Fracture behaviour of nuclear graphite

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ABSTRACT: X-ray Microtomography (XR T) and Electronic Speckle Pattern Interferometry (ESPI) have been used to study the crack propagation behaviour of Gilsocarbon nuclear graphite. ESPI has been used to study the strain distributions and their development around growing cracks. XR T has been used observe the three-dimensional crack shape within the specimen during in-situ loading experiments. Permanent strains are observed ahead of the crack tip and crack bridging ligaments are observed in the crack wake. These observations may be used to interpret the R-curve behaviour of nuclear graphite.

0. INTRODUCTION

Rising resistance to crack propagation, in graphite, has been demonstrated by a number of previous studies [1-4]. In brittle materials, the effect has been associated with both the growth of a bridging zone in the wake of the crack [4, 5] and a damage zone ahead of the crack tip[6]. The R-curve is a

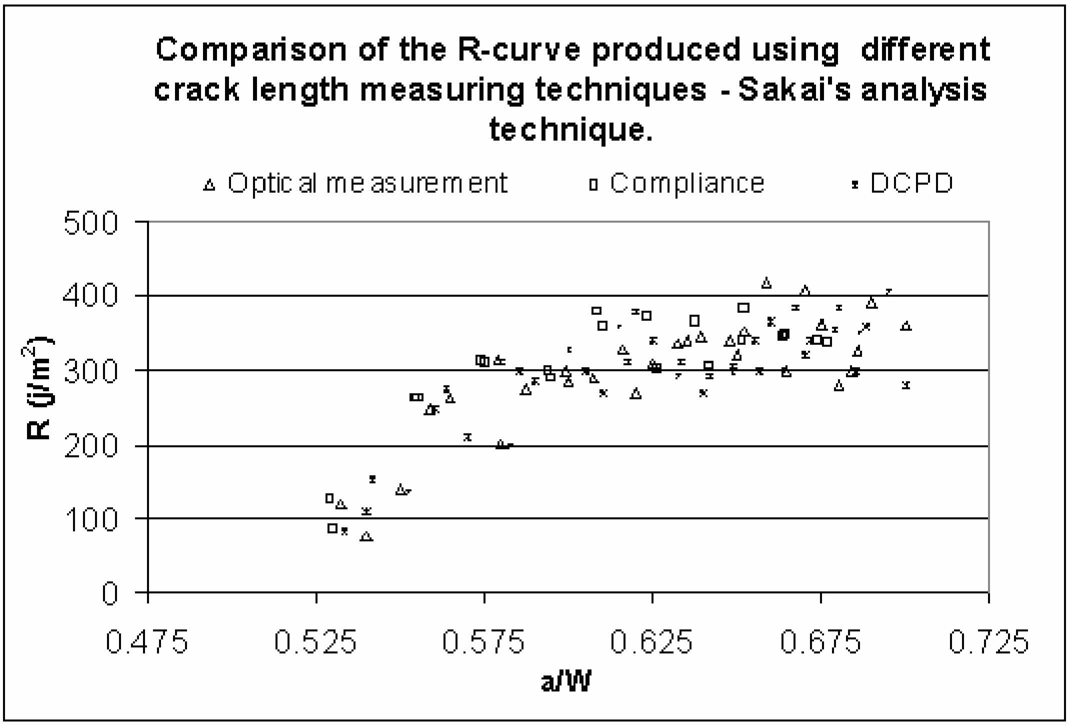


Figure 1: R-curve for Gilsocarbon graphite. Produced using compact tension CT (W=100mm, B=50 mm) specimens and Sakai's analysis technique [7], for crack length monitoring by optical measurement, compliance and direct current potential drop (DCPD). Rising resistance is evident in the first 10mm (a/W = 0.525 to 0.625). Following this resistance stabilises.

common measure of the effect, which defines the energy required to propagate the crack as crack lengths increase [7]. R-curves commonly exhibit a sharp initial rise followed by a plateau [3, 7]. Significant variations however, can result from uncertainties in the measurement of crack length [2, 3]. This has been observed in Gilsocarbon graphite (Figure 1), which demonstrates the uncertainty introduced by different crack monitoring methods.

Electronic Speckle Pattern Interferometry (ESPI) and X-ray Microtomography (XR T) have recently been applied to the observation of crack propagation in graphite. The purpose was to obtain three-dimensional images of the crack within the sample to confirm the crack shape, and to also observe the strain field around the crack tip to obtain evidence for microstructural damage.

1. EXPERIMENTAL DETAILS

Compact tension specimens of Gilsocarbon graphite were cyclically loaded and unloaded under displacement control, in maximum load increments of 200N, until stable cracking took place from the notch tip (Figure 3). The specimen dimensions are given in Figure 2. The thickness was varied between 10 mm and 30 mm. Electronic Speckle Pattern Interferometry (ESPI) [8] was used to generate strain contour maps of the surface by differentiation of measured displacements. X-ray Microtomography[9] (XR T) was used to observe the same specimens, in which the crack opening displacement obtained under load was maintained (Figure 2). This was repeated at intervals as the crack was grown under displacement control.

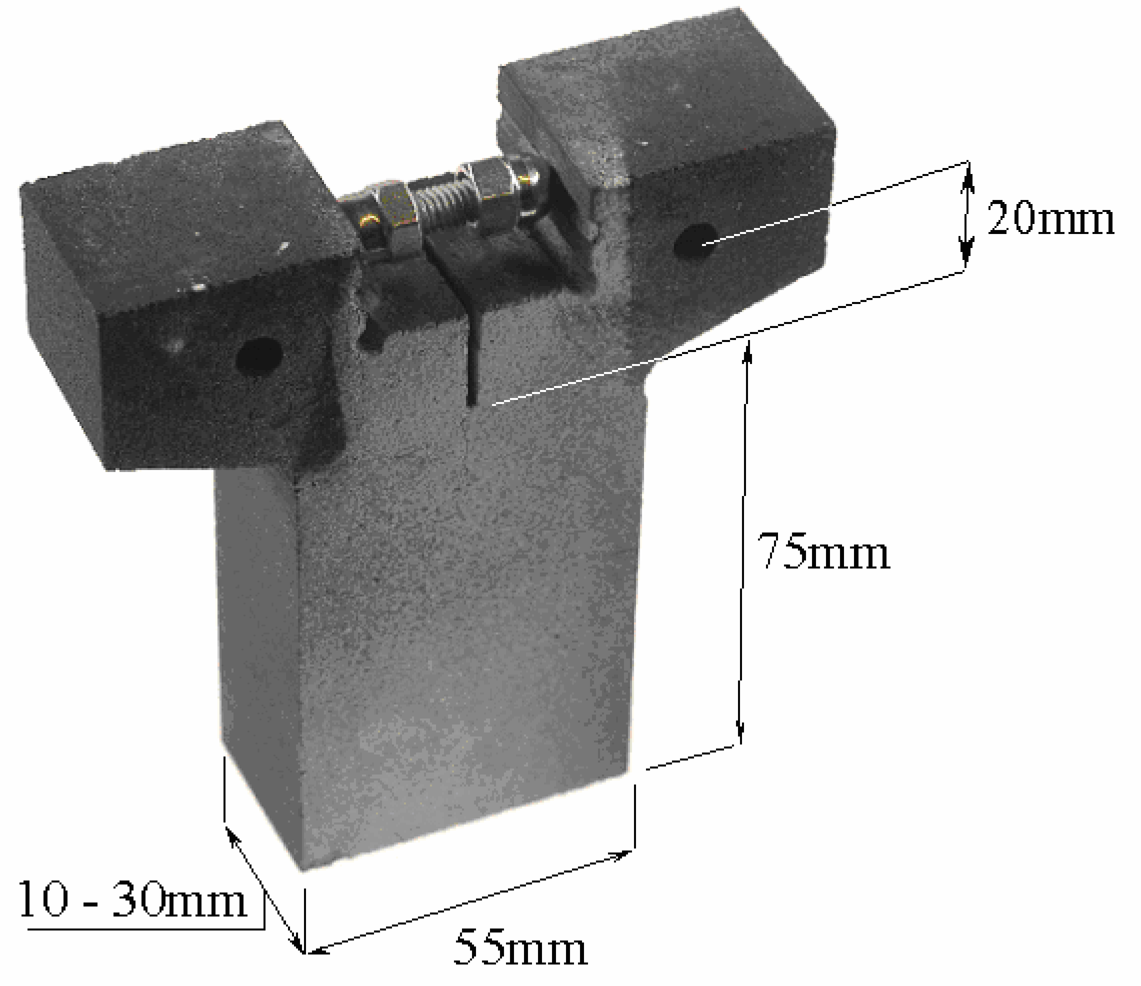


Figure 2: Compact Tension specimen, self-loaded, by a bolt, to maintain the crack opening displacement for X-Ray Tomography.

2. RESULTS AND DISCUSSION

Figure 3 shows the load v displacement history for a typical 10mm thick compact tension specimen. Strain contour maps of the surface indicate no permanent damage around the notch tip before the peak load reaches 500 N. Above 500N permanent residual strain is visible ahead of the notch tip when the specimen is unloaded. This coincides with the first indication of significant hysteresis in the load cycles. The 0.07% contour of the permanently strained zone extends approximately 5mm from the notch tip prior to initiation. Following crack initiation the strained zone size (described by the 0.07% strain contour) increases to approximately 8 – 10mm (Figure 4). The mechanism for this permanently strained zone is not confirmed, but it is currently assumed to be evidence for micro cracking ahead of the crack tip.

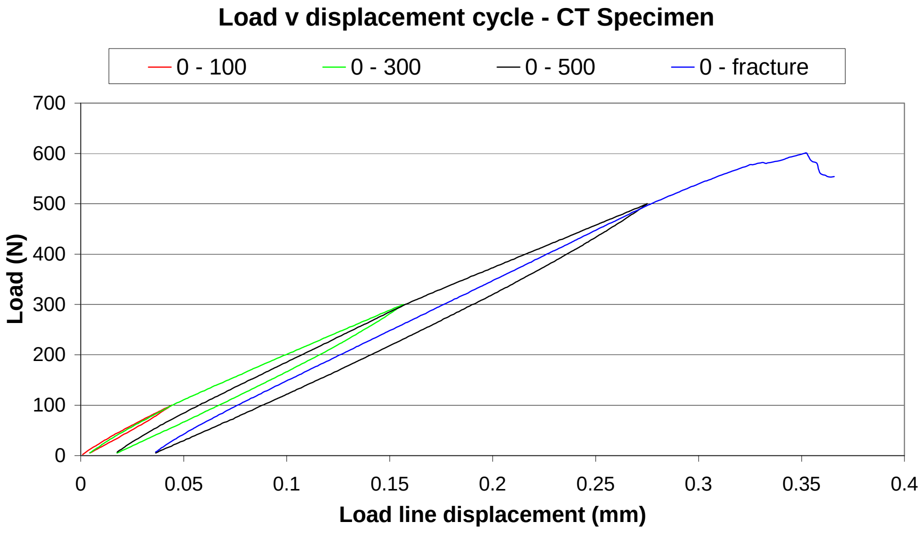
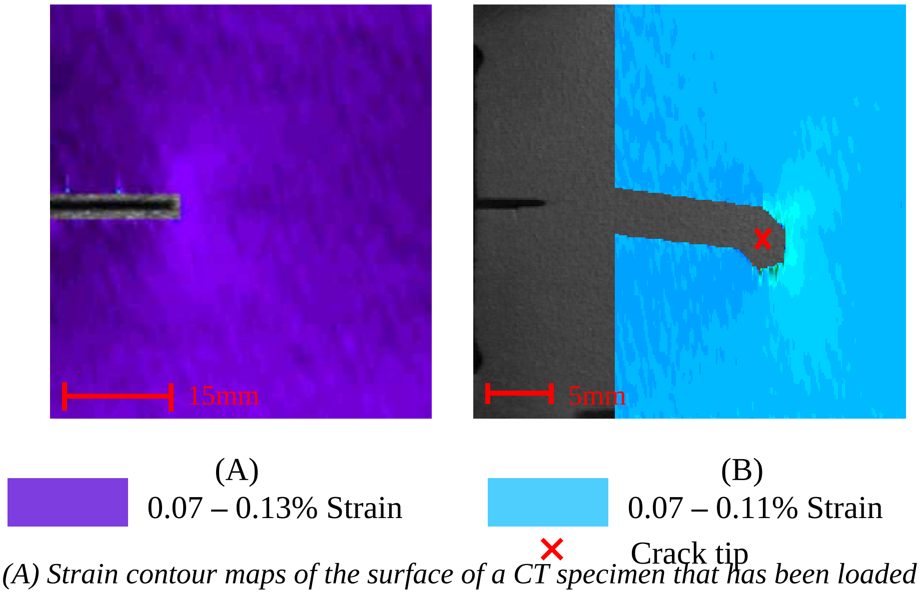


Figure 3 Load v Disp curve for a 10mm thick CT specimen of Gilsocarbon graphite. The specimens were loaded in increments of 200N then unloaded.

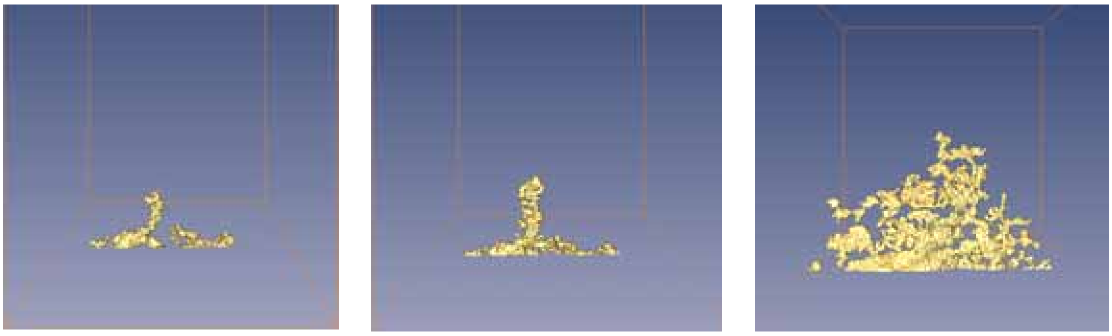


(A)
🟪 0.07 – 0.13% Strain

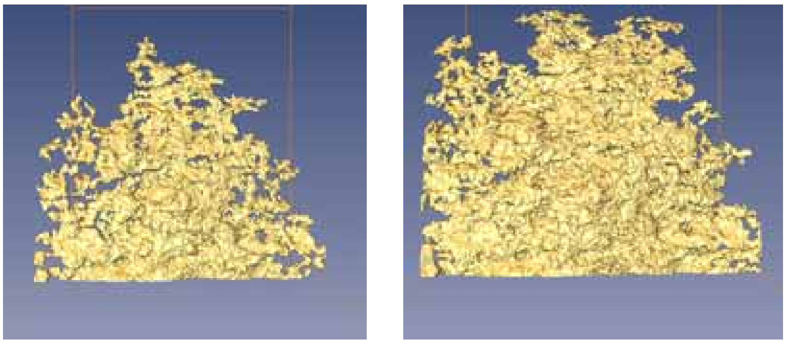
(B)
🟦 0.07 – 0.11% Strain
✕ Crack tip

Figure 4: (A) Strain contour maps of the surface of a CT specimen that has been loaded to 500N then immediately unloaded (B) Strain contour map of a specimen that has been loaded then unloaded following stable crack propagation

Figure 5 shows typical three-dimensional X-ray tomography images of the growth of a crack from the tip of a straight notch in a 40mm wide CT specimen. The crack has been reconstructed by thresholding the three-dimensional attenuation data. Fine detail has not been imaged due to the resolution limit of the technique (70µm for this sample size). Growth through five successive load/unload cycles (at 200N intervals) is shown. The results indicate that initiation takes place in the centre of the specimen. The bowed shape of the crack is maintained as it propagates.



Load cycle 1 Load cycle 2 Load cycle 3



Load cycle 4 Load cycle 5

Figure 5: Computer Tomography images of a crack growing through graphite.

Tomography also shows evidence for discontinuities in the crack. These are observed in a band within approximately 10 mm of the crack tip. These discontinuities are currently assumed to be evidence for crack bridging, which has been reported in other grades of graphite [2].

3. CONCLUSION

ESPI and tomography provide evidence for both micro cracking and crack bridging in Gilsocarbon graphite. The relative contributions of these to the R-curve have not yet been evaluated. The apparent correlation between the size of the bridging zone and the crack length increment over which the early rise in crack propagation resistance suggests that crack bridging may be the dominant mechanism. The reduction in the crack propagation resistance at long crack lengths reported by other authors [6], may be due to the interaction between a micro cracking damage zone and the boundaries of the specimen. Tomography demonstrates that the crack shape in compact tension specimens is not necessarily straight; hence R-curve measurements that assume a straight crack front are not necessarily valid. A new specimen design, which uses side-grooves to control the shape and path of the crack of the crack, is currently being evaluated, using tomography to monitor the crack. This will be applied to a more detailed study of the interaction between the graphite microstructure and the R-curve.

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