3D Experimental Observation of Crack Initiation at Stress Concentrations in Nuclear Graphite

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Abstract. The UK advanced gas-cooled reactor (AGR) nuclear power stations are graphite moderated, using the Gilsocarbon grade of graphite. During reactor lifetime, fast neutron irradiation and radiolytic-oxidation increase the risk of cracking in graphite components from the stress-concentrating keyways. Forward predictions of the remaining reactor lifetimes are supported by structural integrity assessments, with knowledge of the strengths of in-service components derived from data that include the flexural strength of reactor-extracted specimens and notched feature tests of *non-irradiated* graphite. Understanding of the degree of conservatism inherent in these assessments would be increased by knowledge of notch sensitivity in radiolytically oxidised graphite. The presented research is part of a project that aims to quantify the effects of loading mode and geometry on notch deformation and damage in nuclear graphite, with the objective of developing a methodology for a notch sensitivity measurement in small, reactor-extracted, test specimens. The deformation fields ahead of (i) wedge-loaded keyhole-shaped notches and (ii) deep-notched short-beam flexure specimens of virgin Gilsocarbon have been quantified by *in situ* synchrotron X-ray computed tomography (XCT) in experiments EE8519-1 and EE9478-1, respectively, at the Diamond Light Source. The data were analysed by digital volume correlation (DVC), and compared with finite element modelling (FEM), which was aided by the full displacement field mapping of the experimental boundary conditions. The occurrence of non-linear damage development ahead of the blunt and sharp features is explored by mapping deviations from linear-elasticity, with the aim of quantifying the damage-law for non-irradiated graphite. Insights from this analysis are part of the development of specimen geometry for testing small, reactor-extracted, radiolytically-oxidised graphite.

Introduction

The majority of the UK nuclear power stations are the graphite moderated advanced gas-cooled reactors (AGR), operational since the late 1970's. During operation, the components are subjected to continuous fast neutron bombardment and radiolytic oxidation.

The graphite is of Gilsocarbon grade, with a medium to coarse grained microstructure of spherical crystallite particles in a porous matrix. In its virgin state, Gilsocarbon is near isotropic and exhibits non-linear stress-strain behaviour. The reactor environment causes many changes to the crystalline and porosity structures and hence to the properties of the graphite, including volume changes. It is predicted that strains from these changes will ultimately result in tensile stresses across stress-concentrating keyways, increasing the risk of component cracking within the reactor core. These forward predictions of reactor integrity require knowledge of the strengths of in-service components, which are estimated from data that includes the flexural strength of reactor-extracted specimens and notched feature tests of *non-irradiated* graphite. No monitoring of the notch sensitivity of irradiated material is currently undertaken; the confidence in the conservatism of the current assessments could be increased if a suitable test were implemented. This project aims to quantify the effects of loading mode and geometry on notch sensitivity, with the objective of developing a measurement methodology for small, reactor-extracted, test specimens.

Experiments were conducted at the Diamond Light Source, where *in situ* mechanical testing and X-ray imaging were performed, in the form of radiography and X-ray computed tomography (XCT). Two experiments will be described, both focussing on crack initiation from notches in virgin Gilsocarbon, but in different loading modes:

(i) wedge-loaded keyhole-shaped notches (EE8519-1)
(ii) deep-notched short-beam flexure (EE9478-1)

For the region immediately ahead of the notch, the internal 3D deformations were calculated bydigital volume correlation (DVC) of the tomographs and compared with theoretical displacements from finite element modelling (FEM). Full field boundary conditions were calculated from 2D digital image correlation (DIC) of the radiographs, such that the model faithfully represented the experimental conditions. The finite element modelling allows comparisons against linear-elastic predictions, leading to the development and testing of potential non-linear damage models for the quasi-brittle graphite. These insights aid in the development of a notch sensitivity test for radiolytically-oxidised Gilsocarbon using small, reactor-extracted specimens.

Experimental Details

EE8519-1: Wedge-Loaded This experiment involved the driving, and subsequent extraction, of a 10° wedge into a pre-notched section of Gilsocarbon. The tip of the notch was machined to a given radius, simulating a blunt feature (see Fig. 1); the diameters tested were 2 and 4 mm). The samples were cyclically loaded under quasi-static conditions to progressively higher peak loads until a drop in the load with increasing displacement was observed (a 'pop-in'). During loading and unloading, radiographs (X-ray absorption projections, parallel to the slot direction) were collected at 10 N intervals, and X-ray computed tomographs (XCTs) were collected in the loaded and unloaded states. The radiograph field of view (FOV) is 12 x 16 mm with a resolution of 4.8 $\mu m.pixel^{-1}$, while in the reconstructed tomographs, the voxel or 3-D pixel size is $(1.8\ \mu m)^3$ and reconstructed volume of 7 x 7 x 3.5 mm.

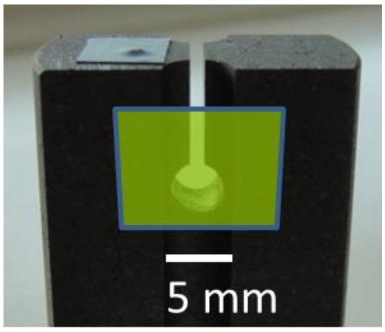

Fig. 1: φ4 mm keyhole notched sample for wedge loading. Radiograph FOV highlighted.

EE9478-1: Deep-notched short-beams The four-point flexure specimens were 6 x 6 x 19 mm Gilsocarbon beams (Fig. 2). Notches were cut of half-beam depth with two tip geometries (two samples of each): 'blunt' 2 mm diameter U notch, and 'sharp' 90° V notch, (Fig. 2(inset)). The samples were loaded under quasi-static conditions to progressively higher peak loads (no unloading) until a drop in the load with increasing displacement was observed (a 'pop-in'). XCTs were collected at loads of 25 N, 80 N, 100 N, 110 N etc., with a voxel size of $(3.24\ \mu m)^3$ and reconstructed volume of 8 x 8 x 7 mm.

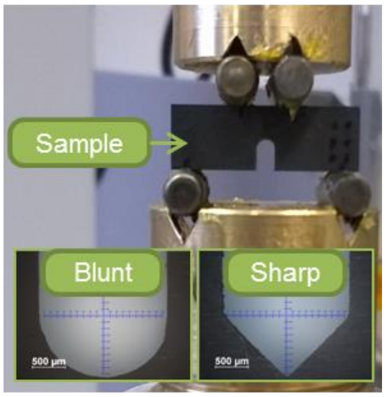

Fig. 2: Short beam flexure sample in loading rig. Sample is 6x6x19 mm. *Inset* Blunt and sharp notch tip micrographs.

Image Analysis After correcting for tomography reconstruction artefacts, LaVision's *DaVis* software was used to perform DVC, generating the 3D internal deformations in a non-destructive fashion. Further corrections to correct for rigid body motions and remove boundary artefacts were made using code developed in MATLAB.

For the wedge-loading, the radiographs were analysed by 2D DIC (again using *DaVis*), from which the general deformation patterns may be observed. The notch opening displacements were calculated for use as model boundary conditions. The deep-notched short-beam flexure samples are smaller in height than to the tomographic FOV, and so the boundaries are observed within the tomographs; this allowed 3D boundary condition measurement by DVC, making radiograph-DIC analysis unnecessary.

Comparison with modelling

The FEM model was generated in Simulia's *Abaqus* software. The calculated boundary conditions are applied to the notch faces, replicating the experimental loading conditions. The resultant displacement field is then exported for comparison with the DVC data, where calculated spatial differences reflect microstructure and potential damage with sub-micron accuracy. Different material behaviours can be input to the model, allowing great flexibility in the fitting of a suitable damage model to the observed deformation.

Conclusion

In situ 3D observations have been made of mechanically deformed virgin Gilsocarbon using synchrotron X-ray imaging. The experiments were designed to explore the crack initiation and damage processes present under different geometries of stress concentration and loading mode.

Through a combination of radiography-DIC, X-ray tomography-DVC and FEM, it has been possible to study damage initiation in a quasi-brittle media, to map deviations from elastic theory in the measured displacement field, and furthermore to begin to test models of damage behaviour.