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FRACTURE TOUGHNESS K_{Ic} AT ANY TEMPERATURE

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Sponsoring Program or Organization

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OAK RIDGE NATIONAL LABORATORY

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A PROCEDURE FOR DETERMINING BOUNDING VALUES ON
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ABSTRACT

With the increasing need to insure quantitative margins of safety in structures which potentially might contain flaws, it is becoming necessary to demonstrate more than just that fracture toughness K_{Ic} is high or unobtainable because of insufficient thickness of the particular product form of interest. This problem comes particularly to the fore when attempting to determine K_{Ic} for irradiated water reactor pressure vessel steels such as ASTM A 533, grade B, class 1 plate steel. Here the problems of reactor space, fluence gradients, gamma heating and economics for large fracture toughness specimens tend to limit the size of specimens, to limit the number of such specimens which can be irradiated and to confound the final results.

In this paper, a method is proposed for determining upper and lower bounds on the fracture toughness of a material at any temperature of interest. Supporting technical arguments and examples are presented referenced to results obtained on the ASTM A 533, grade B, class 1 steel. The significance of the method to HSSST irradiation investigations and to reactor surveillance programs is discussed. The results of research now in progress will assist in further evaluating the method.

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INTRODUCTION

Quantitative methods of fracture prediction of flawed structures have become major items of research within the past few years. This has come about mainly because of the urgent need to assure quantitative and adequate margins of safety in the large thick primary containment pressure vessels of the nuclear central power stations which are becoming quite numerous throughout the United States. Almost all the pressure vessels of interest are fabricated from ASTM A 533, grade B, class 1 steel plate and/or the equivalent forging grade steel ASTM A 508, class 2. Operating pressures range between 1000 and 2500 psi with design temperatures from around 575 to 650°F. Typical wall thicknesses of such vessels are between 6 and 12 in. Of equal importance with the plate and/or forged steels are the weldments. The three types of welding processes which have been used are the electroslog, the submerged arc and the shielded metal arc. Of these the submerged arc welding process has been by far the most widely used in shop fabricated vessels while the shielded metal arc welding process is most often applied to field fabricated vessels.

The two nuclear power systems commercially accepted throughout the United States and, in more general terms, throughout the world are the boiling water reactor system (BWR) and the pressurized water reactor system (PWR). Of these two systems the pressure vessels of the PWR systems are generally conceded to receive a considerable amount of fast neutron bombardment during service life such that significant irradiation embrittlement occurs in the core belt line of the vessel. Thus for the PWR systems at least we have the added problems of assessing margins of safety when the parameter of irradiation has been added.

Linear elastic fracture mechanics is the most universally accepted method of fracture calculation by quantitative means; however, as shown by Shabbits, Pryle and Wessel¹ the static fracture toughness K_{Ic} of the ASTM A 533, grade B, class 1 steel is obtainable only up to about 50°F even when using specimens as thick as 12 in. oriented in the longitudinal direction. Shabbits (see Paper No. 8 of this conference) and Rippling and Crosley (see Paper No. 9 of this conference) have demonstrated that under dynamic and arrest conditions fracture toughness values can be measured

at temperatures over 100°F. Nevertheless, it has become infeasible if not impossible to measure directly toughness levels in the range of temperatures most pertinent to pressure vessel service life (that is, temperatures from 200 to 550°F). Thus while high loads and/or large flaw sizes are considered to be the necessary conditions to promote fractures at temperatures of interest, the margins of safety either in load or strain most often cannot be obtained by linear elastic fracture mechanics methods in a quantitative manner. While irradiation lowers the fracture toughness, current data indicate that here too the fracture toughness becomes quite high at reasonably low temperatures (say 200°F) and high fluence levels (say 5×10^{19} n/cm², $E > 1$ Mev, irradiated at 550°F) (see Paper No. 18 of this conference). Thus the same dilemma of establishing realistic quantitative safety margins exist as before but perhaps to a lesser degree.

The problem of irradiation is a particular challenge since it has already been demonstrated by Mager (Ref. 2, also see Paper No. 18 of this conference) that specimens with thicknesses of 4 in. or greater must be tested in the irradiated condition of interest to attain a fracture toughness K_{IC} value of 100,000 psi $\sqrt{\text{in.}}$. Here then we face a different problem than for the unirradiated plate where we could test specimens in full plate thickness. The problem of reactor space, fluence gradients, gamma heating and economics for irradiating specimens 4 in. thick or greater tend to limit the number of such specimens which can be irradiated and tested as well as confound the degree of quantification of the results. Thus we see an urgent need to develop a method to determine, if not the fracture toughness exactly, at least quantitative bounding values for the fracture toughness.

The basis for the method described in this paper is the equivalent energy method as set forth by Witt (see Ref. 3; see also Paper No. 12 of this conference). The equivalent energy method is an elastic-plastic fracture mechanics approach which to date has proven quite successful for predicting the general elastic-plastic fracture behavior of specimens (structures) fabricated from the ASTM A 533, grade B, class 1 steel (see Paper No. 24 of this conference). Perhaps the major merits of the method is that its basis is well grounded on generally accepted engineering

fundamentals and that there are few if any assumptions which can lead to technical disagreements. In its general context the method reduces to linear elastic fracture mechanics for situations of frangible behavior. Questions relative to the equivalent energy method then are to its generality, applicability and practicality. However, these are areas of engineering interpretation and judgment and do not relate specifically to the technical area.

One of the parameters discussed in Ref. 3 (see Paper No. 12 of this conference) is the quantity identified as K_{Icd} (see Ref. 4 for actual values of this quantity). It is the intent of this paper to explore further the significance of this quantity as related to fracture toughness K_{Ic} . Data will be presented which lends support to the existence of K_{Ic} at all temperatures of interest to nuclear pressure vessels and arguments will be made for calculating upper and lower bound values for such K_{Ic} 's at any temperature. The concept of positive and negative materials is introduced to assist in properly interpreting the bounding values. Two examples of the application of the method are presented in this paper. Finally the significance and applications of the method are discussed including a suggested surveillance program which may well assist in ascertaining quantitative lower bounds on the fracture toughness of the steel in the core region of the vessels while in service.

THE EXISTENCE OF K_{Ic}

A question most pertinent to this paper is "Does K_{Ic} exist at all temperatures of interest for the pressure vessel steels?" Since K_{Ic} is a material constant,⁵ establishing the existence of such a quantity is quite apart from determining its value. From the discussion presented below we shall conclude that K_{Ic} does indeed exist at all temperatures.

First let us recall that Shabbits, Pryle and Wessel¹ obtained K_{Ic} values at 50°F for the ASTM A 533, grade B, class 1 steel in the longitudinal direction by testing 10 in. thick (10 T) specimens. Almost valid data were obtained at 75°F. However, specimens 1/2, 1, 2, 4 and 6 in. thick have also been tested at these temperatures. A plot of the load-deflection curves of these specimens up to maximum load normalized to a

1 T specimen is shown in Fig. 1. Normalized crack depths for each specimen are given so as to account for slight discrepancies observed in the curves. Some of the discrepancies are also due to the gage lengths of the measured displacements. We may conclude that the specimens all behaved in the same manner up to maximum load; that is, each specimen obeyed the laws of geometric similitude up to maximum load on that particular specimen. We also note that as thickness increased the specimens reached a lower maximum load and indeed for the specimen 10 in. thick tested at 50°F, a K_{IC} was obtained. Thus thickness alone has accounted for the possibility of obtaining K_{IC} at 50°F.

We shall now introduce the concept of volumetric energy ratio as discussed in Paper No. 12 of this conference. The volumetric energy ratio is simply the normalized energy (area under the normalized load-deflection curve) of one specimen tested to maximum load divided by the corresponding normalized energy of another geometrically similar specimen tested to maximum load. For compact tension specimens the front face load displacement curve as specified in Ref. 6 will be used as a basis for comparison (in particular, each curve in Fig. 1 before normalization was such a curve). In terms of geometric similitude, then, if two geometrically similar specimens behave in a similar manner up to the same maximum load, the volumetric energy ratio is unity.

In Fig. 1 then we see that, at a given temperature, as thickness increases the volumetric energy ratio when compared to a 1 T specimen increases. That is to say, the specimen behavior diverged with increasing thickness from a volumetric energy ratio of unity; so much so that in fact at 50°F the fracture toughness K_{IC} was obtained.

We now pose the question "Is the behavior exhibited at 50°F and 75°F typical at all temperatures up to 550°F say?" Unfortunately very little data exist for the steel of interest here; however, a program is currently in progress to test 1 T, 6 T and 9 T specimens up to 550°F (UCCND Subcontract 3196 with Westinghouse Electric Corporation). At 550°F 1/2 T, 1 T and 4 T compact tension specimens have been tested. A plot of normalized load deflection curves are shown in Fig. 2. Again we note the same behavior as exhibited in Fig. 1. One may conclude that had one been able to obtain and test a very thick specimen (say 50 in. thick or

Fig. 1. Normalized Load Deflection Curves to Maximum Load for a Series of Compact Tension Specimens Tested at 50°F and 75°F (only for the 1/2 T specimen was a correction made for the displacement gage length).

Fig. 2. Load-Displacement Curves to Maximum Load for a Series of Compact Tension Specimens Tested at 550°F (only for the 1/2 T specimen was a correction made for the displacement gage length).

greater of exactly the same material) the fracture toughness K_{Ic} would have been determined.

Loss^{7,8} has discussed the behavior of the dynamic tear specimens in terms of saturation of energy density. Figure 3 depicts the behavior for the upper shelf temperature region of around 200°F. Again we note a divergence from geometric similitude as thickness increases.

Witt and Berggren^{9,10} have interpreted the dynamic tear data for the A 533, grade B, class 1 steel [HSST plate 01, identified as 12 in. CLASS 1 PLATE (RW) in Fig. 3] on the basis of size effects in energy absorbing capacity (volumetric energy ratio at a given temperature). In Fig. 4 the interpretation is presented. The conclusion agrees with that of Loss in that the behavior in terms of energy diverges from geometric similitude as thickness increases.

Finally Mager¹¹ has reported upper shelf fracture toughness for a higher strength forging grade steel. In this case however the testing of smaller specimens was not performed.

The question of crack extension prior to maximum load may be raised. If such crack growth occurred it would tend to discount to a degree the application of the laws of similitude at maximum load. However for the monotonically increasing loads as applied in the testing of compact tension specimens, the engineers performing the tests are reported to have observed no such growth prior to maximum load on any specimens so far tested. Observations for such crack extensions will be made on the specimens to be tested as identified above.

The expression "divergence from geometric similitude as thickness increases" has been used several times in the above discussion. We may ask what then is meant here? Let us consider then the behavior depicted in Fig. 1 as applied to shelf temperature. If the decrease in load as a function of thickness approaches a limit then as this limit is approached two geometrically similar specimens would approach geometrically similar behavior in energy-absorbing capacity. This means that in Fig. 3 the trend line for the class 1 plate material would eventually converge on the curve depicting geometric similitude. In a similar manner in Fig. 4 we would find the size effect curve approaching a horizontal line. In both of these situations we see that the specimen behavior as a function

Fig. 3. Comparison of Upper Shelf Energy Densities of A 533 and A 302, Grade B Steels from Various Size Dynamic-Tear Specimens (Refs. 7 and 8).

Fig. 4. Size Effects on Energy-Absorbing Capacity of Impact Specimens Tested at Upper Shelf Temperature (Refs. 9 and 10).

of thickness is tending toward geometric similitude; that is, the specimen behavior in a relative sense improves as thickness increases. This behavior is totally incongruous to the observed behavior. We conclude then that the specimens as a function of increasing thickness will never behave, even in the limit, in a geometrically similar manner.

If one accepts the discussion thus far presented in this section, then it necessarily follows that frangible behavior satisfying the condition for calculating K_{IC} will eventually occur as thickness increases. If this does not occur then we are back to the discussion of the above paragraph.

One may raise the question of whether the inverse square root relationship as defined by linear elastic fracture mechanics still holds for the projected frangible behavior obtained at high temperatures from very thick specimens. It is not the intent to pursue this point except to note that the behavior discussed here is simply a generalization of the results presented in Fig. 1 to higher temperatures. Perhaps it is well to note that the equivalent energy method as discussed in Paper No. 12 of this conference does not depend in general on the behavior projected for very thick compact tension specimens.

On the basis of this discussion we conclude that K_{IC} exists for the ASTM A 533, grade B, class 1 steel (even though possibly not obtainable) at all temperatures of interest, in particular up to the operating temperatures of water reactor pressure vessels.

THE FRACTURE TOUGHNESS PARAMETER K_{Icd}

In Paper No. 12 of this conference a fracture toughness parameter K_{Icd} is defined. Further, Witt and Mager⁴ have presented such values obtained from 1 T compact tension specimens up to 550°F. We shall review the manner in which this parameter is calculated and its relationship to fracture toughness K_{IC} .

First let us assume a compact tension specimen of thickness "d" has been tested at some temperature which does not produce K_{IC} . Let us take the curve in Fig. 5 as an example. Here we have the load displacement curve obtained from a longitudinally oriented 1 T compact tension

Fig. 5. Load-Displacement Curve of a 1 T Compact Tension Specimen Tested at 250°F (Ref. 4).

specimen (non-surface material) of ASTM A 533, grade B, class 1 steel tested at 250°F (see Ref. 4). For this discussion however the specifics of the test conditions are immaterial. The maximum load was obtained at Point A. We now ask how many times thicker than the thickness d of the specimen tested would a specimen have to be to reach maximum load at Point D on the linear portion of the curve. It is not at this time obvious that K_{IC} would be found for the specimen failing at Point D. (Later we shall see that for calculating K_{ICd} it is immaterial where Point D is selected as long as it is on the linear portion of the curve.) If we know how thick the specimen would have to be to fail at Point D then we could calculate K_Q and check to see if it were K_{IC} as outlined in Ref. 6. Since we do not know the thickness then we use the one quantity we do know, the volumetric energy ratio between the specimen which would reach maximum load at Point D and the specimen tested with maximum load at Point A. This number is simply the area under the curve to Point A divided by the area under the curve to Point D. Let us call this ratio "b". We now calculate K_{ICd} by simply calculating K_Q for a specimen of thickness "bd" which is assumed to fail at Point D at a load of P_{Q1} normalized to the specimen of thickness d . From Ref. 6

$$K_Q = \frac{P_Q f\left(\frac{a}{w}\right)}{B \sqrt{w}} \quad (1)$$

where P_Q is the load on the specimen at fracture, a is the crack length, w is the width and B is the thickness. For the case at hand then $P_Q = P_{Q1} \cdot b^2$, $B = bd$ and $w = 2bd$. Thus

$$K_{ICd} = \frac{P_{Q1} \sqrt{b} f\left(\frac{a}{w}\right)}{d \sqrt{2d}} \quad (2)$$

In Ref. 4 Witt and Mager have presented K_{IC1} data (K_{ICd} for $d = 1$) for compact tension specimens up to 550°F for nonsurface material oriented longitudinally. Mager has also obtained data from 1/2 T specimens over the same temperature range. A plot of the 1 T results given in Ref. 4 is shown in Fig. 6. (Later we shall see that these data are lower bounds for K_{IC} .)

Fig. 6. Variations of K_{Ic1} as a Function of Temperature for Longitudinally Oriented Compact Tension Specimens Obtained From Nonsurface Material of an ASTM A 533, Grade B, Class 1 12-in.-Thick Plate (Ref. 4).

We now ask how K_{Icd} calculated by Eq. (2) differs from K_{Ic} . First let us see if the selection of Point D has affected the calculation. We shall use the notation $E()$ to indicate the area under the curve up to Point () (for example, E_D is the area under the curve up to Point D). In Fig. 5 we now select Point F other than Point D, on the linear portion of the curve which gives a load of P_{Q2} . Let us define $E_A/E_F = e$ (note that $E_A/E_D = b$). Using Point F to calculate K_{Icd} we have

$$K_{Icd} = \frac{P_{Q2} \sqrt{e} f\left(\frac{a}{w}\right)}{d \sqrt{2d}} . \quad (3)$$

However $E_D/E_F = E_D/E_A \cdot E_A/E_F = e/b$ and from similar triangles, $E_D/E_F = (P_{Q1}/P_{Q2})^2$. Thus $P_{Q1} \sqrt{b} = P_{Q2} \sqrt{e}$ and Eqs. (2) and (3) are identical. Hence we see we can choose any point on the linear portion of the curve and obtain the same value for K_{Icd} .

We shall now derive the relationship between K_{Icd} and K_{Ic} . Let us assume that a specimen of thickness t would fail at Point D and give K_{Ic} . In this case the specimen is t/d times thicker than the specimen of thickness d which was tested; in particular, the load P_{Q1} must be multiplied by $(t/d)^2$ to give P_Q . Thus

$$K_{Ic} = \frac{P_{Q1} \cdot \sqrt{\frac{t}{d}} f\left(\frac{a}{w}\right)}{d \sqrt{2d}} . \quad (4)$$

We note that Eq. (4) differs from Eq. (2) by the factor $\sqrt{\frac{t/d}{b}}$. Now t/d is the ratio of the dimensions and b is the volumetric energy ratio between the specimens (that is, $b = E_A/E_D$). Thus we have

$$K_{Ic} = K_{Icd} \sqrt{\frac{\text{ratio of dimensions}}{\text{volumetric energy ratio}}} \quad (5)$$

where the thicker specimen gives K_{Ic} . Thus for the case where K_{Ic} is unobtainable perhaps due to restrictions on thickness we can obtain K_{Icd} from a smaller specimen which can be tested and at least speculate how the ratio under the radical in Eq. (5) varies.

While we have focused our attention on how K_{Ic} is related to K_{Icd} it is perhaps well to generalize Eq. (5) by noting that for a specimen of thickness p (see Paper No. 12 of this conference)

$$K_{Icp} = K_{Icd} \cdot \sqrt{\frac{r_{p,d}}{s_{d,p}}} \quad (6)$$

where $r_{p,d}$ is the ratio of dimensions, p/d , and $s_{d,p}$ is the volumetric energy ratio between the specimen of thickness d and the one of thickness p .^{*}

THE METHOD FOR CALCULATING BOUNDS ON K_{Ic}

It is the object here to use the concepts thus far presented to propose a method for calculating upper and lower bounds on K_{Ic} at a given temperature and orientation of interest. To do this we need only to consider Eqs. (5) and/or (6). In particular we need only to characterize the behavior of the quantity under the radicals; that is, $r_{p,d}/s_{d,p}$, the ratio of the dimensions of two geometrically compact tension specimens divided by the volumetric energy ratio between them.

One could postulate the characteristics of the pertinent ratio; however, since considerable research is in progress it is perhaps simpler to discuss the data at hand. In Fig. 7 we have plotted the volumetric energy ratio versus thickness at three temperatures with the data at each temperature normalized to a 1 T specimen at the particular temperature. Data have also been obtained for 1/2 T and 1 T specimens up to 550°F (see Fig. 6 for the 1 T data). As noted previously, 6 T and 9 T specimens are currently scheduled for testing. As may be noted in Fig. 7 for the 550°F data and for almost all the data thus far obtained, the volumetric energy ratios from smaller to larger specimens have always been less than the ratios of the dimension. The exceptions have been in the cases where the volumetric energy ratios were about equal to the ratios of the

* These double subscripted quantities are ratios; the first subscript denotes the numerator quantity, the second, the denominator quantity.

Fig. 7. Plot of Volumetric Energy Ratio Curves versus Thickness at 50°F, 75°F and 550°F.

dimensions, such as we have at 50°F and 75°F in Fig. 7. Here however the variations are well within the variation range generally observed for K_{Ic} . Thus we conclude in general that

$$\frac{r_{p,d}}{s_{d,p}} \geq 1. \quad (7)$$

From Eq. (5) we may now claim that in general

$$K_{Ic} \geq K_{Icd} \quad (8)$$

for all d . (Note: For reasons discussed in Refs. 9 and 10 we would select the lower limit on d to be about 0.25 in.)

Assuming the 550°F data shown in Fig. 7 is typical of the general behavior we also note that a straight line connecting the points for any two thicknesses falls below the point for a still greater thickness. Thus we can tentatively conclude that the linear extension of a line connecting the points for any two thicknesses will always produce a result which is nonconservative; that is, the linear extension gives a tougher behavior than actually observed for thicker specimens. Thus, with $(t, s_{d,t})$ being a point on the linear extension, the $\lim_{t \rightarrow \infty} r_{t,d}/s_{d,t}$ when substituted into Eq. (5) will always give an upper bound on K_{Ic} regardless of what thickness is required to obtain K_{Ic} , that is

$$K_{Ic} \leq K_{Icd} \lim_{t \rightarrow \infty} \sqrt{\frac{r_{t,d}}{s_{d,t}}} \quad (9)$$

If two geometrically similar compact tension specimens then are tested at the same temperatures with d the thickness of the smaller and p the thickness of the larger, and with a volumetric energy ratio of $s_{d,p}$, we can determine the limit in Eq. (9) directly. By normalizing the data to the specimen of thickness d we have

$$\lim_{t \rightarrow \infty} \sqrt{\frac{r_{t,d}}{s_{d,t}}} = \sqrt{\frac{(p-d)}{d(s_{d,p}-1)}} \quad (10)$$

and Eq. (9) becomes

$$K_{Ic} \leq K_{Icd} \sqrt{\frac{p-d}{d(s_{d,p}-1)}} \quad (11)$$

For $d = 1$

$$K_{Ic} \leq K_{Ic1} \sqrt{\frac{p-1}{s_{1,p}-1}} \quad (12)$$

In summary

$$K_{Icp} \leq K_{Ic} \leq K_{Icd} \sqrt{\frac{p-d}{d(s_{d,p}-1)}} \quad , \quad p > d \quad , \quad (13)$$

where p and d are thicknesses of geometrically similar compact tension specimens.

Using K_{Icd} as a lower bound for K_{Ic} is equivalent to assuming the specimen from which the number was obtained exhibits frangible behavior. Under this assumption the slope of the line becomes $s_{1,d}/d$ for greater thickness and goes through $(0,0)$. Note that in Fig. 7, in most cases, the point for a greater thickness always lies below the linear extension of a line through $(0,0)$ and the point for any lesser thickness.

A more sophisticated approach to the above discussion would be to assume monotonic convergence to frangibility or divergence from similitude and derive the pertinent relationships; thus, using the data to show the assumption was correct. The author chose not to present such an analysis in this paper.

We now ask why calculate K_{Icd} as a lower limit, why not just take K_Q (see Ref. 6) as obtained perhaps from the load at deviation from linearity, or the secant offset load or the ultimate load. There are several reasons for using K_{Icd} . First, as presented by Witt and Mager,⁴ and reproduced in Table 1 of this paper, we see that we establish a much higher lower bound in the transitional and tough regions than obtained by using the loads suggested above. Secondly, if one knows with confidence the volumetric energy ratio for the condition of interest, perhaps

Table 1. Fracture Toughness Results and Volumetric Energy Ratios Determined from Testing Compact Tension Specimens up to 550°F

Specimen Number	Test Temperature (°F)	Crack Length (in.)	Some Fracture Toughness Parameters (ksi $\sqrt{\text{in.}}$)				K _{Icd} (from Front-Face Displacement) (ksi $\sqrt{\text{in.}}$)	K _{Icd} (from Surface COD) (ksi $\sqrt{\text{in.}}$)	Volumetric Energy Ratio ^e
			KD ^a	KQ ^b	KUC ^c	KFD ^d			
HS2-7-C10	-50	1.022	43.1	58.2	63.6	7.2	61.0		28.7
HS2-7-C8	0	1.010	37.0	46.9	73.9	7.1	76.0	80.6	17.8
HS2-7-C7	25	1.016	41.4	63.6	84.7	7.1	96.0	102.0	11.3
HS2-7-C3	50	1.010	61.6	91.7	97.6	7.0	128.0		6.2
HS2-7-C12	75	1.032	67.5	93.1	103.8	7.3	176.5	194.0	3.3
HS2-28-C5	75	1.029	49.2	61.5	99.5	16.6	143.5		5.0
HS2-28-C10	90	1.027	55.5	66.5	100.5	17.0	203.0		2.5
HS2-28-C2	103	1.024	35.9	56.0	103.4	16.5	184.0		3.0
HS2-7-C5	125	1.034	54.8	89.7	107.5	7.4	312.0	331.0	1.1
HS2-7-C2	150	1.026	55.1	87.1	106.3	7.3	276.0	283.0	1.3
HS2-28-C4	150	1.020	39.0	52.4	106.3	16.3	293.0		1.2
HS2-7-C9	180	1.024	42.0	81.3	105.7	7.3	321.0		1.0
HS2-28-C9	200	1.025	46.3	57.9	104.2	16.6	283.0		1.3
HS2-7-C4	250	1.018	42.4	82.0	105.4	7.1	282.0	338.0	1.3
HS2-7-C11	250	1.016	60.5	85.8	105.8	7.0	269.0	341.0	1.4
HS2-7-C1	350	1.016	62.5	79.6	99.6	7.1	237.0	287.0	1.8
HS2-28-C1	448	1.019	57.0	59.0	104.1	16.5	234.0		1.9
HS2-7-C6	550	1.022	63.5	80.1	96.4	7.2	204.0	212.0	2.5
HS2-28-C8	550	1.014	51.8	69.0	102.5	16.3	206.0		2.4
HS2-7-4D ^f	550	4.149	103.6	145.4	193.6	9.1	256.0		6.2

^aFracture toughness at deviation from linearity in load-displacement curve.

^bFracture toughness at secant offset load.

^cFracture toughness at ultimate load.

^dFracture toughness intensity during fatigue precracking.

^eThis value is normalized to the 1 T specimen tested at 180°F for front-face displacement results only. (See Paper 12; also Refs. 3 and 4 for discussion of volumetric energy ratios.)

^fAll these specimens were 1 T compact tension specimens except this one specimen which was a 4 T compact tension specimen.

obtained from other specimens, then only a single specimen needs to be tested. Thirdly, the K_{Icd} values obtained from compact tension specimens, used in conjunction with the pertinent volumetric energy ratios, have potential applications in rather general equivalent energy fracture calculations (see Paper No. 24 of this conference).

THE CONCEPT OF POSITIVE AND NEGATIVE MATERIALS

Looking at Eq. (7), we note that for the equality, one of the conditions for frangible behavior for two geometrically similar specimens has been met. Indeed the equality has not been observed for other than frangible or near frangible behaviors. (Note: As seen in Fig. 7, the equality is rather closely approximated by all the specimens for thicknesses greater than 1 in. tested at 50°F and 75°F.) One now asks if a situation could exist such that

$$\frac{r_{p,d}}{s_{d,p}} \leq 1 \quad (14)$$

with the equality holding for frangible behavior. The inequality would hold, if at all, then for transitional and tough behavior. In the context of this discussion we are asking if "conditions worse than frangible can exist." This is a legitimate question since what we are really asking is "for tough and transitional behaviors is the toughness of the material such that the degrading effects of increasing thickness exceed the thickness increase?" There are scattered data to indicate that some high strength steels and irradiated A 533 steel may exhibit just this behavior. In this case we find the bounding procedure reversed. That is, referring to Eq. (13)

$$K_{Icd} \sqrt{\frac{p-d}{d(s_{d,p}-1)}} \leq K_{Ic} \leq K_{Icp}, \quad p > d. \quad (15)$$

For purposes of discussion we shall define a material as being "positive" if

$$\frac{r_{p,d}}{s_{d,p}} \geq 1, p > d, \quad (16)$$

and "negative" if

$$\frac{r_{p,d}}{s_{d,p}} \leq 1, p > d. \quad (17)$$

Conceptually these definitions are sketched in Fig. 8. Here we see volumetric energy ratio versus thickness sketched normalized to a 1 T specimen. The line for a positive material exhibits a clockwise (positive) rotation from the 45° line (line representing frangible behavior) while a negative material produces a counterclockwise (negative) rotation. For frangible behavior, the material is both positive and negative.

We might inquire if at a given temperature a material may exhibit both positive and negative behavior. For the specimens of A 533 steel tested to date no such behavior has been exhibited. To exhibit both behaviors implies that, for some intermediate thickness, $r_{p,d} = s_{d,p}$ which is one of the conditions for frangible behavior. Once reaching the equality in behavior, then, as thickness increases, deviating to the opposite inequality and trending toward equality again for frangible behavior is, to say the least, a rather "awkward" behavior.

The existence of negative materials is being further explored and some careful tests will be run. The bounding methods discussed in this paper will be much more meaningful and useful if negative materials, other than frangible, do not exist.

EXAMPLE OF CALCULATING BOUNDS ON K_{Ic}

Two examples will be presented in this section. We shall first calculate the bound on K_{Ic} at 550°F from results on 1 T and 4 T specimens. Using the curve for the 4 T specimen in Fig. 2, we calculate $K_{Ic4} = 256,000 \text{ psi} \sqrt{\text{in.}}$ which is the lower bound. K_{Ic1} calculated from Fig. 2 is $204,000 \text{ psi} \sqrt{\text{in.}}$. The volumetric energy ratio $s_{1,4}$ is 2.54. Using

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Fig. 8. Sketch Showing How Thickness and Volumetric Energy Ratio Vary for Positive and Negative Materials.

Eq. (13) we have

$$256,000 \leq K_{Ic} \leq 204,000 \sqrt{\frac{4-1}{2.54-1}} = 286,000 .$$

Thus, K_{Ic} is bracketed between 256,000 and 286,000 psi $\sqrt{\text{in.}}$

We shall now obtain bound on K_{Ic} at 200°F. The largest compact tension specimen tested at this temperature was 1 in. thick and it gave 283,000 psi $\sqrt{\text{in.}}$ However, up to 12-in.-thick dynamic tear specimens have been tested as reported by Loss.⁸ From those results Witt and Berggren^{9,10} obtained the size effect curve (volumetric energy ratio curve at a given temperature) shown in Fig. 4. We shall for the present assume these data are applicable to compact tension specimens. To obtain conservative results we shall use the upper bound of these data for a thickness of 12 in. to calculate the lower bound for K_{Ic} and the lower bound to calculate the upper bound for K_{Ic} . For a thickness of 12 in., the upper bound volumetric energy ratio is about 5.3. Thus, using Eq. (6)

$$K_{Ic12} = K_{Ic1} \cdot \sqrt{\frac{r_{12,1}}{s_{1,12}}} = 283,000 \cdot \sqrt{\frac{12}{5.3}} .$$

This gives a lower bound of 425,000 psi $\sqrt{\text{in.}}$ For the upper bound we use $s_{1,12} = 4.3$, thus

$$K_{Ic} \leq 283,000 \cdot \sqrt{\frac{12-1}{4.3-1}} = 515,000 \text{ psi } \sqrt{\text{in.}} .$$

Here we have bracketed the fracture toughness between 425,000 psi $\sqrt{\text{in.}}$ and 515,000 psi $\sqrt{\text{in.}}$

The noticeable reduction (80 to 100%) in fracture toughness at 550°F when compared to that at 200°F is consistent with the results presented in Ref. 4 (see Fig. 6).

Perhaps it is interesting to note that a specimen over 100 in. thick would be required to obtain a K_{Ic} at 200°F. At 550°F the thickness is around 50 in.

POTENTIAL APPLICATIONS

At least three potential applications for calculating upper and lower bounds fracture toughness values exist. These are discussed below.

Application to Unirradiated Materials

As demonstrated in the previous section rather tight bounds can be established on K_{Ic} up to 550°F. The establishment of such bounds for both longitudinal and transverse orientations from 1 T, 6 T, and 9 T specimens is currently in progress. In addition, these data will provide quantitative fracture characterizations at higher temperatures and will serve to compare volumetric energy ratios obtained from compact tension specimens with those obtained from the large flawed tensile specimens (see Paper No. 22 of this conference) and the flawed pressure vessels (see Papers No. 4 and 25 of this conference).

Application to the Irradiation Effects Investigations

In order to obtain K_{Ic} for irradiated A 533 pressure vessel steel at temperatures approaching service conditions (200°F to 550°F) it is necessary to irradiate specimens 4 in. thick and greater (see Paper No. 18 of this conference). Serious technical problems arise because of reactor space, fluence gradients and gamma heating. Scheduling is difficult and the expense per specimen is quite high. These factors tend to limit both the number of specimens which can be irradiated as well as confound somewhat the fracture toughness values obtained. However, from broken halves of 4 T specimens (10 in. long by 4.8 in. wide by 4 in. thick) a large number of smaller specimens can be machined and tested. Proper control of the experimental variables must be maintained however as discussed in Paper No. 14 of this conference. Many 1/2 T and 1 T specimens (also some 2 T specimens) can then be tested to establish the bounds on K_{Ic} from the highest temperature at which K_{Ic} is obtained up to 550°F and even above. Based on the bounds calculated in the previous section, more attention must be given to operating temperature fracture toughness than anticipated at the inception of the HSST program.

Application to Reactor Surveillance Programs

In the main, current plans call for using Charpy V-notch impact specimens as surveillance specimens in operating reactors. After removing such specimens from a reactor and testing them one would hope then to correlate such impact data with fracture toughness such that quantitative margins of safety may be determined for the existing or postulated conditions. One such correlation study is reported in Paper No. 3 of this conference. However, as demonstrated by Berggren,¹³ a greater proportion of the measured impact energy is absorbed after maximum load as toughness increases. In particular, neither the Charpy V-notch nor dynamic tear data⁸ exhibit the decrease in toughness at 550°F as shown in the previous section. We see then that no correlation may be entirely satisfactory over the whole temperature and toughness ranges. Hence, impact type surveillance specimens may not be entirely suitable if quantitative fracture calculations are desirable.

Two alternatives exist. If one or two compact tension specimens of thickness 0.394 in. say (Charpy specimen thickness) are included as part of the surveillance program, then the establishment of quantitative fracture toughness lower bound values have a good chance of being obtained. The Charpy specimens would be tested however on an instrumented Charpy machine so that energy to maximum load could be established at all test temperatures. From this a volumetric energy ratio curve could be obtained which, after some confirming research, would probably be the same as for the small compact tension specimen(s). One tests the compact tension specimen(s) at some temperature (a shelf temperature would probably be used so as to discount the notch effect on Charpy specimens) and uses the volumetric energy ratio curve to calculate $K_{Ic}(0.394)$ at the temperatures at which the Charpy specimens were tested. If such values taken as lower bound for K_{Ic} are sufficiently high then the desired fracture calculations may be performed. If the values are questionably low then perhaps adequate volumetric energy ratio curves as a function of fluence and temperature could be obtained from the current HSST related irradiation effects studies. Hence, K_{Icd} values could be calculated for greater thicknesses than 0.394 in. In this method the effect

of the V-notch in the Charpy specimen must be thoroughly explored if volumetric energy ratio curves applicable to the compact tension results are to be satisfactory.

The second alternative is to use several small compact tension specimens (for instance, a 0.394 in. thick impact tension specimen occupies about the same space as a Charpy specimen). This way the K_{Icd} values are determined directly. If necessary, larger specimens (1 T say) could be part of the surveillance program but would severely reduce the number of specimens in a particular size surveillance capsule. These larger specimens could be used to increase the bound on K_{Ic} .

The effectiveness of such a surveillance program as suggested above would be severely hampered if the irradiated material were negative material. As noted before the bounds are reversed in this case. Thus only upper bounds would be calculated directly. With the restriction on size, unrealistically low lower bounds may be calculated by the limiting process described previously.

In the above context Mager has obtained $K_{Ic(1/2)}$ values (longitudinal orientation, center material, for a fluence of 5×10^{19} n/cm², $E > 1$ Mev irradiated at 550°F) of 125,000 psi $\sqrt{\text{in.}}$ tested at 550°F. This value is significant whether the material is positive or negative. That is, if the material is positive then the value is a lower bound and significantly large safety margins exist. On the other hand, if the material is negative, the number is an upper bound and one is faced with finding quantitatively the actual value or a realistic lower bound.

CONCLUSION

The need to obtain fracture toughness K_{Ic} (or perhaps just K_{Icd}) throughout the operating temperature range of nuclear reactors, especially for irradiated conditions, is becoming apparent. This paper has been written in response to this need. Certain portions are somewhat speculative because the necessary backup investigations have not yet been completed. However, the indications from research completed do firmly support the position set forth in this discussion.

The existence of K_{Ic} is discussed. Data are presented from which it is concluded that if specimens of sufficient thicknesses could be tested then the fracture toughness K_{Ic} could be obtained. Since specimens in such thicknesses cannot be obtained, a procedure for finding upper and lower bound values on K_{Ic} from testing smaller specimens is suggested. The procedure applies the equivalent energy method using the fracture toughness parameter K_{Icd} . In particular, it is shown that K_{Ic} is equal to K_{Icd} times the square root of the ratio of dimensions divided by the volumetric energy ratio. By characterizing the pertinent ratio it is shown that both the upper and lower bounds on K_{Ic} can be obtained by testing two geometrically similar but different thickness compact tension specimens. Data to provide further verification of the assumed behavior is currently being obtained.

The concept of positive and negative materials is introduced to better define the transitional and tough behavior of the steel. The existence of negative materials has not been established. However, some data suggest that such behavior may occur.

Upper and lower bounds on K_{Ic} for unirradiated ASTM A 533, grade B, class 1 plate, longitudinal orientation, are calculated at 200°F and 550°F. By assuming volumetric energy ratios from dynamic tear specimens apply to compact tension specimens, K_{Ic} is shown to be between 425,000 and 515,000 psi $\sqrt{\text{in.}}$ at 200°F. Using 1 T and 4 T results from compact tension specimens tested at 550°F, K_{Ic} is shown to be between 256,000 and 286,000 psi $\sqrt{\text{in.}}$ The average difference in K_{Ic} of almost 100% at these two temperatures is consistent with previously reported toughness trends in this temperature interval.

Three potential and immediate applications are discussed. They are (1) obtain bounds on K_{Ic} for unirradiated steel up to 550°F, (2) obtain bounds on K_{Ic} for irradiated steel up to 550°F, and (3) use some Charpy thickness compact tension specimens as reactor surveillance specimens so as to establish lower bound toughness values for in-service conditions.

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