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AEC Research and
Development Report

KNOLLS
ATOMIC POWER
LABORATORY

**Fracture-Toughness
Determinations
of A302-B and Ni-Mo-V
Forging Steel with
Various-Sized Specimens**

Part II

D.F. Mowbray

K. Minassian

December 15, 1964

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FRACTURE-TOUGHNESS DETERMINATIONS OF A302-B AND Ni-Mo-V
FORGING STEEL WITH VARIOUS-SIZED SPECIMENS

PART II

D. F. Mowbray, K. Minassian.

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ABSTRACT

Plane-strain fracture-toughness measurements were made on normalized A302-B steel and a brittle Ni-Mo-V forging steel. Specimens tested included a 0.4-in.-thick single-edge-notched specimen and notched-bend specimens with cross sections as large as 6.0-in. square. The single-edge-notched specimen was used because of its potential use in studying properties of irradiated steel; the large bend specimens were used because of their capability for measuring much higher values of fracture toughness. The test data obtained supplement those from an earlier investigation of a quenched and tempered A302-B steel and the same Ni-Mo-V steel.

The valid plane-strain fracture-toughness data obtained for all three steels are plotted as a function of temperature. The temperature dependence of plane-strain fracture toughness for these steels is discussed, and a correspondence with fracture-specimen shear-lip thickness is demonstrated.

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FRACTURE-TOUGHNESS DETERMINATIONS OF A302-B and Ni-Mo-V
FORGING STEEL WITH VARIOUS-SIZED SPECIMENS

PART II.

D. F. Mowbray, K. Minassian

INTRODUCTION

Nuclear reactor pressure vessels are fabricated from material exhibiting a fracture transition. To avoid conditions conducive to brittle fracture in these vessels, approximate methods are used to identify the temperature boundaries (ductile-brittle transition-temperature regions) below which the operation of reactor pressure vessels is restricted. These approximate methods require that operating limitations be imposed that may be more severe than are necessary for safety. Consequently, a more exact method of determining ductile-brittle behavior could help in alleviating operating restrictions. A quantitative method is desired which would: (1) provide material property data for prediction of the stress levels that could be applied safely in various regions of a reactor pressure vessel in the presence of crack-like defects, and (2) determine the existence of and identify the transition temperature at which there is a pronounced change in resistance to extension of crack-like defects.

Currently, the fracture mechanics concepts of Irwin¹ are best suited for fulfilling these requirements. A recent investigation at this laboratory explored the feasibility of obtaining the fracture-toughness parameters required for applying these concepts to steels used for reactor pressure vessels.² In this initial investigation, plane-strain fracture toughness was determined as a function of temperature with small- and large-sized specimens. The former specimens were small enough to be used for irradiation study; the latter were large enough to ensure valid determinations of plane-strain fracture toughness. Two materials were tested: quenched and tempered (Q & T) A302-B steel and a Ni-Mo-V steel forging. The Ni-Mo-V steel was selected for testing because its strength and impact properties are similar to those of irradiated A302-B steel.

The present investigation is an extension of the work previously completed. Additional tests were conducted on the Ni-Mo-V steel and on a second heat of A302-B steel. This heat of A302-B steel has been the subject of extensive previous study.^{3,4}

SUMMARY OF RESULTS FROM PREVIOUS INVESTIGATION

The significant results obtained from the initial investigation are:

1. Specimens as small as 1/8-in.-thick single-edge-notched (SEN) and Charpy-sized notched-bend (NB) specimens yield valid plane-strain fracture-toughness values only at extremely low temperatures.
2. The variation of plane-strain fracture toughness with temperature was characterized by: (a) a small range of temperature in which there was a transition in the mode of fracture from plane-strain (brittle) to plane-stress (ductile), and (b) a plateau region at temperatures below the transition where a decrease in temperature resulted in a relatively slight decrease in plane-strain fracture toughness.
3. When strictly cleavage fracture occupied the central portion of the fracture surface, the maximum shear-lip thickness formed at the edges of the specimen was independent of specimen size for a particular temperature (within the scatter characteristic of fracture testing).
4. The transition temperature defined by the maximum shear-lip thickness-temperature curve coincided with the transition temperature defined by the plane-strain fracture-toughness curve.

Sufficient data were not available to fully substantiate items 2 and 4. An objective of the present investigation was a further evaluation of the validity of these results. To this end, more large specimens of Ni-Mo-V steel were tested in the plane-strain fracture-toughness transition-temperature region.

At this point it should be emphasized that the Ni-Mo-V steel has been employed, not because it has nuclear applications, but because it gives a good indication of the applicability of the small-sized specimens being evaluated for use in studying radiation-embrittled A302-B steel.

TEST PROGRAM

Material

The A302-B steel used for this investigation was removed from 7-in.-thick rolled plate normalized by the supplier. Details of this heat of A302-B steel, the Ni-Mo-V steel, and the heat of Q & T A302-B steel previously tested are given in Table 1.

TABLE 1. MATERIAL SPECIFICATIONS AND COMPOSITION

Material	Heat Treatment	ASTM Grain Size	Chemical Composition, wt %							
			C	Ni	Mo	V	Mn	Si	P	S
Ni-Mo-V	Austenitizing and tempering treatment characteristic of that for large rotor forgings.	6 to 7	0.30	2.6	0.44	0.09	0.48	0.22	0.03	0.03
A302-B	Solution treatment: 1 hr/in. thickness at 1725 to 1775F; water-quenched. Tempered 1 hr/in., thickness at 1200 to 1250F; air-cooled.	6 to 7	0.20	-	0.50	-	1.15	0.22	0.015	0.027
A302-B	Normalized 1650F 1 hr/in.; air-cooled. Stress-relieved 1200F 1 hr/in. Fan-cooled to 200F; air-cooled.	8 to 9	0.21	0.04	0.50	-	1.34	0.27	0.015	0.010

The standard tensile properties of the three materials have been previously reported^{2,3} and will not be repeated here. However, to illustrate differences in strength and notch toughness among the steels, curves are shown to describe the variation with temperature of 0.2% yield strength (Figure 1) and Charpy V-notch impact specimen fracture appearance (Figure 2). The normalized A302-B steel has lower strength than the Q & T steel and a somewhat higher fracture-appearance transition temperature (~70F). The Ni-Mo-V steel, like irradiated A302-B steel, has higher strength and a considerably higher fracture-appearance transition temperature than do the unirradiated A302-B steels.

Specimens

As in the previous investigation, two basic fracture-test specimens were used: the NB and the SEN. Sketches of the two specimens are shown in Figures 3 and 4.

Figure 3 includes a table listing the various sizes of NB specimens that have been tested during the course of both investigations. In this investigation, the two small-sized specimens (0.2- and 0.4-in. NB specimens) were used only for obtaining shear-lip thickness measurements. The larger NB specimens were used for measuring plane-strain fracture toughness at temperatures where the values of toughness are high; thus use of such huge specimens was necessary to obtain valid plane-strain data. In particular, two tests were conducted on normalized A302-B steel with specimens having the 2.25-in.-square cross section (referred to as 2.25-in. NB specimens), and two on Ni-Mo-V steel with specimens having the 6.0-in.-square cross section (referred to as 6.0-in. NB specimens).

The SEN specimen employed in this investigation was considerably larger than the 1/8-in.-thick specimen (1/8-in. SEN) previously employed. Whereas the previous specimen was designed as small as possible,^{2,5} the present specimen was made as large as possible, but within the dimensions of the irradiation facilities used for pressure vessel material irradiations. Examination of the sketch in Figure 4 will indicate that the specimen has been proportioned to the standard Charpy V-notch impact specimen. The thickness, depth, and length are in proportion to the Charpy specimen dimensions by the factors 1, 3, and 2, respectively. This specimen design will be referred to as the 0.4-in. SEN specimen.

The notch in all the fracture specimens tested was a fatigue crack superimposed on a machined slot. Overall depths were ~25% of the total section depth for the NB specimens and ~35% for the SEN specimens. The fatigue cracks generally extended ~0.030 to 0.050 in. beyond the root of the machined slots. However, the overall notch depths and fatigue-crack lengths of the two 6.0-in. NB specimens of Ni-Mo-V steel differed considerably. The reasons will be discussed on pages 10 and 13.

FIGURE 1. Temperature Dependence of 0.2% Yield Strength of Ni-Mo-V and A302-B Steels.
KS-57239
Unclassified

FIGURE 2. Charpy V-Notch Impact Specimen Fracture Appearance for Ni-Mo-V and A302-B Steels.
KS-57240
Unclassified

1/16 in.

45 deg

0.340-in. MILLED NOTCH WITH ROOT RADIUS OF 0.003 in. PLUS 0.030- TO 0.050-in. FATIGUE CRACK

0.375-in. diam.

4.330 in.

0.0591 in.

1.182 in.

0.394 in.

ROLLING DIRECTION

TRANSVERSE TO ROLLING DIRECTION

**FIGURE 4. Single-Edge-Notched (SEN)
Specimen.**

KS-57242 **Unclassified**

The orientation of the notches and fatigue cracks with respect to rolling direction is illustrated in Figures 3 and 4. In all cases, the maximum tensile stress was applied in the direction of rolling. The 2.25-in. NB specimens of normalized A302-B steel were removed from the one-quarter thickness position of the plate, and the 0.4-in. SEN specimens from mid-thickness.

Specimens were fatigue-cracked, using zero-to-tension cycling at low nominal stress levels. The number of cycles required to produce fatigue cracks of nominal lengths was 20,000 to 50,000 for the large NB specimens, and 100,000 to 200,000 for the small NB and SEN specimens.

Fracture-Testing Equipment and Procedure

The bend specimens were tested by loading the specimen in three-point bending with the notched side in tension. A 300,000-lb Baldwin universal testing machine was used for testing the large specimens, and a 10,000-lb Instron testing machine was used for the small specimens. Load-deflection curves were recorded in all tests.

A 60,000-lb Baldwin universal testing machine was used for testing the SEN specimens. Load-displacement curves were recorded in all tests. Two instruments were employed in each test to measure displacement, and hence to record crack pop-in when it occurred. One instrument was a microformer extensometer, attached to the specimen so that it spanned the slot at the edge of the specimen. The second was a high-extension strain gage, bonded to the specimen at the tip of the fatigue crack. The signal from both the extensometer and the strain gage was recorded on a Sandborn high-speed recorder. Maximum sensitivity of the recorder was used to increase the magnification of the actual displacement signal.

Liquid coolant baths (liquid nitrogen and combinations of liquid nitrogen and ethyl alcohol) were used for testing below room temperature. For elevated-temperature tests, the large specimens were wrapped with heating coils, and the small specimens were placed in heated silicone-oil baths. The loading rates for all tests were characteristic of the standard tensile test rate (0.02 in./min).

The test procedure consisted of loading the fatigue-cracked specimens to failure while recording load-displacement curves. The value of load used for calculating fracture stress and fracture toughness corresponds to the initial instability on the load-displacement curve. In general, three types of load-displacement curves were generated, as illustrated in Figure 5. Curve (1) is indicative of a test in which no gross yielding in the critical section occurs. The initial instability results in complete specimen separation. The fracture stress is calculated from the maximum load, P_1 .

FIGURE 5. Various Types of Load-Displacement Curves Observed in Fracture Tests.

KS-51336

Unclassified

Curve (2) is the type obtained when a crack pop-in precedes gross yielding. Fracture stresses are calculated from the pop-in load, P_2 . The third type of load-displacement curve (3) occurs when the initial instability is preceded by gross yielding in the critical section. Fracture stresses are calculated using the maximum load, P_3 . This test does not yield a true value of plane-strain fracture toughness, because gross yielding has occurred. In the report of test results shown in Table 2, the type of load-displacement curve obtained in each test is identified by the numbers in Figure 5.

TEST RESULTS

A tabulation of the results of the fracture-toughness tests (see Table 2) includes: net-section fracture stress (σ_{NF}), ratio of net-section fracture stress to 0.2% yield strength (σ_{NF}/σ_{YS}), plane-strain fracture toughness (G_{IC}), plane-strain stress-intensity parameter (K_{IC}), and maximum shear-lip thickness. The equations for calculating σ_{NF} , G_{IC} , and K_{IC} are given in Appendix A. The ratio, σ_{NF}/σ_{YS} , was calculated using values of 0.2% yield strength from the curves of Figure 1.

In the previous publication,² the fracture-toughness data were represented by the plane-strain fracture-toughness parameter, G_{IC} . This symbol was used for representing the results of all tests, even those that did not yield valid plane-strain data (i.e., tests in which the nominal

TABLE 2. FRACTURE - TOUGHNESS TEST RESULTS

Specimen No.	Type Specimen	Material	Test Temp, F	σ_{NF} , ksi	$\frac{\sigma_{NF}}{\sigma_{YS}}$	C_{Ic} , in.lb/in ²	K_{Ic} , ksi√in.	Shear-Lip Thickness, in.	Type of Load-Displacement Curve
1	6.0-in. NB	Ni-Mo-V	190	71.7	0.73	256	91.8	0.15	1
2	↓		190	85.1	0.86	366	109.9	0.13	1
2	↓		190	63.6	0.64	208	82.8	-	2
3	3.0-in. NB		-313	26.0	0.17	17	23.7	N11	1
4	↓		80	39.5	0.39	36	34.4	0.15	1
5	↓		162	79.4	0.81	115	61.6	0.55	1
6	0.4-in. SEN		-320	41.0	0.26	16	23.0	N11	1
7	↓		-100	40.6	0.36	16	23.0	N11	1
8	↓		30	61.9	0.59	38	35.4	0.007	2
9	↓		80	97.4	0.95	97	56.5	0.009	2
10	↓		135	80.1	0.80	62	45.2	0.036	2
11	↓		160	95.6	0.96	94	55.6	0.056	2
12	0.4-in. NB		-320	60.3	0.39	12	19.9	N11	1
13	↓		-320	77.7	0.50	20	25.7	N11	1
14	↓		-100	133.9	1.18	59	44.1	0.003	1
15	1/8-in. SEN		-320	46.0	0.30	16	23.0	N11	1
16	↓		-320	60.0	0.39	28	30.4	N11	1
17	↓		-100	118.2	1.03	121	63.0	N11	1
18	↓		-100	119.1	1.04	116	61.7	N11	1
19	↓		80	158.8	1.22	143	68.5	0.015	1
20	2.25-in. NB	A302-B	-141	55.9	0.79	57	43.2	N11	1
21	2.25-in. NB	Normalized	-94	86.5	1.30	142	68.3	0.004	1
22	0.4-in. SEN		-320	40.7	0.37	16	23.0	N11	1
23	↓		-320	46.3	0.43	21	26.3	N11	1
24	↓		-170	92.2	1.23	96	56.2	0.001	1
25	↓		-170	85.4	1.14	79	51.0	0.001	1
26	3.0-in. NB	A302-B	-320	48.9	0.32	56	43.0	N11	1
27	↓	Q & T	-218	57.3	0.58	76	50.0	0.005	1
28	↓		-95	140.6	1.83	452	122.0	0.045	3
29	0.4-in. NB		-320	68.5	0.44	15	22.2	N11	1
30	↓		-320	77.4	0.50	20	25.7	N11	1
31	↓		-320	101.6	0.66	32	32.4	N11	1
32	↓		-230	107.0	1.04	39	35.8	0.004	1
33	↓		-230	144.0	1.40	70	48.0	0.003	1
34	1/8-in. SEN		-320	84.5	0.55	58	43.7	N11	1
35	↓		-320	98.2	0.63	78	50.7	N11	1
36	↓		-320	87.0	0.56	60	44.5	N11	1
37	↓		-250	115.4	1.05	116	61.8	N11	1
38	↓		-250	87.0	0.79	63	45.6	N11	1
39	↓		-200	131.7	1.41	143	68.6	0.006	1
40	↓		-200	143.4	1.53	175	75.8	0.006	1

stress exceeded the yield strength by an excessive amount). In this report, representation of the data in terms of the critical stress-intensity parameter, K_{Ic} , has been utilized because K_{Ic} minimizes the amount of scatter in the data (i.e., $K_{Ic} \propto \sqrt{G_{Ic}}$). Further, to be consistent, the K_{Ic} vs temperature plots, with one exception, contain only valid test results.

The crack-toughness properties (as a function of temperature) of the Ni-Mo-V steel are illustrated in Figures 6 and 7. Each of the figures includes a plot of the K_{Ic} data, which are compared in Figure 6 with the ratio σ_{NF}/σ_{YS} , and in Figure 7 with the shear-lip thickness. Included are test results for the various-sized specimens tested to date, some of which were reported in the previous publication.² The plots of σ_{NF}/σ_{YS} vs temperature are shown, to illustrate the relative measuring capabilities of the various-sized specimens for a steel of this strength and toughness. Also, it should be pointed out that the K_{Ic} data points for 0.4-in. SEN specimens at temperatures above -100F represent tests in which crack pop-in was detected (i.e., Type (2) load-displacement curves - Figure 5).

The crack-toughness properties of the normalized A302-B steel are shown in Figure 8. In the lower half of the figure, K_{Ic} data are plotted - in the upper half, shear-lip thickness data. Included among the K_{Ic} data are results derived from 0.4-in. SEN and 2.25-in. NB specimen tests in the present investigation, and from 7.0-in.-thick $\times$ 13.5-in.-diam spin disk specimens* previously tested by the Westinghouse Research Laboratory.⁶

A plot for the Q & T A302-B steel, similar to the plots of Figures 7 and 8, is included as Figure 9. These data were obtained in the previous investigation and are included as part of this report for comparison with the properties of the Ni-Mo-V and normalized A302-B steels. The data are from tests of 1/8-in. SEN, 0.4-in. NB, and 3.0-in. NB specimens.

Note that three values of K_{Ic} are reported for 6.0-in. NB Ni-Mo-V steel specimens, but that only two specimens were actually tested. This irregularity is the result of crack pop-in having occurred during the fatigue-cycling of one of the specimens. Specimen 2, for which K_{Ic} values of 109.9 and 82.8 ksi $\sqrt{\text{in.}}$ are reported, was first tested with the normal-length fatigue crack (~ 0.300 in.). The load was increased to 300,000 lb, the maximum capacity of the testing machine, without causing specimen failure (300,000 lb corresponded to a K_{Ic} level of ~ 100 ksi $\sqrt{\text{in.}}$). The specimen was then fatigue-cycled at 190F to increase the length of the fatigue crack and decrease the net section area, so that

*The spin disk specimens had milled V-notches (0.001-in. root radii) to simulate cracks and may therefore indicate fictitiously high values of toughness.

FIGURE 6. Temperature Dependence of K_{IC} and σ_{NF}/σ_{YS} for Ni-Mo-V Steel.

KS-57243

Unclassified

FIGURE 7. Temperature Dependence of K_{IC} and Shear-Lip Thickness for Ni-Mo-V Steel.

KS-57244

Unclassified

FIGURE 8. Temperature Dependence of K_{Ic} and Shear-Lip Thickness for Normalized A302-B Steel.

KS-57245

Unclassified

FIGURE 9. Temperature Dependence of K_{Ic} and Shear-Lip Thickness for Q & T A302-B Steel.

KS-57246

Unclassified

the specimen could be fractured with the existing testing machine load capacity. Subsequent fracture testing of the bar yielded a K_{Ic} value of 109.9 ksi $\sqrt{\text{in.}}$. However, posttest examination of the fracture surface revealed that a crack pop-in had probably occurred during the fatigue cycling. A photograph of this fracture surface is shown in Figure 10. An area of cleavage fracture surface surrounded by fatigue surface can be observed. Thus, a second value of K_{Ic} (82.8 ksi $\sqrt{\text{in.}}$) was derived from the maximum fatigue-cycling load and from the crack length that corresponded to the point at which cleavage fracture initiated during the fatigue cycle.

The difference in magnitude of the two K_{Ic} values obtained from this single test (109.9 vs 82.8 ksi $\sqrt{\text{in.}}$) probably reflects small differences in metallurgical structure - differences that one would expect to be present throughout a 40-in.-diam forging. For this test, the difference in K_{Ic} values at the two locations of the bar was amplified, because the test temperature was in a transition region.

To establish that the two 6.0-in. NB specimens had nearly identical toughness properties, a set of Charpy impact specimens was removed from each of the bars (after fracture testing) and tested over a range of temperatures. The two sets of impact specimens yielded essentially identical results.

DISCUSSION

Specimen Evaluation

The K_{Ic} data for Ni-Mo-V steel in Figures 6 and 7 indicate that the small specimens, 1/8-in. SEN and 0.4-in NB specimens, yield values of K_{Ic} in agreement with the results from larger specimens only at temperatures near -320F. At temperatures above -320F, the K_{Ic} values for 1/8-in. SEN specimens are greater than corresponding large-specimen values. This discrepancy is assumed to be the result of statistical flaw effects arising from metallurgical differences, and/or from differences in the state of stress between large and small specimens. Similar observations can be made of 1/8-in. SEN specimen test results in Figure 9 for Q & T A302-B steel. For this steel, however, the 0.4-in. NB specimens yield values of K_{Ic} less than those shown in the large-specimen test results. Such lowering of K_{Ic} values is commonly observed in test results from specimens having a high stress gradient,⁵ and is believed to be due to a suppression of the plastic zone size.

It was possible with the 0.4-in. SEN specimen, by detecting crack pop-in, to measure valid values of K_{Ic} on the Ni-Mo-V steel at temperatures up to 160F. The K_{Ic} -temperature plots of Figures 6 and 7 indicate that 160F is well into the transition-temperature region. Attempts to detect pop-in at temperatures higher than 160F were unsuccessful.

The capacities of different materials to exhibit pop-in are often compared on the basis of a relative plastic zone size. The relative plastic zone size is defined as the ratio of plane-stress plastic-zone size to specimen thickness, r_p/t , where $r_p = K_{Ic}^2 / 2\pi\sigma_{YS}^2$. In the original work of Boyle, Krafft, and Sullivan on aluminum,⁷ it was found that pop-in could be detected when the ratio, r_p/t , was <0.25 . More recently, Steigerwald and Hanna⁸ found that for high-strength steels that show a transition behavior, the probability of detecting pop-in was small when the relative plastic zone size was >0.11 . For the 0.4-in. SEN Ni-Mo-V steel specimen test at 160F, this ratio was ~ 0.10 , which is consistent with the findings of Steigerwald and Hanna. Assuming similar behavior for irradiated A302-B steel, one would expect that a SEN specimen of the size employed in this investigation would be necessary for measuring plane-strain fracture toughness in the transition-temperature region.

Crack pop-in, as exemplified by the Type (2) load-displacement curve in Figure 5, was not detected in 0.4-in. SEN specimen tests of unirradiated A302-B steel. The K_{Ic} data points plotted in Figure 8 for 0.4-in. SEN specimens are for Type (1) load-displacement behavior. It seems highly probable that valid (i.e., elastically contained) tests of unirradiated A302-B steel will result only in Type (1) behavior. In other words, the temperature range in which valid plane-strain toughness can be determined is not enhanced by pop-in detection, and the use of very large specimens becomes necessary.

Temperature Dependence of Plane-Strain Fracture Toughness

The results obtained in the initial investigation indicated that the variation of plane-strain fracture toughness with temperature (for steels of this strength class) can be described by a transition-temperature region and a plateau region at temperatures below the transition. This characteristic appears to hold for the Ni-Mo-V steel, this being the only material for which extensive data have been obtained. The two 6.0-in. NB specimen tests on the Ni-Mo-V steel have extended its K_{Ic} -temperature curve to higher K_{Ic} values in the transition-temperature region, appearing to indicate size-independent behavior in this region.

This temperature dependence of plane-strain fracture toughness appears to hold true for the A302-B steels also, although the data are not extensive. The lone large-specimen data point in the transition-temperature region for the Q & T A302-B steel did not result from a valid test (the net section stress exceeded the yield strength by an excessive amount), but the test is still of value in indicating a high K_{Ic} value at that temperature. An arrow pointing upward has been added to the symbol in Figure 9 to denote that K_{Ic} measured with a specimen large enough to fracture without gross yielding would be higher than the plotted value.

Unclassified

FIGURE 10. Fracture Surface of 6.0-in. NB Specimen
Which Exhibited Crack Pop-in During Fatigue Cycling.
KS-57247

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Nature of Shear-Lip Thickness Transition Temperature

The Ni-Mo-V steel data describing the variation of shear-lip thickness with temperature (Figure 7) include the results from tests on specimens ranging in size from 1/8-in.-thick SEN specimens to 6.0-in.-square NB specimens. These data define a transition-temperature curve that is independent of specimen size, within the scatter characteristic of fracture testing.

For the two heats of A302-B steel, data for such a wide range in specimen size are not available. However, the available data indicate that shear-lip thickness will define a size-independent transition curve, provided the initiation of fracture at the crack tip does not occur by fibrous tearing (i.e., fracture initiation must be by cleavage). It was found that fracture initiates by fibrous tearing in the small specimens (1/8-in. SEN and small NB specimens) of A302-B steels at some critical test temperature, which is a function of the strength level of the steel. The respective critical temperatures for each of the A302-B steels tested are indicated on the shear-lip thickness plots. These temperatures correspond to a plane-stress plastic zone size (as accurately as the limited amount of data permits its calculation) that exceeds one-half the thickness of the 0.4-in. NB specimen, meaning that elastic constraint was not maintained in the specimen transverse direction. In the larger specimens where thickness is sufficient to prevent complete loss of constraint, fracture initiates by cleavage, and significant shear-lip thickness measurements can be made.

The amount of fibrous tearing that occurs in small specimens ahead of the crack tip increases with increasing test temperature. Depending upon the test temperature, there will be varying amounts of cleavage surface in the central portion of the fracture surface following the fibrous tearing. These cleavage areas are bordered on the edges of the specimen by shear lips. Most probably, however, because of a strain-rate effect, the thickness of these shear lips does not correspond to the thickness of shear lip formed when fracture initiation at the crack tip is by cleavage.

In the previous publication,² a few small-specimen data points for Q & T A302-B steel were shown beyond the above-mentioned critical temperature. Although fibrous tearing did occur during the fracture of these specimens, and although the resulting shear-lip measurements did appear to be consistent with the rest of the data, the resulting shear-lip formation is not associated with the cleavage mode of fracture initiation, and has therefore been omitted from the present data plot (Figure 9).

As noted previously,² the transition temperature defined by the maximum shear-lip thickness curve coincided with the transition temperature

defined by the plane-strain fracture-toughness curve. A further observation is that the plateau region of the K_{Ic} -temperature curves corresponds to nil shear-lip formation.

CONCLUSIONS

The experimental results obtained during the course of two investigations on the fracture behavior of unirradiated A302-B steels and a Ni-Mo-V steel with properties simulating irradiated A302-B steel support the following general conclusions:

1. A SEN specimen 0.4 in. thick is of sufficient thickness to measure K_{Ic} values on the Ni-Mo-V steel at temperatures well into the transition-temperature region.
2. If the fracture behavior of irradiated A302-B steel is similar to that of Ni-Mo-V steel, then the 0.4-in.-thick SEN specimen has potential application for evaluating the fracture toughness of irradiated A302-B steels. (This is currently without experimental support, however.)
3. The fracture behavior of the steels, as represented by the plane-strain fracture-toughness parameters, shows ductile-brittle transition-temperature regions below which little change in K_{Ic} values occurs with decreasing temperature.
4. The shear-lip thickness formed on the specimen fracture surfaces is independent of specimen size if fracture initiates by cleavage rather than by fibrous tearing.
5. The shear-lip thickness-temperature curves appear to coincide with the K_{Ic} -temperature curves.

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APPENDIX A. EQUATIONS USED FOR CALCULATING σ_{NF} , G_{Ic} , AND K_{Ic}

The net-section fracture stress (σ_{NF}) reported for the NB specimens is the nominal stress calculated from simple beam theory as follows:

$$\sigma_{NF} = \frac{1.5 P \ell}{t(d - a)^2} , \quad (1)$$

where P = load at pop-in or complete specimen fracture, lb.
 ℓ = beam span, in.
 d = specimen depth, in.
 a = defect depth (notch depth plus length of fatigue crack), in.
 t = specimen width, in.

The expression used for calculating the NB specimen plane-strain fracture toughness (G_{Ic}) is as follows:⁹

$$G_{Ic} = \frac{(1 - \nu^2)}{E} (d - a) \sigma_{NF}^2 f\left(\frac{a}{d}\right) , \quad (2)$$

where E = Young's elastic modulus, psi.
 ν = Poisson's ratio.
 f = function of a/d plotted in Reference 9.

The net-section fracture stress reported for the SEN specimens is the maximum stress at the crack tip considering bending and axial load, calculated as follows:

$$\sigma_{NF} = \frac{P}{(W - a)t} \left(1 + \frac{3a}{W - a}\right) , \quad (3)$$

where P = load at pop-in or complete specimen fracture, lb.
 W = specimen width, lb.
 a = defect depth (notch plus fatigue crack), in.
 t = specimen thickness, in.

Values of G_{Ic} for SEN specimens were calculated from the following expression:

$$G_{Ic} = \frac{\alpha P^2}{W t^2 E} , \quad (4)$$

where the quantity α , which varies with defect depth, was obtained from the compliance data reported in Reference 10.

The G_{Ic} data were converted to the plane-strain stress-intensity parameter, K_{Ic} , by the following expression:

$$K_{Ic}^2 = \frac{EG_{Ic}}{1 - \nu^2} \quad (5)$$

In calculating values of G_{Ic} , the plane-strain plastic-zone correction term¹¹ was added to the measured crack length. This zone size was assumed, after Srawley and Brown,¹¹ to be equal to:

$$\frac{EG_{Ic}}{6\pi\sigma_{YS}^2}, \text{ or } \frac{r_p}{3}.$$

Also, an elastic modulus of 30×10^6 psi was used in making the pertinent calculations for both materials.