J-integral evaluation of ductile material using X-Ray Tomography and Digital Volume Correlation (DVC)

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Abstract Four metal matrix composite, double notch tension samples were used in fracture tests. Each double notch tension sample had a different combination of thickness and notch length. Displacement vectors within the material were extracted after Digital Volume Correlation (DVC) analysis was performed. Crack Opening Displacement (COD) profiles were determined. The J-integral, a measure of the strain energy release rate, was calculated from individual tomogram virtual 2D slices and plotted through the thickness of the sample. It was found that treating the J-integral slice by slice does not provide an accurate representation of energy release rate across the crack front. A method to evaluate the J-integral for the entire volume of a sample is being developed.

Introduction

Fracture tests were performed using a metal matrix composite of aluminium matrix and titanium particles. The reason that this material was used is that its titanium particles which have a different X-ray attenuation coefficient to aluminium, provide a speckle pattern for the digital volume correlation (DVC) analysis of X-ray tomograms. Improving the understanding of fracture could be used to reduce conservatism in safety assessments of components in safety critical industries without increasing the risk of unexpected failure.

During the fracture tests, X-ray tomograms were recorded from all four samples at I12 beamline, Diamond Light Source. Load frames were installed on I12's stage to uniaxially load the sample in-situ until they fracture. Digital Volume Correlation (DVC) was then be performed on each set of tomograms to measure the full displacement field. A series of bespoke codes were then used to find the crack opening displacement (COD) and find the positions of the crack mouth and the crack tip [1]. These values could then be input to another algorithm that was used to calculate the strain energy release rate (J) from the displacement field [2].

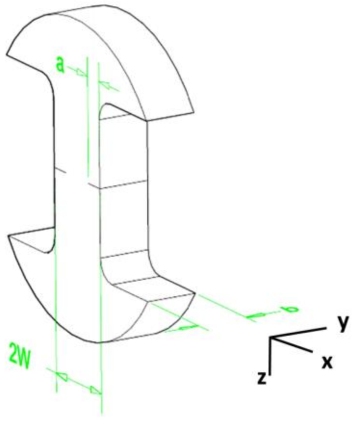

Fig. 1: Diagram of sample showing dimensions in table 1.

Method

Double notch tension samples dimensions given in Fig. 1 and Table 1 were used. Two experiments were performed, the experiment with sample thickness b=5mm used a 10kN testing rig and a 100kN testing rig was used for the sample with b=20mm. A uniaxial force was applied to each sample to initiate fracture, in the sample with b=5mm, a load of 3.8kN caused fracture for a/W=0.1 and 3.5kN for a/W=0.5. A load of 20kN caused fracture in the sample with b=20mm and a/W= 0.5 and 25kN for b=20mm and a/W=0.1. Due to the obstruction of the incident beam by the loading frame, limited angle X-ray tomography was performed, the angle was 145.5°. For the samples with b=5mm, the beam energy was 61.86keV and for the samples with b=20mm, the beam energy was 60keV.

	Thick sample	Thin sample
Long notch	a/W=0.5, b=20mm	a/W=0.5, b=5mm
Short notch	a/W=0.1, b=20mm	a/W=0.1, b=5mm

Table 1: Dimensions of samples used, 2W=8mm for all samples.

Digital Volume Correlation was performed on all four samples with an undeformed image that was not under load as a reference and the tomogram in which a crack has visibly initiated. DaVis 8.4 software from LaVision was used to perform DVC [3]. For all samples, DVC was performed with a subset size of 64, 32 and 16 voxels for each respective pass. The overlap was 50% in the first and second passes with an 80% overlap in the third pass. It was possible, using the displacement fields output to segment the crack using a Phase Congruency (PC) algorithm. This finds edges in an image by comparing the alignment of phases, found by Fourier decomposition. The active contour or snake algorithm was used to segment the crack in three dimensions, after selecting a mask close to which the crack was found [1] [4].

To calculate the strain energy release rate (J), a python script was written that used Abaqus 6.14 to evaluate a contour integral from the displacement field measured by DVC [5]. The crack is modelled as a straight line between the crack tip and the crack mouth and a rectangular region around this is deleted and meshed with new elements with double nodes along the crack path to allow for the crack to open. A larger rectangular region is selected to be the free region, to which boundary conditions would not apply. Two meshes were used at the crack tips, a coarse mesh with an area of 8x4 mm^2 and step size of 0.3 mm.

The nonlinear elastic model of Ramberg-Osgood was used with parameters extracted from a tensile test. Abaqus' contours integral calculation was used, and 25 contours were extracted for each calculation ensuring contour independence. This method allows the calculation of the strain energy release rate of each tomogram virtual slice through the sample thickness separately. Eq. 1 shows the formula which allows the calculation of the stress intensity factor (K) for each slice.

$$J = \frac{K_I^2}{E} \quad (1)$$

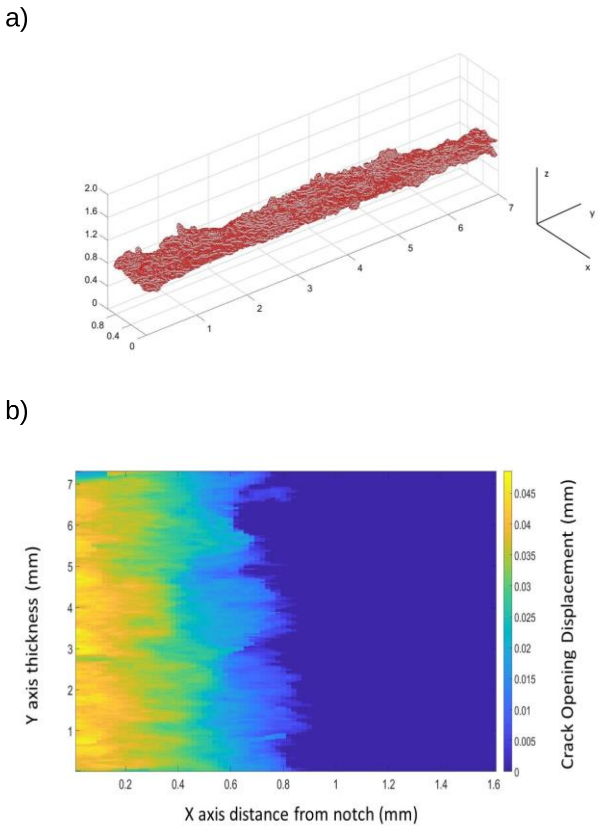

Fig. 2: (a) The 3D segmentation of a crack from the b=20mm, a/W=0.1 sample, all axes in mm. (b) COD shown in x, y plane for (a) a/W=0.1 in sample with b=20mm.

Results and Discussion

Using these algorithms, the 3D segmentation of the crack in a thin sample with a/W=0.1 is shown in Fig. 2a. Fig. 2b shows of the variation of crack opening displacement of the crack depicted in Fig 2a. It can be seen that the crack length is uniform across the sample thickness and the crack opening displacement profile is consistent along the crack front. This shows the alignment of the test was achieved with high precision. Fig. 3 shows the distribution of stress intensity factor along the thickness of the specimen with b=5 mm (note that region of interest analysis means that slightly less than 5 mm was analysed). It can be seen that a higher energy release rate is calculated at the edge of the sample compared to the its centre line. This is in contrast with previous finite element work [6] that showed the stress intensity factor at the surface of a propagating crack can be lower than its centre line. This could arise from ignoring the work of fracture carried out by the stress parallel to the crack front, which is inevitable when analysing the data virtual slice by virtual slice in 2D mode.

Therefore, a code to calculate the J integral through the whole tomography stack in a 3D configuration, which accounts for the out of plane work of stress is currently being developed with which the data will be re-analysed.

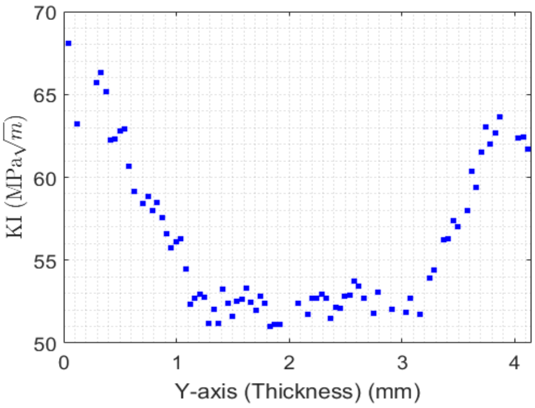

Fig. 3: Variation of stress intensity factor along the crack front calculated by Digital Volume Correlation and Finite Element analysis.

References

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