THE EFFECT OF SPHERICAL FLAWS ON THE FRACTURE BEHAVIOR OF H-451 AND IG-11 GRAPHITES

G. R. Romanoski
Oak Ridge National Laboratory
P.O. Box 2008, Oak Ridge, TN 37831-6088 USA

Introduction

Graphite is used as a nuclear moderator and a structural material in the core of gas-cooled reactors. The design and strength assessment of graphite core components is generally based on a maximum principal stress failure criterion to define limitations on maximum local stress. The probability of failure is unacceptable when the maximum principal stress exceeds some minimum ultimate strength of the graphite as determined by applying statistical methods to a large number of tensile test results. The minimum ultimate strength may be viewed as representing the strength of the graphite matrix including the influence of: cohesive strength of the binder phase, filler coke particle size, as well as intrinsic microcracks and microporosity. These intrinsic micro-flaws are present in significant numbers in every cm^3 of graphite and control strength by operating cooperatively to serve as sites of crack initiation and as a path of easy propagation. In addition to microscopic flaws, significantly larger flaws (1 mm to 10 mm) may be present as anomalies from processing, or machining and handling damage. These large disparate flaws may control the strength of a core component by operating independently as the dominant crack initiation site. The need for applying fracture mechanics to component strength assessment becomes obvious when one considers the possible presence of these larger flaws. This investigation extends the scope of an earlier one on the fracture behavior of small planar flaws [1,2] by addressing the effect of small hemispherical flaws on the flexural strength of H-451 and IG-11 graphites.

Experimental

Four-point bend specimens of square cross-section measuring: 25 mm x 25 mm or 50 mm x 50 mm were used in this investigation. A single hemispherical flaw was machined in the center of the tensile surface of most specimens. Hemispherical burs were used to introduce defects to a depth equal half their diameter for the size range from 16 mm to 1.6 mm. Hemispherical defects were approximated using 118° microdrills for the size range from 1.6 mm to 0.13 mm. Four specimens were tested for each defect size considered. A number of specimens without artificial flaws, i.e., containing only intrinsic flaws, were also tested. These test results will here be compared to the results of a previous investigation where planar flaws were introduced perpendicular to the tensile axis as circular section slots with a thickness of .25 mm and a notch root angle of 45°. Crack depth ranged from a = 10 mm to 0.025 mm and the surface length ranged from 2c = 10 mm to 0.55 mm. Tests were conducted in strict accordance with ASTM standard C651-91 [3].

Results and Discussion

All specimens were loaded to failure, the peak load was measured, and the fracture origin was noted as being at the artificial flaw or away from the flaw. Fracture at artificial flaws occurred by extending a crack perpendicular to the tensile axis of the specimen coincident with the flaw. Failure away from artificial flaws, i.e., at intrinsic flaws, always occurred between the loading points in the region of constant tensile stress.

Test results are shown in Figs. 1 and 2 as a plot of fracture stress versus flaw depth for specimens containing: a planar flaw, a hemispherical flaw, or no artificial flaw (in which case failure occurred only at intrinsic flaws). The open symbols represent failure at the artificial flaw and the closed symbols represent failure away from the artificial flaw. First consider the planar flaws. At longer flaw depths, the fracture stress is proportional to the square root of crack depth and, therefore, fracture toughness and flaw size controlled strength. Fracture toughness approaches 1.2 $MPa\sqrt{m}$ for H-451 graphite and 1.0 $MPa\sqrt{m}$ for IG-11 graphite at the longer flaw depths. As the artificial flaw size was reduced, failure occurred at higher stress levels until the fracture strength was equivalent to the unflawed specimens, i.e., the mean flexural strength. At the transition crack depth, half of the specimens failed at the artificial flaw and half failed at intrinsic flaw(s). The transition crack depth was 1.0 mm for H-451 graphite and 0.050 mm for IG-11 graphite. Transition defect dimensions are comparable to the filler coke particle size for these graphites.

Specimens containing a hemispherical flaw exhibited fracture stresses and transition lengths significantly greater than specimens containing a planar flaw of equal depth. It is apparent that fracture stress versus flaw dimension does not follow the simple relationship that worked for fracture mechanics treatment of planar flaws, particularly at the larger flaw dimensions tested. The fracture stress converges to the mean flexural strength as intrinsic flaws dominate as the preferred fracture initiation site. The defect tip acuity is obviously lower for the hemispherical defect, particularly at large diameters. Hemispherical surface pits cause a stress concentration at their surface that is approximately two times the nominal stress. Therefore, if the appropriate failure criterion for these graphites was the local maximum principal stress, then we would expect fracture to occur at 50% of the flexural strength and be independent of pit diameter. However, fracture strengths exhibited maximum reductions of 34% and 38% and decreased with increasing pit diameters.

This presentation will first review the few established approaches for quantifying fracture at hemispherical surface pits. A new approach will be introduced that identifies a local failure criterion that is applicable for both planar and hemispherical flaws, and is consistent for the complete range of defect sizes considered here.

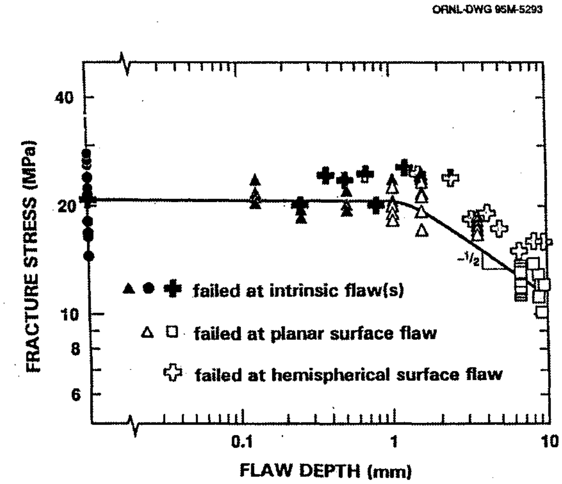

Figure 1. Fracture stress versus flaw depth for H-451 graphite.

Conclusion

The fracture behavior of small artificial flaws provides a valuable window to identify the effective size of strength controlling intrinsic flaws. Furthermore, this experimental approach helps to define the limitations of continuum mechanics treatments of very small flaws approaching the dimensions of intrinsic flaws.

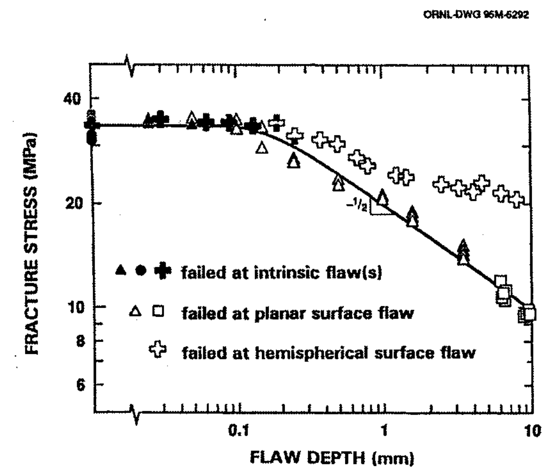

Figure 2. Fracture stress versus flaw depth for IG-11 graphite.

References

[1] Romanoski GR. Fracture Behavior of Small Flaws in H-451 and IG-11 Graphites, Extended Abstracts, 22nd Biennial Conf. on Carbon. UC San Diego (California. USA): American Carbon Society, 1995;766-767

[2] Romanoski GR. Carbon Materials for Advanced Technologies. in press Elsevier Science.

[3] ASTM Standard C651-91 Standard Test Method for Flexural Strength of Manufactured Carbon and Graphite Articles Using Four-Point Loading at Room Temperature. ASTM, 1916 Race Street, Philadelphia, PA 19103.