CRACK GROWTH IN NUCLEAR GRAPHITES USING R-CURVE ANALYSIS

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INTRODUCTION

British gas-cooled reactors are graphite-moderated and cooled by CO_2. During service, the moderator core bricks are subject to neutron irradiation and radiolytic oxidation, which induce dimensional changes / internal stresses and reduce strength, respectively. Historically, the fracture behaviour of polygranular graphites has been characterised by Linear-Elastic Fracture Mechanics, but graphites exhibit marked non-linearity in their stress-strain curves and irreversible deformation mechanisms like crack branching and bridging which are characteristic of elastic-plastic materials. The internal stresses within the core bricks may eventually lead to failure of the graphite brick by fast fracture at the end of a reactor's life. Fracture is predicted to originate at the key-way root and travel to the bore, Figure 1(a). Currently, a critical stress criterion has been adopted to predict whether a brick will eventually fail during prolonged service based upon the fact that stress-strain curve becomes increasingly linear with neutron irradiation. However, increasing oxidation tends to increase the non-linearity in the stress-strain curve and so there may be other parameters, such as energy based failure criteria, which are better suited to predict failure, Figure 1(b). In this paper, the crack growth resistance R, is considered and is defined as the energy required per unit crack area increase. Therefore R includes both the elastic and plastic components of the fracture energy. Two independent graphical methods to determine R were evaluated in this work, described by Sakai and Bradt (1) as Method 1 (the loading-unloading technique) and Method 4 (the universal dimensionless diagram technique). The first method requires the comparison of two adjacent load cycles (to zero load) to determine the envelope of energy consumed in propagating the crack whilst the second method compares the load-displacement curve (without the need for load cycles) with that of an ideal elastic material.

EXPERIMENTAL

Compact tension specimens were machined from AGR moderator graphite (a fine grained isotropic graphite with spherical filler particles of mean size 0.5 mm ∅) with breadth, width and initial crack length of 1, 5 and 1 cm, respectively. The samples were tested using an Instron 1195 with COD gauge to generate a load versus load-point displacement curve as shown in Figure 2(a). The load-displacement curve was analysed using both Methods 1 and 4 as described in (1) to generate R curves, Figure 2(b). The crack length was calculated using a compliance calibration curve.

RESULTS AND DISCUSSION

Typically this work has shown similar R curves from both of the independent methods used. For AGR moderator graphite a high resistance to crack initiation is observed followed by a slightly decreasing resistance to crack propagation and crack termination, Figure 2(b). Few studies involving R-curves for polygranular graphites or carbon materials have been undertaken. Sakai *et al.* (2) found for a Japanese isotropic nuclear graphite, Figure 3(a), a rise in R with crack initiation followed by a steady-state value for crack propagation. Decreasing values in crack resistance as the crack front approached the sample edge have been observed. The steady state value of R found by Sakai *et al* (~230 J/m^2) is similar to the results for AGR graphite (~200 J/m^2) in this work. Allard *et al.* (3) for anthracite-based carbon materials found similar behaviour (with a plateau value of ~250 J/m^2) except that the R-curve rose as the crack front approached the sample edge which they attributed to an increase in the process zone. Similar to these other materials, the R curve for AGR moderator graphite also shows a steady-state value during crack propagation and crack termination, even if a tiny decrease is observed. No important change is observed for crack termination. This may be indicative of a small process zone and limited sub-critical cracking.

CONCLUSIONS

The R curve for AGR moderator graphite has been determined using two independent methods. Both methods show similar results which differ from other carbon materials in that a relatively high resistance to crack initiation is observed followed by a slightly decreasing crack propagation and crack termination.

ACKNOWLEDGEMENTS -

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REFERENCES

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2. Sakai M, Yoshimura J, Goto Y, and Inagaki M. R-Curve Behaviour of a Polycrystalline Graphite: Microcracking and Grain Bridging in the Wake Region. J. Am. Ceram. Soc 1988;71: 609-616.
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FIGURE 1 (a) and (b): Schematics of AGR brick cross-section and stress-strain curves

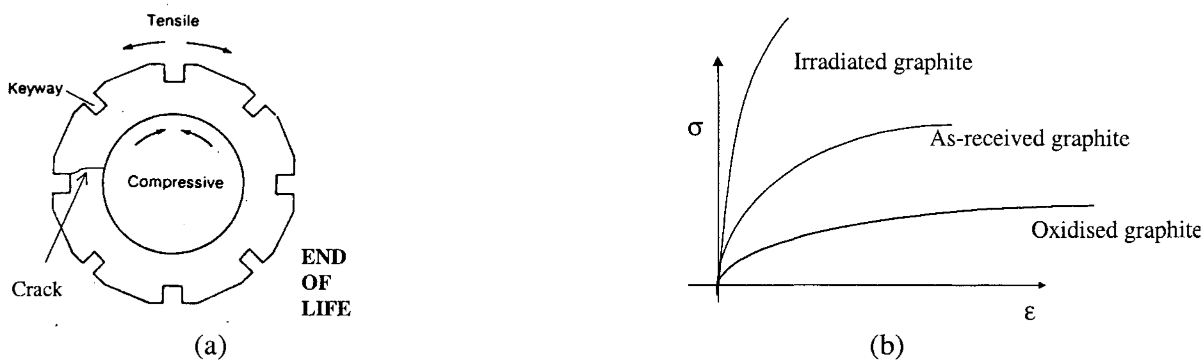


FIGURE 2 (a) and (b): AGR graphite typical load-displacement curve with corresponding R curves.

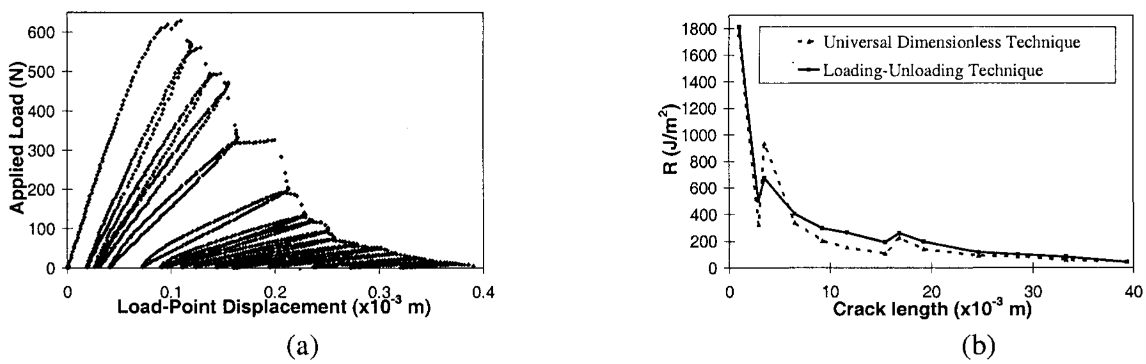
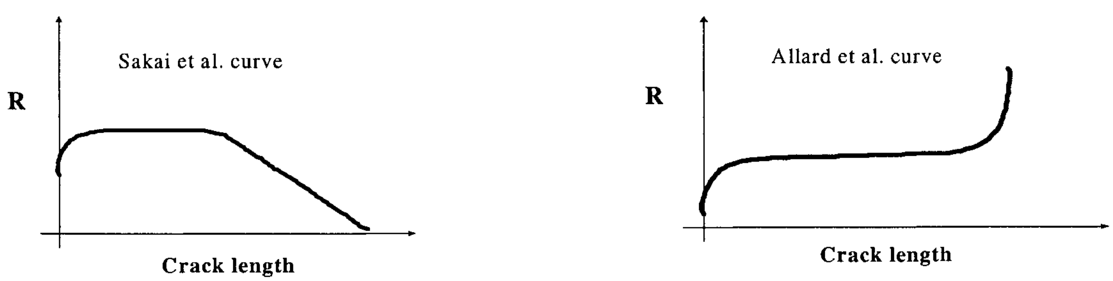


FIGURE 3 (a) and (b): Schematic R curves from Sakai *et al.* (2) and Allard *et al.* (3).



(a) Isotropic nuclear graphite

(b) Anthracite-based carbon