FULL 3D DAMAGE CHARACTERISATION OF SIC/SIC COMPOSITE TUBES BY X-RAY TOMOGRAPHY

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Summary: Matrix cracking in SiC/SiC composite tubes is characterised from in situ tensile tests performed under x-ray synchrotron tomography. Digital volume correlation is used to estimate semi-local strains and to detect and extract cracks from the 3D images. Two populations of cracks can be distinguished. Their spatial distribution within the tube thickness is studied and their evolution is quantitatively analysed, for instance in terms of subvoxel opening.

1. INTRODUCTION

SiC/SiC composite tubes are studied for nuclear fuel cladding applications either in advanced fission/fusion reactors or in currently existing reactors. They are made of a 2D-braided preform of SiC fibres, which is densified by the SiC matrix using chemical vapour infiltration (CVI) process. They exhibit a nonlinear damageable mechanical behaviour governed by the progressive development of a network of micro-cracks. Understanding damage mechanisms is required for building micromechanics-based models able to reproduce and predict its complexity. Surface cracking has been deeply studied from biaxial tests on tubes together with surface observations and Digital Image Correlation [1]. The purpose of this work is to complete these partial results with a full 3D volume characterisation of damage and its evolution.

2. EXPERIMENTAL METHOD

In situ tensile tests have been performed under X-ray computed tomography (XRCT) on the PSICHE beamline of the French synchrotron facility SOLEIL using a dedicated uniaxial loading machine. Several load levels have been successively applied to each specimen, from the end of the elastic behaviour to the ultimate failure of the tube. XRCT images of the central part of tubes have been recorded under constant load. The fibre architecture is commonly considered as an essential factor influencing the mechanical behaviour of composites, so tubes of three different braiding angles (±30°, ±45°, ±60°) have been tested in order to study the effects of the braiding angle on the damage mechanisms.

Several procedures have been developed and used to analyse XRCT images and to qualitatively and quantitatively characterise both microstructure and subvoxel damage mechanisms inside the material:

- Porosity is extracted from the reference image (unloaded state). Micro- and macro- pores can be distinguished according to their geometrical characteristics. Their spatial distributions are analysed and can be used to locate the braiding layers.
- Average strains for different radial positions in the tube thickness are calculated using a kinematic optimization procedure from the displacement field measured using Digital Volume Correlation (DVC).

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- Using a DVC-based image subtraction technique [2], 3D cracks are extracted from the heterogeneous microstructure for all loading levels. A specific treatment has been developed to overcome remaining artefacts within the subtracted images.
- The evolution of the detected cracks is first studied qualitatively by a direct visualization in 3D of the cracks within the segmented microstructure. A more quantitative analysis allows to extract statistical quantities to characterise the crack network. In particular, crack surface area and subvoxel crack opening are quantified using the local orientations of the detected cracks and the grey levels of the corresponding voxels in the subtracted image.

3. RESULTS

First results have been obtained from the XRCT images of the ±45° braiding. Fig. 1 provides an example of detected cracks, coloured according to local orientation and overlaid onto the microstructure. They can be classified into two families according to their local orientations: circumferential cracks, perpendicular to the tensile direction and in-plane cracks, which open within the tube thickness. The in-plane cracks (blue) seem to result from the deviation of the circumferential cracks (red), and their growth to be guided by the adjacent SiC fibres.

The crack surface density, defined as the ratio between total crack surface and solid volume, evolves linearly with the tension level for circumferential cracks. It grows more progressively for in-plane cracks, with a fast rate before failure. The evolutions of average crack opening of circumferential and in-plane cracks are very similar to those of the average axial strain et the average radial strain respectively. In particular, this indicates that the measured positive radial strain, which is the sign of a deterioration within the tube thickness, is mainly due to the opening of the in-plane cracks, which occurs in a second stage of the loading. The post processing has been automated and similar characterisation will be obtained for the two other tested braiding angles (±30°, ±60°), in order to study the effect of the fibre architecture on the damage evolution.

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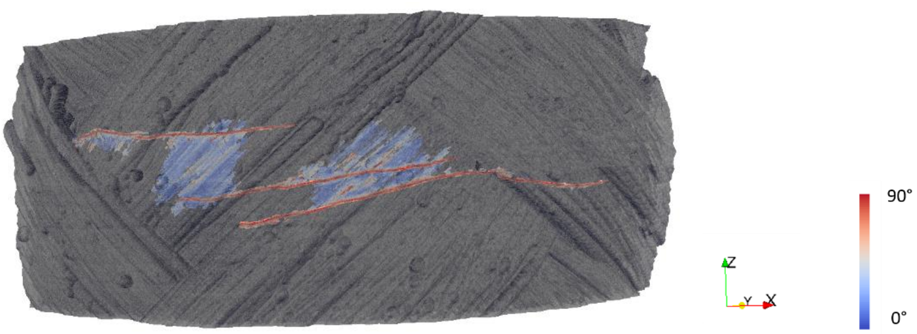

Figure 1: Detected cracks at 204 MPa in a part of the tube (height: 1.5 mm) coloured according to the local orientation angles and superimposed onto the surrounding microstructure.

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