JUL 16 1965

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CONF-650114-1

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SMALL SPECIMENS, SUITABLE FOR IRRADIATION DAMAGE
STUDIES ON REACTOR STRUCTURAL MATERIALS

by

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January 4, 1965

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A paper to be presented at the ASTM Subcommittee for Fracture Testing
of Medium Strength Metals, January 12, 1965, in Washington, D. C.

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January 4, 1965

ASTM Subcommittee Meeting

SMALL SPECIMENS, SUITABLE FOR IRRADIATION DAMAGE
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Introduction

It is now commonly recognized from the growing amount of information on the neutron irradiation effects on metals that, in general, strength increases are accompanied by significant losses in ductility and increases in transition temperatures with increasing exposure to in-reactor environments. Because such effects have been of concern for some time, many of the programs throughout the world which have been set up to evaluate irradiation effects have done so in both the fields of flow and fracture. Although many of these studies have yielded relevant information on the fracture properties of irradiated materials (especially ferrous materials), there still exists a great need to acquire information on the fracture behavior of materials which have been exposed to particular in-reactor environments. The in-reactor environment that we, at Hanford, are interested in is hot water at 280 C. There also is a developing interest in high temperature gas environments. The determination of ductile-to-brittle transition temperatures and plane strain fracture toughness data on materials irradiated in contact with hot water using conventional specimens, e.g. notch bend, round notch tensile, singly and doubly notched plate, etc., requires an irradiation space not readily available in the Engineering Test Reactor at Arco, Idaho (in which we conduct most of our irradiations), or in other test reactors. Recognizing the need for determining the effects of hot water irradiations on the fracture behavior of candidate reactor

materials and the lack of suitable irradiation space for relatively large size specimens, we have recently initiated studies to determine the feasibility of using the double cantilever beam (DCB) specimen. The purpose of this paper is to present the techniques involved, the general behavior of the specimen, and some preliminary test results. In addition, some applications are discussed.

Specimen Design

Figure 1 illustrates the design of the DCB specimen on which much of the work has been performed. The specimen is small enough that a practical number may be inserted in the ETR facilities and large enough to prevent gross yielding below the transition temperatures in the materials of primary interest. Also shown in Figure 1 is one of the methods of loading which has been used. The purpose of the initial saw cut, C_0 , is to facilitate easier starting of the crack. The width of the saw cut is nominally 0.015 in. The grooves running at mid-width along the length of the specimen prevent the bending stresses from breaking off one of the arms. The root radii of the grooves are nominally 0.001 in. The selection of the optimum groove depth is rather critical since, if the grooves are too deep, crack propagation inward from the groove tip results. Trial and error was found to be the best method of determining the appropriate groove depth, since calculations based on simple elastic beam theory tend to underestimate the necessary groove depth. As will be pointed out later, the grooves also provide important restraints in the width direction of the specimen.

Specimen Behavior

As has been pointed out by Berry,⁽¹⁾ unstable crack propagation is impossible for any crack length in the DCB specimen if the specimen is

composed of a material which possesses a strain energy release rate independent of crack velocity. Since most, if not all, structural materials exhibit some degree of rate sensitive flow behavior, crack instabilities can occur in the DCB specimen but due solely to a decrease in the energy absorption rate with increasing crack velocity. Such behavior, as is typical of A302-B, Zircaloy-2, and 7075-T6 aluminum, is shown schematically in Figure 2. Although crack instabilities occur, as are shown in Figure 2 by the sharp drops in load, the crack length is increased during an instability by only a small amount, usually two-tenths of an inch. Given a suitable method of reducing the data to relevant fracture information, one has a source of both the requirements for crack initiation and the conditions for crack arrest. Of particular importance is that from a single DCB specimen of this design we have been able to obtain as many as 30 to 35 such pairs of data. This is certainly suitable for conducting a rather extensive sub-transition study.

Calculation of Fracture Toughness

The calculation of the critical strain energy release rate or the fracture toughness may be accomplished once the relationship has been ascertained between the applied load, f , the resultant extension of the arms, y , for a given crack length, c . Although each arm of the specimen behaves in a manner similar to a cantilever beam, simple beam theory neglects the strain energy stored in the unbroken part of the specimen. Instead, an empirical relationship is used which has the following form:

$$y = \frac{f}{cE} \phi \quad (1)$$

where E is the modulus of elasticity and ϕ is a function of the crack length and moment of inertia. The function ϕ is determined experimentally from the compliance or spring constant of the specimen for a given crack length. This experimental determination has been carried out on DCB specimens made of 7075-T6 aluminum of the same dimensions as in Figure 1.

Measurements of compliance were taken from the slopes of load vs. extension Instron recordings and crack lengths were measured with a traveling microscope. An example of the results of such a determination is shown on the log-log plot in Figure 3. A straight line affords a good fit to the data in Figure 3 over nearly the entire range of crack lengths indicating the function ϕ may be replaced by the relationship

$$\phi = Bc^n \quad (2)$$

The values of the constants, B and n, given in Figure 3 were obtained from computer calculations. Combining equations 1 and 2, the strain energy release rate may now be easily derived giving:

$$\mathcal{G} = \frac{E(n-1)y^2}{4RW} \left(\frac{Bf}{E_y} \right)^{\frac{n}{n-1}} \quad (3)$$

Application of the DCB Specimen to Fracture Testing

(A) Experimental

The data presented in this paper were obtained from two materials, A302-B and Zircaloy-2. The A302-B possesses a typical heat composition. It was received in the hot-worked and normalized condition in the form of 4-inch thick slabs. The specimens were milled from the slab in such a manner that the plane of crack propagation was perpendicular to the slab plane.

The Zircaloy-2 is a zirconium alloy which is used extensively in process tubes and fuel cladding. The material herein described contains Zr plus 1.35% Sn, 0.130% Fe, 0.097% Cr, and 0.056% Ni. It was received in the hot-rolled condition and was subsequently annealed at 600 C. The original plate thickness was 0.500 in. and the specimens were milled from the plate with the length parallel to the rolling direction. The room temperature mechanical behavior of annealed Zircaloy-2 is as follows: 52,000 psi; 0.2% yield strength, 65,000 psi ultimate strength, and 27% reduction in area.

The tests were conducted using an envelope made of an absorbent insulating material which surrounded the specimen. Low temperatures were achieved by adding varying amounts of liquid nitrogen to the insulating material. Temperature was measured with a thermocouple held by means of a clip in the groove at the crack tip. After each fracture event, the thermocouple was moved to the new crack tip location. To afford remote testing, a special cryostat capable of automatic temperature control and measurement is presently being built.

(B) Results

Fracture toughness data as a function of temperature for A302-B are shown in Figure 4. More data would have been presented had not the specimen had too shallow a groove depth (0.050 in.) to prevent breaking off an arm (in a brittle manner) after the crack had reached approximately mid-length. Although it is highly desirable to obtain a relatively large amount of information from a properly designed DCB specimen, it is also very important that the fracture toughness data be obtained under plane strain conditions. As shown in Figure 4, the

crack initiation fracture toughness data from the DCB specimen is in good agreement with the plane strain fracture toughness data from the notched bend specimens of Mowbray⁽²⁾ and the biaxial specimens of Manjoine.⁽³⁾ Interpolated data from the Results of Krafft and Sullivan⁽⁴⁾ obtained from round notch tensile specimens also are in good agreement with the data in Figure 4. This agreement coupled with the fact that nominal stresses, calculated both parallel and perpendicular to the crack plane, are well below yield strength values, provide assurances that the data from the DCB specimen has been obtained under conditions of plane strain and not plane stress. The side grooves must be credited with providing the necessary lateral restraints in a specimen of relatively narrow thickness.

Although the amount of data in Figure 4 is limited, a distinct difference in temperature dependence is evident between crack initiation requirements and conditions leading to crack arrest. This behavior is in good agreement with that found by Krafft and Sullivan⁽⁴⁾ in their tests on A302-B using notched rounds. Their data indicates that the higher the time derivative of the stress intensity factor, $\dot{K}$, the smaller the increase in fracture toughness with increasing temperature. The $\dot{K}$ corresponding to the crack initiation values in Figure 4 are constant and relatively low (approximately 100 psi/ $\sqrt{\text{in}}$ /sec). In contrast to this, the high crack velocities prior to arrest correspond to $\dot{K}$'s of the order of 10^{12} to 10^{14} psi/ $\sqrt{\text{in}}$ /sec resulting in a fracture toughness at arrest which is much more independent of temperature than the initiation values over the range of temperatures shown in Figure 4.

The specimen from which the Zircaloy-2 data were obtained had deeper side grooves (0.060 in.) than the A302-B specimen. This groove depth prevented premature failure of the specimen thus enabling more data to be obtained, as shown in Figure 5, than was possible with the A302-B specimen.

As the data in Figure 5 shows, the crack initiation and crack arrest conditions for Zircaloy-2 exhibit the same degree of temperature dependence. Although information relating the fracture toughness to a rate parameter for Zircaloy-2 is not available at this time, one can speculate that such behavior is influenced by the temperature independent rate sensitivity index of zirconium deformation behavior between -196 C and room temperature.⁽⁵⁾

A comparison of this data with that of Hoagland and Bement⁽⁶⁾ obtained from notch bend specimens nearly one-half of an inch wide indicates again that the degree of restraint provided by the side grooves is sufficient to ensure plane strain conditions. In fact, more restraint is available in the DCB than in the larger notch bend specimens as is evidenced by the lack of gross deformation up to a temperature of -70 C.

For the temperatures above -70 C the load-extension behavior became non-linear prior to crack initiation. Such non-linearities can be the result of two causes: 1) slow crack growth, or 2) plastic bending of the arms. By partial unloading to obtain the slope of the load-extension line and extrapolating to zero load one can obtain the true extension value that is used to calculate the fracture toughness

at crack initiation and arrest. This procedure is illustrated schematically in Figure 6. This correction is not to be confused with a plastic zone size correction which has not been applied to this data.

Discussion

These initial studies have indicated the feasibility of using relatively small size DCB specimens for determining the effects of irradiation damage to the fracture behavior of reactor structural materials. Indeed, certain experiments that we, at Hanford, are presently contemplating dictate the use of this technique because of the amount of data that can be obtained. For example, it is known that Zircaloy-2 slowly absorbs hydrogen from hot, pressurized water causing severe embrittlement due to the formation of zirconium hydride platelets. This hydride embrittlement abetted by neutron irradiation may cause brittle failure at temperatures as high as the operating temperature of Zircaloy-2 process tubes. An experiment has been planned to investigate the effects of irradiation damage on the plane strain fracture toughness of Zircaloy-2 containing different levels of cold work and hydrogen. Such an investigation would be difficult, at best, using conventional, single-shot, fracture specimens.

The fact that fracture toughness data relative to crack arrest, as well as crack initiation, is obtained from the DCB specimen is of added importance in determining the extent of crack propagation in a structure for a given loading condition. A comparison of Figures 4 and 5 reveals that although the fracture toughness of A302-B at say -125 C is higher than for Zircaloy-2, the crack would propagate farther in a structure made

of A302-B than of Zircaloy-2. It is anticipated that sophistication of the techniques presented here will provide important information relating the fracture toughness to rate effects.

Finally, it is important to note that the fracture toughness data is obtained from the severest of stress concentrations - that of an actual crack formed from monotonically increased loading conditions.

Some of the questions relative to specimen design encountered in this study must go unanswered. More experimental information needs to be gathered and some stress analysis solutions should be made to aid in the proper design of the specimen, especially where small sizes are required. It is hoped that more widespread interest concerning the use of this specimen will develop and that this interest will stimulate solutions to at least some of these problems.

Acknowledgments

The author gratefully acknowledges the assistance of M. D. Jones in conducting the experimental work and also the stimulating discussions with J. C. Tobin. The work discussed in this paper was performed under Contract No. AT(45-1)-1350 between the Atomic Energy Commission and the General Electric Company.

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SPECIMEN DIMENSIONS
INCHES

L	h	b	w	c
7	1	0.250	0.130	1½

FIGURE 1 DCB SPECIMEN AND LOADING ARRANGEMENT

FIGURE 2. TYPICAL DCB SPECIMEN FRACTURE BEHAVIOR AT CONSTANT CROSSHEAD SPEED.

FIGURE 3.

RESULTS OF DCB SPECIMEN CALIBRATION
ON 7075-T6 ALUMINUM

FIGURE 4. VARIATION IN FRACTURE TOUGHNESS WITH TEMPERATURE FOR A302-B. COMPARISON IS MADE WITH OTHER INVESTIGATORS.

FIGURE 5. VARIATION IN FRACTURE TOUGHNESS WITH TEMPERATURE FOR ZIRCALOY-2

FIGURE 6. METHOD OF CORRECTING EXTENSION WHEN PLASTIC BENDING OCCURS.