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Analysis of crack propagation in nuclear graphite using three-point bending of sandwiched specimens

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Abstract

The aim of this paper was to assess the suitability of the sandwiched beam in three-point bending as a technique for determining fracture toughness and R-curve behaviour of nuclear graphite using small beam specimens. Surface displacements of the cracked beam specimen were measured using Electronic Speckle Pattern Interferometry (ESPI) and Image Correlation in order to accurately monitor crack propagation and frictional contact between the test specimen and the sandwiching beams. The results confirmed that solutions based on the simple beam theory could overestimate the fracture toughness of graphite. Finite element analysis using a Continuum Damage Mechanics failure model indicated that both friction and shape of the notch played an important part in providing resistance to crack growth. Inclusion of these factors and the use of more accurate load vs. crack length curves derived from the FE model would provide a satisfactory measure of fracture toughness in small beam specimens under such a loading configuration. The particular graphite tested, IG-110, showed a decrease in fracture toughness with increasing crack length.

1. Introduction

Graphite is used for the construction of structural components as well as neutron moderators in nuclear reactors. As graphite is a brittle material, cracking of these components can occur under the influence of thermal and mechanical stresses, especially those in relation to the dimensional and property changes induced by irradiation. The potential for using fracture mechanics to assess the structural integrity of nuclear graphite components has therefore become increasingly important and many attempts have been made to measure the fracture toughness of graphite [1–4,6].

Strictly speaking, standard methods of fracture toughness measurement only apply to homogeneous specimens containing a sharp crack, which in metals is typically produced by fatigue crack propagation from a machined notch. Crack branching often occurs when attempts are made to fatigue a sharp crack into brittle materials which have an inhomogeneous structure. Because of this difficulty, no standard fracture toughness test for brittle materials such as graphite has been established yet.

The first attempt to apply fracture mechanics principles to the fracture of nuclear graphite was probably that due to Corum [1]. He performed notched beam bend tests on an extruded graphite, used for the Experimental Gas-Cooled Reactor (EGCR), and evaluated the critical strain energy release rates based on linear elastic fracture mechanics. Calcined Continental-Lake Charles petroleum coke was used for this graphite, with a coal-tar pitch as the binder. The coke had needle-type particles, with a maximum particle size of ~0.8 mm. A typical beam specimen was 305 mm long, 31.7 mm wide and 31.7 mm deep. Notches of different depths were placed in the specimens using a 0.24 mm thick

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jeweller's saw. Both the compliance measurement method and an analytical solution for the stress intensity factor were used to calculate the mode-I critical strain energy release rates (G_{IC}), and the two sets of results were reported to be in good agreement. However, there were uncertainties in measuring the compliance due to the nonlinear stress–strain behaviour of the graphite. G_{IC} values of about 70 and 50 J/m^2 for specimens whose axes are parallel and transverse to the direction of extrusion, respectively, were reported. The propagation of cracks was reported to be predominantly inter-granular. Lower G_{IC} values were observed for notch length-to-beam depth ratios (a/W) less than 0.2, for which the attributed causes included the occurrence of slow crack growth prior to unstable crack propagation, a sizable zone of inelastic deformation at the notch tip or pre-existing cracks or flaws. For example, if the shorter notches were assumed to have effective lengths equal to one or two maximum grain sizes (equivalent to the particle size) larger than the initial saw cut, the G_{IC} values recalculated with the adjusted lengths were roughly constant for all notch lengths.

Rose [2] measured the fracture toughness of virgin pitch coke graphite using curved notched beams cut from sleeves and subjected to bending. All tests were such that the direction of stressing was perpendicular to the extrusion direction of the graphite components. The notches had a root radius of about 0.5 mm and depth of 0.5–7.9 mm, giving notch depth to beam depth ratios between 0.03 and 0.52. By measuring acoustic emission, he demonstrated that micro-cracking took place prior to the main failure, with the quantity of micro-cracking decreasing with increasing notch depth. A modified solution based on Linear Elastic Fracture Mechanics (LEFM) was used to estimate K_{IC}. Similar to Corum [1], Rose found that consistent values of K_{IC} (1.2 MPa m$^{1/2}$) were obtained using the analytical method if an additional crack length of 0.6 mm was added to the original notch depth to account for the presence of inherent flaws. This applied also to unnotched specimens. However, the results from the compliance method to obtain the critical strain energy release rate showed a decrease in the measured fracture toughness with increasing notch depth.

Sakai et al. [3] used the compact tensile test with a chevron notch under loading and unloading to determine nonlinear elastic–plastic fracture parameters for an isotropic fine grain size polycrystalline graphite, IG-11, produced by Toyo Tanso Co. Ltd., Japan. These included the nonlinear critical strain energy release rate, the crack growth resistance, the J integral and the plastic energy dissipation rate. They found that about 38% of the total fracture energy was consumed as plastic energy. All of the fracture parameters decreased with increasing crack length for crack length to specimen width ratios (a/W) between 0.6 and 0.9. For zero plastic energy dissipation, i.e. as the crack length approaches the specimen width, the other three fracture parameters converge to give a lower limit of 73 J/m^2, which equates to a fracture toughness of 0.95 MPa m$^{1/2}$ for Young's modulus of 9.8 GPa and Poisson's ratio of 0.2.

In a separate paper [4], Sakai et al. examined the R-curve or crack growth resistance behaviour of another fine-grain polycrystalline graphite, IG-110, using the compact tensile test, ASTM E399 [5], with different notch depths ($0.3 < a/W < 0.9$). They showed that the R-curves rose sharply at first, then reached a plateau before falling off gradually for a/W ratios > 0.6. The initial sharp rise of the R-curves was attributed to grain bridging of the crack surfaces behind the primary crack tip, which had an initial root radius less than 10 μm, much smaller than those used in the other works mentioned. The final fall was attributed to the diminishing of material to sustain the micro-cracking process zone in front of the crack tip as the latter approaches the end face of the specimen. Note that the range of a/W values over which the R-curves fell off was the same as that for the IG-11 graphite mentioned above. The fracture toughness for stable crack propagation within the plateau region for this graphite was found to be 1.2 MPa m$^{1/2}$. Similar R-curve behaviour was found by Ouagne et al. [6] for PGA and IM1-24 graphites which are used as moderators in British Magnox and AGR nuclear reactors, respectively.

IG-110 was also investigated by Fazluddin using notched beams in three-point bend tests [7]. The crack lengths were monitored using the compliance method. Fig. 1 shows the resulting K_R curve reported in [7]. As can be seen from the figure, the K_R value of IG-110 changes very little over the range of crack lengths ($0.35 < a/W < 0.9$) examined, which is in contrast to the results reported by Sakai et al. [4] for this graphite using the compact tensile test.

From the above discussion, it is clear that the fracture toughness of graphite is ∼1 MPa m$^{1/2}$, with $K_R \sim K_{IC}$, but the actual value measured seems to be sensitive to the test configuration, notch depth to specimen depth ratio, the geometry of the notch tip as well as the method of analysis. Similar observations on the same graphite have been made by Burchell et al. [8] who compared data from six different test geometries.

The sandwich beam bend test has been proposed by Pancheri et al. [9] as a method for pre-cracking brittle specimens since it is capable of producing sharp cracks with a certain length in a controlled manner. In this method, a rectangular beam with a saw cut of the material being tested is put between two sandwiching steel beams; see Fig. 2. The sandwich is then loaded in three-point bending. As the load increases, the crack would start to extend and, as it does so, the stiffness of the cracked beam would decrease and loading would be shed to the two sandwiching steel beams. The propagating crack would then slow down and arrest unless further load is applied. The test was applied to two different types of alumina, one with and one without significant R-curve behaviour, i.e. increase in fracture toughness with crack length. Using toughness data obtained from other tests, good agreement between theory