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DEVELOPMENT OF TEST PROCEDURES

Contract No. AT(11-1)-1477

FRACTURE TOUGHNESS OF REACTOR PRESSURE VESSEL STEELS

Sponsor: DRD&T Program Branch

By

E. J. Ripling and Phillip Crosley

For the period May 1, 1965 to May 1, 1966

Issued May 31, 1966

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

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SUMMARY

A tapered double cantilever beam specimen for fracture toughness testing has been developed, and experimental compliance calibrations of the specimen have been carried out.

The effect of side grooves has been investigated with the testing of 7075-T651 and 2024-T351 aluminum alloys. The results indicate that the use of side grooves promotes plane strain fracturing, and that, when plane strain conditions are satisfied, measured values of K_{Ic} are not affected by groove depth.

A technique of alternating fatigue with increasing load testing has been used for testing 5456-H321 aluminum alloy. Initiation of rapid fracture in specimens pre-cracked in fatigue (rather than in increasing load) occurred at lower values of the crack extension force, indicating that this technique promotes plane strain fracturing.

Very high loading rates have been used for room temperature testing of A302-B specimens pre-cracked in fatigue. With pulse loading, crack arrests were obtained. The procedure offers the promise of yielding room temperature plane strain fracture toughness data, for fracture initiation and arrest of A302-B steel with specimens of a reasonable size.

INTRODUCTION

Basic design work on a double cantilever beam fracture toughness specimen is completed. The use of the specimen requires accurate compliance data, and recent work has been concerned with experimental calibration of linear compliance change specimens.

In extending the testing procedure to materials of high toughness and low yield strength (such as A302-B steel), the effect of side grooves in promoting plane strain fracturing, the feasibility of initiating rapid fracture after fatigue crack extension, and the effect of high loading rates are being studied. The effect of side grooves has been investigated with two aluminum alloys, 7075-T651 and 2024-T351. The technique of alternating fatigue with increasing load tests and the use of very rapid loading rates is being introduced for the testing of tougher materials, 5456-H321 aluminum alloy and A302-B steel.

COMPLIANCE CALIBRATION OF TAPERED DCB SPECIMENS

A strength of materials analysis of the double cantilever beam fracture toughness specimen indicates that dC/da * is proportional to the quantity

$$\frac{3a^2}{h^3} + \frac{1}{h} = m \quad (1)$$

If a specimen is contoured so that $m = \text{constant}$, the specimen compliance is a linear function of crack length.

When the linear compliance change condition is satisfied,

$$\mathcal{G}_{Ic} = \frac{P_c^2}{2b_n} \frac{dC}{da} = \frac{P_c^2}{2b_n} \frac{8}{Eb} m' \quad (2)$$

where m' is a constant determined from experimental compliance measurements. (If the strength of materials beam analysis gave an accurate value of compliance, m' would be equal to m defined by Eq. 1.)

A specimen contoured to $m = 4$ (Fig. 1) was used for fracture toughness tests of aluminum alloys. Fig. 2 shows the load-extension curve obtained from a specimen of 7075-T651 alloy. With crack lengths in the range from approximately one to three inches, the crack propagated in jumps of less than 1/4 inch. The critical load P_c for the reinitiation of fracture after each increment of crack extension was the same ($P_c = 4300 \text{ lb.}$). The fact that P_c was constant indicates that the design criterion given by Eq. 1 did, in fact, give

* The analysis and the notation used in describing the DCB specimen is given in a previous report (BNWL-CC-355).

a linear dependence of compliance on crack length. The value of dc/da , however, was greater than predicted by beam theory.

Experimental compliance calibrations to determine the value of $\underline{m'}$ for specimens designed to $m = 4$ are being carried out. The specimens are machined from 1/4, 1/2, and 1-inch thicknesses of 2024-T351 aluminum, and with different groove depths ranging from $b_n/b = 1.00$ to $b_n/b = 0.30$. Specimens are saw cut to various depths to simulate different crack lengths (Fig. 3a), and the 3/64-inch saw cut width is compensated by increasing the height of the specimen. (Specimens cut with a 0.015-inch jewelers saw, with no compensation for the saw-cut width gave identical results.) Deflections are measured with the "clip gage" shown in Fig. 3b. The grooves in the arms of the gage are located on the ridges directly in line with the loading holes of the specimen. The total deflection measured is from 0.020 to 0.040-inch depending on the crack length.

The results of the compliance calibration work completed to date are shown in Fig. 4. As the curves show, the compliance increased linearly with crack lengths between 1 and 3 inches. With crack lengths increasing beyond three inches, there was a progressive deviation from linearity resulting from the hinging action of the back end of the sample. The data on 1/2 and 1 inch thick specimens with no side grooves, show $\underline{m'} = 5.45 \text{ in}^{-1}$ which is approximately 35 percent greater than the theoretical value, $m = 4$. The excellent agreement with four different specimens indicates the reliability of this figure. With a 1/4 inch thick specimen, the value of $\underline{m'}$ was lower, probably as a result of a greater tendency for the specimen to buckle, and the value is not reliable. For a 1/2 inch sample with $b_n/b = 0.5$, the measured value of $\underline{m'}$ was 5.86 in^{-1} or about seven percent above the value for ungrooved specimens. A difference of this magnitude is not inconsistent with the amount of material removed with the side grooves; however, since the value comes from measurements on only one specimen, it cannot be considered as reliable in the measurements on the ungrooved specimens. A more complete definition of the effect of side grooves on specimen compliance is expected from the calibration work now in progress.

EFFECT OF SIDE GROOVES ON PLANE STRAIN FRACTURE TOUGHNESS MEASUREMENTS

The utility of side grooves in promoting straight crack extensions has been treated in an earlier report. As indicated above side grooves have the additional effect of increasing dC/da , which, however, is directly measurable. More important questions are whether or not side grooves affect the thickness required for plane strain fracturing, and whether measured values of plane strain fracture toughness, K_{Ic} , are influenced by side groove depth. To provide some answers to these questions, tests have been carried out on 7075-T651 and 2024-T351 aluminum alloys, both because testing procedures for these alloys are established, and because tests can be made with no side grooves or very shallow grooves as well as with deep grooves.

Tests were made on 1/4, 1/2 and 1 inch plates of the two alloys with specimens designed to $m = 4$, and the fractures were propagated parallel to the rolling direction. For this testing direction, the cracks ran straight even in the absence of side grooves for 7075-T651 alloy, but not for the 2024-T351. To calculate the values of K_{Ic} , the experimental compliance values, $m' = 5.5$ for ungrooved specimens and $m' = 5.9$ for $b_n/b = 0.5$ were used. The m' values for other groove depths were based on the assumption that m' is a linear function of b_n/b . This assumption cannot contribute an appreciable error for b_n/b in the range 0.5 to 1.00, but could have a measurable effect when extrapolated to $b_n/b = 0.3$.

The data on the 7075-T651 aluminum are shown in Fig. 5. In the ungrooved specimen K_{Ic} values of 166, 136, and 83 in-lb/in² were obtained for the 1/4, 1/2 and 1 inch plates, respectively. The high values (compared to grooved specimens) and their decrease with increasing plate thickness indicate that fracture did not occur under plane strain conditions. Crack extension was accompanied by dimpling, and examination of the fracture surfaces showed shear lips extending over a significant portion of the crack width, with the proportion of slant to flat fracture decreasing with increasing

plate thickness. The use of even very modest side grooves ($b/b = 0.95$) gave large reductions in the measured $\mathcal{L}_c$, and with b/b in the range 0.9 to 0.3 fracture toughness values for all three plate thicknesses were in the range 50-55 in-lb/in² which appears to be the plane strain toughness for this material. The fracture surfaces in the grooved samples showed very limited shear lip development, and there was no measurable reduction in width across the crack plane.

It is evident that side grooves by suppressing shear lip formation were very effective in promoting plane strain fracture. The fact that the fracture toughness remained constant over the broad range of b/b from 0.9 to 0.3 suggests that once grooves are deep enough to promote complete plane strain fracturing, the toughness value is not influenced by further side grooving.

For the one-inch plate of the 2024-T351 alloy the measured fracture toughness values were 225, 147, 117, and 142 in-lb/in² for b/b ratios of 0.95, 0.80, 0.50, and 0.30 respectively. These results would indicate that the 50 percent grooves developed a higher level of constraint than the deeper grooves, and that the plane strain fracture toughness is 117 in-lb/in², or possibly lower. For the 1/2 inch plate measured fracture toughness values fell into two groups averaging around 150 and 180 in-lb/in², respectively. There was no systematic variation with side groove depth. The fracture surfaces in these specimens were not flat, and hence these values could not be considered plane strain fractures. In some specimens, the cracking load increased as the crack extended from a value corresponding to $\mathcal{L}_c = 150$ up to $\mathcal{L}_c = 180$ in-lb/in² with no obvious changes in fracture appearance. In the 1/4 inch plate the fracture toughness was 473 in-lb/in² for $b/b = 0.95$ and 300-325 in-lb/in² for various deeper grooves, indicating that the thickness was insufficient to promote plane strain fracturing even with side grooves. Nevertheless, side grooves do reduce measured values of fracture toughness by promoting plane strain fracture and therefore can reduce the specimen thickness requirements for valid $\mathcal{L}_{Ic}$ measurements. As the data for the 2024 alloy show, however, side grooves do not completely eliminate the need for thick plates to evaluate $\mathcal{L}_{Ic}$ values for tough materials.

MEASUREMENT OF PLANE STRAIN FRACTURE TOUGHNESS OF 5456-H321 ALUMINUM ALLOY

A major goal of this research project is to establish the reliability of the double cantilever beam specimen, by showing that it yields results in agreement with other techniques. A cooperative testing program operated through ASTM Committee E 24, Sub III serves this purpose. One of the materials being tested in this program is a one-inch plate of 5456-H321 aluminum alloy.

Specimens designed to $m = 4$ as well as more steeply tapered specimens ($m = 3$), both with $b_n/b = 0.5$, were used for testing this material. The combination of one-inch plate width and 50 percent side grooves was not sufficient to produce plane strain fracture in straight increasing load tests. Crack extension was accompanied by plastic bending of the arms of the specimen, and for specimens tested perpendicular to the rolling direction cracks did not extend straight. The value of $\mathcal{L}_c$ was of the order of 210 in-lb/in² for cracking parallel to the rolling direction.

Because of the failure to obtain plane strain fractures in straight increasing load tests, a procedure of alternating fatigue with increasing load testing was adopted. Fracture surfaces obtained with this technique are shown in Fig. 6. As can be seen the portions of the fracture produced in the increasing load tests are clearly demarcated from the fatigue portions, and the increasing load fracture surfaces are flat for appreciable distances beyond the fatigue cracks. The critical load P_c for the initial extension of each increasing load test was independent of the position of the fatigue crack; however, with extension of the crack, the cracking load showed a continuous increase. Using the load values corresponding to the initial crack extension, i.e. the "pop-in" values, the values of $\mathcal{L}_c$ were 130 and 150 in-lb/in² for cracks propagated parallel and perpendicular to the rolling direction, respectively. Although the "pop-in" was not as well defined as was hoped for, it is felt that these values are very close to the plane strain fracture toughnesses, $\mathcal{L}_{Ic}$, of this material.

ROOM TEMPERATURE FRACTURE TOUGHNESS MEASUREMENTS ON A302-B STEEL

The technique of alternating fatigue with increasing load testing is being used also in testing A302B steel. Specimens tested to date were one inch thick with $b/b_0 = 0.50$ and contoured to $m = 3$. The specimens were pulse loaded in order to enhance the possibility of obtaining plane strain fracturing at room temperature, and if possible, to obtain crack arrests. Load-time and deflection-time traces were recorded on an oscilloscope.

The fracture surfaces obtained in one specimen are shown in Fig. 7. The first fatigue crack was extended to just beyond the saw cut wing. The specimen was then pulse loaded and the oscilloscope trace shown in Fig. 8 was obtained. The loading rate was of the order of 200 lb/msec up to the point of fracture. Fracture occurred at 16,600 lb. as evidenced by the abrupt discontinuity in the load and deflection traces. The corresponding value of $\mathcal{L}_c$ was 300 in-lb/in². (This same value was obtained with a second specimen tested at a loading rate of 250 lb/msec.) The response time of the clip-gage was not sufficient to give a record of the deflection for the first 15 to 20 msec following fracture initiation, so that crack growth in this range was not successfully monitored. The trace of the load curve indicates that crack arrest occurred about 20 msec after the onset of fracture, which, as can be seen from the fracture surface, occurred at a crack extension of 1.5 inches. The load value at this point, 13,900 lb., should permit a calculation of $\mathcal{L}_c$ for crack arrest. Unfortunately, however, this crack position is beyond the linear compliance change region and the necessary compliance data for such a calculation are not available. After another 0.4 inch of fatigue crack propagation the specimen was again pulse loaded. Fracture occurred at 16,000 lb. If it is assumed that this load value also corresponds to $\mathcal{L}_c = 300$ in-lb/in², a value of dC/da for this crack length can be calculated, and with this information limits for $\mathcal{L}_c$ for crack arrest can be calculated from the 13,900 lb. load value. The calculation gives $\mathcal{L}_c = 210-225$ in-lb/in² for crack arrest.

The pulsing technique appears to offer the possibility of obtaining plane strain fracturing at room temperature with specimen of reasonable thickness, and also of measuring fracture toughnesses for crack arrest. The first series of tests using this technique will be concerned with the influence of specimen width, side groove depth, and loading rate in order to determine the effect of these variables on measured values of fracture toughness as well as to develop the optimum test procedure.

Fig. 1. LINEAR COMPLIANCE CHANGE SPECIMEN USED FOR TESTING ALUMINUM ALLOYS.

Fig. 2 LOAD DEFLECTION DIAGRAM.
7075-T651 ALUMINUM, 1" THICK.

Fig. 3a SPECIMEN FOR COMPLIANCE CALIBRATION.

Fig. 3b CLIP GAGE.

Curve	b (in.)	b _n (in.)	b dC/da (μ -in/lb)	m' ($\ln^{-1}$)
1	0.50	0.25	4.69	5.86
2	0.50	0.50	4.38	5.47
3	1.00	1.00	4.36	5.45
4	0.50	0.50	4.36	5.45
5	0.25	0.25	4.10	5.13

Fig. 4 COMPLIANCE CALIBRATION RESULTS.

Fig. 5 EFFECT OF SIDE GROOVES ON MEASURED FRACTURE TOUGHNESS OF 7075-T651 ALUMINUM ALLOY.

Fig. 6 FRACTURE SURFACES OF 5456-H321 ALUMINUM ALLOY.

Specimen #1: Crack propagated parallel to rolling direction.

Specimen #2: Crack propagated perpendicular to rolling direction.

Fig. 7 FRACTURE SURFACE OF A302-B STEEL.

Fig. 8 LOAD-TIME AND EXTENSION-TIME TRACES FOR PULSE LOADED A302B STEEL SPECIMEN.