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X-ray micro-tomography coupled to the extended finite element method to investigate microstructurally short fatigue cracks.

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Abstract. In this paper we will present how it is possible to couple a 3D experimental technique with a 3D numerical method in order to calculate the stress intensity factors along the crack front taking into account the real shape of the crack. This approach is used to characterize microstructurally short fatigue cracks that exhibit a rather complicated 3D shape. The values of the stress intensity factors are calculated along the crack front at different stages of crack propagation and it can be seen that the crack shape irregularities introduce rather important fluctuations of the values of K_I , K_{II} and K_{III} along the crack front. The values of K_I obtained taking into account the real shape of the crack are significantly different from the ones calculated using an approach based on a shape assumption

Introduction

In the tolerant defect approach to fatigue, the prediction of the fatigue life time is based on the integration of Paris type crack propagation law, and hence on the estimation of the stress intensity factor at the surface. In real structures, the cracks are, at least at the initial stage of their propagation, *part-through* cracks. To calculate the stress intensity factor for such cracks, it is hence necessary to make a *shape assumption*. The shape assumption usually made consists in assuming that the crack has semi-elliptical shape. In the case of microstructurally short cracks (*i.e* crack that have a size in the range of the grain size) these assumption is questionable considering that these cracks exhibit a rather complicated shape as it has already been shown by Ludwig *et al.*[1].

To avoid any shape assumption and to determine the value of the stress intensity factors along the crack front taking into account the real shape of the crack we have *coupled* the *X-ray micro-tomography* with the extended finite element method (*X-FEM*).

In the first section, we will present briefly the X ray micro-tomography technique, the X-FEM, and how it is possible to couple them. In a second section, this coupled approach is applied in the case of a corner crack subjected to tensile cyclic loading: the real values of the mixed mode stress intensity factors are compared to the one based on a shape assumption.

X-ray microtomography coupled to the Extended finite element method

Visualization of the 3D shape of the crack with X-ray microtomography. The X-ray micro-tomography is a non destructive imaging technique used to visualize in three dimensions the internal structure of the mater. The quality of the synchrotron source allows to acquire 3D images with a resolution up to $1\mu\text{m}$, which is comparable to the resolution that can be reached in conventional optical microscopy.

In-situ fatigue test have been carried out using the tomographie of the beam line ID 19 of the ESRF. At different stages of the fatigue experiment, tomographic scans of the sample containing cracks have been acquired in order to follow in-situ the *evolution* of the 3D shape of crack in a cast aluminum alloy. An example of the evolution of the crack shape is presented in [2]. For further details about this material and the experimental device used the reader can refer to [3]. The 3D tomographic images are processed (filtering, thresholding and segmentation are successively applied) in order to visualize the 3D geometry of the crack which is initially embedded in the aluminum alloy. In the next paragraph, we will describe how the X-FEM has been specifically developed to calculate the values of the stress intensity factors taking into account the *real shape of cracks extracted from tomographic images*.

Coupling of the X ray micro-tomography with the X-FEM. The X-FEM is a numerical method introduced by Belytschko *et al.* [4]. The main advantage of this method is that it allows to determine the stress intensity factors along the crack front of 3D crack *without explicitly meshing these cracks* in the structure. To better capture the stress and strain field at the crack tip, some enrichment functions are locally added to the displacement field of the elements that are cut by the crack or that contain the crack.

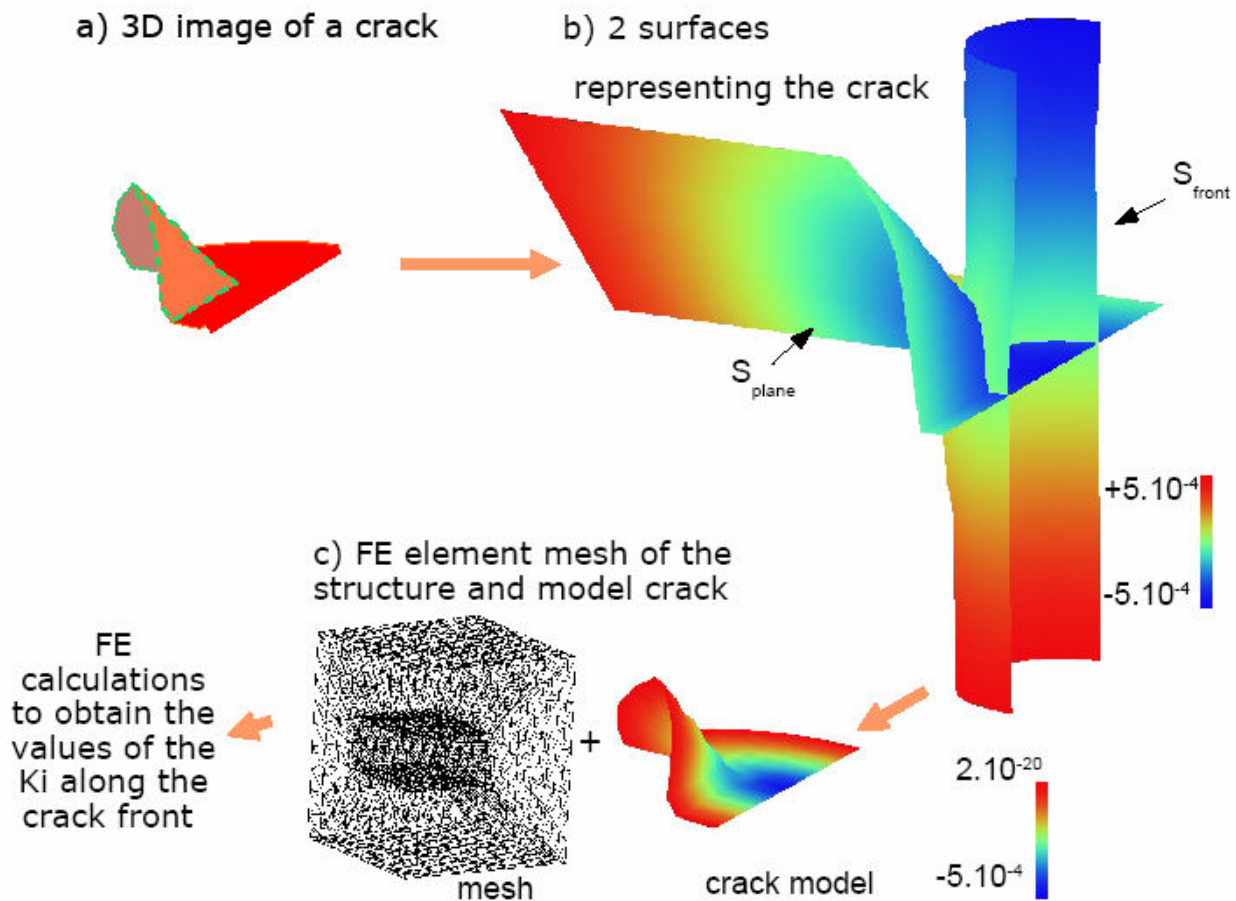


Fig.1. Schematic representation of the different steps necessary to introduce the real geometry of the crack in the FE element mesh of the structure (c): the real crack extracted from a 3D image (a) is modeled as the intersection of two surface S_{front} and S_{plan} (b).

Modeling of the 3D shape of the crack using the level-set. As in the X-FEM the cracks are not explicitly meshed in the structure, this method have been coupled to another numerical method, called the *level-set method*, in order to *define the 3D geometry of the crack*. The concept of level-set

has been introduced by Setian *et al.* [5] to represent 3D interfaces and will be applied in our case to represent a 3D *surface i.e a crack*.

As it is represented schematically in Fig.1, the real 3D shape of a real crack (Fig1 a)) is defined as the intersection of two surfaces that are represented in Fig. 1 b) : one surface called S_{front} defines the crack front and the other one called S_{plane} defines the crack plane. In Fig.1 b), the gray scale level on the surface S_{front} corresponds to the signed distance value to the crack plane (the distance vary between $5 \cdot 10^{-4}$ and $-5 \cdot 10^{-4}$). Each of these surfaces is defined by a level-set function, which simply gives for each point in the x,y,z space, the signed distance value to the surface S_{front} and S_{plane} .

The next step is to *construct* these 2 surfaces S_{front} and S_{plane} from the tomographic image of the crack. To achieve this aim, a C++ algorithm has been especially been written to determine the 2 level-set functions. More details on the way these level-set function are obtained and how there are they are coupled with the enrichment function at each node of the structure can be found in Ferrié *et al.* [6].

At this step, the level-set functions associated with the surfaces S_{front} and S_{plane} are defined. To introduce the “model crack” in the mesh as it is schematized in Fig. 1 c), we only need to defined the value of 2 level-set functions at each node of the mesh.

Calculation of the stress intensity factors : Once the level-set function are defined, it is possible to determine the values of the mixed mode stress intensity factors. The values of the stress intensity factors, K_I , K_{II} and K_{III} , along 3D curved cracks are determined using a general crack-tip interaction integral introduced by Gosz and Moran [7,8].

One example of calculation of the K_I , K_{II} and K_{III} values on a corner crack.

The approach presented in the previous section is applied in the case of a corner crack initiated at the corner of a porosity of a sample of cast aluminum alloy. These porosities constitute privileged initiation sites and represent one of the main engineering microstructural features of this alloy as it is discussed it [3]. The tensile cyclic loading applied is normal to the (x-y) plane as represented in Fig. 2. b). The planes (x-z) and (y-z) correspond to the sample surfaces.

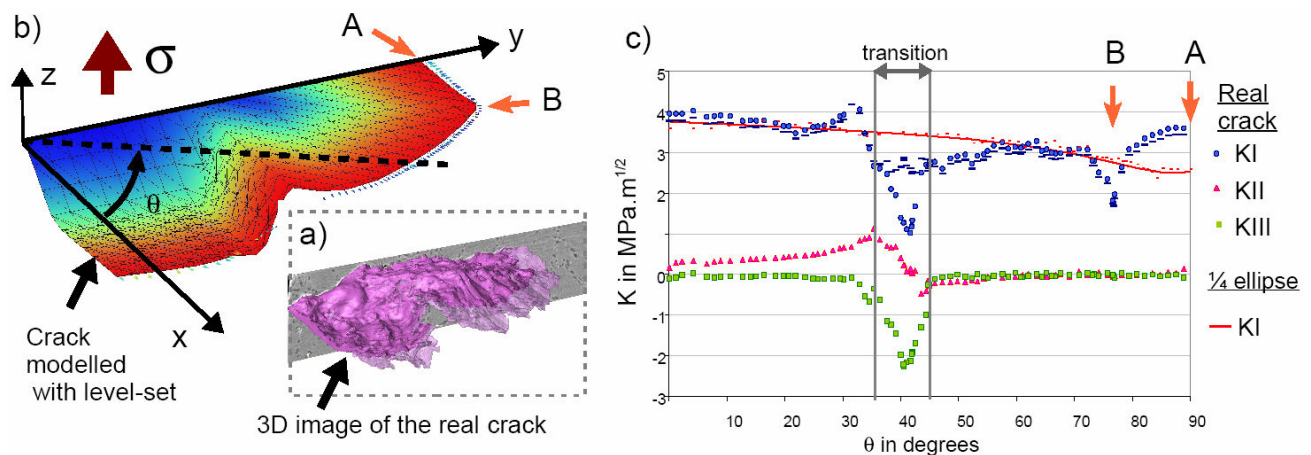


Fig. 2. a) 3D view of the real crack extracted from the tomographic image. b) Crack modeled using 2 level set functions. The points A and B correspond to strong irregularities in the crack front. c) Evolution of the stress intensity factor K_I , K_{II} and K_{III} calculated along the crack front (the angle θ is defined in a)). The values of K_I based assuming that the crack has a quarter elliptical shape is also represented for comparison.

A view of the 3D image of the *real crack* extracted from a the tomographic image is presented Fig. 2 a). This real crack has been modeled using the level set method presented in the previous section and the *model crack* obtained is represented in Fig. b). One of the main feature of this crack is that the intersection of the crack front with the free surface (see point A in Fig. 2 b)) is close to 90°. The crack front exhibits also a very angular profile at the point B as represented in Fig. 2 b).

First, the evolution of the K_I , K_{II} and K_{III} along the front of the *real crack* have been calculated using the X-FEM method. The values obtained are represented in Fig.2 c) as a function of the angle θ defined in Fig.2 b). As it can be seen in the curve Fig.2 c), the crack front irregularities A and B induce fluctuations of the values of K_I

Then, the values of the stress intensities factors have been calculated using the approach based on a *shape assumption*: the crack is assumed to be perpendicular to the stress axis (*i.e* along the z axis) and the crack front is supposed to be in the shape of a $\frac{1}{4}$ of an ellipse. The values of K_I based on the shape assumption are represented in Fig. c) as a function of the angle θ . At the point A, the approach based on a shape assumption can lead to an underestimation of the values of K_I of 30%. Similar results have been obtained for the other steps of the propagation.

Conclusion

During their propagation, short fatigue cracks interact strongly with the microstructure and can hence exhibit a rather complicated 3D shape. To describe the propagation of these cracks, one approach consists in integrating long crack growth laws. Generally in real structures these short cracks are part-thought cracks, and hence, the calculation of the stress intensity is based on a shape assumption.

To avoid such a shape assumption, we have coupled the X-ray micro-tomography with the X-FEM method in order to calculate the stress intensity factors K_I , K_{II} and K_{III} along the crack front of *real cracks*. In the case of a crack subjected to a tensile cyclic loading, it has been shown that crack shape irregularities result in variations of K_I along the crack front. Locally, K_I can reach values that are 30% greater than the ones calculated assuming that the crack as an elliptical shape. Furthermore, as the crack plane of the crack investigated in our work is not perfectly perpendicular to the stress axis, non negligible values K_{II} and K_{III} are observed. It can hence be concluded that the shape assumption usually employed to determine the stress intensity factors of microstructurally short fatigue cracks is not satisfactory.

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