OBSERVATION OF MIXED MODE FRACTURE IN NUCLEAR GRAPHITE USING ESPI

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Introduction

Due to its excellent neutronic, thermal and mechanical properties, graphite has been used in nuclear reactor cores, not only as a moderator and reflector but as a major structural component. During reactor operation, the graphite components are subjected to combined loading such as external forces and internal stresses resulting from irradiation-induced dimensional and material property changes and due to thermal gradients. Fracture mechanics-based structural integrity assessments of graphite components may require understanding the mechanisms and failure criteria of graphite under both single mode and mixed mode loading. In this study, in order to gain an understanding of the effects of mixed mode loading on the fracture behavior the deformation zone ahead of a notch, under mixed mode I and mode II loading, were observed using ESPI (Electronic Speckle Pattern Interferometry).

Experimental

Material and Specimen

The material used in this study was molded, near-isotropic IM1-24 nuclear graphite made from spherical Gilsocarbon filler particles of about 0.5mm diameter and a coal tar pitch binder. The bulk density is 1.81 g/cm^3, and the Young's modulus and Poisson ratio are 12.4 GPa and 0.17, respectively. For mixed mode fracture tests, we used centrally notched disk specimens with the size of 40 mm in diameter and 5 mm in thickness. The notch length and width were 12.5 mm (i.e., a/R=0.3125) and 2.5 mm, respectively.

Mixed Mode Fracture Tests

The specimens were loaded diametrically using a 50 kN capacity universal testing machine with a crosshead speed of 0.05 mm/min at ambient air. At first, loading was continued till failure at a notch inclination angle (β) of 0^o (pure mode I), 10^o, 20^o and 30^o with respect to the loading direction to confirm a fracture load for each notch angle condition. Then, the specimens were loaded in increments of 50 N and unloaded in step up to 85 % of the fracture loads to investigate the residual strain fields around the notch tips.

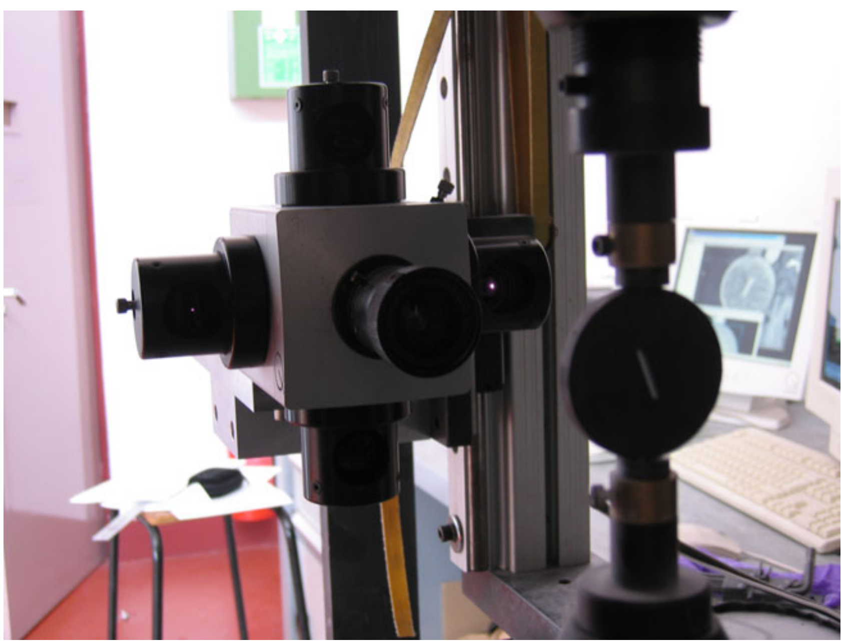


Figure 1. ESPI system used in this study.

Results and Discussion

Load-Displacement Curve

Figure 2 shows typical load-displacement curves for various notch inclination angles. The fracture load decreased as the notch inclination angle increased. The dependence of the fracture load on the notch inclination angle in the mixed mode loading condition can be understood by examining the stress distribution of notch tip formulated by Atkinson. For pure mode I ($\beta = 0^o$), the tensile tangential stress is maximum but the shear stress is zero so that the crack propagates only under the influence of the tangential stress. However, for mixed mode I-II ($0^o < \beta < 30^o$), the shear stress is positive with a maximum value at around $\beta = 35^o$ and the tangential stress is still tensile. Sharp crack initiated by the shear deformation at the notch tip might intensify the tangential stress so that the crack could be propagated at relatively low fracture load with increasing the notch inclination angle.

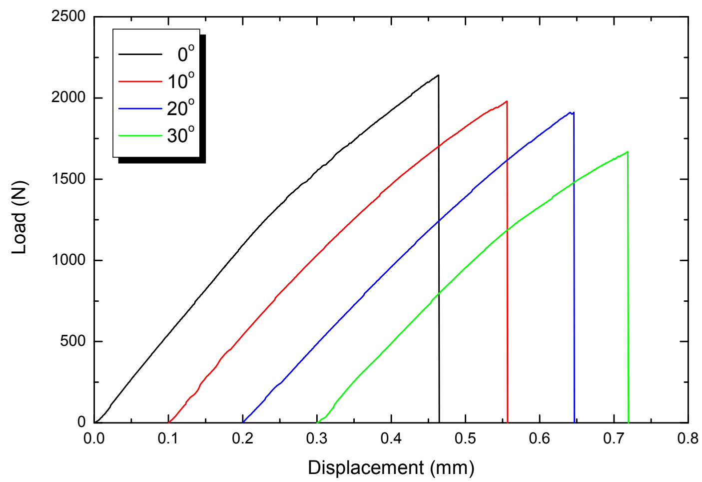


Figure 2. Load-displacement curves under mixed mode I-II loading.

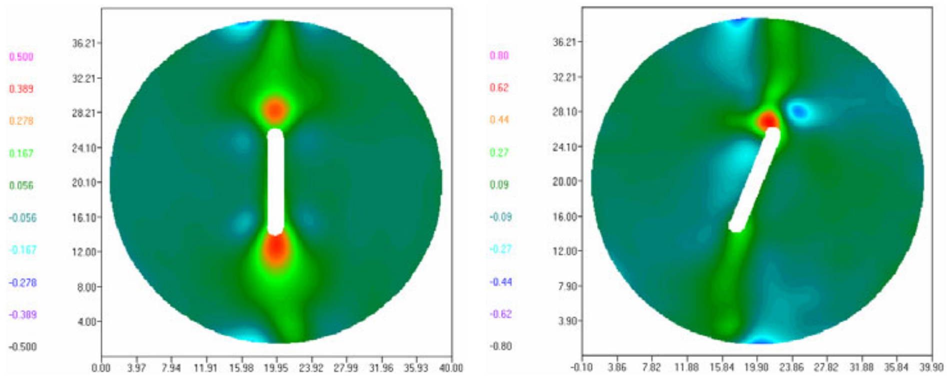
Deformation Behavior

Figure 3 shows the strain distributions at the 85 % of their fracture loads for pure mode I (0^o) and mixed mode I-II (30^o). The tangential strain was formed along the notch line and was concentrated at the notch tip regardless of the notch inclination angle. Although the applied load for the pure mode I (1800 N) was higher than that for the mixed mode I-II (1600 N), the tangential strain was much higher under the mixed mode I-II (~ 0.62 %) loading than the pure mode I (~0.389 %) loading. The shear strain field ranging from 0.27 % to 0.67 % was formed along the notch line in the mixed mode I-II but it was not observed in the pure mode I. These deformation behaviors observed using ESPI coincide well with the reason why the fracture load decreased with increasing the notch inclination angle in the mixed mode loading.

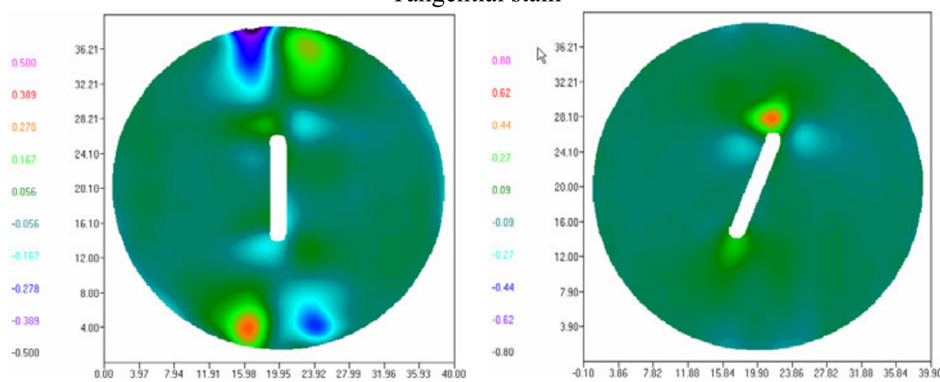
Figure 4 shows the residual strain distributions of the disk surfaces loaded to the 85 % of their fracture loads and then unloaded. As a whole, the residual strain was compressive and formed along the loading line and notch tip. The residual tangential strain at the notch tip was higher in the pure mode I (~ 0.167 %) than in the mixed mode I-II (~ 0.053%), whereas the tangential strain formed under the mixed mode loading was much higher that formed under the pure mode I loading. The residual shear strain for the mixed mode I-II was about 0.083 % at the notch tip. The mechanism for the formation of residual strain was not confirmed but it can be assumed to be related with micro-cracking and basal plane slip ahead of the notch tip.

Conclusion

The fracture load of the nuclear graphite decreased as the notch inclination angle increases under the mixed mode loading ($0^o < \beta < 30^o$). The reason is attributed to stress intensification due to crack initiation by shear deformation at the notch tip and was confirmed by observing the deformation behavior of the disk surface using ESPI. The residual strain fields observed ahead of the notch tip is considered to be related with irreversible processes such as micro-cracking and basal plane slip.



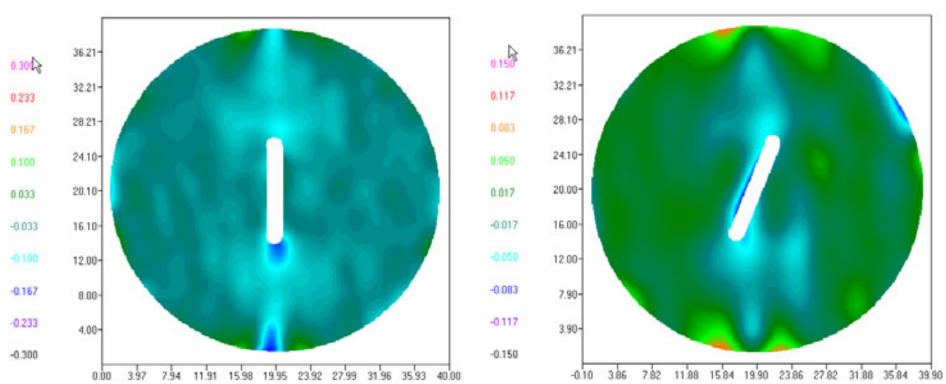
Tangential stain



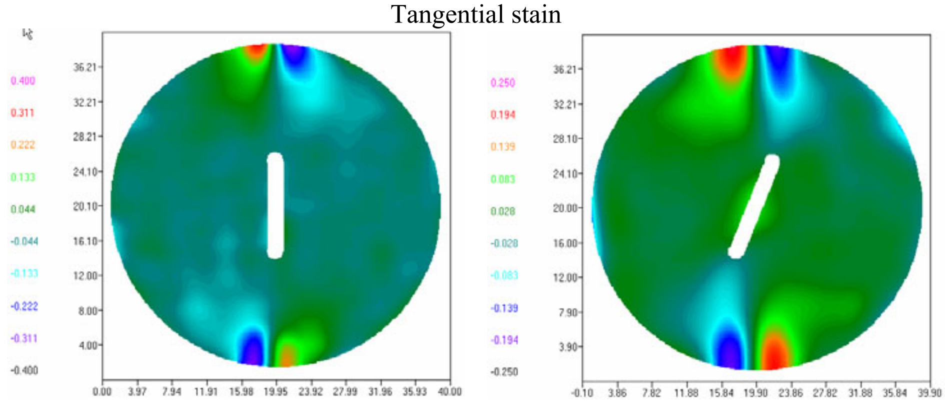
Shear stain

(a) Pure mode I (0^o) (b) Mixed mode I-II (30^o)

Figure 3. Strain distributions of the disk surfaces at the 85 % of the fracture loads



Tangential stain



Shear stain

(a) Pure mode I (0^o) (b) Mixed mode I-II (30^o)

Figure 4. Residual strain distributions of the disk surfaces loaded to 85 % of the fracture loads and unloaded

Acknowledgement

This work was supported by the Korea Research Foundation Grant (KRF-2005-214-D00196).

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