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Informal Report

TENSILE TESTING AND SCANNING ELECTRON MICROSCOPE EXAMINATION
OF CHARPY IMPACT SPECIMENS FROM THE HFBR

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ABSTRACT

The Materials Technology Group of the Department of Nuclear Energy (DNE) at Brookhaven National Laboratory (BNL) has performed a fractographic examination of neutron irradiated and unirradiated Charpy "V" notch specimens which have been deformed to failure in a tensile testing apparatus. The evaluation was carried out using a scanning electron microscope (SEM) to evaluate the fracture mode. Photomicrographs were then evaluated to determine if ductile areas were present on the fracture surfaces of the specimens. The irradiated tensile tests (Charpy "V" notch configuration) showed minimum notch tensile strengths of 37.2 Ksi before failure. The unirradiated 6061 T-6 material exhibited a minimum notch tensile strength of 41.9 Ksi.

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DEFINITIONS

Fracture normally occurs in two stages:

- a) Nucleation of the crack
- b) Propagation of the crack

Fractographically, fractures can be either intergranular or transgranular in appearance. Intergranular cracking occurs in grain boundaries while transgranular cracking follows a path through the grains.

Most service/test failures cracks display a combination of various fracture modes which for the case of this examination would include:

- a) Microvoid coalescence/dimple rupture:

In metallic materials which fracture under single load or by tearing, the fracture surfaces show numerous depressions in microstructures. These surface features are known as *dimples* in fracture terminology and, hence, the name *dimple rupture* is given to this type of fracture mode. Dimples form by a process of *microvoid* nucleation on or around sites where local plastic deformation is high. Microscopic inhomogeneities like precipitates, inclusions, grain boundaries, etc., act as preferred sites for microvoid nucleation. Under increasing strain, microvoids grow, *coalesce*, and eventually rupture to produce dimples on the fractured surfaces.

- b) Transgranular cleavage:

This fracture exhibits little or no plastic deformation and occurs along low-index, well-defined crystallographic planes. This type of fracture is

common in bcc and hcp materials. In fcc materials, the cleavage mode is restricted to external conditions, e.g., cracking of aluminum alloys in the presence of mercury, stress-corrosion cracking of brass, and corrosion fatigue in some alloys.

Cleavage mode of fracture is favored under high triaxial stress (at the root of a notch), at high deformation rates (impact testing) and low temperature conditions.

c) decohesive rupture:

Separation of fracture surfaces along weak fracture paths is known as *decohesive rupture*. Two main factors that can promote this mode of fracture are: (1) morphological variables such as copious *grain-boundary precipitation* and formation of *low-strength phases* and *defect structures* along grain boundaries; (2) environmental factors which promote environment-material interaction such as *stress-corrosion cracking* and *hydrogen embrittlement*, which, in turn, leads to ultimate failure under applied load.

The above definitions for these three fracture modes were taken from the IITRI Fracture Handbook, "Failure Analysis of Metallic Materials By Scanning Electron Microscopy," Chicago, January 1979.

1. INTRODUCTION

In October 1988, the Reactor Division (RD) of Brookhaven National Laboratory contracted with the Materials Technology Group of the Department of Nuclear Energy (DNE) to machine and test specimens from an HFBR control rod follower.

The purpose of the program was twofold:

- a) Four tensile specimens were required to be machined and tested (HFBR Technical Specification Requirement).
- b) The Shewmon committee had requested BNL to perform evaluations of the fracture toughness of the HFBR beam tube materials. After extended discussions with the Structural Analysis Division of DNE, it was decided that Charpy impact specimens would be machined and tested.

Charpy impact specimens were chosen because they could be reproducibly machined and tested in the BNL Metallurgical Hot Cell with the equipment and personnel available at the time of program inception.

Authors Note: These data were documented in BNL Informal Report 43367, August 1989.

On July 18, 1989, an HFBR review committee evaluated the materials work performed and provided the following guidance in their summary and recommendations:

"We believe that cracks can open up in the beam tubes of the HFBR reactor only if, and when, they are exposed to tensile stresses, or large shear stresses. These might be large transient stresses, or continued exposure to smaller tensile stresses. A detailed stress analysis has shown that the external pressure on the beam tubes maintain compressive stresses in all regions of the body of the beam

tubes (but not in the tips of the cooling fins) during normal operation. Tensile stresses can only develop in the body of the beam tubes when there are depressurization transients. Even then the maximum credible tensile stresses are quite low, and the maximum stress intensity that could develop beneath a long crack which lay in the worst location and penetrated 60% of the way through the wall thickness is low (<1000 psi/in).

Measurements of the toughness of the irradiated beam tube material indicate that while exposure to the high neutron flux has significantly reduced its toughness, the remaining toughness is still estimated to be a factor of 7 above this level of 1000 psi/in.

Based on the available evidence we would expect that the beam tubes do not constitute an undue safety risk for the continued operation of the HFBR. Analysis shows that tensile stresses are found only under upset conditions and fracture at the upset stress levels if the tubes are badly flawed. However, we believe the following tests should be carried out to better establish the safety margin against brittle fracture:

1. Because the toughness test results that have been completed give only approximate values, we recommend the following tests should be carried out, one immediately, and the other in the future:
 - a. A fractographic examination of the fracture surface of the notched impact specimens (the so-called Charpy specimens) should be performed to estimate the amount of plastic deformation required for propagation of the crack. This test should proceed immediately. If there is evidence of ductility then there is sufficient margin for safe operation. If there is no evidence of ductility, then the test described in b), below, should be done before restart.

Authors Note: This fractographic study has been documented in BNL Informal Report 43602, October 1989 [2].

- b. Test should be performed to more quantitatively characterize the fracture resistance (fracture toughness) of the irradiated material. This could be done by pulling side-notched samples cut from the irradiated control rod follower, as discussed with the BNL staff. If the fractographic examination indicates plastic deformation, these tests should be completed within the next year..."*

This report [2] is the documented results of the tensile tested Charpy impact specimens and subsequent scanning electron microscope (SEM) evaluation described in "b" above.

2. TESTING

In order to accomplish the aforementioned task, a total of six Charpy impact type specimens were tensile tested. Three of the specimens had been irradiated in the Brookhaven National Laboratory (BNL) High Flux Beam Reactor (HFBR). They were identified as C-A, C-3 and C-7 [1]. Three other non-irradiated specimens were also tested; two of aluminum alloy 6061 T-6 (identified as "A" and "B") and one specimen machined from 1100 series aluminum.

These specimens were tensile tested in accordance with the tensile test procedure outlined in a previous report [1]. The first two specimens tested (Table 1) were the 6061 T-6 alloy specimens identified as "A" and "B". They attained notch tensile strengths of 41.9 and 49.8 ksi, respectively.

The 1100 series aluminum specimen attained a notch tensile strength of 44.6 ksi.

The first irradiated specimen tested was identified as C-A. This specimen was loaded in the tensile test apparatus and then placed under load. The specimen had 66.2 ksi load on the pins prior to one of the fixture pins breaking. A second attempt was made to break the specimen under tensile load using a pin of higher tensile strength. This attempt resulted in 80 ksi load being applied before the specimen broke near a bolt hole (reduced area section), not at the notch. Since the effective cross section of material was significantly reduced with the breakage of the specimen, no more attempts were made to tensile test specimen C-A.

In order to increase the load bearing capacity of the pins, a special fixture was designed and manufactured (Figure 1 and 1a). This fixture incorporated two pins on each side of the notch and corresponding to four holes drilled in the Charpy specimens.

The first specimen tested in the new fixture was C-3. This specimen attained a notch tensile strength of 38.8 ksi and broke in the notched areas of the specimen.

The second specimen (C-7) was tested in a similar manner and sustained a load of 37.2 ksi before fracturing at the bolt holes (not the notch).

The graphs for the tensile tests have been included as Attachments 1-6 of this report.

3. EXAMINATION

Sections (including the fracture surface) were cut from the 1100 series aluminum specimen, specimen "B" from the 6061 T-6 alloys and C-3 (irradiated HFBR follower specimen). These fracture faces were then mounted and examined by scanning electron microscopy (SEM).

In addition to a low magnification fractograph of the entire fracture surface, "typical" fractographs at higher magnification were taken near the notch, middle and opposite (to notch) sides of the fracture.

Figures 2 - 7c are the fractographs of the fracture faces on the three specimens examined. In the case of the two non-irradiated specimens tested, the fracture faces had "typically" large areas of dimpled ruptures (ductile) in evidence.

Although much less abundant, the fracture face on specimen C-3 also exhibited areas of dimpled rupture which is indicative that some ductility was present during the notch tensile testing of the specimen.

4. CONCLUSIONS

The tensile testing and subsequent examination of fracture faces from Charpy "V" notch specimens have led to the following conclusions:

- 1) The notch tensile strength of HFBR follower specimen C-3 was 38.8 ksi. The notch tensile strength of HFBR follower specimen C-7 was at least 37.2 ksi. The range of the notch tensile strength of the non-irradiated aluminum specimens was 41.9 - 49.8 ksi.
- 2) The fracture face of HFBR follower specimen C-3 did exhibit some areas of dimpled rupture (indicative of ductility).

5. REFERENCES

- 1) Czajkowski, C.J., Schuster, M.H., Roberts, T.C., Milian, L.W., "Tensile and Impact Testing of an HFBR Control Rod Follower," BNL Informal Report 43367, August 1989.
- 2) Czajkowski, C.J., "Fractography Evaluation of Impact and Tensile Specimens from the HFBR," BNL Informal Report 43602, October 1989.

TABLE 1

Notch Tensile Test Results
(Charpy "V" Notch Configuration)

SPECIMEN I.D.	NOTCH TENSILE STRENGTH (ksi)
1) 6061 T-6 - "A"	41.9
2) 6061 T-6 - "B"	49.8
3) 1100 Aluminum	44.6
4) C-A	Specimen broke at bolt hole but attained 66.2 ksi prior to failure (first attempt).
5) C-3	38.8
6) C-7	Specimen broke at bolt holes but attained 37.2 ksi prior to failure.

Figure 1a. Sketch of grip used to tensile test Charpy "V" notch specimens.

Figure 1b. Sketch of holder/grip for tensile testing Charpy "V" notch specimens.

Figure 2. Low magnification SEM photograph of 6061 T-6 specimen "B" after tensile testing.

Figure 3a. Higher magnification fractograph taken near notch. ("B")

Figure 3b. Higher magnification fractograph taken "opposite the notch" of the specimen. ("B")

Figure 3c. Fractograph taken near the middle of the specimen. ("B")

Figure 4. Low magnification SEM photograph of "1100" series aluminum specimen after tensile testing.

Figure 5a. High magnification fractograph taken near notch "1100" alloy.

Figure 5b. High magnification fractograph taken "opposite the notch" on the specimen.

Figure 5c. Fractograph taken near the middle of "1100" specimen.

Figure 6. Low magnification SEM photograph of the fracture face on specimen C-3 after tensile testing.

Figure 7a. Some ductility is seen on the fractograph near the notch on C-3 (arrows).

Figure 7b. Ductile areas (dimpled rupture) are also seen near the opposite side of C-3 (arrows).

Figure 7c. Ductility was also evident in the center of C-3 (arrows).

Attachment 1 - Reduced copy of tensile chart for 6061 T-6 "A" and "1100" series tensile tests.

Attachment 2 - Reduced copy of tensile chart for 6061 T-6 "B" specimen.

Attachment 3 - Reduced copy of tensile chart for first attempt on specimen C-A.

Attachment 4 - Reduced copy of tensile chart for second attempt on specimen C-A.

Attachment 5 - Reduced copy of tensile chart for specimen C-3.

Attachment 6 - Reduced copy of tensile chart for specimen C-7.