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Letter to the Editors

Effect of thickness on the fracture toughness of irradiated Zr–2.5Nb pressure tubes

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Abstract

The effect of thickness on the fracture toughness of irradiated cold-worked Zr–2.5Nb pressure tube material was measured. With thickness between 2 and 4.2 mm, the fracture toughness decreases with increasing thickness. The crack initiation toughness, $J_{0.2}$, leveled off at about 3 mm, but the crack growth toughness, $\mathrm{d}J/\mathrm{d}a$, was still dropping as the thickness increased to 4.2 mm. Comparison with data from two irradiated heat-treated Zr–2.5Nb pressure tube materials indicates that their difference in fracture toughness may be explained by the thickness effect. © 1997 Elsevier Science B.V.

1. Introduction

Pressure tube nuclear reactors use tubes with different diameters and wall thicknesses. In order to ensure that leak-before-break will occur in case of an accident, the fracture toughness of the material is required. The fracture toughness has been measured by burst testing 0.5 m long tube sections or small curved compact specimens [1,2]. When the full thickness of the pressure tube is used, the toughness measured is valid for that tube geometry. However, fracture toughness is known to depend on the thickness of the specimen [3,4], when the thickness of the specimen does not satisfy the plane strain condition for a valid K_{1c}. This report provides data to predict the change of fracture toughness of irradiated Zr–2.5Nb due to thickness. Comparison with data on heat-treated Zr–2.5Nb with different wall thickness seems to confirm the prediction.

2. Materials

Materials from an irradiated cold-worked Zr–2.5Nb pressure tube were taken for these tests. This irradiated pressure tube was removed from the Bruce Nuclear Generating Station Unit 1, lattice position L08, and will be identified as B1L08 in this paper. This standard cold-worked Zr–2.5Nb pressure tube had a wall thickness of 4.2 mm thick with 101 mm inside diameter. Standard cold-worked Zr–2.5Nb pressure tubes were extruded at 840°C, cold-drawn 25% and autoclaved 24 h at 400°C. At the axial location from which the specimens were taken, the fluence was 7.7×10^{25} $\mathrm{n/m^2}$ ($E > 1$ MeV).

The published data of two heat-treated Zr–2.5Nb pressure tubes were compared to data for the cold-worked material. The standard fabrication process for heat-treated Zr–2.5Nb pressure tube was: extrusion at 840°C; solution treated at about 870°C, water quenched; cold drawn about 15%; tempered at 500°C for 24 h; machined and pickled; and autoclaved at 400°C for 72 h. One of the two heat-treated pressure tubes investigated came from the fuel channel H6 of the NPD reactor (NPD-H6). This tube was removed to investigate its post-service properties [5]. The wall thickness was 2.3 mm and the inside diameter 83 mm, with a fluence of about 3×10^{25} $\mathrm{n/m^2}$ ($E > 1$ MeV). The other heat-treated pressure tube was removed from the KANUPP reactor, channel G12 (KANUPP-G12). The wall thickness of the KANUPP pressure tube was 4.1 mm, similar to the cold-worked pressure tubes. The inside diameter of the tube was 82.55 mm. The estimated fluence

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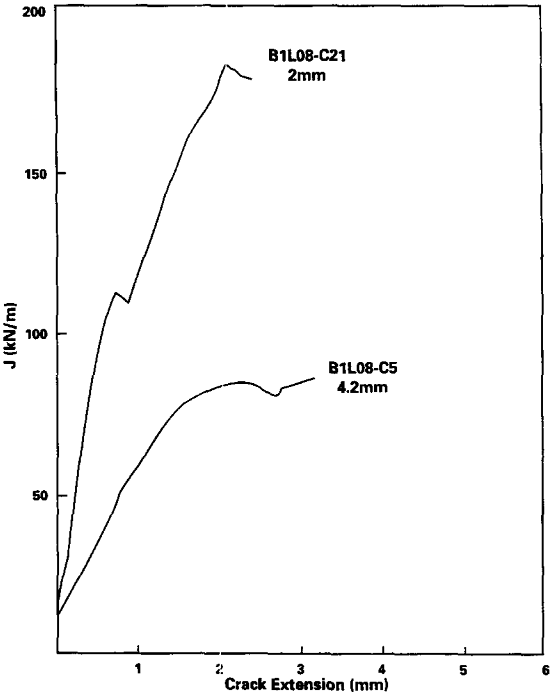

Fig. 1. J-resistance curves for two specimens. B1L08-C21 was 2 mm thick, B1L08-C5 was 4.2 mm thick.

of this pressure tube is 4.1×10^{25} n/m^2 ($E > 1$ MeV). Details of this tube's history and properties are reported by Cheadle et al. [6].

3. Test methods

Blanks 5 cm × 5 cm were cut from the pressure tubes. For the cold-worked materials, they were chemically thinned to thickness between 2 to 4.2 mm, and then spark-machined into 17 mm curved compact toughness specimens using standard techniques [7]. The crack plane was in the radial-axial plane with the propagation direction in the axial direction.

The J-integral resistance curve was used to represent the fracture toughness. The fracture tests were conducted at 280°C in air at a constant displacement rate of 0.25 mm/min, which is approximately equal to an initial stress intensity factor rate of 0.2 MPa $\sqrt{m}$/s. The crack extension was measured by the dc potential drop method. The test was stopped when the potential drop indicated that the crack had extended 3 mm. After the test, the fracture surface was photographed to determine the actual crack extension and was used as a calibration of the potential drop. More details of the test method can be found in Refs. [2,7,8].

The J-integral used was calculated according to ASTM E-813(81), assuming that the flat-plate equations can be used for the curved specimens. Because of the small size of the specimens, this assumption would not introduce significant error [1]. Details of the calculation can be found in Refs. [2,8]. Two parameters were derived from the J-resistance curve: (1) the J-integral at 0.2 mm crack extension, $J_{0.2}$, is taken as the J-integral at crack initiation and (2) the slope of the J-resistance curve, $\mathrm{d}J/\mathrm{d}a$, be-

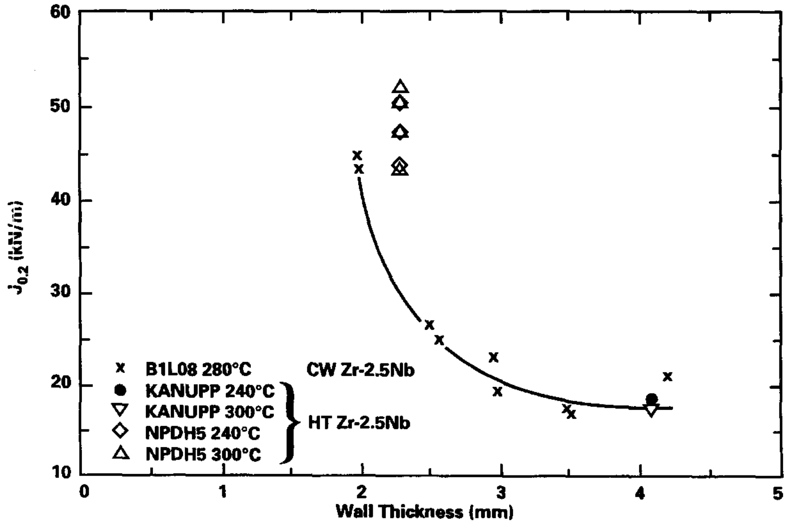

Fig. 2. Effect of specimen thickness on the initiation fracture toughness $J_{0.2}$ of cold-worked Zr–2.5Nb. Heat-treated materials from NPD and KANUPP are plotted for comparison.

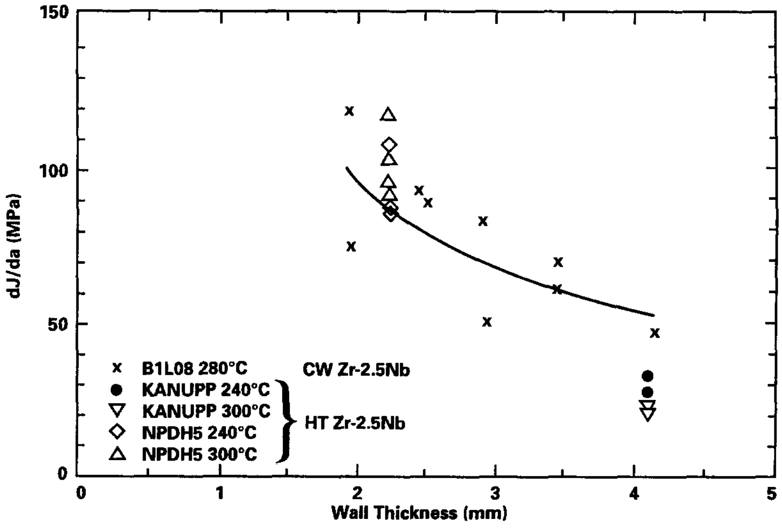

Fig. 3. Effect of specimen thickness on the crack growth fracture toughness d*J*/d*a* of cold-worked Zr–2.5Nb. Heat-treated materials from NPD and KANUPP are plotted for comparison.

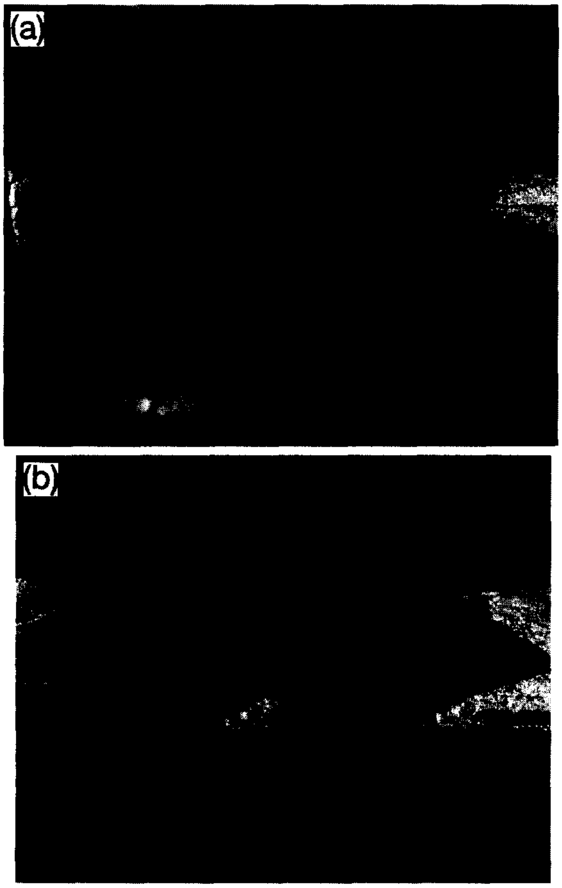

Fig. 4. Stereo pairs of fracture surfaces of two specimens with different thicknesses. (a) Wall thickness $b = 2$ mm, (b) $b = 3.5$ mm.

tween 0.15 and 1.5 mm exclusion lines as defined by ASTM E-813(81), a parameter that indicates the resistance to crack growth. d*J*/d*a* is also referred to as crack-growth toughness. Using these two parameters, an approximate *J*-resistance curve can be constructed and the critical crack length can be estimated.

4. Results

The *J*-resistance curves of some representative specimens with different thickness are shown in Fig. 1. As with other irradiated Zr–2.5Nb materials [2], small crack jumps were evident, even at the smallest wall thickness where the toughness was highest. Fig. 2 shows that $J_{0.2}$ decreases with increasing wall thickness. It seems to level off at about 3 mm. The crack-growth toughness, d*J*/d*a*, also decreases with increasing thickness. It does not level off within the range of thickness examined (Fig. 3). The data from the heat-treated Zr–2.5Nb materials are also plotted on Figs. 2 and 3 for comparison.

Fractography established that the fracture morphology can range from a mixed-shear and flat-fracture mode to 100% shear with decreasing thickness. Fig. 4 shows two stereo pairs of two specimens with different thicknesses. It shows that the thinner the specimen, the higher the percentage of the sheared region.

5. Discussion

For most tests of the Zr–2.5Nb pressure tube materials, the crack fronts were not uniform. The dc potential drop method would average out the non-uniform crack fronts and provided an effective crack length. The experimental technique used in Ref. [8] provided an averaged J-integral based on the effective crack length. It is recognized that the J-integral will depend on the shape of the crack front [9]. Leitch and Shewfelt had conducted finite element calculation for the non-uniform crack fronts for specimen geometries relevant for testing CANDU reactor pressure tubes: 17 mm curved compact toughness specimen and tubular geometries [10]. For irradiated cold-worked Zr–2.5Nb pressure tube materials, the error in calculating the J-integral using the method in Ref. [8] and the finite element method in Ref. [10] is approximately 10–15%. The error depends on the depth that the crack front tunnels.

Fig. 2 shows that $J_{0.2}$ levels off at about 3 mm, but $\mathrm{d}J/\mathrm{d}a$ did not in the range of thickness we studied. This may be explained by the size of the plastic zone developed during the fracture process. The plastic zone involved in the fracture process was small at 0.2 mm crack extension. The plastic zone for plain stress can be estimated by [4]

$$r = \frac{1}{2\pi}\left(\frac{K_1}{\sigma_y}\right)^2, \tag{1}$$

where σ_y is the flow stress, which is 750 MPa for our B1S04 section. From Fig. 2, the plastic-zone size can be estimated using the relation: $K_1 = \sqrt{EJ_1}$, where E is the Young's modulus, which is 93 GPa at 280°C [8]. The results showed that at 0.2 mm crack extension, the plastic-zone size, r, ranged from 1.2 mm for wall thickness $b = 2$ mm and $r = 0.8$ mm at $b = 4.1$ mm. The ASTM minimum thickness requirement for plain strain condition would be satisfied at 3 mm. Thus, our results are consistent with the fracture mechanics theories. As the crack propagates, $J_1(K_1)$ increases, and so will the plastic zone size. Our data show that $\mathrm{d}J/\mathrm{d}a$ is still dropping at $b = 4.2$ mm.

Data from NPD-H6 and KANUPP-G12 are plotted on Figs. 2 and 3 for comparison. The difference in toughness of these two irradiated heat-treated Zr–2.5Nb materials followed the trend line of the cold-worked tube well. The fluences of the three tubes are different, but as the fracture properties of zirconium alloys are not a strong function of fluence after a fluence of about 2×10^{25} n/m^2 [2], the difference in fluence of these materials should not affect the results significantly. The different test temperature should not affect the results either, as it has been shown that the fracture properties of irradiated Zr–2.5Nb are insensitive to temperature above 200°C [2]. From these results, it seems that the difference in toughness of the two heat-treated pressure tubes might be explained by the thickness effect.

6. Conclusions

Experiments on irradiated cold-worked Zr–2.5Nb pressure tube material, with specimen thicknesses in the range of 2 and 4.2 mm, showed that the fracture toughness decreases with increasing specimen thickness. The initiation toughness, $J_{0.2}$, leveled off at about 3 mm thickness, but the crack growth toughness, $\mathrm{d}J/\mathrm{d}a$, was still dropping as the thickness increased to 4.2 mm. These data can serve as a guide to predict the change of fracture toughness due to wall thickness. The difference in the fracture toughness of two irradiated heat-treated Zr–2.5Nb materials might be explained by the thickness effect.

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