolation needed). An example of the simulation results is shown in Fig. 5. This figure shows that the experimental crack front cannot be simulated using a single propagation law; this was expected given the fact that, as mentioned before, different crack growth rates were observed in the bulk and at the surface.

The lower crack growth rate observed at the surface was assumed to be due to crack closure. In this material, Plasticity Induced Crack Closure (PICC) is considered to be the main mechanism responsible for closure. At the surface of the sample where plane stress prevails, a larger plastic zone is expected, leading to a closure level higher than in the bulk. This 3D aspect of closure has been reported various times in the literature (*eg* in reference [10]). A constant ratio of $\Delta K_{eff}/\Delta K$ of 0.4 was assumed at the sample surface. This value is typical of the closure mechanism in this material. The closure level was then assumed to vary from 0.4 at the surface to 0 in the bulk *linearly*. With this simple assumption, a very good correlation was found between the calculated experimental crack fronts all through the fatigue life of the sample. An example is shown in Fig.5. More details on the simulation of crack propagation can be found in reference [7]

³the crack being planar, only the K_I (Mode I) factor is calculated

Conclusion The availability of powerful synchrotron X ray sources coupled with the development of new detectors has enabled the development of high resolution X ray microtomography setups which deliver images of internal features in optically opaque materials with a spatial resolution close to that of optical microscopy. In the work reported here, this technique has been applied to the field of fatigue. The 3D shape of fatigue cracks grown *in situ* can be determined, providing unique experimental data. For Al alloys, it has been shown that fatigue cracks with a size comparable to the grain size exhibit an irregular crack front which is caused by the presence of grains which impede or promote crack propagation. Those irregularities on the crack front induce variations in the stress intensity factor which tend to balance the effect of the microstructure. When the crack size is much larger than the grain size the crack shape becomes very planar and the crack front is very smooth. For the experimental conditions investigated the value of the crack growth rate was found higher in the bulk than at the surface. This anisotropy has been attributed to a 3D closure effect: the closure level being higher at the surface (plane stress) than in the bulk (plane strain). A good agreement between experimental and simulated crack fronts is found when the 3D correction of crack closure between bulk and surface is taken into account.

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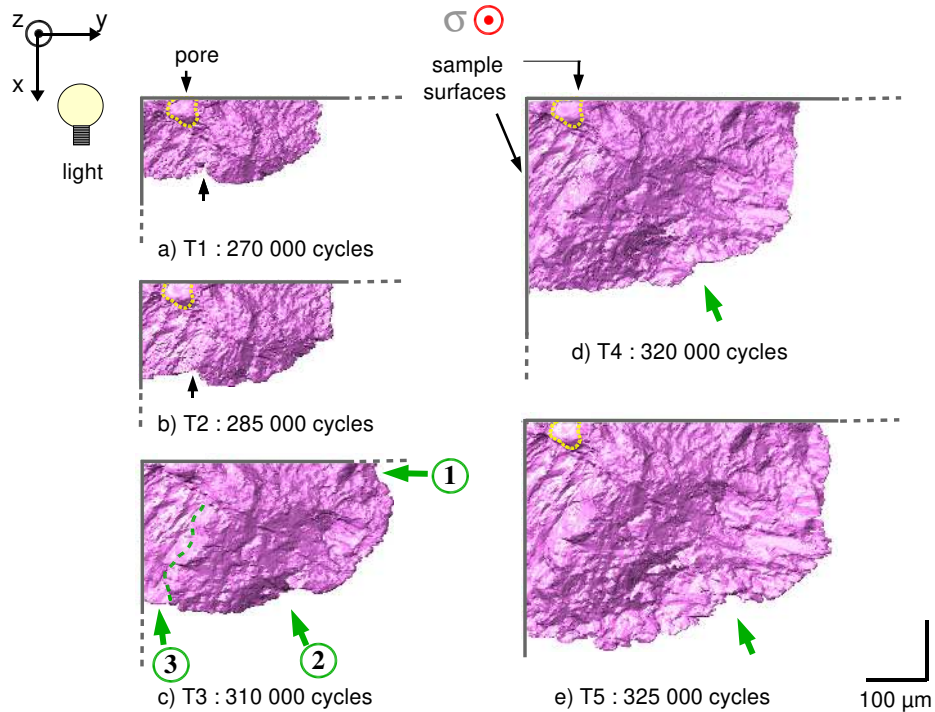


Fig. 1: 3D rendition of a small fatigue crack growing inside a cast Al alloy.

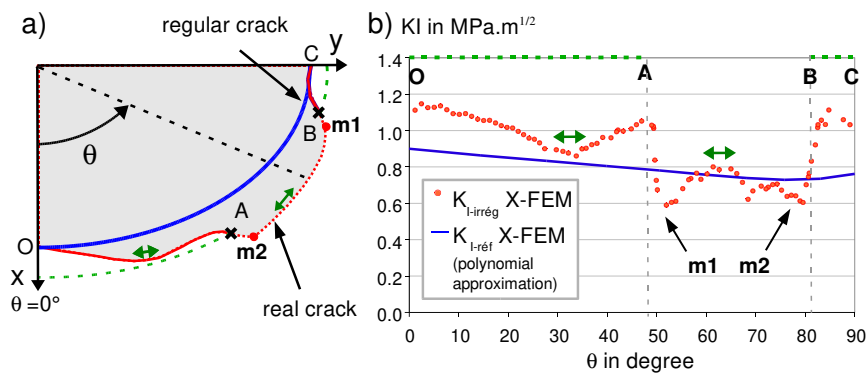


Fig. 2: a) Schematic drawing of the crack shown in Fig. 1 c after 310 000 fatigue cycles. b) Values of the mode I stress intensity factor K_I obtained by XFEM. The solid line represents the variation of K_I for a crack a regular front between points O and C

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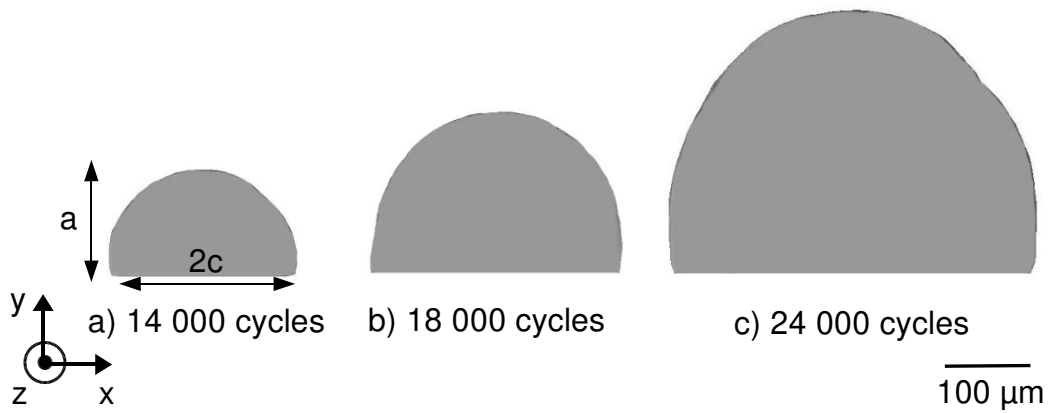


Fig. 3: Reconstructed images of a fatigue crack growing inside an Al-Li material. The very regular shape of the crack (smooth crack front and planar propagation) stems from the very small material grain size ($\sim 1\ \mu\text{m}$ which promote homogeneous deformation).

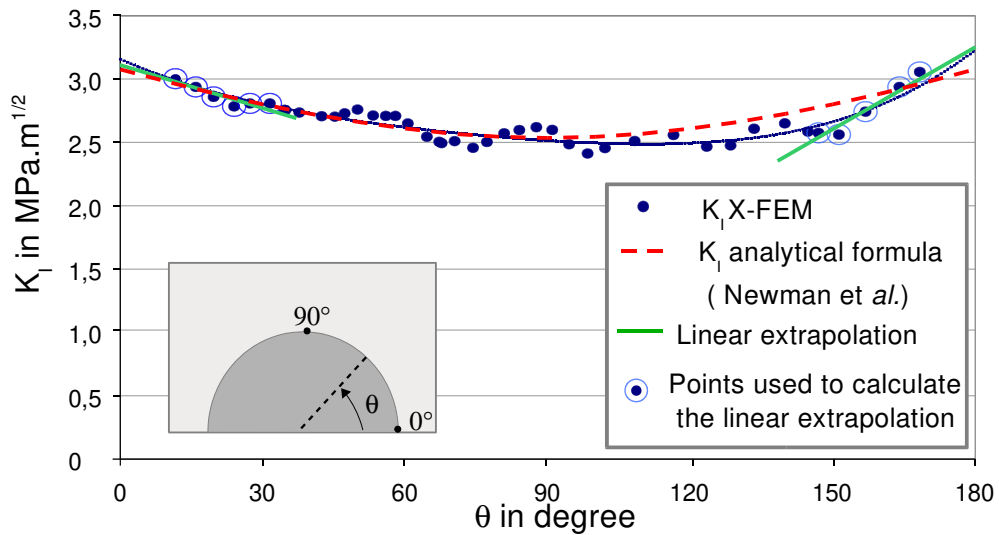


Fig. 4: Evolution of the K_I values along the crack front of a semi elliptical crack obtained by finite element and analytical calculations.

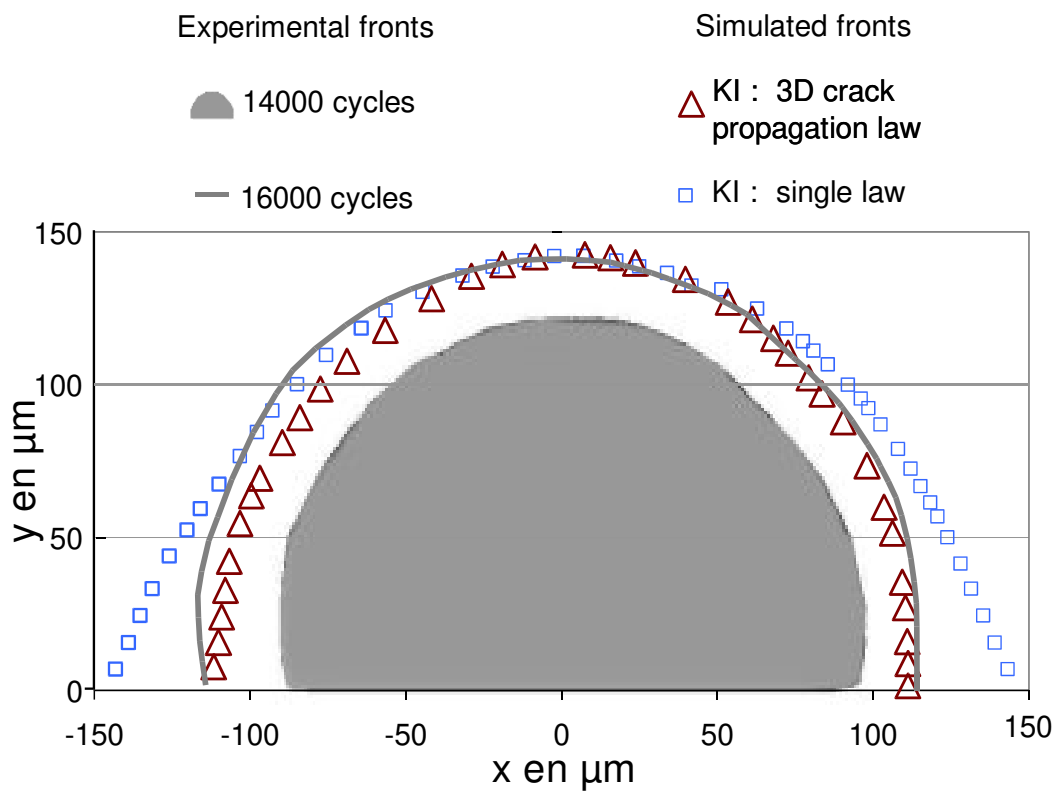


Fig. 5: Comparison between experimental and simulated crack fronts with and without correction for 3D crack closure.