FRACTURE BEHAVIOR OF SMALL FLAWS IN H-451 AND IG-11 GRAPHITE

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INTRODUCTION

Graphite is used as a moderator and a structural material in the core of the Modular-High Temperature Gas-Cooled Reactor (MHTGR). Although design is based on a maximum principal stress failure criterion (MPSFC), fracture mechanics is an important consideration in assessing the structural integrity of core components. This paper suggests an approach for considering both the MPSFC and fracture mechanics in design.

The MPSFC may be used to define limitations on the maximum local stress. The probability of failure is unacceptable when the maximum principal stress exceeds some minimum ultimate strength, S_u. The minimum ultimate strength is determined by applying statistical methods to a large number of tensile test results where S_u is the stress above which the probability of failure of a tensile specimen is 99% with 95% confidence. The minimum ultimate strength may be viewed as representing the intrinsic strength of the graphite matrix including the influence of: cohesive strength of the binder phase, filler coke particle size, intrinsic porosity, etc.

The need for applying fracture mechanics to component strength assessment becomes obvious when one considers the possible presence of macroscopic flaws in graphite. Macroscopic flaws of 3-mm diameter are typical in H-451 graphite, however, flaws as large as 15 mm have been found. Further evidence of macroscopic flaws has been noted in studies of tensile strength where defects were of sufficient size to result in some specimens having nearly zero strength, often breaking during machining.

The relevant defect sizes for which the strength of a large section component, such as a graphite core support, is controlled by the minimum ultimate strength or fracture toughness may be addressed by considering the plot of failure stress versus crack length [1] shown in Fig. 1. The stress required to cause failure in H-451 graphite was calculated for a penny shaped flaw of diameter = 2a. The transition crack length, 15.7 mm, bounds the apparent regimes of applicability of the two failure criteria. The darkly shaded regions represent failure conditions for which MPSFC or fracture mechanics may be nonconservative. The transition crack length is strongly influenced by S_u. The choice of an overly conservative value of minimum strength based on small specimen tests would suggest that S_u governed minimum strength up to longer crack lengths than is actually the case in large section components. The objective of this work was to determine the effect of small macroscopic flaws on the flexural strength of two grades of nuclear graphite, H-451 and IG-11.

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 artificial flaw was machined in the center of the tensile surface of most specimens. The flaw geometry perpendicular to the tensile axis was a circular section with a slot thickness of 0.25 mm and notch root angle of 45°. Crack depth ranged from a = 0.025 to 10 mm and the surface length ranged from 2c = 0.55 to 22 mm. A number of specimens contained no artificial flaw, i.e., contained only intrinsic flaws. Six specimens were infiltrated under vacuum with a polyurethane bearing fluorescent dye to mark surface connected porosity. Tests were conducted in strict accordance with ASTM standard C651-91 [2].

RESULTS AND DISCUSSION

All specimens were loaded to failure, the peak load was measured and the fracture origin noted as being at the artificial flaw or away from the flaw. Fracture at artificial flaws occurred by extending the plane of the flaw perpendicular to the tensile axis of the specimen. 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 for IG-11 graphite are shown in Fig. 2 as a plot of fracture stress versus crack depth for specimens containing an artificial flaw and specimens containing no artificial flaw, in which case failure occurred only at intrinsic flaws. At longer crack lengths, the fracture stress is proportional to the square root of crack depth and, therefore, fracture toughness and flaw size controlled strength. 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 is 0.050 mm for IG-11 graphite. It is notable that this value is comparable to the mean filler coke particle size for this graphite.

Test results for H-451 graphite are shown in Fig. 3 as a plot of fracture stress versus crack depth. The transition from artificial flaws controlling fracture strength to intrinsic flaws controlling strength occurred at 1 mm for this graphite. Although the mean filler coke particle size is around 0.5 mm, filler coke particles as large as 1 mm are common. Here again, at the transition crack depth, half of the specimens failed at the artificial flaw and half failed at intrinsic flaw(s).

The physical basis of the MPSFC is tensile strength measurements where failure is dominated by intrinsic flaws. The results of this investigation suggest that this failure criterion should be used with caution when larger flaws may be present. Fracture stress versus flaw depth plots of Figs. 2 and 3 provide important information on defect tolerance and specific requirements which should be considered for nondestructive evaluation. For example, if we choose to use only the minimum ultimate strength concept to assess structural integrity, we must insure that highly stressed volume elements of graphite components are free of flaws greater than the transition crack length (to the required confidence level) or accept a suitable knock-down on the allowable stress. If fracture mechanics is used in addition to minimum ultimate strength, nondestructive evaluation methods should be employed to determine that cracks larger than the critical crack length for the design allowable stresses are absent from highly stressed regions of core components. The flaw sizes of concern in strength assessment appear to impose demanding requirements on nondestructive evaluation regardless of the graphite selected.

An alternative approach to assessing flaw content of structural graphites is to measure tensile strength using very large volume specimens, e.g., specimens of 75-mm diameter or larger with uniform gage sections. Sampling of these large volumes will allow a statistical determination of the occurrence of large disparate flaws. Thus, the burden and expense of overly stringent nondestructive evaluation requirements could be avoided.

CONCLUSIONS

The regimes of applicability of MPSFC and fracture mechanics should be determined explicitly by small flaw fracture testing. The design of graphite core components should be reconciled with these results.

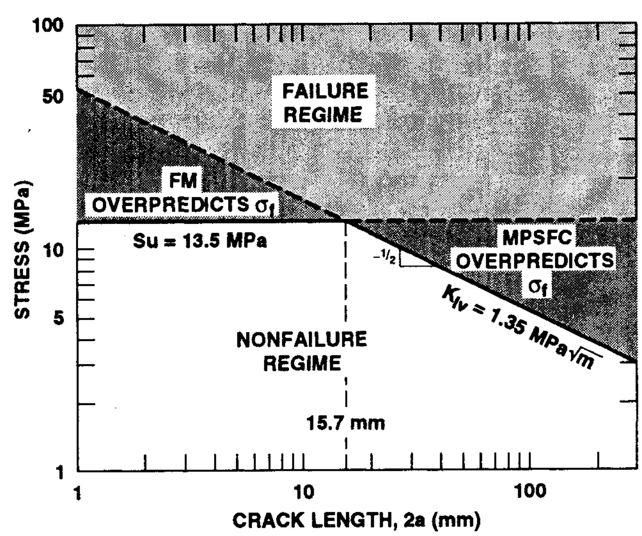

Figure 1. Fracture stress versus crack length for H-451 graphite

ACKNOWLEDGEMENT

Research sponsored by the Division of MHTGRs, Office of Advanced Reactor Programs, U. S. Department of Energy

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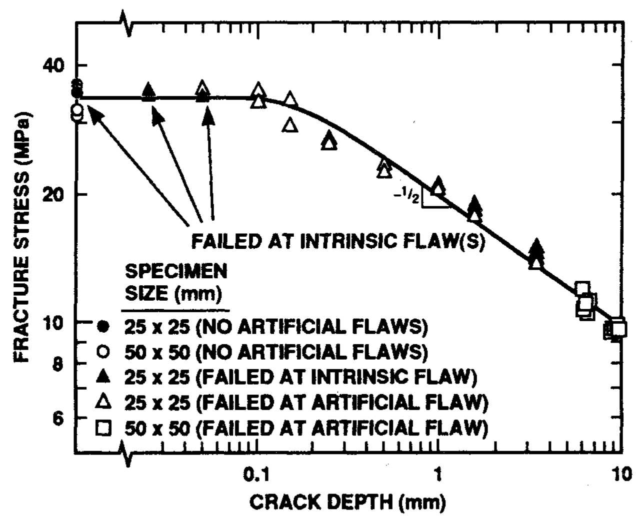

Figure 2. Fracture stress versus flaw depth for IG-11 graphite

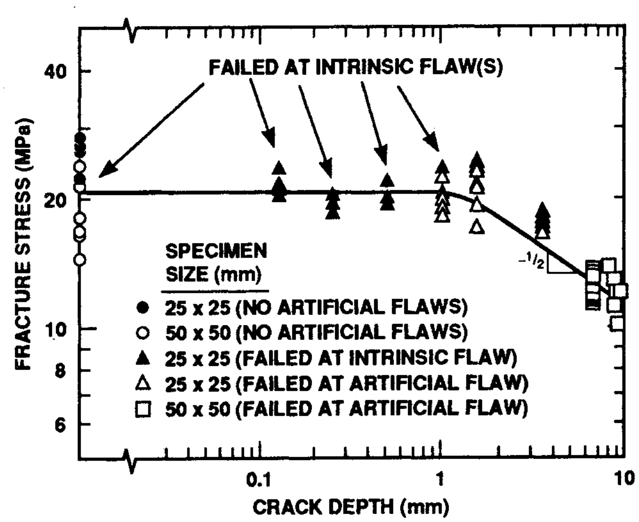

Figure 3. Fracture stress versus flaw depth for H-451 graphite