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EVALUATION OF SUBSIZE IZOD SPECIMEN DESIGNS FOR DETERMINING THE NOTCH TOUGHNESS OF ZIRCALOY-2

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SUMMARY

This report covers the findings of a program initiated to correlate Zircaloy-2 subsize Izod impact data with Charpy-V and drop-weight data. Standard ASTM Charpy-V specimens cannot always be used due to insufficient thickness of Zircaloy-2 stock, and subsize specimens are often desirable due to space restrictions during irradiation studies.

Subsize Izod impact specimens of various geometries and notch configurations and standard ASTM Charpy-V specimens were prepared from bar and plate stock and tested. Drop-weight tests were also conducted and the NDT (nil-ductility transition) temperature was determined for ½-in. Zircaloy-2 plate.

Results show that the impact properties of Zircaloy-2 are sensitive to hydrogen concentration, specimen and notch geometry, specimen orientation, and notch orientation. No subsize specimen design was found which yielded impact curves similar to those obtained with standard Charpy-V notch specimens, but designs suitable for in-pile testing were found.

It was shown that Zircaloy-2 has the property of arresting a moving crack even at temperatures of −100°C and lower.

INTRODUCTION

Considerable interest has been expressed in the use of subsize notch-bar impact specimens for the evaluation of the notch toughness of Zircaloy-2. This interest stems from the space limitations associated with irradiation studies, the limited thickness of Zircaloy-2 stock of interest, and the cost of using standard-size specimens.

The purpose of this study was to determine the effect of specimen geometry, cross-sectional area, and notch configuration on the shape and position of subsize Izod impact curves; to arrive at a subsize design suitable for use in radiation-damage studies; and to supply information which would assist in understanding the fracture characteristics of Zircaloy-2.

The selection of a suitable subsize specimen design for irradiation studies was based upon the following considerations: (1) the energy level of the ductile or high-energy portion of the impact curve should not exceed the capacity of the hot-cell testing machine (i.e., 200 in.-lb) and (2) the energy levels of the impact curves should not be so low as to mask changes in impact strength as a result of irradiation.

It was also desirable that the specimens demonstrate any change in the notch toughness of Zircaloy-2 caused by hydrogen pickup, radiation damage, or other embrittling influences which might result from service in fissioning uranyl sulfate solutions.

It was realized that impact data could not be applied rigorously to practical engineering considerations. Pellini and his associates have shown, however, that such data can be used as a guide in designing to prevent brittle fracture of steel structures.[1] The possibility of similar correlations for Zircaloy-2 was to be investigated.

MATERIAL

The Zircaloy-2 used in this study was 3/8-in. rod (51 ppm H_2) and 1/2-in. plate (16 ppm H_2). The composition of these materials as obtained at the Oak Ridge National Laboratory (ORNL) are shown below in Table 1.

Table 1. Analyses of Zircaloy-2 Rod and Plate

	Composition (wt %)							
Description	Sn	Fe	Cr	Ni	C	O_2	N_2	H_2
3/8-in. rod	1.45	0.19	0.15	0.04	0.018	0.092	< 0.0005	0.0051
1/2 × 15 × 30 in. plate	1.43	0.12	0.165	0.045	0.010	0.058	< 0.005	0.0016

[1] P. P. Puzak, A. J. Babecki, and W. S. Pellini, Welding J. 37(9), 391–410-s (1958).

After receipt of the 3/8-in. Zircaloy-2 rod at ORNL, it was annealed at 1000°C for 30 min in argon and then allowed to cool slowly to room temperature while still in the protective atmosphere. The rod was then cold swaged from a diameter of 0.380 to 0.290 in. (41% reduction of area), annealed at 800°C for 30 min in argon, and furnace cooled. The bar was then swaged at 300°C to an 0.225-in.-square cross section (23% reduction of area).

The Zircaloy-2 plate obtained from the vendor had been hot worked (straight rolled) in the $\alpha + \beta$ field (approximately 850°C) from a $6\frac{1}{2}$-in.-diam ingot to the final plate dimensions of $\frac{1}{2} \times 15 \times 30$ in. This procedure produced considerable preferred orientation in the plate, as is shown later in this report and elsewhere.[2]

TESTING PROCEDURE

Zircaloy-2 subsize multiple-break Izod impact specimens were machined from 0.225-in.-square cross-section swaged rod and $\frac{1}{2}$-in. hot-rolled plate. The specimen geometry and dimensions for seven different notch configurations are shown in Fig. 1. In order to determine the effects of anisotropy, subsize Izod and Charpy-V specimens from both the longitudinal and transverse directions were machined with notches both in and perpendicular to the rolling plane. The orientation of these specimens with respect to the plate is illustrated in Fig. 2.

The subsize specimens were tested in a modified Tinius Olsen plastic impact tester having a 200-in.-lb capacity and a pendulum velocity of 11.3 fps. The desired test temperature was reached by supplying or removing heat from an anvil that held the specimens in place. The specimens were held at temperature for approximately 10 min before breaking. A capacitor discharge welder was used to spot-weld a copper-constantan thermocouple to the anvil about 1/16 in. away from the edge of the notch.

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[2]M. L. Picklesimer and G. M. Adamson, Jr., Development of a Fabrication Procedure for Zircaloy-2, ORNL-CF-56-11-115 (Nov. 21, 1956).

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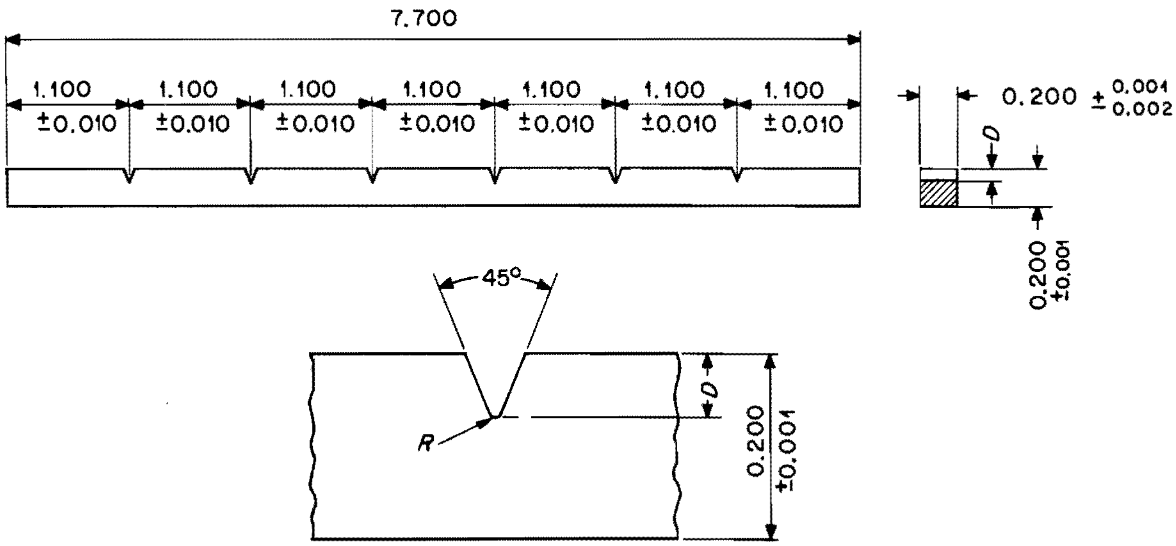

DESIGN	DEPTH OF NOTCH	ROOT RADIUS	REMARKS
A	0.060	0.010	0.200-in. SQUARE CROSS SECTION
B	0.030	0.010	0.200-in. SQUARE CROSS SECTION
C	0.015	0.005	0.200-in. SQUARE CROSS SECTION
D	0.040	0.005	0.200-in. SQUARE CROSS SECTION
E	0.030	0.005	0.200-in. SQUARE CROSS SECTION WITH NOTCH MACHINED ON THREE SIDES (COMPRESSION SIDE WAS NOT NOTCHED)
F	0.030	0.010	
G	0.020	0.005	0.204-in. CYLINDRICAL SPECIMEN WITH CIRCUMFERENTIAL NOTCH

Fig. 1. Subsize Izod Multiple-Break Notch-Bar Specimen Designs.

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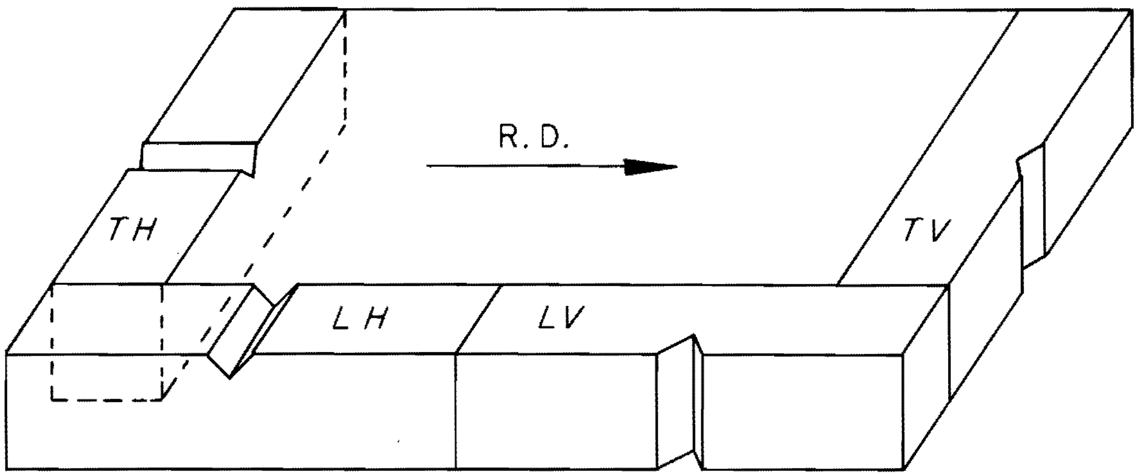

Fig. 2. Description of Notch Orientations Used.

The Charpy-V specimens were tested in a Sonntag Universal impact machine, Model Sl-1, having a 120-ft-lb capacity and a pendulum velocity of 16.4 fps. The specimens were heated in a vise modified to allow resistance heating by passing an electric current through mild-steel electrodes located at each end of the specimen. A capacitor discharge welder was used to spot-weld copper-constantan thermocouples to each specimen as close as possible to the center of the notch face. Specimens tested below room temperature were immersed in liquid nitrogen for 20 min, transferred to the vise of the impact tester, allowed to warm to the desired temperature, and broken.

DISCUSSION OF RESULTS

In the early stages of the study, the only Zircaloy-2 available was the swaged rod containing 51 ppm H_2. Preliminary data concerning the influence of notch geometry on the energy levels of impact curves and the midenergy transition temperatures were obtained and the results are shown in Fig. 3. Impact curves obtained with specimens of designs A, B, and D appear to be fairly similar in shape and position. This is surprising since, in general, increasing the depth of the notch and decreasing the root radius (especially in steel) tend to increase the notch sensitivity or the inability of metal to flow below the notch and would therefore move the curves to higher temperatures. However, further decreasing the notch depth and increasing the area under the notch, as was done in the case of design C, resulted in the impact curve showing a very large increase in energy required for fracture.

Designs A, B, and D produced sigmoidal-shaped impact curves with fracture energies of sufficient magnitude, especially in the ductile or high-temperature region, to permit measurement of changes that might occur as a result of irradiation. The high-energy portion of the impact curves representing designs E and F (i.e., those notched on three sides) appear to be too low to serve effectively for irradiation studies since irradiation would probably lower the energy of the ductile portion of the curve still further. The midenergy transition temperatures for all

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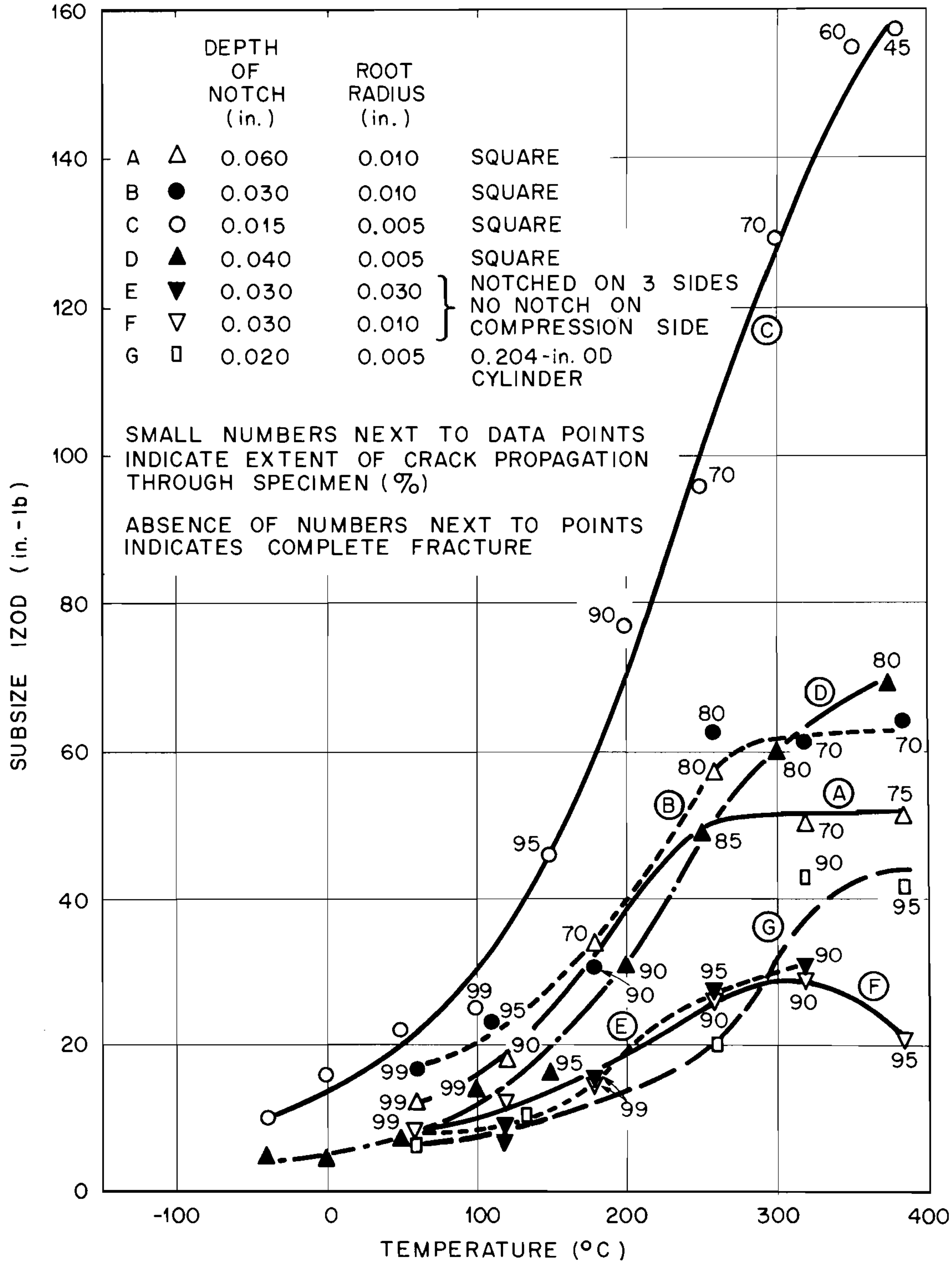

Fig. 3. Subsize Impact Strength of Swaged Zircaloy-2 Rod (51 ppm H_2) with Various Specimen Geometries.

of the designs with a square cross section were about 200 ± 25°C as compared to about 275°C for specimens having a round cross section, i.e., design G.

The upper (ductile) portions of the impact curves for the square designs A, B, E, and F start at a temperature between 250 and 300°C and for designs C and D at some temperature above 350°C. All of the square designs exhibited some degree of notch toughness above 200°C, as shown by the fact that complete fracture of the specimens did not occur above this temperature. Specimens having circular cross sections (design G) showed complete fracture at 260°C; only at higher temperatures was evidence of appreciable ductility seen. It is felt that the occurrence of incomplete fracture is evidence of notch thoughness as the sample was capable of arresting a moving crack.

All of the designs tested indicated that the ductility of the Zircaloy-2 rod containing 51 ppm H_2 decreased below about 200°C which is approximately the temperature at which the brittle hydride phase goes into solution. Above this temperature, the effect of notch geometry was a controlling factor in determining the energy required to fracture the specimen.

In the latter stages of the study $\frac{1}{2}$-in. Zircaloy-2 plate (16 ppm H_2) became available. A variety of information was obtained from this plate since it was large enough for full-size standard ASTM Charpy-V notch specimens and longitudinal and transverse drop-weight specimens. Additional data were obtained with subsize Izod specimens including modifications with side notches. Comparisons were made between the Izod and Charpy-V specimens for various sample and notch orientations.

Impact curves H and I shown in Fig. 4 compare results obtained on Izod samples with varying notch depth but with the area below the notch held constant (i.e., 0.190 in. square). With the exception of being displaced to the left, the curves are similar to their counterparts used on Zircaloy-2 rod and shown in Fig. 3 as C and D. Design H with a midenergy-transition range of −50°C showed the greatest displacement. A comparable value of 100°C for design I indicated lower fracture energies for the more severe notch.

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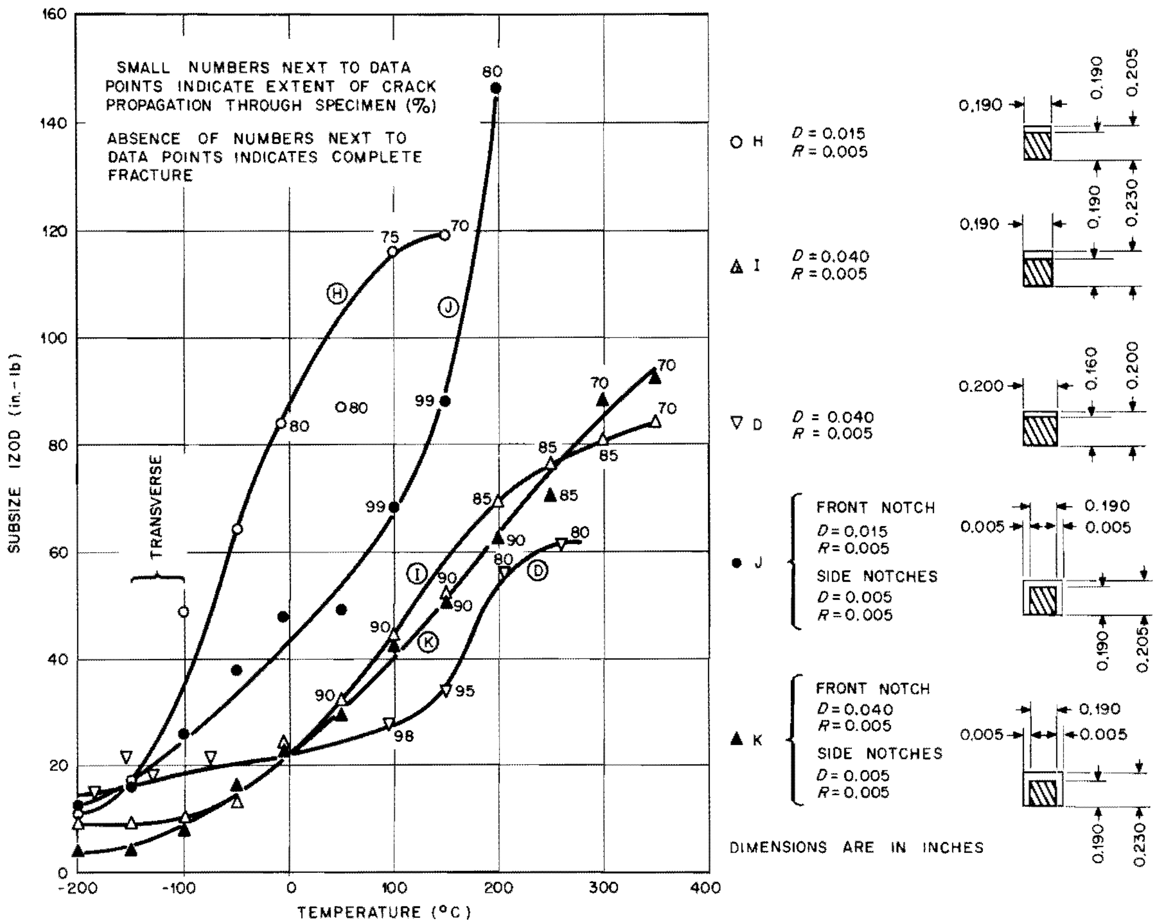

Fig. 4. Effect of Notch Depth and Side Notches on Impact Strength of Subsize Izod Specimens. (Material is as-received $\frac{1}{2}$-in. Zircaloy-2 plate, 16 ppm H_2. All specimens have the TH orientation.)

Data from specimens with design D show that reducing the area under the notch does have a significant effect at all temperatures. Curve D is much flatter than that obtained from the thicker specimens with design I although the midenergy ranges are fairly comparable.

A direct comparison of the notch toughness of the two lots of Zircaloy-2 may be obtained by comparing the curves obtained from specimens of design D in Figs. 3, 5, and 6. The analyses in Table 1 show the carbon, oxygen, and hydrogen are lower in the plate and this is reflected by the increased notch toughness for four orientations as shown by comparing design D in Figs. 5 and 6 with design D (rod) in Fig. 3.

The toe or the brittle portion of the impact curve determined with specimens of designs I and K (Fig. 4) coincided with the transverse NDT temperature which occurred between −100 to −150°C. Due to insufficient material, the transverse NDT was not determined more accurately. Also, in order to conserve material, the drop-weight plates were $\frac{1}{2} \times 2\frac{1}{2} \times 14$ in. instead of the standard $\frac{1}{2} \times 3\frac{1}{2} \times 14$ in. The NDT temperature is that temperature below which the plate cannot be plastically deformed in the presence of a crack; whereas, at temperatures above NDT the crack would not propagate even with some plastic deformation of the plate. Additional evidence of notch toughness in this material is that specimens having designs H and I developed incomplete fractures in the specimens broken at or above −5 and 50°C, respectively.

Also shown in Fig. 4 are curves for impact specimens of designs J and K which were used to study the effect of side notches. The cross-sectional area, the notch depth, and the root radius in the leading notch are the same as for designs H and I. It was thought that the side notches would reduce lateral contraction and thus decrease the fracture energy. This was actually the case for design J. In the case of design K, the side notches did not seem to appreciably influence the shape or position of the impact curve. The most pronounced effect of the side notches was that, in both cases, complete fracture was produced at temperatures at about 100°C higher than for specimens without the side notches.

Comparisons of impact curves from specimens of two orientations (LH and TH) of subsize Izod design D and the corresponding curves for standard ASTM Charpy-V specimens are shown in Fig. 5. The subsize D

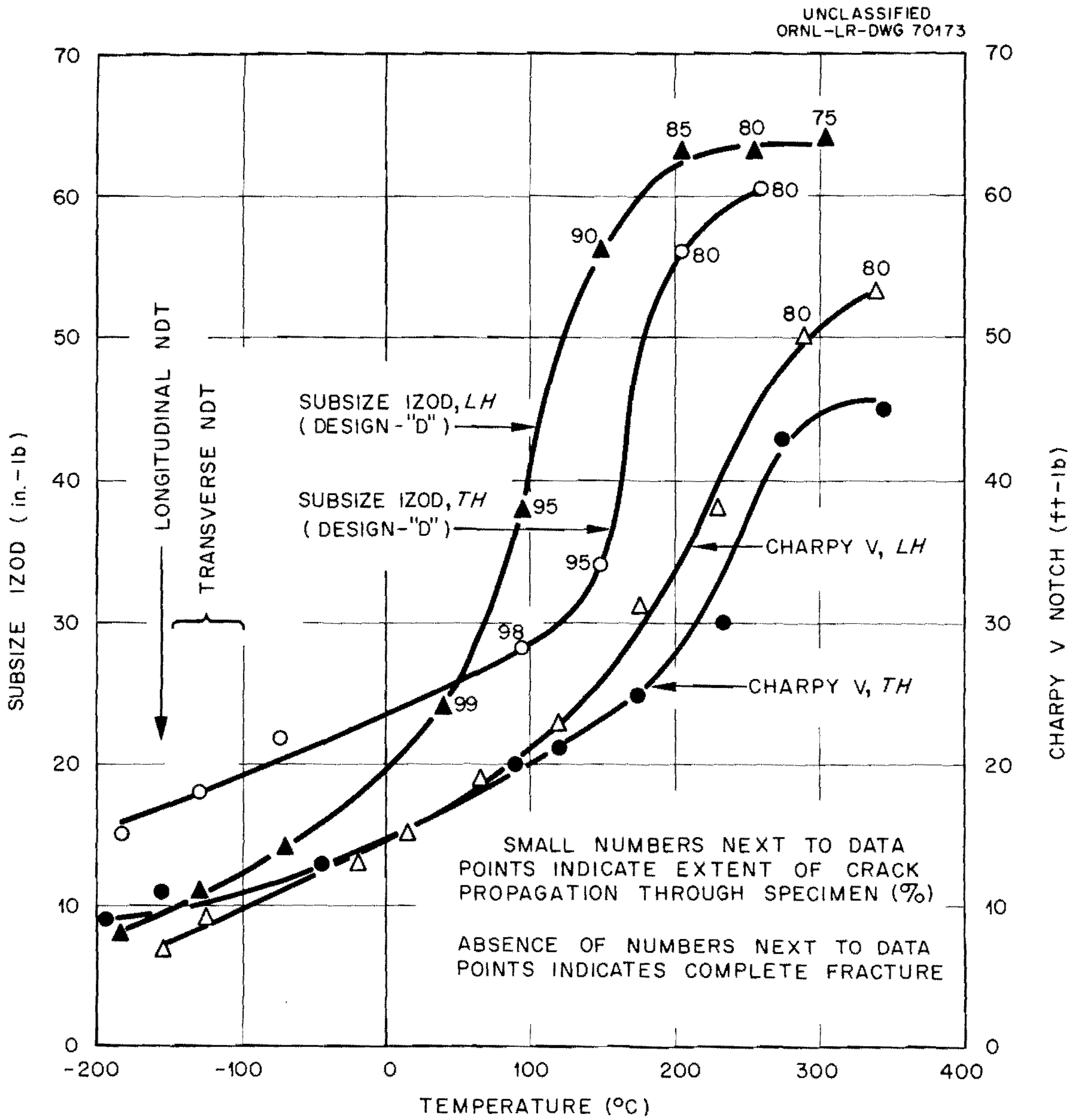

Fig. 5. Comparison of Charpy-V and Subsize Izod (0.200-in. Square, Depth of Notch is 0.040 in., and Root Radius is 0.005 in.). Material is $\frac{1}{2}$-in. Zircaloy-2 plate, 16 ppm H_2. Orientation is as noted.

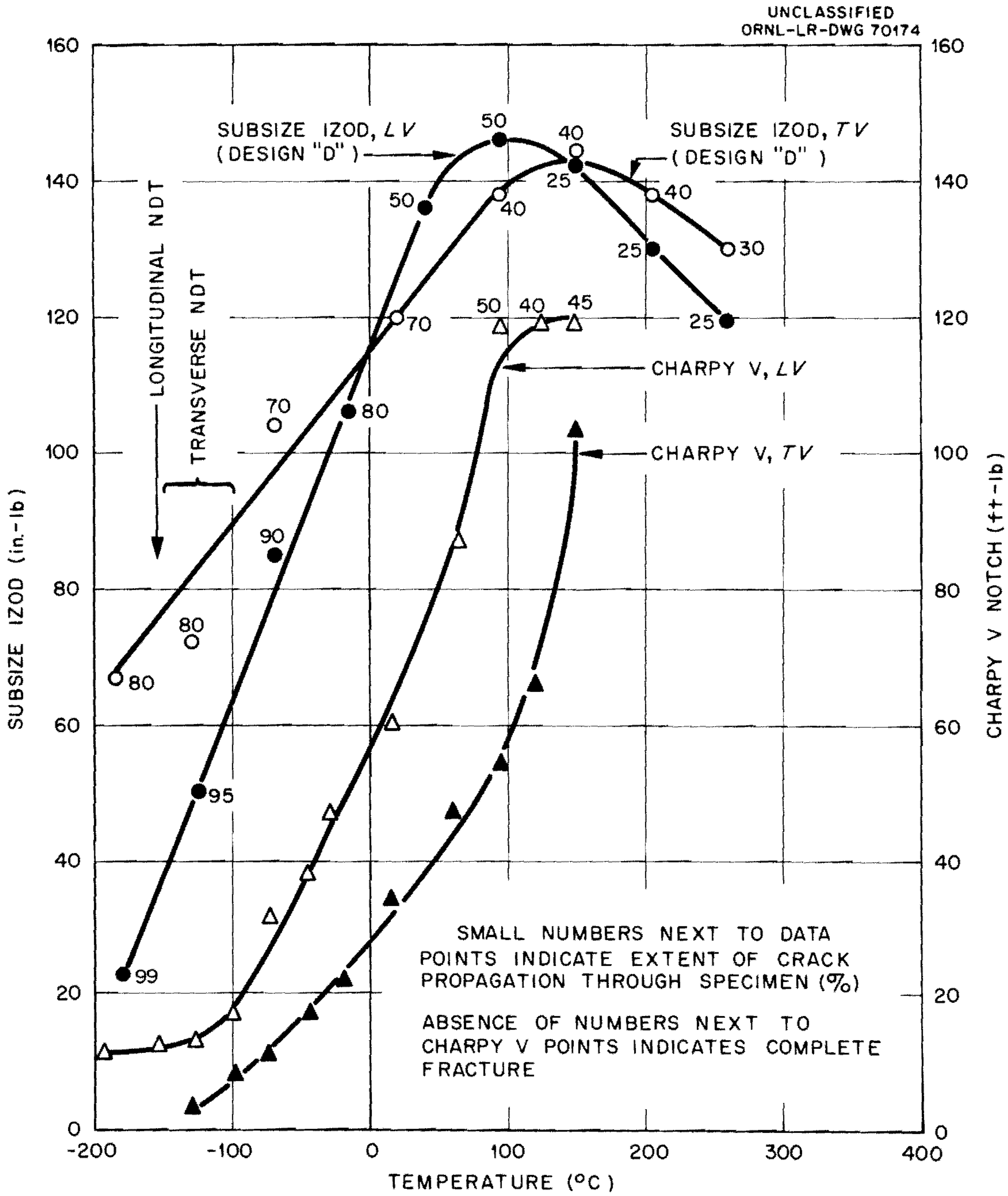

Fig. 6. Comparison of Charpy-V and Subsize Izod (0.200-in. Square, Depth of Notch is 0.040 in., and Root Radius is 0.005 in.). Material is ½-in. Zircaloy-2 plate, 16 ppm H_2. Orientation is as noted.

specimens have practically the same notch configuration as the standard Charpy-V specimens except that the cross-sectional dimensions are only half as large. The general shapes of the curves and the relationships between the LH and TH curves are similar, but none of the breaks in the curves occur at corresponding temperatures. The midenergy transition temperatures for both the Izod curves were lower than those from the Charpy specimens.

Comparisons of the four curves with vertical notches (TV and LV) are given in Fig. 6. No similarities in shapes or transition temperatures are apparent, the subsize curves showing the more optimistic data. It should be noted that the energies required for fracture are much higher with this orientation than with the notch in the plane of the plate, requiring changes in scales on the two vertical axes. Also, the curves are located at lower temperatures. The greater resistance to fracture for the specimens with vertical notches is shown by the low numbers for the percentage of crack propagation. There seems to be a size effect for this property that is more evident in the small Izod specimens. The comparison of the two groups of curves in Figs. 5 and 6 shows that the impact properties of Zircaloy-2 vary with the type of specimen used, the orientation of the specimen, and the orientation of the notch. With such wide variations, it is obvious that care must be used in extrapolating these results to service conditions.

Differences were also observed in the fracture patterns of the impact specimens. Specimens that had the notch in the plane of the plate, both the longitudinal and transverse directions (LH and TH) exhibited a shear lip. Superficially, the impact fractures resemble those found in steels except that the shear lip was present even at temperatures below the NDT temperature.

Both Charpy-V and subsize Izod specimens having the LV and TV orientations had fractures that were "S" shaped. There was no sudden change in fracture appearance with decreasing temperature for any of the orientations studied. There was a gradual decline of the ductile-appearing fractures characteristic of higher temperatures. The fact that the LV and TV orientations did not show a shear lip is probably related to the fact that most of the slip planes are aligned so as to permit slip only in directions closely parallel to the rolling plane. The formation of a shear lip for specimens with LV and TV orientations is not favored since deformation cannot occur by slip in the plate thickness direction.

CONCLUSIONS

1. With Zircaloy-2 both the shapes of the impact curves and the fracture energies are functions of the specimen and notch geometry, specimen orientation, and notch orientation.

2. Poorer impact properties are indicated for samples with the notch cut in the plane of the plate than for those with the notch in the thickness direction.

3. The midenergy transition temperature was lower for the subsize Izod samples than for Charpy V-notch samples.

4. Specimens cut from the longitudinal direction, in most cases, gave slightly higher energy values than those from the transverse direction.

5. The notch toughness of the Zircaloy-2 plate for four orientations was greater than that for the rod material – the plate material being much lower in hydrogen, oxygen, and carbon.

6. In Zircaloy-2 rod material containing 51 ppm H_2 the ductility decreased below about 200°C which is approximately the temperature at which the brittle hydride phase goes into solution. Above this temperature, the effect of notch geometry was a controlling factor in determining the energy required to fracture the specimen.

7. As the notch severity was decreased, the impact curves shifted to lower temperatures and higher energies.

8. Increasing the cross-sectional area below the notch shifted the curves toward higher energy values.

9. Subsize Izod specimens of design D appear to be suitable for in-pile testing, but only if used for following changes in toughness and with care being used to assure corresponding orientations of all samples tested.

10. As indicated by both longitudinal and transverse drop-weight tests, Zircaloy-2 has excellent crack-propagation-arresting properties.

ACKNOWLEDGMENT

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