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Crack Arrest Fracture Toughness of a Structural Steel (A36)

A toughness parameter identified as K_a is developed for calculating critical crack sizes in weldments made of ferrite-pearlite steels used for bridges and ships

BY E. J. RIPLING AND P. B. CROSLEY

ABSTRACT. In most structures, cracks that initiate from a pre-existing crack-like defect lead to catastrophic fracture. Weldments are unique in this respect, however, in that the pre-existing defects are almost always associated with the weld or heat-affected zone, while most of the structure consists of base metal. Hence, prevention of crack initiation continues to be important in the weld and heat-affected zone, but the most important fracture property of the base metal is its ability to arrest a fast propagating crack that initiated in the weld.

In the past five or more years, it has been shown that plane strain crack arrest fracture toughness K_{Ia} is a material property that can be used to predict the performance of thick-walled structures. This suggests that the use of a similar parameter might be used to calculate critical crack sizes in weldments made of ferrite-pearlite steels. Hence, the test method developed for K_{Ia} testing was used to test full thickness specimens of 50.8 mm (2 in.) and 25.4 mm (1 in.) A36 steel over a range of temperatures that might be experienced in service. Since the stress state in these tests is dictated by the section thickness, and may or may not be one of plane strain, the toughness parameter is identified as K_a, rather than K_{Ia}.

It was found that at temperatures from −50°C (−58°F) to room temperature or slightly above, the steel fractured by cleavage. In spite of this brittle fracture appearance, the values of K_a were relatively high, ranging from about 55 to 170 MPa-m$^{1/2}$ (50 to 155 ksi-in.$^{1/2}$). This range of toughnesses means that the critical flaw size may vary by a factor of about 1:10 without a change in fracture appearance. These K_a values are far higher than would have been estimated from the published values of the toughness for A36 steel.

Introduction

It is generally accepted that fractures in service occur by the extension of pre-existing flaws. In weldments, these flaws or flaw-like defects are almost always associated with the weld, seldom with the base metal. Hence, cracks are expected to initiate in the weld or HAZ and propagate into the base metal. In the course of extending from the weld to the base metal, the crack attains a high velocity so the most important fracture property of the base metal is its ability to arrest such a running crack. This requirement was recognized at least three decades ago. In 1953, Robertson introduced the first widely accepted test for measuring the crack arresting capability of low and intermediate strength steels of the type used in welded structures (Ref. 1). Modifications of his test have been adopted as standards in Great Britain, Japan and the United States (Ref. 2).

By far the most commonly used crack arrest test, at present, is the Pellini-Puzak Drop Weight Test (DWT) described in ASTM Test Method E208 (Ref. 3). In spite of the fact that this is seldom thought of as an arrest test, the method requires that a crack be initiated in a brittle weld that is placed on the tensile side of a three-point bend bar. The test is a pass-or-fail type, and the test is said to "pass" if the initiated crack arrests before it extends to the specimen's corners.

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Both the Robertson test, with or without its modifications, and the DWT measure a transition temperature—the former by plotting the fracture stress as a function of temperature, and the latter by identifying the Nil-Ductility-Transition (NDT) temperature of the steel. Neither of these tests was designed to relate stresses and critical crack sizes with a measured material property, although Pellini has proposed a method for estimating critical crack sizes by indexing steels with respect to their NDT and yield strength (Ref. 4). His method has the advantage of being very inexpensive and convenient, but it is based on the assumption that all toughness vs. temperature curves are similar.

More recently, test methods have been developed for measuring the value of the stress intensity factor, K_{Ia}, at which a crack extending in plane strain will arrest. Defining crack arrest capability in terms of a fracture mechanics parameter has obvious advantages in that it allows one to calculate the length at which a running crack will arrest when it extends from a high to a low stress field, or from a less tough to a more tough region.

Despite the fact that there is as yet no ASTM standard test method for K_{Ia} testing, the presently used method has been intensely evaluated on the intermediate strength steels, A533B and A508. It has been shown that K_{Ia} is specimen-insensitive, i.e., it is independent of both the type of specimen used to measure it, and the magnitude of the driving force used to initiate the crack (Ref. 5). In a series of

Table 1—Mechanical Properties and Chemical Analysis of A36 Steel

Plate thickness		Yield Point		Tensile strength		Elongation in	Elongation in					
mm	(in.)	MPa	(ksi)	MPa	(ksi)	200 mm, %	50 mm, %	C, %	Mn, %	P, %	S, %	Si, %
						Supplied by mill						
25.4	(1)	283	(41.1)	486	(70.5)	27	—	0.24	1.07	0.010	0.029	—
50.8	(2)	270	(39.1)	498	(72.2)	27	—	0.21	0.99	0.020	0.025	0.212
						ASTM requirements						
25.4	(1)	250 min.	(36)	400-550	(58-80)	20	23	0.25 max.	0.80-1.20	0.04 max.	0.05 max.	—
50.8	(2)	250 min.	(36)	400-500	(58-80)	20	23	0.26 max.	0.80-1.20	0.04 max.	0.05 max.	0.15-0.40
						Plate						
25.4	(1)	243	(35.3)	465	(67.5)	—	31.6	0.23	1.06	0.011	0.021	< 0.05
50.8	(2)	251	(36.4)	498	(72.3)	—	32.2	0.24	0.95	0.016	0.026	0.21

thermal shock tests on 152 mm (6 in.) thick walled cylinders, it was also shown that calculations based on K_{Ia} accurately predicted the location at which rapidly propagating cracks would arrest. In these tests, the inside walls of cylinders, which contained flaws, were rapidly cooled. This produced a thermal gradient through the thickness that, in turn, developed the stress gradient that caused the cracks to initiate in a high stress region, and arrest at a lower stressed region (Ref. 6,7). These thick walled vessel tests, in conjunction with the tests that showed K_{Ia} to be specimen insensitive, have led to a general acceptance of K_{Ia} as a material property (Ref. 6).

Crack toughness parameter K_{Ia} applies specifically to the process of crack arrest. There is no *a priori* reason, then, for K_{Ia} to have any particular relationship to a crack toughness parameter, such as K_{Ic}, which is associated with the onset of crack extension from a pre-existing fatigue crack. Experience has shown, however, that K_{Ia} does define a realistic lower limit to crack initiation toughness measurements, particularly to so-called "dynamic" K_{Ic} measurements obtained at fast loading rates. In engineering applications, then, it appears possible to regard K_{Ia} as a general fracture toughness parameter that may be used to estimate the flaw tolerance of a structure as well as to assess the specific problem of crack arrest.

The success of demonstrating that K_{Ia} is a material property—and especially the ability to calculate running crack jump lengths—suggests that a crack arrest material characterization be applied to lower strength ferrite-pearlite steels of the type used in structures such as bridges and ships. The restrictions placed on testing these materials are expected to be less severe than for K_{Ia} testing of very thick, higher strength structures. For the latter, the specimens generally are far less thick than the structures, so that it was

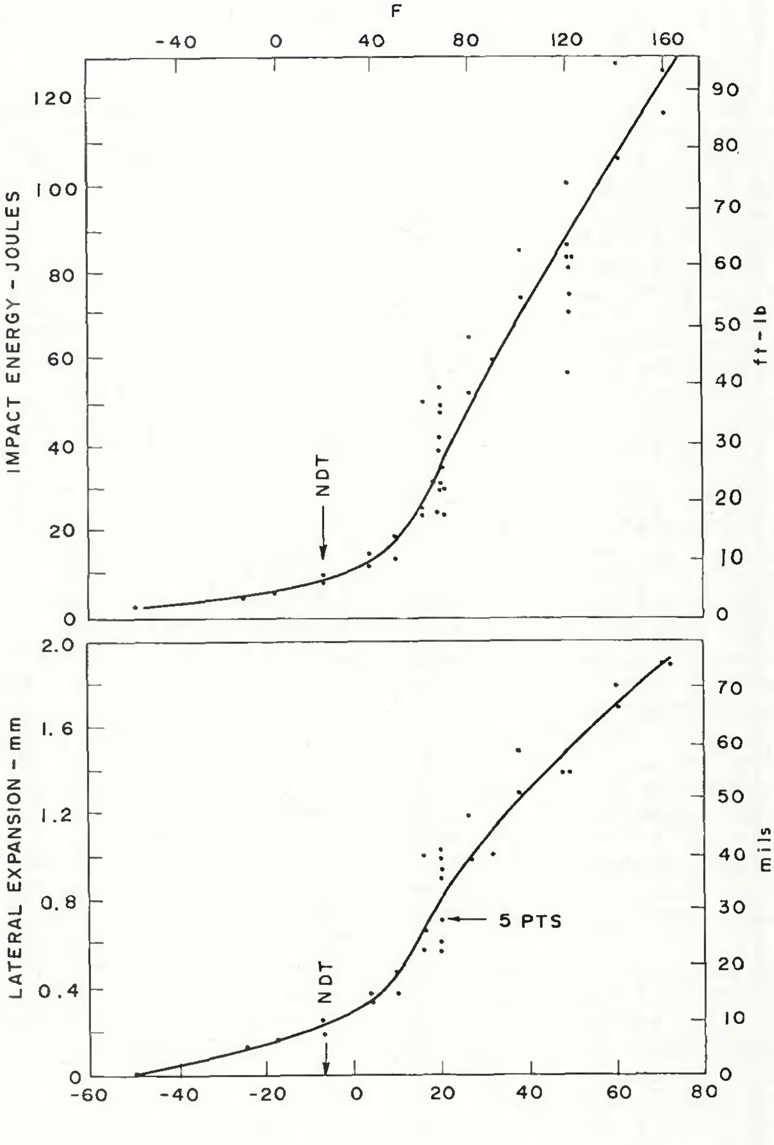

Fig. 1—CVN impact and lateral expansion as a function of testing temperature for 50.8 mm (2 in.) thick A36 steel. L-T direction

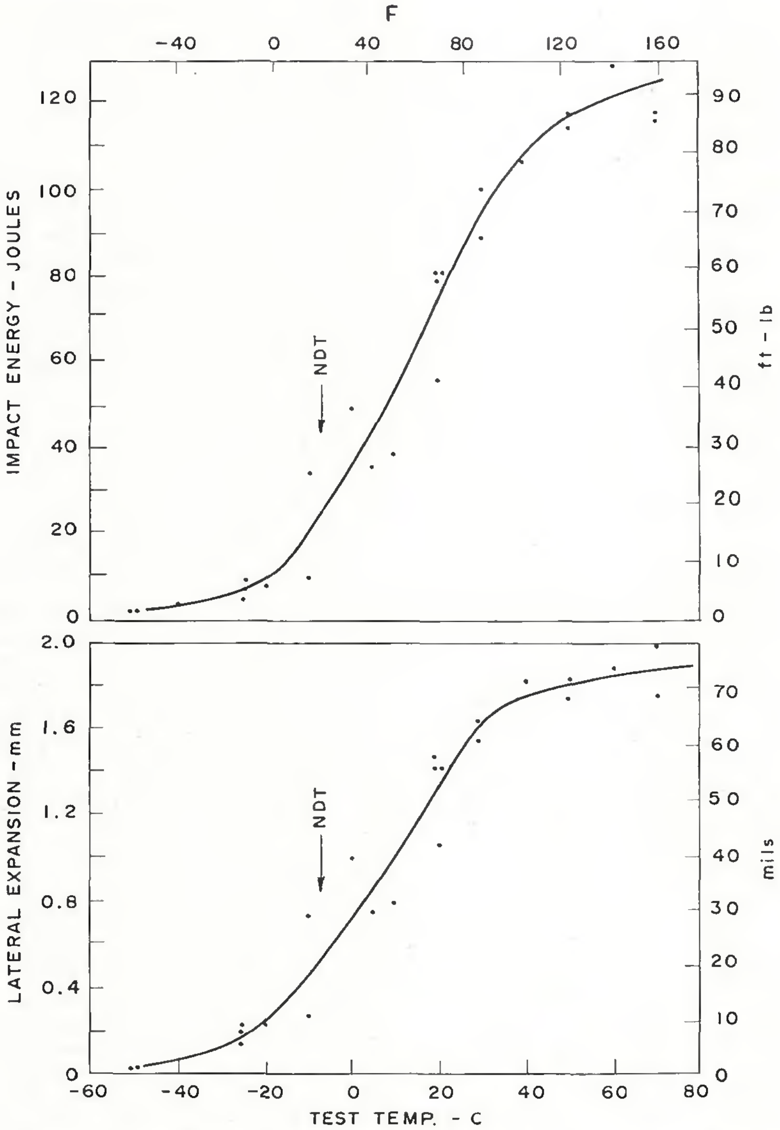

Fig. 2 — CVN impact energy and lateral expansion as a function of testing temperature for 25.5 mm (1 in.) thick A36 steel. L-T direction

essential that the test be designed such that the crack extend in plane strain prior to arresting. Structural steels, on the other hand, are generally used in moderate thicknesses — say less than 75 mm (3 in.); for these, it is convenient to test in full thickness. This not only avoids the need to assure that the crack extends under a condition of plane strain, but is also a more realistic test of the material if the arrest toughness is a function of section thickness.

Tests similar to those used for K_{Ia} evaluation were run on full thickness 25.4 mm (1 in.) and 50.8 mm (2 in.) thick plates of A36 steel. To distinguish these tests from those in which plane strain cracking is assured, they are referred to as "flat" crack tests in this study, and the symbol for the toughness value is K_a. The relationship between K_{Ia} and K_{Ic}, (i.e., that K_{Ia} is the lower limit of initiation toughness of rate sensitive materials, as they are tested more and more rapidly) is also expected to apply to K_a. Specifically, K_a is assumed to be the lowest value of K at which cleavage cracking can occur for a specified test temperature and section thickness.

Material Characterization

Specification Values

Two plates of steel, one 25.4 mm (1 in.) and the other 50.8 mm (2 in.) thick, both certified to be A36, were purchased from a local warehouse. The mechanical properties, chemical analyses supplied by the mill, and the ASTM specification for these values are shown in Table 1. Similar measurements were made at the quarter point of the plates, and these values are also given in Table 1.

DWT and CVN Tests

NDT was measured according to ASTM Test Method E-208, and was found to be −7°C (+20°F) for both plates.

A relatively large number of CVN tests were made on the test plates to get some idea of the uniformity of its toughness, in order to anticipate the expected scatter in K_a. The purchased plates were 2.44 × 0.46 m (8 × 1.5 ft), and CVN specimens were cut from near the plate ends and center. The blanks for the thinner plates were taken at the two thickness quarter-points, which essentially evaluated the full plate thickness. For the thicker plate, both the quarter-points and center were used, in order to evaluate the full plate thickness. The thicker plate was tested only in the L-T direction (Fig. 1), while the thinner one was tested in both the L-T and T-L directions — Figs. 2 and 3.

Despite the fact that the NDT temperatures for the two plates were the same, the CVN temperature curve for the thicker plate is shifted to a temperature about 20°C (35°F) higher than the curve for the thinner plate, when both were tested in the L-T direction.

The toughness scatter in the thicker plate also appears to be greater than that in the thinner one. This was found to result from a systematic difference in toughness through the thickness of the 50.8 mm (2 in.) plate. The latter is shown by the data in Fig. 4, where CVN data collected on specimens cut near the plate surface and center are shown for three testing temperatures. At the two higher temperatures, where the toughness was high, specimens taken near the center of the plate were noticeably tougher than those taken near the surface. At the lower temperature, this difference was not as pronounced, probably because the CVN test is not sensitive to differences at these low levels of toughness.

The occurrence of a tougher center than surface in a plate is unusual. Because of this, the chemical composition, tensile properties, and microstructure were also examined through the thickness. There was no systematic difference in C, Mn, Si, P or S as a function of position. There was a slight difference in yield strength, however, as indicated in Table 2 but not in tensile strength nor ductility. The microstructure did vary with thickness (Fig. 5), the surface being finer grained than the center. The latter variation is uncommon in plate, but this "normal" microstructure is not consistent with the "abnormal" toughness profile.

Test Procedure

Crack arrest fracture toughness tests were made by using the modified compact specimens shown in Fig. 6, and the test procedure described in the literature (Ref. 8). The compliance calibration given previously (Ref. 8) was found to be incorrect so that a more recent, experimentally derived, K expression was used:

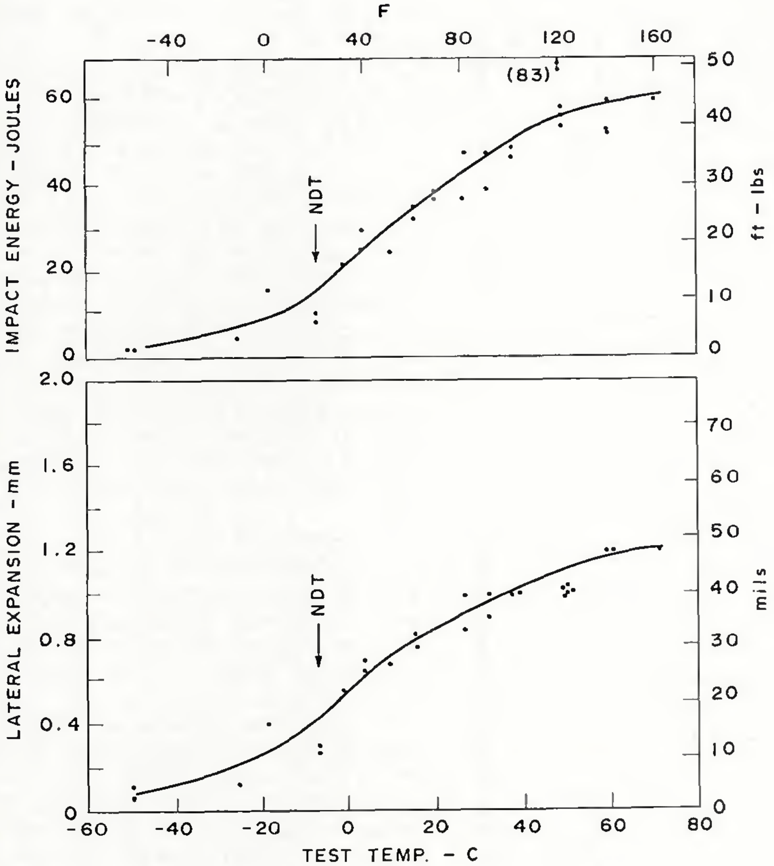

Fig. 3—CVN impact energy and lateral expansion as a function of testing temperature for 25.4 mm (1 in.) thick A36 steel. T-L direction

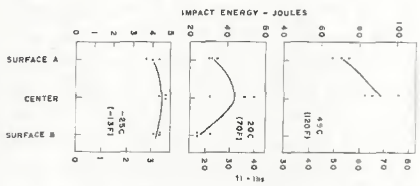

Fig. 4—Through-thickness variation of CVN toughness for 50.8 mm (2 in.) thick plate

$$\frac{K\sqrt{W}}{E\Delta}\left(\frac{B_N}{B}\right)^{1/2} = \frac{2.2434\,(1.7162 - 0.9x + x^2)\sqrt{1-x}}{(9.85 - 0.17x + 11.0x^2)} \quad (1)$$

where w = distance from center of loading hole to end of specimen; E = Young's modulus; Δ = displacement measured at 0.25 W; B_N = net specimen thickness on side-groove plane; B = gross specimen thickness; x = a/W; a = crack length.

The test procedure cited is concerned with the measurement of a plane strain toughness value. This requires that the crack tip plastic zone be small enough, relative to the specimen thickness, to produce a thickness independent K_{Ia} value. The specific size requirements satisfying this condition have not, however, as yet been established.

The aim of the K_a measurements being discussed here is not to produce a plane strain condition at the crack tip. Instead, it is to obtain a toughness measurement characteristic of the thickness being tested. A minimum thickness requirement, therefore, does not exist. There are, nevertheless, two conditions which must be satisfied in order to make a K_a measurement.

1. A "pop-in" must occur. Evaluation of crack extension by stable tearing is outside the intended scope of the K_a methodology.

2. The crack tip plastic zone must be small enough, relative to in-plane specimen dimensions, to preserve the applicability of linear elastic analysis. The limiting dimension is the distance (W − a) from the arrested crack front to the end of the specimen.

Test Results

Tensile Tests

Tensile tests were conducted at 52°C (125°F) on the thicker plate, and at 20, −25 and −50°C (70, −13 and −58°F) for both plates on specimens cut from the quarter-plane in the L-T direction, and at the latter three temperatures for the thinner plate in the T-L direction. From the results shown in Fig. 7 it is apparent that, although the tensile strength of the thicker plate is somewhat higher than that of the thinner one, in general the tensile properties of the two plates are similar.

Toughness Tests

Test Results. Crack arrest fracture toughness tests were conducted on both plates with full thickness specimens from −50°C (−58°F) to room temperature, and at temperatures slightly above for the thick plate. The dependence of K_a on testing temperature for the latter is shown in Fig. 8. The toughness increased in a smooth, continuous fashion over the complete testing range; and over this range, K_a increased by a factor of about three, meaning that the critical flaw size increased almost ten-fold. (The dashed line on Fig. 8 corresponds to plasticity corrected K_a values which are discussed later.)

The maximum temperature at which K_a data could be collected was limited by the onset of ductile tearing. At temperatures about 60°C (110°F) or more above NDT, only ductile tearing occurred. Immediately below this temperature, there was a range of about 15°C (27°F) over which some specimens cracked in

Fig. 5—Microstructure through 50.8 mm (2 in.) plate thickness: A—surface; B—6 mm (0.24 in.) from surface (scratch shows edge of side groove plate); C—23 mm (0.47 in.) from surface; D—center. Nital etch; X62 (reduced 53% on reproduction)

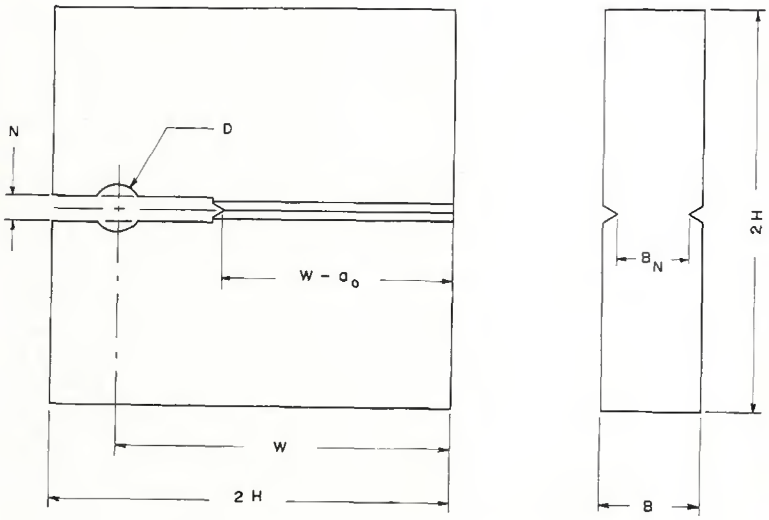

Fig. 6 — MRL crack-arrest test specimen. W = 169.3 mm (6.67 in.); H = 101.6 mm (4.00 in.); B_N = 0.75 B; $W - a_o$ = 110.1 mm (4.33 in.); D = 25.4 mm (1.00 in.); N = 12.7 mm (0.50 in.)

cleavage and others by tearing; however, in no case did a crack start in cleavage and arrest by tearing. Arrest occurred in these specimens, not because of a change in fracture mode but because of a decrease in driving force, K.

One other feature of the fracture appearance of these specimens is worth noting: the arrested crack front was curved rather than straight, the crack length being longer near the plate surface than at its center — Fig. 9. It was shown earlier that the CVN impact energy was also lower near the plate surface than at the center (Fig. 4) so that the crack front appearance shown in Fig. 9 must be a reflection of the toughness variation through the plate thickness.

The thinner plate, as shown in Fig. 10, acted much like the thicker one in that K_a again increased in a smooth continuous fashion over the testing range. The most noticeable difference in the two plates was that the thinner one cracked in cleavage only up to room temperature, while the thicker one continued to show cleavage to a considerably higher temperature. This dependence of the cleavage-tearing transition on plate thickness is consistent with observations made by Pellini et al (Ref. 4), but the difference of 18°C (32°F) is larger than they would suggest for a 2:1 change in thickness.

Although there is some scatter in the data, the dependence of K_a on test temperature for the two test directions can be adequately represented by a single curve, suggesting that K_a is insensitive to crack direction. When this curve is compared with the one obtained on the thicker plate (Fig. 11), the former is seen to lie above the latter, and the distance between the two increases as the temperature increases. This, of course, suggests that the difference between the two is caused by a difference in constraint. For this reason, some tests were made on 25.4 mm (1 in.) thick specimens cut from the 50.8 mm (2 in.) plate. Since the CVN data indicated that the plate was tougher near the surface than near the center, the specimens were cut from both of these locations — Fig. 11.

The center specimen data fell close to the curve obtained on the thinner plate, suggesting that the difference between the two curves in Fig. 11 is a result of a difference in constraint. The three data points obtained on the thinner near-surface specimens, on the other hand, fell close to the curve obtained on the thicker plate. Hence, it must be concluded that the toughness difference between the thick and thin plate is partly constraint and partly plate quality. This difference between surface and center toughness is also consistent with the fracture appearance shown in Fig. 9.

Size Requirements for K_a Testing. As stated previously, there are no thickness requirements for K_a testing so long as cracking occurs with a pronounced "pop." If the crack in the test specimen is to model the one in the structure, however, it is essential that the stresses in the vicinity of the arrested crack tip be the same in the specimen and structure — that is, the specimen crack tip stresses should not be influenced by the edges of the specimen. Hence, the smallest in-plane dimension, the uncracked ligament length ($W - a_f$), must be large compared with the plastic zone size (r_y). The latter can be calculated for the limiting cases of plane stress and plane strain:

$$r_y \text{ (plane stress)} = \frac{1}{2\pi}\left(\frac{K_a}{\sigma_{ys}}\right)^2$$

$$r_y \text{ (plane strain)} = \frac{1}{2\pi}\left(\frac{K_a}{\sqrt{3}\,\sigma_{ys}}\right)^2 \qquad (2)$$

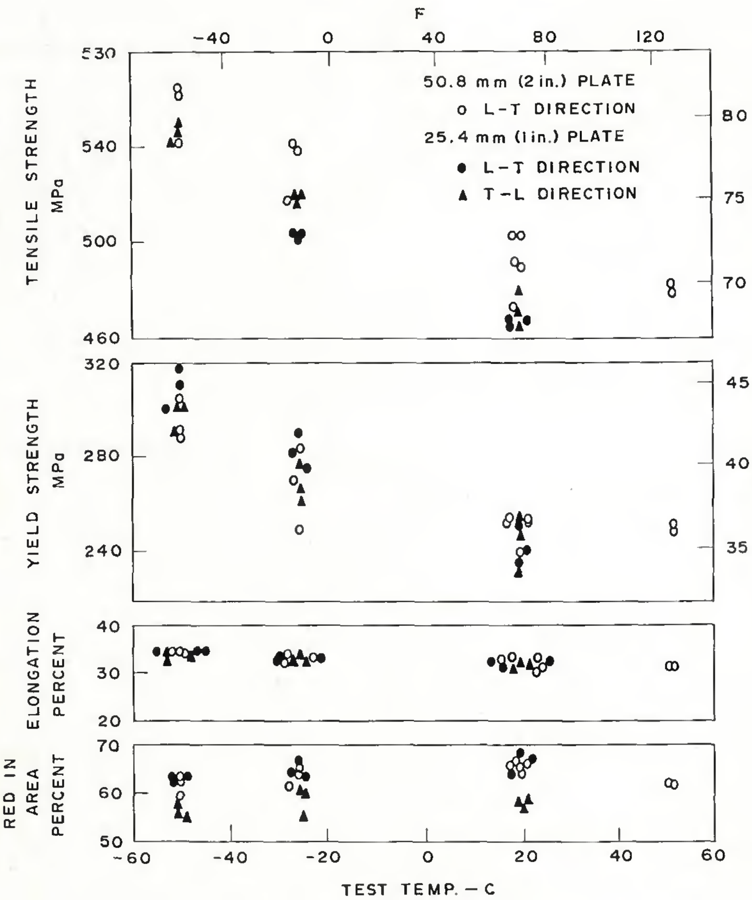

Fig. 7 — Tensile properties of A36 steel plates

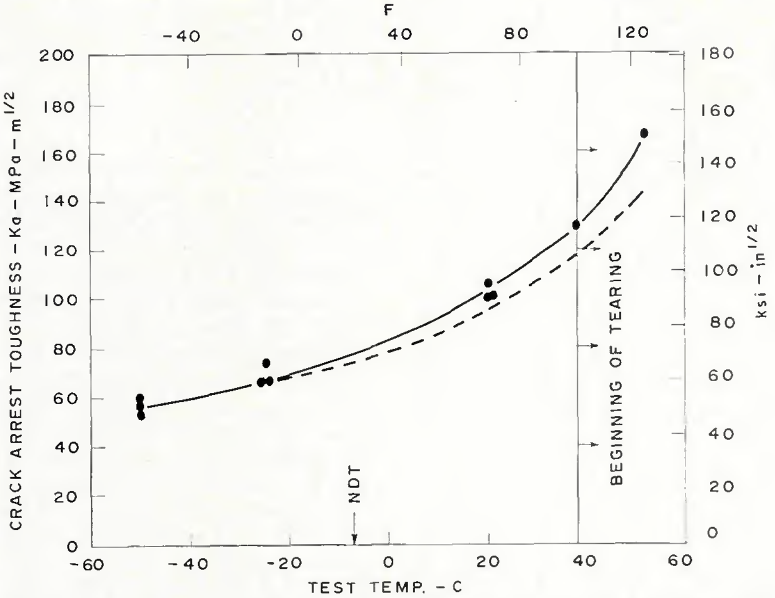

Fig. 8—Effect of test temperature on the crack arrest toughness of 50.8 mm (2 in.) thick A36 steel tested in the L-T direction

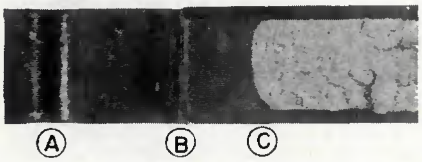

Fig. 9—Fracture appearance of 50.8 mm (2 in.) thick specimen: A—loading point; B—end of machined notch; C—end of crack jump, marked by heat tinting

where σ_{ys} = yield strength.

Since the test is concerned with the transition from a running to a stationary crack, rather than the more common transition from an essentially stationary to a running crack, there is some question of what is the appropriate value for σ_{ys}. Irwin (Ref. 9) has suggested that the yield strength of a running crack might be equivalent to the yield strength for a one millisecond loading time. Assuming that the yield strength is elevated 40 MPa (6 ksi) per order of loading rate, then five orders of loading rate would elevate the static yield strength by 200 MPa (30 ksi). Using this value of elevated yield strength, the ratio of uncracked ligament length ($W - a_f$) to plastic zone size is shown in Fig. 12.

The minimum acceptable ratio of ($W - a_f$) to r_y can only be established on the basis of extensive testing. In assessing the results obtained here, however, the requirement given in ASTM Standard E561, (Ref. 10) may be consulted. This requirement is: $(W - a) \geqslant 4/\pi\ (K/\sigma_{ys})^2$, which is equivalent to remaining ligament being at least equal to eight plane stress plastic zones. As can be seen in Fig. 12, this condition was satisfied by most of the tests on the A36 steel. If the idea of eight plastic zone sizes is retained while the plane strain rather than plane stress plastic zone is considered appropriate, all of the values satisfy the requirement.

A plastic correction is commonly made by adding an amount r_y to the measured crack length. In the more usual case when K is calculated from a load, the K thus modified exceeds the uncorrected one. The K_a calculation, however, is based on a displacement measurement, and the plasticity correction lowers the value of K_a.

The K_a data presented in this paper were not corrected for plasticity, but the effect of an r_y correction was investigated. The dashed curve in Fig. 8 shows the effect of making a crack length correction equal to the plane stress r_y value. At the higher temperatures where increased toughness and decreased yield strength lead to large crack tip plastic zones, an effect is noticeable. The magnitude of the lowering of K_a is, however, not significant in terms of the expected scatter in K_a measurements or with respect to conclusions which can be based on the results presented here. Moreover, a substantially smaller correction based on a plane strain rather than a plane stress r_y would probably be more appropriate for these tests. Consequently, K_a values based on the measured crack length without a plasticity correction have been used in this paper.

Discussion

Temperature Referencing of K_a to CVN and NDT Data

The ASTM Boiler and Pressure Vessel Code allows K_{Ia} values to be implied by temperature referencing to CVN and NDT test data (Ref. 11)—at least for the higher strength quenched and tempered steels such as A533 and A508. The procedure is based on the use of a reference curve, K_{IR}, which is thought to be the lowest measured value of plane strain fracture toughness as a function of the reference temperature. The latter is chosen to be the highest of the following three temperatures:

1. NDT.
2. The temperature at which the CVN impact energy is 68 joules (50 ft-lb) minus 33°C (60°F).
3. The temperature at which the CVN lateral expansion is 0.89 mm (0.035 in.)

Table 2—Through-the-Thickness Tensile Properties of 50.8 mm (2 in.) A36 Plate

Specimen no.	Location	Yield strength MPa	Yield strength (ksi)	Tensile strength MPa	Tensile strength (ksi)	Elongation, %	Reduction of area, %
A60	Surface	265	(38.4)	496	(71.9)	33.6	64.4
A61	Surface	264	(38.3)	492	(71.4)	31.8	66.4
	Avg.	265	(38.4)	494	(71.6)	32.7	65.4
A62	¼ plane	252	(36.6)	512	(74.3)	31.4	66.3
A63	¼ plane	253	(36.7)	508	(73.7)	32.9	65.7
T7	¼ plane	255	(37.0)	492	(71.4)	32.9	65.3
T8	¼ plane	240	(34.8)	472	(68.5)	33.6	64.7
T9	¼ plane .	252	(36.5)	490	(71.1)	30.0	66.6
	Avg.	250	(36.3)	495	(71.8)	32.2	65.7
A64	Center	250	(36.3)	505	(73.2)	32.1	62.9
A65	Center	245	(35.5)	503	(73.0)	32.1	66.6
	Avg	248	(36.0)	504	(73.1)	32.1	64.8

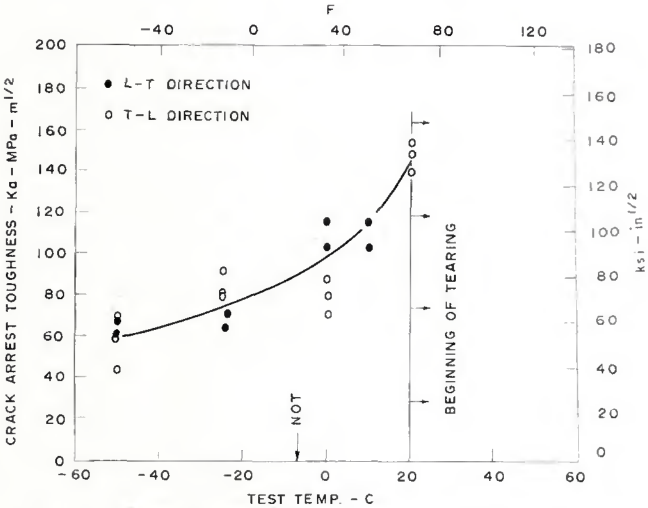

Fig. 10—Effect of test temperature on the crack arrest toughness of 25.4 mm (1 in.) thick A36 steel

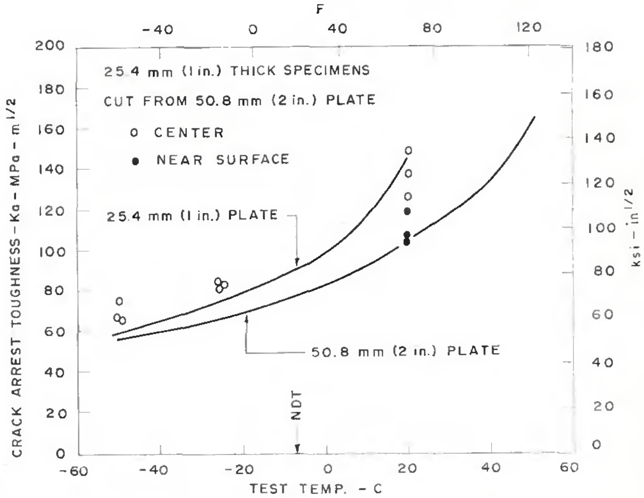

Fig. 11—Comparison of 25.4 (1 in.) and 50.8 mm (2 in.) plate toughness with toughness of 25.4 (1 in.) specimens cut from 50.8 mm (2 in.) plate. L-T direction

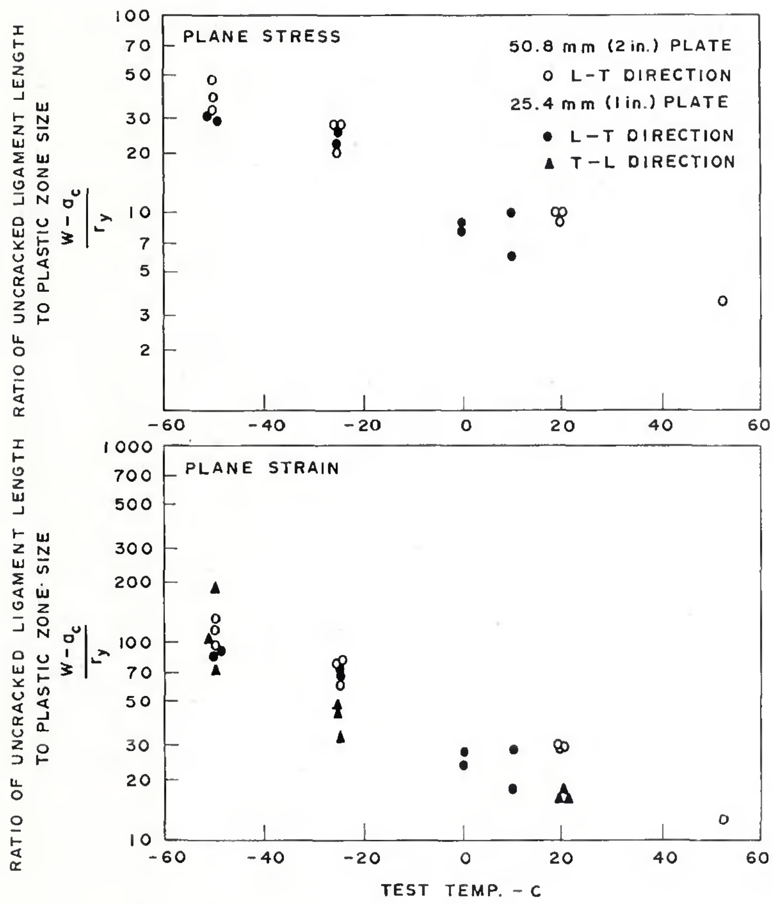

Fig. 12—Ratio of uncracked ligament length to plastic zone size for plane stress and plane strain cracking

minus 33°C (60°F).

For the two plates tested on this program in the L-T direction, the highest of these temperatures was NDT for the thinner plate, and the 68 joules (50 ft-lb) minus 33°C (60°F) temperature for the thicker one. The K_a data are plotted as a function of these reference temperatures and compared with the reference curve, K_{IR}, in Fig. 13.

On the basis of the limited K_a data collected on this program, it appears that K_{IR} indexing for this type of steel is unreasonably conservative, especially above NDT. This is not to suggest an inadequacy of the K_{IR} approach for the higher strength steels for which it was developed. Indeed, for the latter steels, it may actually be somewhat nonconservative above NDT (Ref. 5).

Pellini suggested a somewhat different indexing procedure. His reference curve was based on a K vs. temperature relationship for low and intermediate strength steels implied from drop weight test data, but indexed by NDT (Ref. 12)—Fig. 14. His indexing procedure may use a temperature shift that is selected for the application of the steel in question. For impact loading or a crack pop that might extend from an arc strike, the temperature shift is zero, i.e., NDT is the reference temperature.

For most structures, such as bridges, he suggests that loads are applied more slowly, on the order of one to two seconds; consequently, he shifts the reference temperature down 40°C (70°F), and for still slower loading, he implies a static K_{Ic} curve, which is shifted still lower. The K_a data collected on this program would most closely correspond with his K_{Id}-reference temperature curve, which does appear to be a reasonable lower bound of the K_a data—Fig. 14.

Flaw Tolerance of A36 Steel Based on Full Thickness K_a Values

The purpose of measuring the critical values of stress intensity factor for any material, of course, is to determine its flaw tolerance. For the problem of crack arrest, "flaw tolerance" takes on a different meaning from its most common one.

As an example of critical crack size in the K_a sense, consider a crack extending from a region of tensile residual stress or a hard heat-affected-zone in the vicinity of a weld, into a lower stressed or tougher region. The crack arresting ability of the structure would be determined by whether, as the crack extended, the

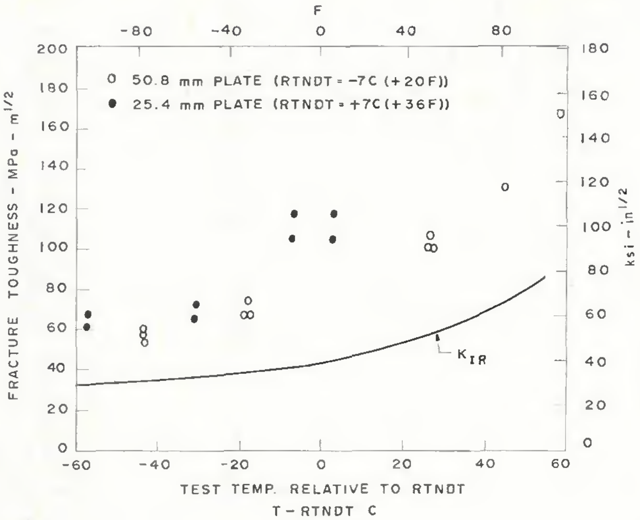

Fig. 13—Comparison of crack arrest toughness values with K_{IR} reference curve

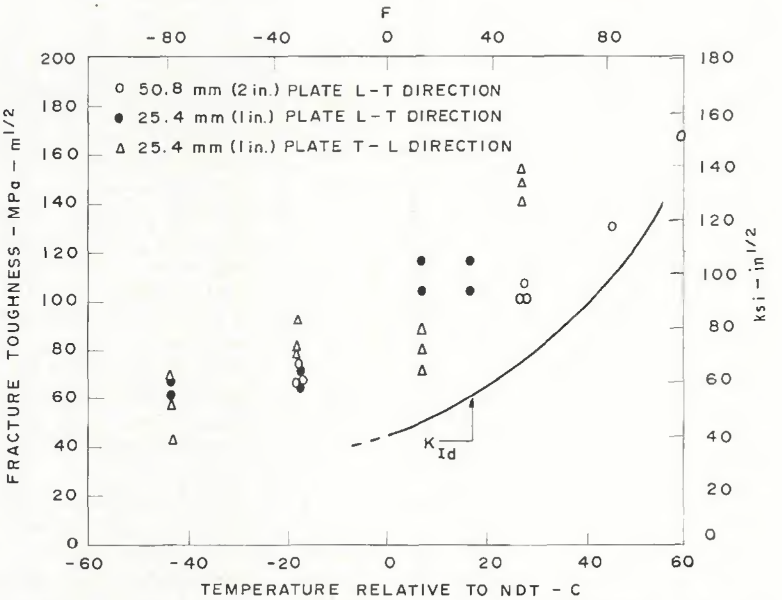

Fig. 14—Comparison of crack arrest toughness values with Pellini K_{Id} reference curve

value of K would drop below the crack arrest toughness, K_a. The "flaw size" then is the size of the region within which the crack will arrest at the given stress level.

In these examples the critical crack size would be the effective extent of the residual stress region or hard spot. This situation is difficult to analyze in a general case (although not for specific cases), so that in this section K_a is considered as a measure of minimum crack toughness applicable to crack initiation, as discussed earlier.

In order to estimate critical crack sizes, we assume a large structure containing a through thickness crack subjected to tensile loading. The crack length $2\,a_c$, is given by:

$$a_c = \left(\frac{K_a}{\sigma}\right)^2 \frac{1}{\pi} \qquad (3)$$

where σ = stress, both applied and residual.

The critical crack sizes are given in Fig. 15 for both plates as a function of testing temperature for yield strength and 2/3 yield strength loading. Remembering that all of these data were collected on cleavage cracks, the flaw tolerances are surprisingly large. For room temperature σ_{ys} and $2\,\sigma_{ys}/3$ loading, the critical crack sizes are 110 and 250 mm (4.3 and 9.8 in.) for the thick plate, and 230 and 514 mm (9.0 and 20.0 in.) for the thinner plate.

One of the most common fracture criteria, developed especially for ship steels, assumes that structures are safe so long as they are used at temperatures at which the steel has at least 20 joules (15 ft-lb.) of CVN impact energy. The 20 joule temperature for the thick and thin plate, and the critical crack sizes ($2\,a_c$) at these temperatures, read from Fig. 15, are shown in Table 3. If one assumes loading to a dynamic yield stress, values of $2\,a_c$ are reduced to about one-third of the values in Table 3.

According to Table 3, the 20 joule (15 ft-lb) fracture criterion essentially states that steels should not be used at temperatures below those at which they can arrest at least a 1T crack on static yield stress loading. This seems a reasonable level of flaw tolerance and might explain the success of this fracture criteria.

Another popular method for estimating flaw tolerance is to use the Pellini Fracture Analysis Diagram (FAD), as discussed in the Introduction. Although Pellini distinguishes between small and large thickness sections, both plates tested in this program would be considered small thickness. For such plates Pellini suggests that the critical crack size ($2\,a_c$) for yield stress and ¼ yield stress loading at NDT is < 25 mm (< 1 in.) and 0.6 m (2 ft.), respectively. Based on the data in Fig. 15, these critical values are as shown in Table 4. Hence, again, the critical crack sizes estimated from the Pellini FAD is conservative.

Comparison of K_a and K_{Ic} Values Obtained on Both Slow and Fast Loading

The K_a values shown in Figs. 8 and 10 are even more surprising when compared with published values of plane strain crack initiation toughness of A36 steel, Fig. 16. The K_{Ic} and K_{Ic} (.002)* curves in Fig. 16 were collected on a heat of A36 having an NDT of −1°C (+30°F), which is close to the NDT of the steel tested on this program.

The initiation data were presented only over the temperature range for which the data were valid according to ASTM E399, so that K_{Ic} data were not shown above −80°C (−112°F) nor K_{Ic} (.002) above 10°C (50°F). Hence, K_{Ia} cannot be compared with K_{Ic}. There is a significant temperature overlap of K_{Ic} (.002) and K_a data, however, and it is seen that K_a is 1½ to 2 times K_{Ic} (.002).

As discussed above, earlier studies have shown K_{Ia} to represent the minimum value of $K_{Ic}(t)$ with increasing loading rate, so that the relative positions of the $K_{Ic}(t)$ and K_a curve are opposite to what would be expected. A number of reasons might be suggested for this. The most obvious reason is that the reversed order is due to the scatter found in different heats of A36, even when the values of NDT are similar. A more likely possibility is that $K_{Ic}(t)$ is measured with specimens containing an extremely

In this section K_{Ic} refers to standard fracture tests according to ASTM E399, and $K_{Ic}(t)$ refers to identical tests, rapidly loaded. The (t) is the loading time in seconds, i.e., K_{Ic} (.002) refers to tests in which the load is increased from zero to the fracture load in 2 milliseconds.

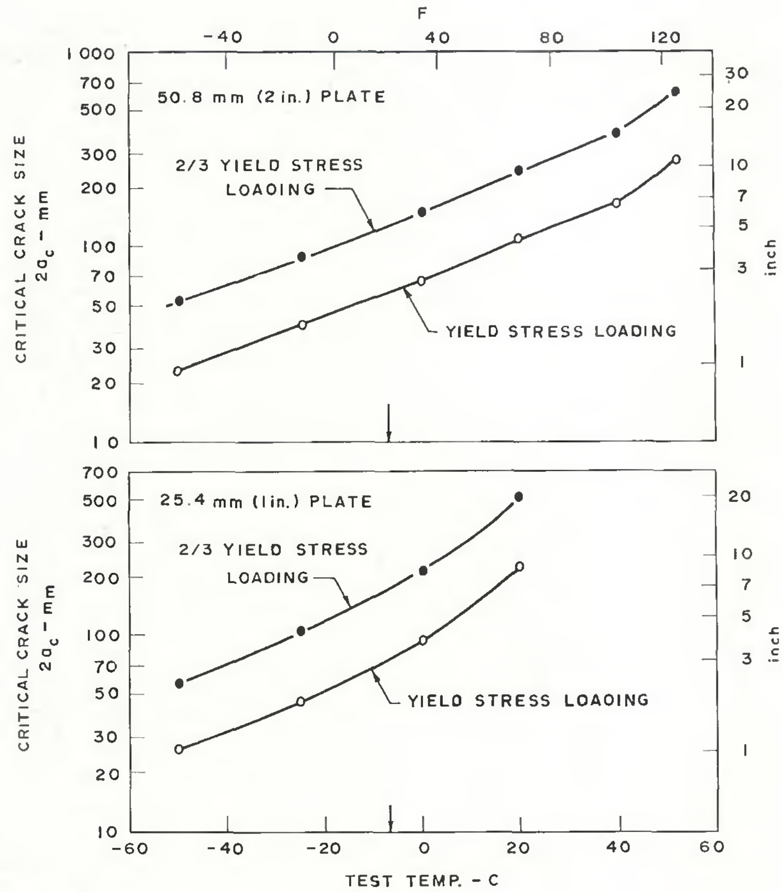

Fig. 15—Critical crack sizes as a function of temperature

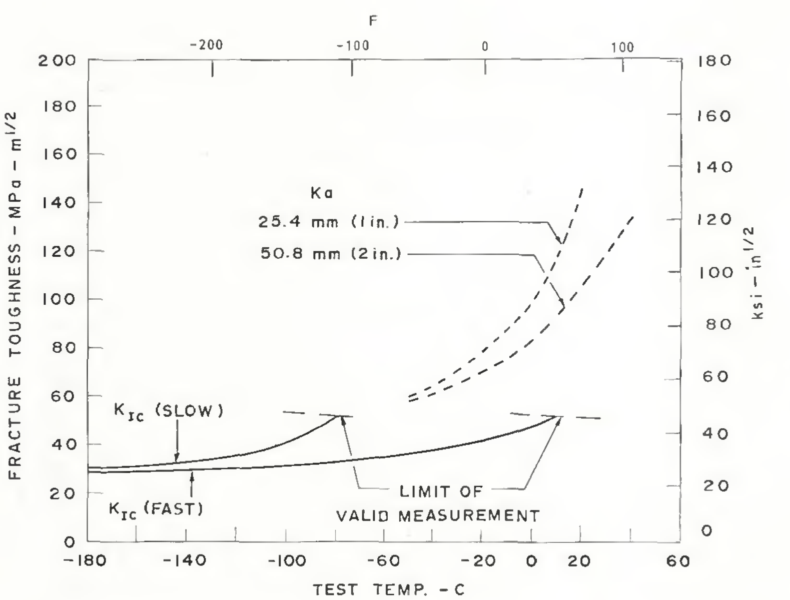

Fig. 16—Comparison of plane strain crack initiation toughness and full thickness K_a of A36 steel. K_{Ic} (slow) and (fast) curves from Ref. 12

smooth precrack, produced by low amplitude fatigue, while K_a is measured on specimens having a rougher fracture surface, typical of running cracks. This smooth precrack may artificially lower $K_{Ic(t)}$ by causing a small segment of crack extension before the load increases to the higher values needed for cracks to extend from a rougher surface. If this is true, the effect would be more pronounced in low strength steel than in intermediate strength steels such as A533 or A508.

Conclusions

1. The test method developed for measuring K_{Ia} is satisfactory for measuring full thickness crack arrest toughness (K_a) of structural steels.
2. For A36 steel tested in full thickness, 50.8 mm (2 in.) and 25.4 mm (1 in.) long cracks initiate, extend, and arrest in a cleavage mode up to a temperature considerably above NDT. Over some narrow, higher temperature band, cracking occurs by either cleavage or tearing, and above this band only tearing occurs. In no case did cracking within a single specimen initiate in cleavage and arrest in tearing. The temperature interval between NDT and the start of ductile cracking was a function of thickness.
3. The arrested crack front in the thicker plate was not straight, and this was shown to result from a non-uniform toughness over the plate thickness.
4. The thinner plate was somewhat tougher than the thick one. This appeared to result from both a difference in restraint and plate quality.
5. Values of K_a estimated from the ASME K_{IR} reference curve are overly conservative, while those estimated from the Pellini (K_{Id}) reference curve are only moderately conservative.
6. The K_a data collected on this program shows that the 20 joule (15 ft-lb) fracture criteria is essentially a statement that steels should not be used at temperatures below those at which a 1T crack can be arrested on yield stress loading. This seems a reasonable requirement and might explain the success of this criterion.

Table 3—20 Joule Temperatures for Thick and Thin Plates and Corresponding Critical Crack Sizes

Plate Thickness		Direction	15 ft-lb transition temperature		$2a_c$			
					σ_{ys} Loading		$2\sigma_{ys}/3$ Loading	
mm	(in.)		°C	(°F)	mm	(in.)	mm	(in.)
50.8	(2)	L-T	10	(50)	85	(3.3)	190	(7.5)
25.4	(1)	L-T	−10	(14)	70	(2.8)	160	(6.3)
		T-L	0	(32)	95	(3.7)	210	(8.3)

Table 4—Critical Crack Lengths at Yield Strength and ¼ Yield Strength Loading

Plate thickness		$2\ a_c$			
		σ_{ys} Loading		$\sigma_{ys}/4$ Loading	
mm	(in.)	mm	(in.)	m	(ft.)
50.8	(2)	60	(2.4)	0.96	(3.1)
25.4	(1)	75	(3.0)	1.2	(3.9)

7. In spite of the fact that K_a is expected to be either equal to or less than rapid load K_{Ic} [$K_{Ic}(t)$] when measurements are made on the same plate thickness, the values of the former were almost twice as high as published values of the latter. This may simply be a result of heat-to-heat variability or it may be associated with the different type of precrack used in $K_{Ic}(t)$ and K_a testing.

8. Since it is relatively simple to measure K_a, this might be an ideal parameter for characterizing the toughness of low strength steels.

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The tests described in this paper were carried out for the Oak Ridge National Laboratory as a portion of an effort to develop a standard method for crack arrest toughness testing.

An INVITATION From WRC To Authors Interested in Presenting Papers on "Hydrogen and Cracking in High Strength Steels" on the Professional Program of the 64th AWS Annual Convention in Philadelphia, Pennsylvania, April 24-29, 1983

The High Strength Steel Subcommittee of the Weldability Committee of the Welding Research Council is inviting Authors to submit for its consideration the results of outstanding and previously unpublished work on development, research, or application of hydrogen measurement, control, critical levels, or moisture problems relating to the welding of steels with yield strengths exceeding 80 ksi.

Minimum 500 word abstracts (not more than 1,000 words) must be submitted by April 20, 1982, to the Welding Research Council, 345 E. 47th Street, New York, NY 10017 for pre-screening by a special WRC task force committee before review by the AWS Technical Papers Committee for the AWS Annual Convention in Philadelphia. Authors can expect notification during June 1982 regarding preliminary acceptance of their papers, with final notification due on or about November 1.

Finished papers should be available by October 1982 for possible pre-convention publication in the *Welding Journal.*