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Engineering Significance of Statistical and Temperature-Induced Fracture Mechanics Toughness Variations on Fracture-Safe Assurance

F. J. Loss

Reactor Materials Branch
Metallurgy Division

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NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT

An appraisal is made of linear elastic fracture mechanics (LEFM) as a method for fracture-safe assurance of carbon and low-alloy steels. The theoretical advantage of an exact flaw size-stress level relationship offered by LEFM is contrasted with the limitations posed in actual application. These limitations relate to statistical variations in K_{Ic} and K_{Id} data. The variations considered here are (a) data scatter at a given temperature, and (b) toughness variations between different heats of a given alloy. In an engineering context, LEFM is considered applicable only in the temperature region representing the initial development of the brittle-ductile transition that characterizes low-alloy steels. In this region statistical variations in the data can result in critical flaw sizes that are significantly smaller than the values calculated on the basis of limited experimental data.

The prime objective in determining fracture toughness is for use in evolving a fracture control plan that assures structural integrity under a variety of environmental and loading conditions. Often the exact flaw size is unknown, particularly if the structure has not yet been built. Since the toughness increases sharply in the transition region, a practical solution is to choose a minimum operation temperature that assures a high fracture toughness such that postulated flaws cannot propagate in an unstable manner.

The objective of being able to define the temperature range and statistical distribution of K_{Id} curves is met equally by the use of Dynamic Tear (DT) and K_{Id} tests. The DT test, as contrasted with LEFM methods, is shown to be an effective engineering tool with which to determine the Fracture Transition Elastic (FTE) temperature; above this temperature, plane strain constraint is lost for the given thickness, and flaws cannot propagate at stress levels less than yield. The determination of a minimum operating temperature based on dynamic LEFM values, when modified by conservatisms necessitated by statistical variations in the data and inaccuracies in temperature measurement, is shown to be essentially equivalent to the FTE temperature.

PROBLEM STATUS

This is a special interpretive report; work on other phases continues.

AUTHORIZATION

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ENGINEERING SIGNIFICANCE OF STATISTICAL AND TEMPERATURE-INDUCED FRACTURE MECHANICS TOUGHNESS VARIATIONS ON FRACTURE-SAFE ASSURANCE

INTRODUCTION

Carbon and low-alloy steels are known to exhibit a sharp transition from brittle to ductile fracture behavior within a small temperature interval. This fact has formed the basis for various qualitative procedures (e.g., Fracture Analysis Diagram, Robertson Test, Charpy V-Notch Test, and Drop Weight Test) used in assuring the fracture-safe performance of structures. Linear elastic fracture mechanics (LEFM) offers an analytical approach that relates fracture toughness to the critical flaw size and stress level under conditions of plane strain constraint. This method is ideally suited to the very high strength steels that are incapable of exhibiting ductile behavior in the presence of even the smallest flaws. The appeal of analytical exactness has precipitated application of LEFM methodology to the lower strength, transition temperature steels for which the assumption of linear elastic behavior is valid in only a small useful temperature range. The practical use of LEFM for structural application of these steels therefore requires consideration of certain limitations which heretofore have not been clearly addressed. It is the purpose of this report to assess the role of these limitations on the evolvement of fracture control plans for low-strength structural steels.

It is necessary to understand that carbon and low-alloy steels generally exhibit large increases in the dynamic plane strain toughness K_{Id} within a narrow temperature region beginning at the Drop Weight-NDT temperature. The static plane strain values K_{Ic} exhibit a similar transition beginning at approximately 40° to 175°F (22° to 97°C) below the NDT temperature. This sharp increase in toughness has often been characterized by means of impact tests such as the Charpy V-Notch Test. In addition to defining the transition temperature region, these tests define other regions, bounding the transition region, where the toughness is relatively insensitive to temperature. These regions are known as upper and lower shelf toughness. It must be noted that the practical application of LEFM rests chiefly in the transition temperature region for these steels. The upper shelf toughness, for example, is generally so high as to invalidate the requirements of the linear elastic analysis. On the other hand, while LEFM analysis is applicable below the transition temperature region, the actual values of K_{Ic} and K_{Id} (and the associated critical flaw sizes) are very low. However, to be economically competitive, structures necessarily have regions of high stress, and this fact requires the absence of even very small defects (a few tenths of an inch) when the toughness is very low. It is unrealistic to meet this requirement in the terms of general engineering structures. Thus, the only practical way of using these metals below the transition temperature is to enforce large safety factors and low stresses.

In principle there is no drawback to applying LEFM techniques in the transition temperature region. In actuality, however, one is confronted with a statistical variation in toughness for a given class of steel. Unless extensive (and expensive) fracture mechanics tests are conducted on each plate, weld, and forging in a given structure, one must accept the fact that the K_{Ic} vs temperature behavior for one heat of steel may differ significantly from the behavior of another heat. If one foregoes this testing requirement, then fracture-safe analysis

procedures must be based on a lower bound curve of toughness vs temperature derived from a statistically significant sampling of specimens from many heats of a particular alloy and processing method.

Upon obtaining a lower bound curve one must still account for the large changes in K_{Ic} and K_{Id} values (and associated critical flaw sizes) in the narrow transition range. This fact complicates the application of fracture mechanics by requiring exact control of the temperature of the structure. For example, temperature variations of less than 20°F (11°C) can result in significant changes in the critical flaw sizes (by factors of two to three) for a given stress level. Finally, one must note that valid LEFM values are obtainable in the transition temperature region only for thick sections. Increasing thickness is required to provide plane strain constraint in response to the inherent metallurgical increase in microfracture ductility with temperature.

Fracture-safe assurance using LEFM now will be discussed in terms of the preceding data trends. LEFM methods then will be contrasted with other methods that can give equivalent results for fracture-safe assurance based on relatively simple analyses and inexpensive test procedure.

TRENDS OF K_{Ic} AND K_{Id} VALUES WITH TEMPERATURE

To critically assess the utility of fracture control plans based on LEFM, it is first necessary to understand the nature of the K_{Ic} and K_{Id} variations with temperature for certain structural steels. Later it will be shown how these variations can influence the critical flaw sizes. Unfortunately, few valid fracture mechanics data exist in the transition temperature region because of the requirement for increasingly large specimens*. The majority of the published data for thick sections have been obtained by the Westinghouse Corp. These data (1,2) describe chiefly A533-B plate and rotor forging material (NiMoV, NiCrMoV, and CrMoV alloys).

It is characteristic of carbon and low-alloy structural steels to exhibit a sharp increase in the K_{Ic} and K_{Id} values near the NDT temperature. This trend is illustrated in Fig. 1 for A533-B steel using data derived from the largest known specimens (12-in.-thick static, 8-in.-thick dynamic) (1,2). The curves were drawn as lower bound curves for one plate of A533-B steel. However, there is no assurance that these curves represent the lower bound for A533-B plates in general. Similar trends are shown for A517-F steel (Fig. 2) (3) and for 22NiMoCr37 steel forgings (Figs. 3 and 4) (4). The latter steel is a European equivalent to A508 Class 2 forging material. The trends to note in these figures are (a) a sharp increase in the absolute values of K_{Ic} and K_{Id} in a relatively small temperature interval (e.g., doubling of K_{Ic} or K_{Id} over a 50°F interval), and (b) a large scatter in the K values in the region of sharp increase (e.g., a 50% increase in the lower bound K_{Id} value at a given temperature).

*The thickness requirement is derived from the recommendation of ASTM Committee E-24 on Fracture Testing of Metals. The current recommended practice requires the thickness B to satisfy the relation $B \geq 2.5(K_{Ic}/\sigma_{ys})^2$ where σ_{ys} is the static yield stress. It is generally assumed that compliance with this requirement will also ensure valid dynamic toughness K_{Id} when the dynamic yield stress σ_{yd} is substituted for σ_{ys}. However, this assumption has not been verified through a dynamic stress analysis that relates crack-tip stresses to boundary value loading and also accounts for stress wave interaction in the specimen and in the structural prototype.

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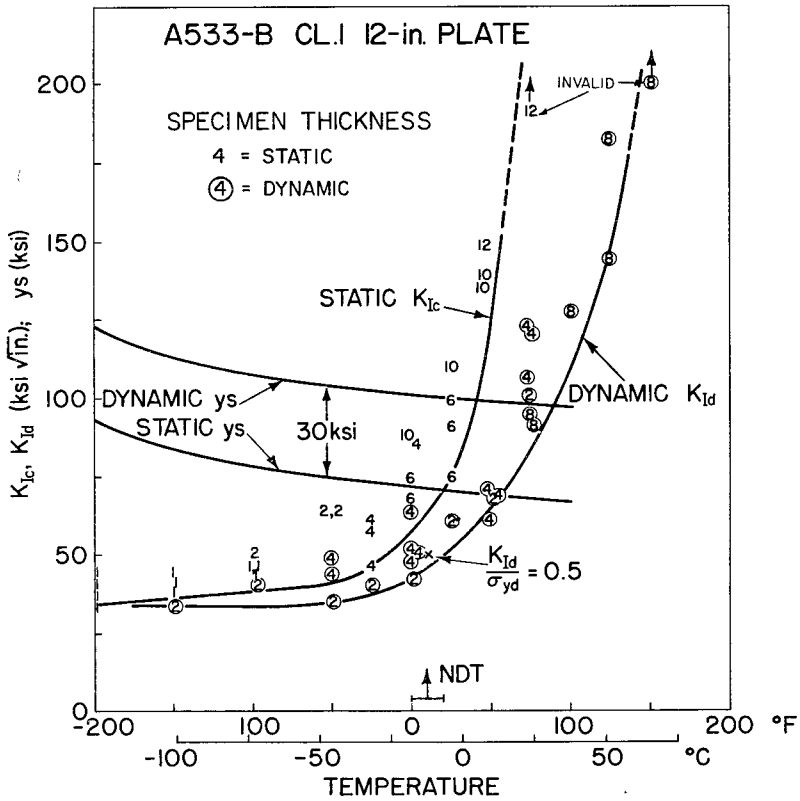

Fig. 1—Trends of K_{Ic} and K_{Id} values from a 12-in. A533-B Class 1 steel plate. Both sets of data exhibit sharp increases in toughness with the development of the brittle-ductile transition region as indexed by the NDT temperature. The invalid points signify that the test results did not meet the thickness requirements of ASTM E-24 and this reflects the inability of 8- and 12-in.-thick specimens to define valid LEFM values as the toughness increases. The dynamic yield stress was obtained by a 30-ksi elevation of the static yield stress curve. (Westinghouse Corp. data.)

Note also that the ASTM thickness requirement has necessitated use of very thick specimens (up to 12-in. thick) to "track" the K_{Ic} transition; even this thickness does not enable valid numbers to be obtained above a temperature of NDT+50°F (28°C) for the A533-B steel in Fig. 1. The reader should keep in mind that failure to meet the ASTM thickness requirement can result in a loss of plane strain constraint and an entry into an elastic-plastic or fully plastic regime where LEFM theory is no longer applicable. In other words, the thin section is tougher than the thick section. Realistically, most structures other than nuclear pressure vessels do not involve thicknesses in excess of the 8 or 12 in. that may be required to obtain valid K_{Ic} numbers in the transition region. In this event, it may not be possible to define K_{Ic} values for these lesser thicknesses, except at temperatures below the operating range of the structure. If this is the case it is apparent that techniques other than LEFM must be sought if the flaw size-toughness relationship is to be quantitatively established. Unfortunately, other quantitative techniques have not been refined to the point of engineering usefulness because of the difficult mathematical and material modeling procedures required.

As an alternative to the use of new techniques one may consider equating the toughness of the thinner section to the lower plane strain values that would be obtained with sufficiently thick specimens. The disadvantages of this procedure are (a) the full toughness potential of the thinner material will not be realized, and (b) lower bound curves presently do not exist for specific alloys from which to pick this minimum expected plane strain toughness.

Engineering emphasis for application of LEFM methods to low-strength structural alloys must be placed on the dynamic toughness property because of the strain rate sensitivity of these steels. It is realized that many structures are not dynamically loaded and that dynamic toughness may not be controlling. However, static loading, per se, does not guarantee that static toughness is relevant to a fracture control plan. One argument is that local areas of inhomogenity or areas otherwise degraded by the environment, e.g., strain aging, may cause an existing flaw to rapidly advance through a few grains of metal. This action can result in dynamic control of the remaining fracture extension even though the structure, as a unit, is not dynamically loaded.

Compared to the scarcity of static K_{Ic} data for a particular alloy, dynamic K_{Id} data are practically nonexistent. The prime reason for this fact is that the testing techniques (no standards available) and specimen preparation are costly and presently require the interpretation of a highly skilled scientist. In view of this scarcity of data, the NDT temperature offers a simple means of approximating the value of the dynamic K_{Id}/σ_{yd} ratio at this temperature. It has been shown (5) that the NDT temperature corresponds approximately to a K_{Id}/σ_{yd} ratio of 0.5. This determination was based on correlations of the NDT temperature with Westinghouse Corp. and U. S. Steel K_{Id} measurements and encompasses seven different structural alloys.

Figures 1 and 2 indicate that the NDT temperature corresponds with a K_{Id}/σ_{yd} ratio of 0.5 based on measured K_{Id} values. The dynamic yield stress in Fig. 1 was obtained by adding 30 ksi to the static yield stress at all temperatures. This value corresponds to an approximation

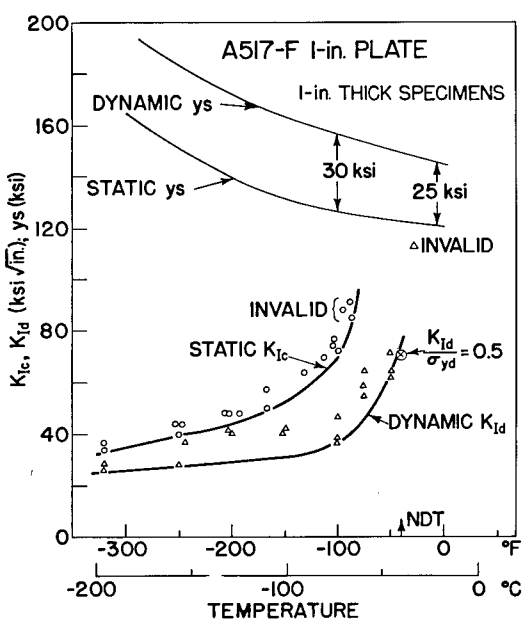

Fig. 2—Trends of K_{Ic} and K_{Id} values from a 1-in. A517-F steel plate. Note the sharp increase in K_{Id} that is beginning to evolve near the NDT temperature. The dynamic yield stress was obtained by means of a rate-temperature parameter as discussed in the text. Note that the NDT temperature corresponds to a K_{Id}/σ_{yd} ratio of 0.5. (U.S. Steel data.)

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of Krafft (6) which suggests a 5-ksi increase in yield strength per order magnitude increase in strain rate. The dynamic yield stress in Fig. 2 was calculated by Shoemaker and Rolfe (3) using a rate-temperature parameter. Note that this determination of σ_{yd} is in agreement with the assumption of a uniform 30-ksi elevation of dynamic yield stress*. The K_{Id} curves in Figs. 3 and 4 have been estimated by translating the static K_{Ic} curves along the temperature axis such that the value of K_{Id} at the NDT temperature corresponds to a K_{Id}/σ_{yd} ratio of 0.5. In translating the K_{Ic} curve it is realized that its shape may differ from that of the K_{Id} curve. This fact is important if exact K_{Id} values are required for flaw size computations. However, the present purpose is solely to estimate the K_{Id} trends based on the only information that is available.

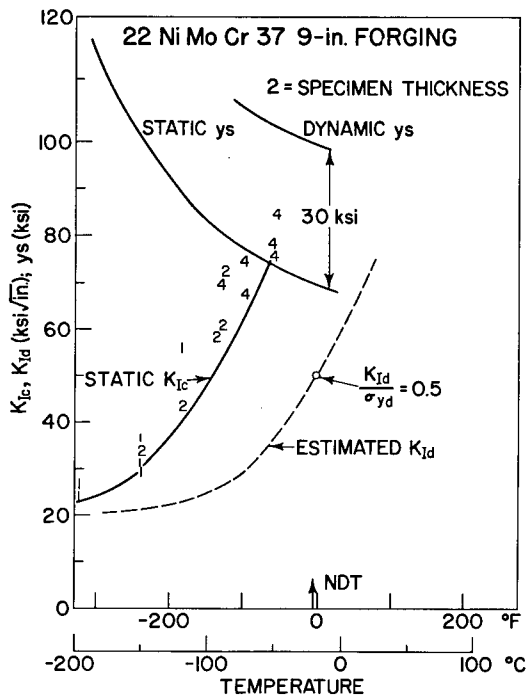

Fig. 3—Trend of K_{Ic} for a 9-in.-thick European forging steel equivalent to A508 Class 2. The K_{Id} curve was estimated by translating the K_{Ic} curve to go through K_{Id}/σ_{yd} = 0.5 at the NDT temperature. (Siemens data.)

Another method of estimating the K_{Id} curve, suggested by investigators in the field, is to translate the K_{Ic} curve by a fixed temperature increment. In principle, this increment would be obtained from a comparison of actual K_{Ic} and K_{Id} curves for a particular alloy. The drawbacks of this approach can be seen from Figs. 1-4. At the K level corresponding to the K_{Id} at the NDT temperature, the temperature differences between the static and dynamic curves are not unique; instead they range from 40° to 143°F (22° to 80°C).

Even for one alloy such as A533-B steel the temperature differences between the K_{Ic} and K_{Id} curves can be quite different. Figure 5 illustrates the K_{Ic} and K_{Id} data of Fig. 1 plus additional K_{Ic} data (7) from a 6-in.-thick A533-B Class 2 plate from the same

*The definition of "dynamic" has been purposely left vague in view of different methods used by various investigators in defining rates of dynamic loading. It is felt that these differences do not seriously detract from the conclusions reached.

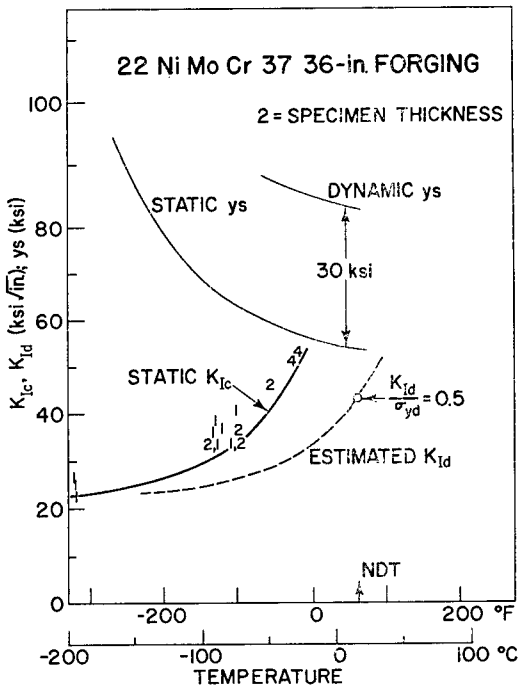

Fig. 4—Trend of K_{Ic} values for a 36-in.-thick European forging steel equivalent to A508 Class 2. The K_{Id} curve was estimated as in Fig. 3. (Siemens data.)

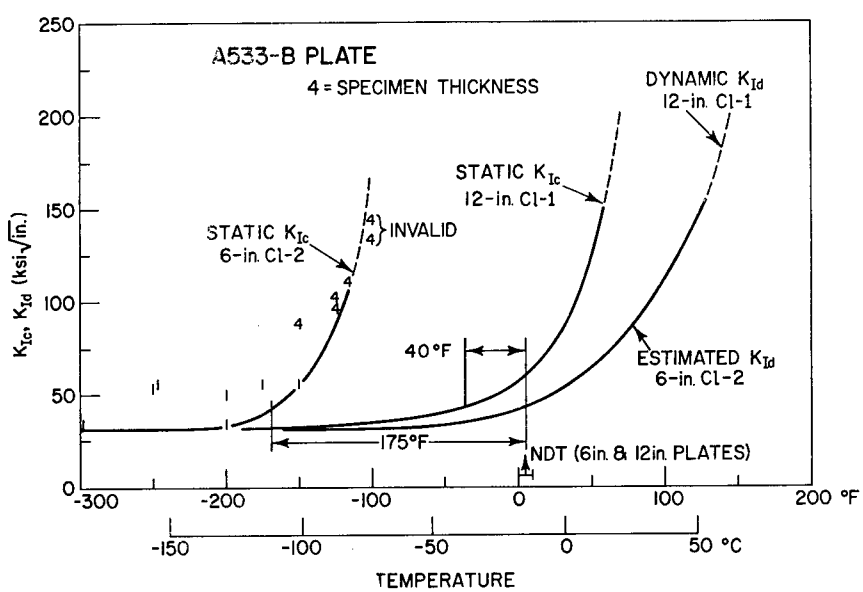

Fig. 5—The K_{Ic} values trend of a 6-in.-thick A533-B Class 2 steel plate superimposed on the K_{Ic} and K_{Id} curves of the 12-in.-thick A533-B Class 1 steel plate illustrated in Fig. 1. The K_{Id} curve for the 6-in.-thick plate is considered to be represented by the same K_{Id} curve for the 12-in.-thick plate because both plates have the same NDT temperature, exhibit essentially the same yield strength, and also exhibit similar thick-section DT test trends. Note the large difference between the temperature displacements of the K_{Ic} and K_{Id} curves for both plates. (Westinghouse Corp. data.)

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manufacturer. The actual properties (i.e., chemical, tensile, and yield strength) of the Class 2 plate (5) overlap the ASTM Class 1 specification. Figure 5 indicates a range of 40° to 175°F (22° to 97°C) in the K_{Ic}–K_{Id} temperature difference that can take place. Note that in the absence of actual K_{Id} values the K_{Id} curve for the Class 2 plate was taken identical to that of the Class 1 plate. This assumption is based on the fact that the NDT temperatures for both curves were identical and the Dynamic Tear (DT) test results from both plates were similar (5). The DT test will be discussed later.

EFFECTS OF K_{Ic} AND K_{Id} VARIATIONS ON THE CRITICAL FLAW SIZE

With the preceding description of the K_{Ic} and K_{Id} trends as background it is now possible to assess the significance of the indicated toughness variations in terms of the critical flaw sizes. There are many equations relating the K_{Ic} value to the critical flaw size and stress level; each equation is unique to a specific geometry. For discussion purposes the following equation (8) for a semielliptic surface flaw in tension will be considered since this flaw geometry is common to many structures.

$$K_{Ic}/\sigma_{ys} = 1.1(\sigma/\sigma_{ys})\sqrt{\pi a/Q}. \tag{1}$$

Here a is the flaw depth (in.), Q is a tabulated flaw shape factor (dimensionless), and σ is the local stress (ksi) if the flaw were not present. This equation is assumed to be applicable under dynamic loading when the appropriate values for dynamic stress are substituted for σ and σ_{ys}.

When considering toughness variations such as those in the transition temperature region, it is better to think in terms of the ratio K_{Ic}/σ_{ys} or K_{Id}/σ_{yd} rather than the K_{Ic} or K_{Id} values themselves. The ratio (or more exactly, the ratio squared) is proportional to the size of the plastic zone at the crack tip; this measure of plastic deformation is a better indication of resistance to crack extension than is the K_{Ic} number itself. To simplify the following discussion, Eq. 1 has been plotted in terms of the critical flaw depth at a given K/σ ratio (see Fig. 6).

Consider first the effect on critical flaw size of a 20°F (11°C) temperature change in the transition region. It is evident from Figs. 1-5 that K_{Ic} and K_{Id} (or K_{Ic}/σ_{ys} and K_{Id}/σ_{yd} can increase 50% or more over selected 20°F temperature intervals. Conversely, K_{Ic} or K_{Id} can decrease by 33% in the same temperature interval. From Eq. 1 the critical flaw size varies as the square of the K/σ ratio. Thus, if the ratio decreased by 1/3 (to 2/3 its value at the higher temperature) then the critical flaw size decreases to less than half (i.e., 4/9) of its original value. The effect of this decrease in the ratio is shown graphically in Fig. 7. For example, the critical flaw depth at 3/4 σ_y loading drops from 4.25 in. to 1.85 in. as the K/σ ratio drops by 1/3 from 2.0 to 1.33.

Even larger changes in critical flaw sizes associated with a 20°F temperature interval are possible near the high-temperature end of the transition. In Fig. 1, for example, the value of K_{Ic} at 50°F would be approximately 50% less than the extrapolated value of K_{Ic} at 70°F; this drop means that the critical flaw size at 50°F will be only 1/4 its value at 70°F. Stating this phenomenon in another way, the same depression in the K/σ ratio resulting from a 20°F drop in temperature in the lower portion of the transition region will be achieved within a smaller temperature drop in the upper portion of the transition region. This fact

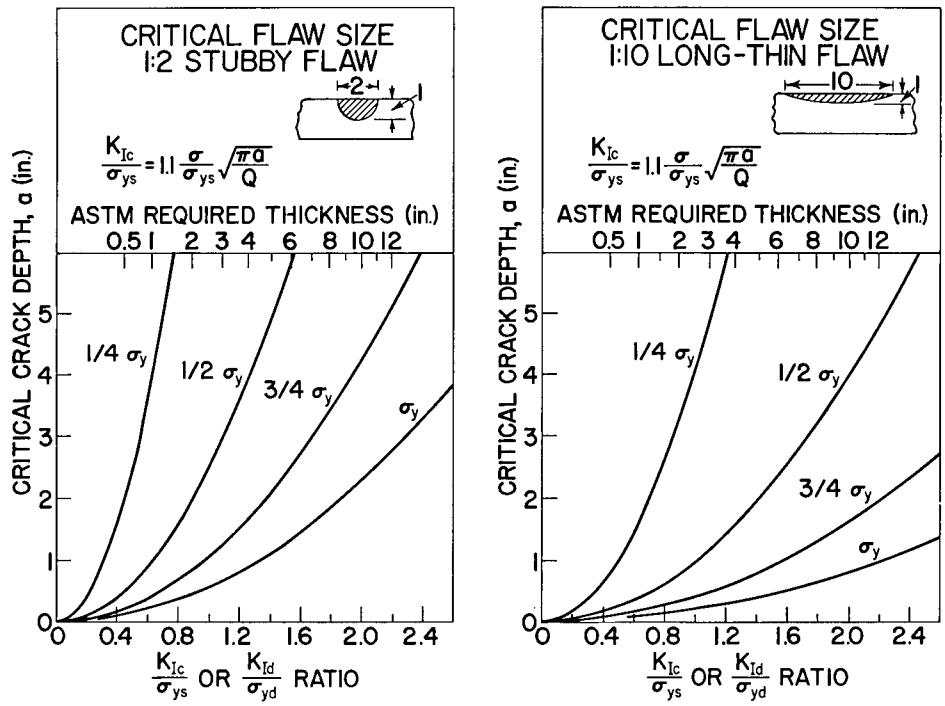

Fig. 6—Representation of the fracture mechanics equation relating the flaw size and fracture toughness to the critical depth a of surface flaw for a plate in tension. The specimen thicknesses must be greater than the requirements illustrated in the upper portion of the graphs before the equation is applicable at the corresponding K_{Ic}/σ_{ys} ratio. The parameter on the curves denotes the local stress level in the region of the flaw.

can be quite significant to the fracture control plan for a structure when this plan is based upon LEFM flaw size calculations. Unfortunately, insufficient K_{Ic} data exist with which to further refine this flaw size-temperature dependence since large K/σ ratios are involved; these ratios can only be determined with large specimens.

Consider next the effect on critical flaw size resulting from scatter in the K_{Ic} data at a given temperature. The data presented in Figs. 1-5 do not statistically define the full extent of this scatter. However, one must conclude from these data that the scatter band is at least as great as an envelope formed by the lower bound curve and a curve that is raised by an amount equal to 50% of the lower bound curve for each temperature. Consequently, if the toughness were by chance measured at the upper end of the scatter band for a given temperature, the actual toughness could be only 2/3 of this value. That is, 2/3 of the K_{Ic} value at the upper limit of the scatter defines the same degree of scatter as a 50% increase in the K_{Ic} value at the lower limit of the scatter. The critical flaw size is then less than one-half of the value calculated from the K_{Ic} measured at the upper limit of the scatter. Figure 7 depicts the flaw size variation resulting from a scatter band of this magnitude.

Finally, consider the effect on critical flaw size resulting from the statistical distribution in the toughness of many heats of a given alloy. This factor is relevant when the exact

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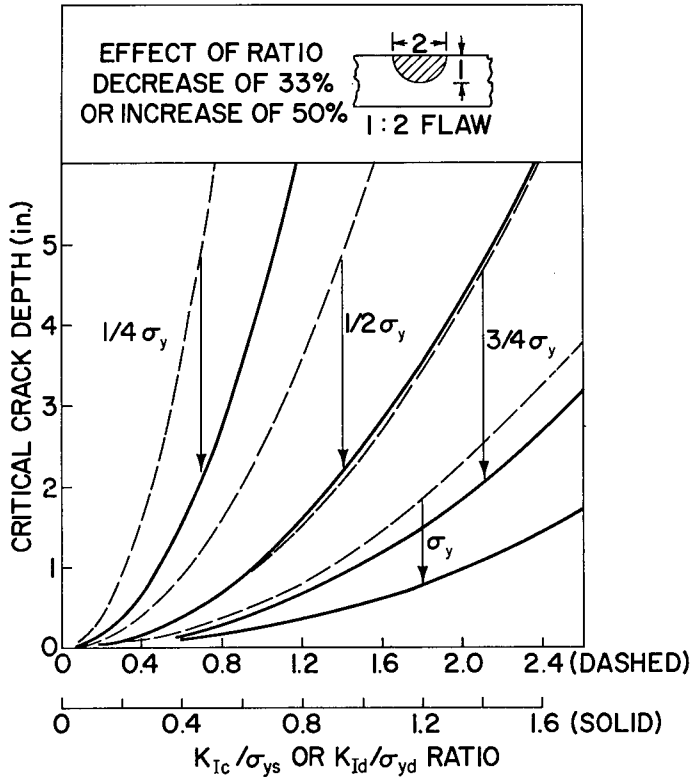

Fig. 7—The representation of the surface flaw equation of Fig. 6 has been redrawn to show the effect on critical crack depth of a 33% decrease in the K_{Ic}/σ_{ys} ratio (or conversely, a 50% increase in this ratio). Note that this decrease in the ratio results in flaws that are critical when they are less than one-half the size originally required (i.e., critical flaw depth decreases from 4.8 in. to 2.2 in. as the ratio decreases from 1.5 to 1.0 for 1/2 σ_y).

toughness for a particular region in a structure has not been measured and reliance is placed on, say, a set of toughness vs temperature values for a "representative" plate or weld. However, data from common structural alloys with which to define this statistical variation do not exist. Nevertheless, it is reasonable to assume that if statistical lower bound K_{Ic} or K_{Id} curves were determined for many heats of a given alloy, these curves would result in a K_{Ic} or K_{Id} band vs temperature as opposed to a single curve. It is considered reasonable to approximate the width of this band as 60°F (33°C) as is done in Fig. 8. This assumption is based on previous investigations (9,10) which showed the NDT temperature distribution for many heats of several structural steels to be at least 60°F. If the NDT temperature corresponds to a fixed ratio of K_{Id}/σ_{yd}, as discussed earlier, it then appears reasonable to postulate the existence of a 60°F wide statistical distribution in the lower bound K_{Ic} or K_{Id} curves. An example of this distribution is shown in Fig. 8. The K_{Id} curve representing the A533-B steel of Fig. 1 was used as a basis; the band in Fig. 8 was formed by translating this curve 60°F upward in temperature.

Figure 8 illustrates that the K_{Id} for the "worst" heat of an alloy could be only 1/2 as great as that from the "best" heat at a given temperature. In actual practice, assume that a structure contains material from several different heats while K_{Id} values have been measured from only one heat. In this event one is forced to assume that the *test heat* was, in fact, the *best heat*, and the K_{Id} values for the other heats may be 50% lower at a given temperature (i.e., the K_{Id}/σ_{yd} ratio drops by 50% also). This, in turn, means that the critical flaw size could be 1/4 of the value calculated on the basis of the same heat. The possible degradations in critical flaw sizes resulting from this K_{Ic} variation are depicted in Fig. 9.

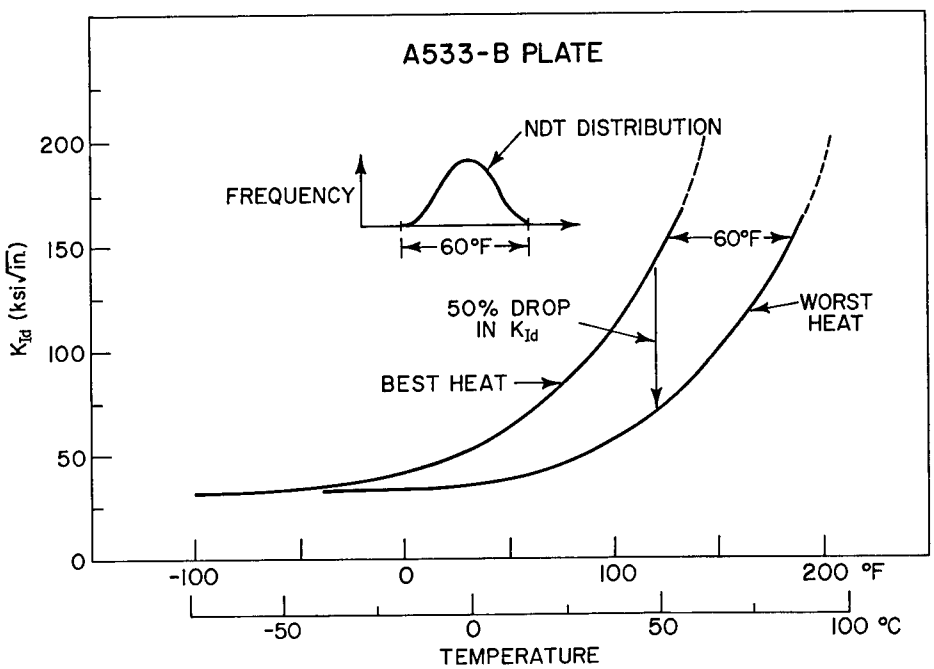

Fig. 8—Estimated envelope of K_{Id} curves representing the statistical distribution resulting from many heats of a given alloy. Each of the two curves represents the lower bound of the scatter from the "best" and "worst" heats. The K_{Id} curve from the A533-B plate in Fig. 1 was used as a basis. This curve was translated 60°F (33°C) in proportion to the distribution of NDT temperatures resulting from a study of many heats from each of several structural steels. Note the possible 50% drop in the K_{Id} value between the "best" and "worst" heats.

In an actual application one must consider the combined effect of the statistical variations and data scatter when assessing the critical flaw sizes. For example, suppose that in the previous case insufficient data were obtained from the best heat to define its lower bound curve of K_{Id} vs temperature. In other words, assume that the experimentally determined values represent the upper boundary of the scatter band as previously discussed. Thus the K_{Id} for the worst heat, instead of being lowered to 1/2 of the best heat value due to the

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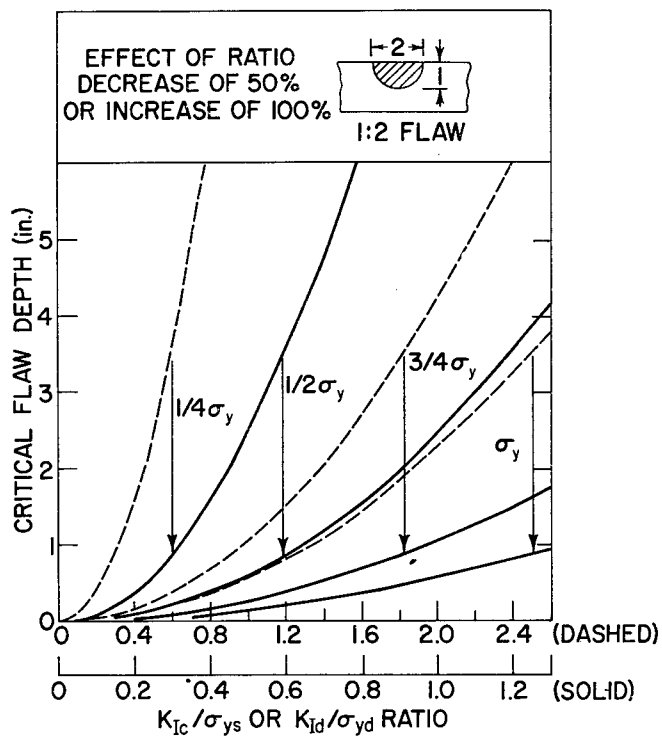

Fig. 9—The critical flaw size representation of Fig. 6 has been redrawn to show the effects of a 50% drop in the K_{Id} value (or K_{Id}/σ_{yd} ratio) resulting from the variations in fracture toughness due to the statistical distribution shown in Fig. 8.

statistical distribution, would be lowered to 1/3 of this value (i.e., 33% additional degradation in K_{Id} due to data scatter). The resulting critical flaw size for the worst material is then 1/9 of the value calculated from the K_{Id} measured from the best heat.

In addition to the above degradation in K_{Id}, recall that inaccuracies in temperature determination can further reduce the size of the critical flaw. An error of 20°F (or less at the upper end of the transition region) could reduce the K_{Id} of the worst material to 2/9 of the best heat value (i.e., 33% additional degradation in K_{Id} due to a 20°F temperature decrease); the critical flaw size is then only 1/20 of the expected value.

The preceding example is not meant to represent the average uncertainty in formulating a fracture control plan, but it is presented as a cautionary note to the casually informed user of LEFM. The point to be made is that there can be great uncertainties in the "exact" critical flaw size determined with fracture mechanics. To avoid this uncertainty one must be assured that the K_{Ic} measured in a test specimen actually represents the minimum toughness at any point in a structure at which a flaw may be present. It is often difficult, and certainly very expensive, to obtain this assurance. Consequently, other methods have been developed which offer inexpensive and reliable means for the collection of statistical data which are required to evolve fracture control plans of high engineering confidence levels. The Dynamic Tear (DT) test will now be considered as one such approach.

DYNAMIC TEAR TEST DEFINITION OF THE TOUGHNESS TRANSITION

The DT test offers a simple engineering method for defining the toughness trends in the transition temperature region. This evaluation technique (11) consists of measuring the energy required to fracture a dynamically loaded specimen containing a sharp notch; interpretative procedures (11-13) have been developed with which to relate the specimen energy absorption to the flaw size tolerances of all the common structural steels.

Figure 10 compares the DT and K_{Ic} trends for the A533-B steel shown in Fig. 1. The 12-in.-thick DT specimens provide a direct comparison with the similar thickness K_{Ic} and K_{Id} specimen data obtained by the Westinghouse Research Laboratories. Note that the DT specimen defines the full range of material toughness from the brittle lower shelf to the ductile upper shelf, whereas the LEFM data are restricted to the temperature region of frangibility comprising the lower one-third of the DT curve. Many fracture control plans require that service be limited to temperatures that are represented by the upper half of the DT curve (i.e., arrest criteria such as used for ships and reactor vessels). It is therefore important to ascertain the temperature range related to this toughness level. LEFM techniques cannot provide this information because the inherent metal ductility in this temperature regime invalidates the requirements of linear elastic behavior.

The use of the DT test to characterize the behavior of thick sections does not demand the testing of large specimens. Previous NRL research (14) has shown that it is possible to characterize thick-section material by means of a standard DT specimen of 5/8-in. thickness; the DT trends of the larger thicknesses are obtained by temperature elevation of the 50% DT shelf energy level as illustrated in Fig. 11 for the material described in Fig. 10. These temperature elevations are on the order of 20° to 40°F (11° to 22°C) for sections 2 to 3 in. thick, and ~70°F (39°C) for sections 12 in. thick.

The 50% shelf energy level corresponds approximately to the Fracture Transition Elastic (FTE) temperature. Above this temperature it is no longer possible to achieve fracture at

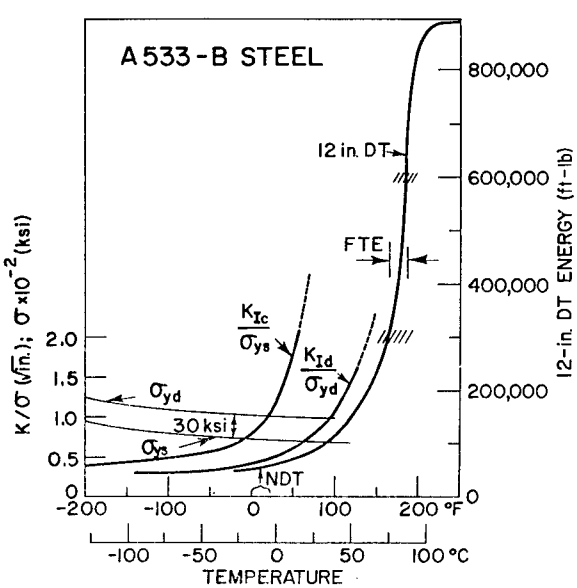

Fig. 10—Comparison of 12-in. DT test results with the thick-section fracture mechanics data of Fig. 1. The sharp transition in fracture toughness that evolves at temperatures above the NDT temperature is reflected by the fact the K_{Id} values are no longer definable at temperatures higher than those corresponding with the lower third of the DT curve. The FTE temperature is characterized by the narrow temperature interval corresponding to the middle third of the DT curve.

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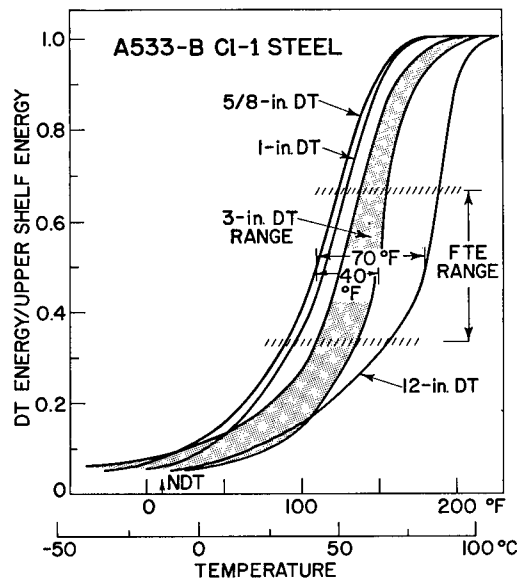

Fig. 11—Definition of the elevation in the FTE temperature resulting from the mechanical constraint associated with increasing thickness. Fracture energy from various thickness DT specimens has been normalized on the basis of the upper shelf level energy. The FTE temperature is defined by the narrow temperature interval corresponding to the middle third of the DT curve for the specific thickness. The data are from the same plate described in Fig. 10.

local stress levels less than the yield stress* and, consequently, dynamic K_{Id} values are unobtainable. Since the DT curve rises sharply in this temperature region, only small differences in FTE temperature result from choices of other fractions of DT shelf energy (e.g., 1/3 or 2/3) to approximate this temperature. Hence, the FTE temperature may fall in the region defined by the middle third of the DT curve as shown in Fig. 11. The elevation in the FTE temperature with thickness is a reflection of thickness-induced mechanical constraint. This fact restricts plastic flow and enables LEFM values to be obtained at higher temperatures (using appropriately thicker specimens). The fact that valid K_{Id} data are not obtainable at the FTE temperature has been documented in Ref. 14. Additional verification that the FTE temperature corresponds to requirements of yield stress loading has been demonstrated by Czechoslovakian tests of the Robertson-type on reactor pressure vessel steel (15).

The 50% DT energy level corresponds to the requirement of yield stress loading only if the upper shelf level is high, as is usually the case for carbon and low-alloy steels. (The presence of adequate shelf level toughness can be simply demonstrated with the DT test.) For high-strength steels or low-alloy steels that have been embrittled by irradiation, the 50% DT energy level may no longer correspond to the FTE temperature. The consequences of the resulting low shelf energy are discussed in Refs. 11, 13, and 16.

The use of the DT test in place of LEFM tests does not eliminate the need for statistical data to characterize different alloys. However, since small size DT specimens can be used to characterize thick-section behavior, there is no need to conduct large expensive tests as are mandatory to measure K_{Id} values. The DT specimen does not require expensive machining since saw-cut surfaces will suffice. The author estimates that the cost of preparing and testing 5/8-in. DT specimens in order to characterize a given material is about 1% of the cost of a

*Obviously, one can still obtain a fracture at nominal stress levels below yield if a sufficiently large flaw is present which results in plastic overload of the remaining ligament. However, this cannot be considered linear elastic behavior.

similar characterization using machined, fatigued-cracked, and instrumented LEFM specimens of similar size; the use of thicker K_{Id} specimens would be considerably more expensive. This is a distinct advantage when confronted with the necessity of obtaining a "data bank" of toughness trends to characterize different alloys and to obtain the limits of the statistical toughness distribution for a specific alloy and its weldments.

ENGINEERING APPLICATION OF TOUGHNESS TRENDS

The object in obtaining fracture toughness values is primarily for the purpose of formulating a fracture control plan that will assure structural integrity under a variety of loading and environmental conditions that depend on the specific structure. The toughness numbers by themselves have been overemphasized through research publications, while the meaning of these numbers as to structural integrity has been generally neglected. For example, the fact that a K_{Ic} value doubles in a given temperature increment is not necessarily significant. In Fig. 10, consider the consequences of doubling the K_{Id}/σ_{yd} ratio from 0.3 at −20°F (−29°C) to 0.6 at 80°F (27°C). The increase in critical flaw depth (Fig. 6) at yield stress loading is from 0.02 in. to 0.07 in. Obviously, this large percentage increase in flaw size is of little significance as far as an engineering structure is concerned. Both flaw sizes are difficult to detect in a consistent manner unless the structure is of very simple geometry. On the other hand, the critical depth of a flaw loaded to only 1/4 yield stress would increase from 0.4 to 1.5 in. over the same increase in the K_{Id}/σ_{yd} ratio. The point to be made is that low values of K_{Id} permit the materials to be used effectively only at low values of stress. If the structure contains points of stress concentration where stresses up to yield level are possible then these materials cannot be safely used. In the above example it is evident that for purposes of a fracture control plan it would have sufficed to have a simple technique with which to distinguish the region of low toughness from that of high toughness; a refined LEFM calculation was not appropriate.

The fracture control plan must stipulate a certain minimum toughness. This toughness is required in order to ensure fracture safety from flaws of unknown magnitude, assuming the structures have not yet been built. Therefore, some value of flaw size must be chosen as reasonably probable. The probability of finding all flaws larger than this by nondestructive means must also be incorporated in the fracture control plan. For normal engineering structures such as pressure vessels, ships or bridges, the author feels that it is reasonable to require a minimum K_{Id}/σ_{yd} ratio of 1.5 to 2.0. This range of values places the depth of the critical surface flaw for yield stress loading at 1/2 to 2-1/4 in., depending on the flaw shape (see Fig. 6).

To implement a fracture control plan of this type, it is necessary to demonstrate that at the lowest operating temperature the material exhibits a K_{Id}/σ_{yd} ratio at least as great as the required minimum. To gain this assurance it is obvious that lower bound K_{Id} values must be established for the material. If the lower bound values have not been established, then the possible errors discussed in the previous sections must be used to either increase the required minimum K_{Id}/σ_{yd} value, or alternatively to increase the minimum operating temperature to take advantage of the sharp increase of K_{Id} with temperature.

From Fig. 6 it can be seen that specimens of 5- to 10-in. thickness are required to measure ratios between 1.5 and 2.0. As explained earlier, it is difficult and expensive to obtain data with specimens of this size. The DT test provides an attractive alternate means for assuring the required level of toughness. The DT test has the advantage of accurately indexing

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the temperature region in which K_{Id} exhibits a sharp increase. When this test is used to define the FTE temperature for the section size in question, it automatically assures that the K_{Id}/σ_{yd} requirement of 1.5 to 2.0 has been satisfied. In other words, the FTE temperature signifies that local stresses greater than yield are necessary to propagate a fracture. Therefore, the K_{Id}/σ_{yd} ratio must be greater than 1.5-2.0. In fact, the ratio is so large at the FTE temperature that it is undefinable in linear elastic terms.

In Fig. 10 it can be seen that a K_{Id}/σ_{yd} value of 1.5 to 2.0 is equivalent to a minimum allowable temperature corresponding to one-third of the thick-section DT shelf energy. The choice of a minimum temperature based on a ratio value of 1.5-2.0 is therefore somewhat less conservative than that which would have resulted from the selection of the FTE temperature in the absence of LEFM data. In addition, the thick-section DT curve can be drawn from small-section (5/8-in.) DT data by using a 70°F (39°C) elevation of the 50% energy level and knowing that the DT energy/area values for all size specimens reach a common level at the NDT temperature (Fig. 11 and Ref. 14). When one accounts for uncertainties involved in the application of LEFM data, such as scatter and K_{Id} degradation resulting from temperature variations, it appears that a reasonable choice of a minimum structural operating temperature should be the FTE temperature.

The same conclusion is reached when considering sections that are not thick enough to measure a valid ratio of 1.5 to 2.0. Suppose the structural element thickness is 3 in. For this thickness only, valid K_{Id}/σ_{yd} values less than 1.1 can be measured. Therefore, if a minimum toughness that is equivalent to a ratio of 1.5 to 2.0 is required as part of the fracture control plan, it means that the structure operating temperature must be somewhere above the temperature corresponding to the measurable K_{Id} limit for that thickness. For the steel in Fig. 10, for example, the temperature corresponding to a ratio value of 1.1 is 100°F (38°C). Knowing that the K_{Id} values increase sharply in this temperature region, one might add 20°F (11°C) to the above temperature to achieve the level of toughness commensurate with the requirement that $K_{Id}/\sigma_{yd} \geqslant 1.5\text{-}2.0$. In an actual case, the minimum operating temperature would be chosen somewhat above 120°F (49°C) to account for possible inaccuracies in temperature measurement. The addition of 20°F (11°C) to account for this factor does not seem unreasonable. Therefore, one concludes that the minimum operating temperature for this structure should be close to 140°F (60°C). As seen from Fig. 11, this procedure is exactly equivalent to choosing the minimum operating temperature on the basis of the FTE temperature for a 3-in. section.

SUMMARY

The successful application of LEFM as a method for fracture-safe assurance requires an understanding of its limitations. These limitations have been discussed to evolve a balance between the theoretical exactness of LEFM and the realities associated with actual applications. The primary objective in characterizing the toughness of metals is to provide input to a fracture control plan. This plan is formulated to assure structural integrity under a variety of mechanical loads and environmental conditions.

LEFM has appeal for use in a fracture control plan because the method describes an analytical correspondence between the critical flaw size and stress level once the plane strain fracture toughness has been determined. The primary application of LEFM rests with the ultra-high-strength steels that are incapable of exhibiting ductile behavior in the presence of flaws. It is a natural tendency to attempt similar applications for the lower strength structural steels.

The carbon and low-alloy steels differ from the high-strength steels in two significant aspects. First, the structural grade steels can exhibit ductile behavior in the presence of flaws. This fact is the result of a brittle-to-ductile transition in fracture toughness that evolves within a relatively small temperature interval. Consequently, linear elastic theory loses applicability as this transition evolves. In a practical sense, LEFM is applicable only in the temperature regime associated with the initial development of the toughness transition. Second, the structural steels exhibit a strain rate sensitivity whereby the dynamic toughness can be considerably degraded from the static toughness. Conservative fracture-safe assurance practices therefore dictate the use of dynamic toughness.

The sharp increase in ductility in the transition temperature regime means that LEFM cannot be used to define the full toughness potential of a material that is to be used at temperatures near the upper end of the transition. Other analysis techniques, such as those describing elastic-plastic behavior, have not yet been developed to the point of engineering applicability. Consequently, other methods must be relied upon.

The corresponding increase in specimen thickness required to measure K_{Ic} or K_{Id} values in the transition temperature region presents another limitation for a structure whose thickness is less than that required to measure a K_{Ic} value at the operating temperature. One can only conclude that the toughness is higher than that measurable with specimens of thickness equal to that of the structure, but the advantage of an exact flaw size-stress level definition has been lost.

When actually applying LEFM methods to structural steels one must be concerned with a statistical distribution of the data. At a given temperature the scatter can be such that the critical flaw size may be less than half of the value calculated on the basis of an experimentally determined K_{Ic} value that represents the upper region of the scatter band. Unfortunately, few K_{Ic} and even fewer K_{Id} data exist with which to characterize the more common structural alloys. One is therefore forced, in the interest of conservatism, to conduct many fracture mechanics tests from the specific heats of steel used in a structure; this also includes each weld, heat-affected zone (HAZ), and forging. This procedure is generally impractical for engineering structures because of the expense involved. In practice, a temperature increment would be added to the minimum allowable operating temperature that has been determined on the basis of limited data.

In order to characterize a given alloy it must be realized that many heats of this alloy will result in a band of K_{Ic} values vs temperature, and this band may be 60°F (33°C) wide. Unfortunately, insufficient fracture mechanics data exist to define these trends for structural alloys. However, it is important to note that because of the sharp variations of K_{Ic} and K_{Id} trends in the transition region over a 60°F statistical band, the critical flaw size for the material used in a structure might be only one-fourth that determined on the basis of fracture mechanics tests on another heat of the same alloy.

Use of the LEFM values in a fracture control plan requires that the above statistical variations be combined. In addition, even relatively small errors in measuring the temperature of a structure (or the inability to exactly define the temperature limits of operation) can result in large changes in toughness. Consideration of these factors detracts from the quantitativeness offered by LEFM; in actual practice a temperature margin must be added to the lowest permissible operating temperature to assure that even the statistically worst properties are adequate to meet the requirements of the fracture control plan.

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The FTE temperature determined with the DT test defines a temperature above which stresses greater than yield level are required to propagate a fracture. Measurement of this toughness level is associated with loss of plane strain constraint, and this level therefore exceeds that which can be determined with LEFM specimens of the same thickness as the DT specimen. It is concluded that specification of the FTE temperature as the minimum operating temperature in a fracture control plan is essentially equivalent to evolving this temperature on the basis of experimentally determined K_{Id} values of the desired toughness level and then adding a temperature increment to account for the data scatter and variations in the actual temperature of operation.

The DT test offers a method of assessing fracture toughness that is significantly less expensive than the LEFM tests. With the DT test it is realistic (in an economic sense) to establish statistical toughness distributions for various alloys. When viewed in the context of the very sharply increasing toughness in the transition region, it is difficult to justify the use of an expensive LEFM test procedure. The objective of being able to define the temperature range and statistical distribution of K_{Id} curves is met equally by the use of DT or K_{Id} tests. The DT test can be used to project toughness levels down to the frangible region, while LEFM tests can be used to project toughness levels above those where plane strain constraint cannot be maintained.

REFERENCES

1. Wessel, E.T., Clark, W.G., Jr., and Pryle, W.H., "Fracture Mechanics Technology Applied to Heavy Section Steel Structures," Proceedings of the Second International Conference on Fracture, Brighton, April, 1969; "Fracture", London: Chapman and Hall, 1969.

2. Shabbits, W.O., "Dynamic Fracture Toughness Properties of Heavy Section A533 Grade B Class 1 Steel Plate," Westinghouse R&D Report WCAP-7623, Dec. 1970.

3. Shoemaker, A.K., and Rolfe, S.T., "The Static and Dynamic Low-Temperature Crack-Toughness Performance of Seven Structural Steels," Engineering Fracture Mechanics, 2:319-339 (1971).

4. Klausnitzer, E., "Fracture Toughness Tests on Forgings from 22NiMoCr37," Siemens/Aktiengesellschaft, Erlangen, Germany. Presented at Fifth Annual Information Meeting, Heavy Section Steel Technology Program, Oak Ridge, Tenn., Mar. 25-26, 1971.

5. Loss, F.J., and Pellini, W.S., "Coupling of Fracture Mechanics and Transition Temperature Approaches to Fracture-Safe Design," in "Practical Fracture Mechanics for Structural Steels," London: Chapman and Hall, 1969; also, NRL Report 6913, Apr. 14, 1969.

6. Krafft, J.M., and Sullivan, A.M., "On Effects of Carbon and Manganese Content and of Grain Size on Dynamic Strength Properties of Mild Steel," Trans. ASM, 55:101-118 (March 1962).

7. Wessel, E.T., unpublished data, 1969.

8. Irwin, G.R., "Crack-Extension Force for a Part-Through Crack in a Plate," Trans. ASME, J. Appl. Mech., 29:651-654 (1962).

9. Pellini, W.S., and Puzak, P.P., "Fracture Analysis Diagram Procedures for the Fracture-Safe Engineering Design of Steel Structures," Welding Res. Council Bull. Ser. 88 (1963); also, NRL Report 5920, Mar. 15, 1963.

10. Pellini, W.S., and Puzak, P.P., "Practical Considerations in Applying Laboratory Fracture Test Criteria to the Fracture-Safe Design of Pressure Vessels," NRL Report 6030, Nov. 5, 1963.

11. Pellini, W.S., "Evolution of Engineering Principles for Fracture-Safe Design of Steel Structures," NRL Report 6957, Sept. 23, 1969.

12. Pellini, W.S., "Integration of Analytical Procedures for Fracture-Safe Design of Metal Structures," NRL Report 7251, Mar. 26, 1971.

13. Pellini, W.S., "Advances in Fracture Toughness Characterization Procedures and in Quantitative Interpretations to Fracture-Safe Design for Structural Steels," Welding Res. Council Bull. 130, May 1968; also NRL Report 6713, Apr. 3, 1968.

14. Loss, F.J., "Effect of Mechanical Constraint on the Fracture Characteristics of Thick-Section Steel," Nuclear Eng. and Design, 17 (No. 1):16-31 (Aug. 1971).

15. Kalna, K., "Research on Strength and Resistance to Brittle Fracture of Large Bodies," Skoda Concern, Nuclear Power Plants Div., Pilzen, Czechoslovakia, Report No. ZJE 82, 1970.

16. Loss, F.J., Hawthorne, J.R., and Serpan, C.Z., Jr., "A Reassessment of Fracture-Safe Operating Criteria for Reactor Vessel Steels Based on Charpy-V Performance," Trans. ASME, J. Basic Eng., 93 (Series D, No. 2):247-258 (June 1971).

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13. ABSTRACT

An appraisal is made of linear elastic fracture mechanics (LEFM) as a method for fracture-safe assurance of carbon and low-alloy steels. The theoretical advantage of an exact flaw size-stress level relationship offered by LEFM is contrasted with the limitations posed in actual application. These limitations relate to statistical variations in K_{Ic} and K_{Id} data. The variations considered here are (a) data scatter at a given temperature, and (b) toughness variations between different heats of a given alloy. In an engineering context, LEFM is considered applicable only in the temperature region representing the initial development of the brittle-ductile transition that characterizes low-alloy steels. In this region statistical variations in the data can result in critical flaw sizes that are significantly smaller than the values calculated on the basis of limited experimental data.

The prime objective in determining fracture toughness is for use in evolving a fracture control plan that assures structural integrity under a variety of environmental and loading conditions. Often the exact flaw size is unknown, particularly if the structure has not yet been built. Since the toughness increases sharply in the transition region, a practical solution is to choose a minimum operation temperature that assures a high fracture toughness such that postulated flaws cannot propagate in an unstable manner.

The objective of being able to define the temperature range and statistical distribution of K_{Id} curves is met equally by the use of Dynamic Tear (DT) and K_{Id} tests. The DT test, as contrasted with LEFM methods, is shown to be an effective engineering tool with which to determine the Fracture Transition Elastic (FTE) temperature; above this temperature, plane strain constraint is lost for the given thickness, and flaws cannot propagate at stress levels less than yield. The determination of a minimum operating temperature based on dynamic LEFM values, when modified by conservatisms necessitated by statistical variations in the data and inaccuracies in temperature measurement, is shown to be essentially equivalent to the FTE temperature.

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