ESRF	**Experiment title:** In situ characterization of fatigue cracks in metals by 3D image correlation based on tomographic 3D images	**Experiment number:** MA 501
Beamline: ID19	**Date of experiment:** from: 14 march 2008 to: 18 March 2008	**Date of report:** 18 May 2009
Shifts: 12	**Local contact(s):** W. Ludwig	*Received at ESRF:*

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Report:
High resolution tomography has been used to monitor *in situ* the 3D growth of a fatigue crack in samples made of nodular graphite cast iron. The medium resolution tomography setup of ID19 equipped with the FRELON 2k camera has been used (voxel size in the reconstructed images: 5.06 μm). A RuB4C multi-layer producing a monochromatic beam with an energy of 60 keV was used. This energy was chosen in order to ensure a minimum transmission of 10% of the incoming beam across the highly attenuating ferrous material investigated. The exposure time was set to 3 seconds, 600 views have been recorded during each scan (total scan time 45 minutes), the sample-detector distance was set to 70 mm.
All the studied samples initially contained a fatigue through-crack with an average size ranging from 700 to 1000 μm (sample cross section 1.6 $\times$ 1.55 mm^2). For each sample the experiment runs as follows:

1. A series of scans of the sample under increasing tensile loads applied *in situ* with a specially designed fatigue rig was recorded.
2. A number of fatigue cycles was applied *in situ* to the sample ($R = 0.1$, frequency: 25 Hz, constant load amplitude).
3. Radiographs of the crack observed "edge on" were used to detect crack growth.
4. If no significant crack growth occurred, the sample was cycled again.
5. When significant growth occurred, step 1 was repeated and so on.

It was possible to grow the pre-existing crack through the remaining ligament of material for three samples corresponding to 47 scans and 22 fatigue stages to analyze. The size of the 3D images required to perform image correlation being relatively small (340×340×512 voxels), the reconstruction time of the samples was small enough to allow Digital Image Correlation (DIC) measurements to be performed (at least on some reconstructed blocks) during the experiments. Crack opening could be monitored, and crack propagation was detected by resorting to DIC.

DIC analysis of the 3D images taken at different load levels gave access to the **full three-dimensional displacement field inside the entire specimen volume** (dimensions 1.457 × 1.457 × 1.457 mm^3), to the best of the authors' knowledge, it is the first time that crack opening displacement fields are measured at a local scale by applying DIC on 3D images obtained with synchrotron tomography during *in situ* propagation of fatigue cracks. The extremely stable beam delivered at ESRF allowed for direct DIC processing of the 3D images with no correction of dilation as required in the case of laboratory tomography [1]. The 3D geometry of the cracks in the sample was automatically extracted from the residual image registration error using a specifically designed procedure [2] and compared well to the crack shapes obtained from direct image analysis . In some cases a substantial number of cycles was required to make the crack propagate (Figure 1 a).
The analysis of the displacement field revealed, as expected, that the cracks were mainly loaded in mode I and Crack Opening Displacement (COD) maps corresponding to this mode were plotted for each fatigue step (Figure 1 b). Careful analysis of such plots gave clear evidences of crack closure, namely, the crack tips were closed for loads well above the minimum one used during the test.
From the 3D displacement field, the values of stress intensity factors (SIFs) were extracted along the crack front [1, 2] using an original procedure and specially written code. Comparisons with COD maps revealed that crack closure corresponded to a nearly constant value of K_I (hence called K_{op}) close to 6 MPa $\sqrt{\text{m}}$. This estimate is in very good agreement with values of K_{op} found in the literature for cast iron. Propagation (resp., non propagation) of the cracks was observed whenever the local K_I SIF was largely above (resp., below) the value of K_{op}.
Last, the values of the SIFs derived from the measured displacement field were compared to those obtained from a Finite Element Calculation of the sample containing the real 3D shape of the crack described by two level sets [3]; the first one describing the crack surface and the second one the crack front. The kinematic boundary conditions applied to the FE model are those derived from the DIC measurement. This last step is essential as the real loading prescribed onto the sample included slight deviations from pure uniaxial loading, presumably because of the dissymmetry of the crack geometry. An excellent agreement was found between the calculated and "measured" SIF values as can be seen in Figure 1 c.

The wealth of information brought by the experiment reported herein is invaluable to understand the mechanisms of fatigue crack growth in metals in relation with 3D geometry and crack closure. One journal paper [2] based on these measurements has been accepted for publication, another one is being prepared, and the results will also be shown at the next International Conference Fracture in July 2009 [4].

References

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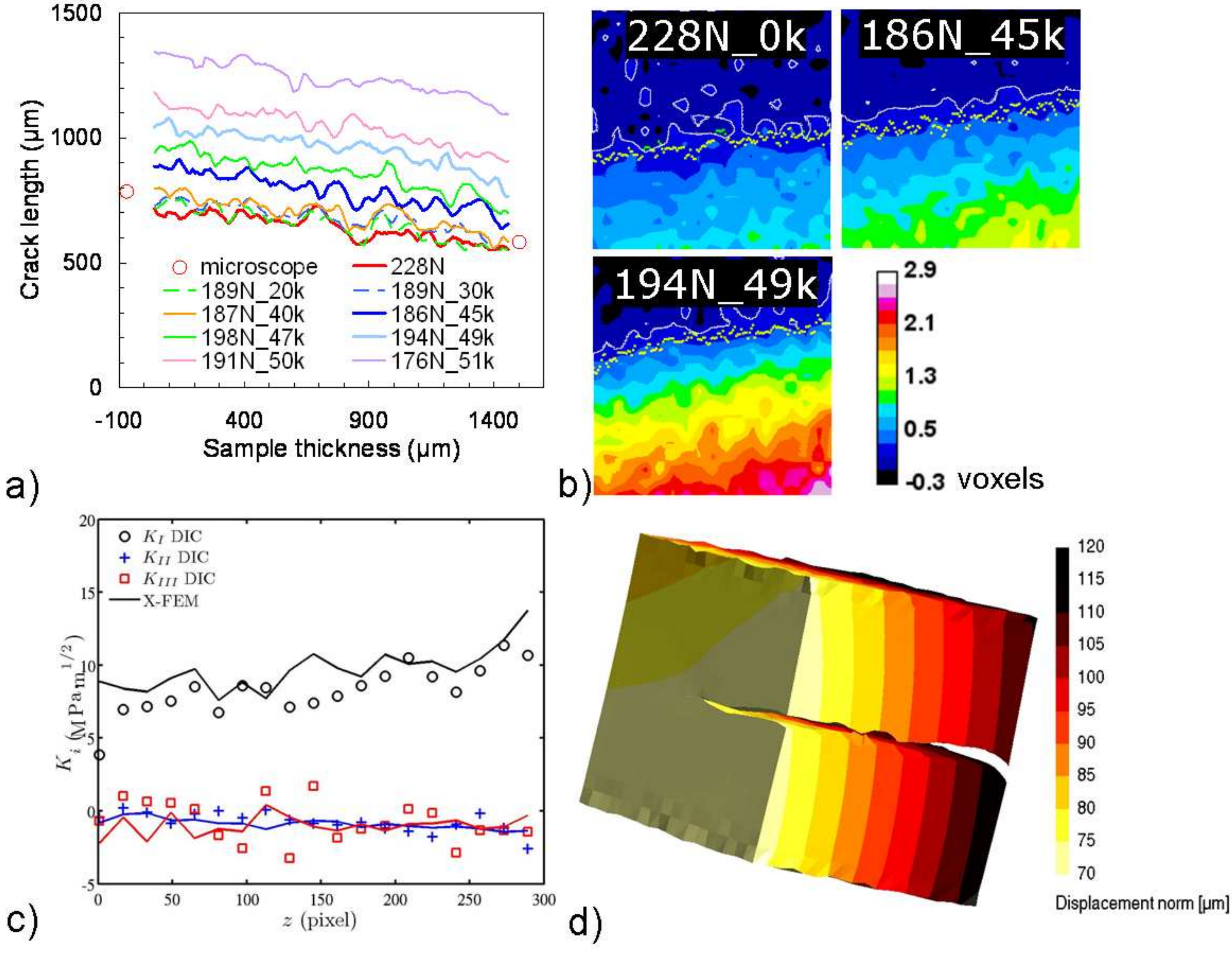

Figure 1: a) Successive crack front positions. b) COD maps (scale bar in voxel; 1 voxel = 5.06 μm. c) Comparison between SIF values obtained from DIC and from FE analyses. d) 3D rendition of the deformed configuration