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M. B. REYNOLDS

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NUCLEONICS LABORATORY
VALLECITOS NUCLEAR CENTER
GENERAL ELECTRIC
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M. B. Reynolds

ABSTRACT

The problems met in attempting to apply linear elastic fracture mechanics to moderately tough materials in thin sections are discussed. The possibility of using impact tests to estimate the toughness of such materials is suggested and the test conditions which must be met are listed.

INTRODUCTION

Over the years there have been developed a number of tests to classify, if not actually measure, the sensitivity of engineering alloys with respect to the presence of cracks, flaws, or other stress concentrators. Of these tests, the plane strain fracture toughness test is unquestionably the most sophisticated. The advent of linear elastic fracture mechanics and the success with which the technique has been used to predict the failure behavior of flawed brittle structures has led many to hope that the same or similar techniques could be used to predict the failure behavior of ductile structures. The virtue of linear elastic fracture mechanics has been that it made possible the prediction of the load limit for a flawed structure in terms of flaw size and a single material parameter, the plane strain fracture toughness, K_{Ic}. The material property contribution to the fracture process can be specified completely by a single constant only so long as there is negligible plastic deformation at the tip of the advancing crack. As the size of this plastic zone increases, particularly in relation to the size of the structure, it is necessary to correct the measured crack length by an amount dependent on the ratio of the toughness (K_{Ic}) to the yield stress of the material. It should be noted that use of yield stress in the crack length correction term amounts to use of a second material property constant in the expression relating load limit to flaw size. The plane strain fracture toughness K_{Ic} is proportional to the square root of G_{Ic}, the fracture energy per unit area of fracture surface. K_{Ic} can then be a material constant and independent of structure size only if the energy expended in forming the layer of plastically deformed material accompanying the advancing crack is proportional to the crack area produced. For this condition to be met, the material thickness measured in a direction parallel to the crack edge must be great enough that maximum elastic constraint (and therefore minimum plastic zone size) is achieved over all but a negligible fraction of the length of the crack front. It is also necessary that the structure width be great enough relative to the crack depth that the inverse square root stress field characteristic of linear elastic fracture mechanics is not greatly distorted by the proximity of a free surface. How great this width needs to be depends somewhat upon the toughness-yield stress ratio for the material; obviously the advancing plastic zone boundary must not intersect a free surface on the side of the structure opposite the crack front.

FRACTURE TOUGHNESS DETERMINATION

In a fracture toughness (K_{Ic}) test, a specimen containing a crack prepared according to standardized procedures as specified by the Americal Society for Testing and Materials[(1)] is loaded monotonically until unstable crack extension leading to failure occurs. Ideally, in a brittle material, the specimen should load linearly and elastically* up to the instability load. Because of the plastic deformation at the crack tip before crack extension, perfect linearity up to instability is not always achieved, and a K_{Ic} test is not "valid" unless the deviation from linearity lies within specified limits. There are also specified limits to the ratio of specimen width to crack depth as well as to specimen thickness. This latter specification requires that for a "valid" K_{Ic} determination the specimen thickness must be at least $2.5\,(K_{Ic}/\sigma_{ys})^2$. It is an unfortunate fact that catastrophic failures have sometimes occurred in materials which are neither manufactured nor used in section thicknesses great enough to permit fabrication of a valid fracture toughness specimen based on the ASTM thickness criterion.

A "valid" K_{Ic} value is that number which defines a lower limit for the load which a flawed, thick-section structure can support.** It is quite possible that a flawed real structure, particularly in section thickness less than that required for a valid K_{Ic} test, will fail at a load greater than that which would be predicted from the limiting K_{Ic} value. In fact, a K_c value from less than optimum test conditions may be more nearly descriptive of the actual failure load than is the true thick section K_{Ic} value. For example it has been found possible to estimate failure loads in axially flawed low carbon steel pipes in terms of a constant having the dimensions of a stress intensity factor in spite of the fact that the section (wall) thickness was much less than that required for a valid fracture toughness test.*** Also, the values obtained in these pipe tests are not markedly different from those which would be obtained by extrapolation of valid K_{Ic} versus temperature curves for similar material.[4] These values should not be unexpected. The load limit for a brittle structure which can be treated by linear elastic fracture mechanics decreases monotonically with increasing flaw size and so does that for a structure made of material of sufficiently low yield strength that flaw extension occurs by ductile necking and tearing rather than by brittle fracture. The mathematical expression relating load limit to flaw size, in general, will not be so simple for the ductile case as for the brittle, but such expressions can be generated from experimental data in combination with some physical intuition. Furthermore, as the toughness of the material decreases, the relation of load limit and flaw size predicted by such an expression should approach that of linear elastic fracture mechanics. Deviation from the ideality of linear elastic fracture mechanics does not occur suddenly and discontinuously when a certain limiting combination of values of toughness, yield strength, and section thickness is reached. Rather there appears to be a "gray zone" in which constants having at least the dimensions of stress intensity factor can be measured under less than ideal test conditions and can be used to make approximate, if not completely accurate, estimates of limit loads for structures of section comparable to that of the test specimen.

Methods of Estimating Approximate Fracture Toughness

The ASTM restrictions on specimen size for valid K_{Ic} tests were mentioned above. In some cases, a standard fracture toughness specimen (for example the 1X WOL specimen) will load linearly to a sharp instability although the K_{Ic}-to-yield strength ratio for the material is greater than the acceptable limit for the specimen section thickness. The critical stress intensity factor calculated from the instability load in this case should be indicative of the fracture behavior of the material in structures of this section thickness even though it does deviate from the true value of K_{Ic}.

* As indicated by crack opening or other suitable measure of deformation.

** Increasing refinement of K_{Ic} measurement techniques should result in decreasing values until a limiting value is reached. This minimum value should represent the true K_{Ic} for the material.

*** Eiber, et al.,[2] obtained a value of approximately 300 ksi $\sqrt{\text{in.}}$ at about 600°F; Reynolds[3] obtained a value of approximately 100 ksi $\sqrt{\text{in.}}$ at 60°F. Both investigators used ASTM A106B pipe.

One source of approximate fracture toughness information which is of some value is the impact test. It was pointed out that G_{Ic} is a measure of the energy required to create unit area of fracture surface. The impact fracture energy measured in a conventional Charpy test is the sum of the energy required to create the central flat fracture and the shear lips at the boundaries of the fracture surface. The energy required to form the shear lips normally is much greater than that to form the flat fracture. If the energy per unit area of flat fracture surface can be obtained either by extrapolation based on tests of specimens of different thickness[(5)] or by suppressing the shear lips to negligible dimensions, this value W/A may be used to estimate an upper limit on K_{Ic}.* We may safely assume that

$$G_{Ic} \leq \frac{W}{A}$$

and that

$$K_{Ic} \leq \sqrt{E(W/A)}$$

Shear lip suppression may be accomplished with varying degrees of success by nitriding, side notching, or fatigue pre-cracking the impact specimen used for fracture toughness estimation. Because of the increase in yield strength with increasing strain rate exhibited by most materials, dynamic fracture toughness values are lower than static K_{Ic} values. This effect may to some extent compensate for the effect of plastic deformation (shear lip formation) at the specimen surfaces. To measure the rather low (a few foot-pounds) fracture energies obtained in such tests, a low range impact test machine is required and corrections should be made for the kinetic energy of broken specimens. If all necessary corrections are made, the data obtained for materials of reasonably low toughness, such as low-strength ferritic steels, by the impact test are comparable with data obtained with standard fracture toughness specimens.

To illustrate this point, a comparison of the data from several specimen types is presented in Figure 1. All specimens with the exception of three of A106B were made from a single 1 × 1-inch bar of cold-rolled steel. Specimens used included:

<u>IMPACT</u>

5.5 × 1.0 × 1.0 cm, nitrided, 0.008 cm notch root;
5.5 × 1.0 × 1.0 cm, nitrided, 0.025 cm notch root;
5.5 × 1.0 × 0.5 cm, nitrided, 0.025 cm notch root;
5.5 × 1.27 × 1.27 cm, nitrided, 0.008 cm notch root and notched on 3 sides.

<u>STATIC</u>

1 × WOL, nitrided;
1 × 2 × 5.5 cm, 3 point-bend (pre-cracked Charpy).

The impact tests were made with a Manlabs Test machine of 24-ft-lb maximum capacity. Impact velocity was approximately 11.2 ft/sec.

In loading the nitrided WOL specimens, initial pop-in which corresponded to the fracture of the nitride case was followed by crack arrest when the crack had extended into the tougher base material. Upon increasing the load, the specimens loaded linearly until a second pop-in followed by complete brittle fracture occurred. The load at the second pop-in was taken to be representative of the base material and was used in the calculation of K_c.

*Assuming the Poisson ratio ν to have the usual value of 0.3, the factor $(1 - 2\nu)$ in the expression relating K_{Ic} to G_{Ic} contributes but 5% to the value of K_{Ic} and may be neglected here.

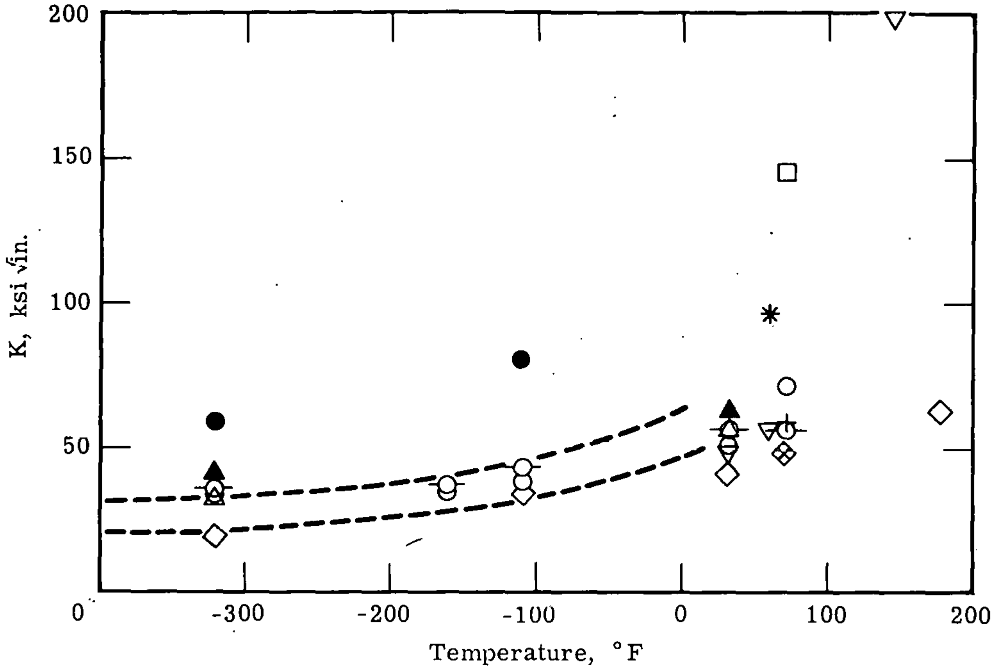

FIGURE 1. K VALUE: SPECIMEN DEPENDENCE

The dotted lines in Figure 1 envelop the valid K_{Ic} data obtained by Wessel(4) for A302B pressure vessel steel. Since this scatter band will also encompass available K_{Ic} versus temperature data for a surprising number of low-to-medium-strength ferritic steels at temperatures below the brittle-ductile transition, it is felt to be a reasonable standard against which to compare the impact test data. The fracture toughness of those materials which exhibit increasing yield strength with increasing strain rate decreases with increasing fracture velocity. Hence, the impact test K_c values may be expected to lie below the A302B scatter band if the tests have been properly conducted; that they do not at low temperatures is probably because specimen residual kinetic energy, fraction, and other experimental errors become more significant at low energy values and lead to positive errors in the measured fracture energy. Negative errors, which would appear to exist if comparison with the A302B data is valid, would lead to conservative estimates of the load limits for real structures. It may be noted in passing that a scatter band encompassing the impact data in Figure 1 would be little wider than the A302B band.

There are several ways of suppressing shear lip formation. All of them have some disadvantage which must be evaluated with reference to the material of interest. Fatigue cracking the notch in a Charpy specimen has little or no effect on shear lip formation along the sides of the specimen, but does produce some decrease in measured fracture energy because of the reduction in energy required to initiate fracture. Surface nitriding is most effective in suppressing shear lip formation, but the process requires exposure of the specimen to elevated temperatures with possibility of resultant metallurgical changes. In the experiments upon which the data reported were based, subjecting standard Charpy specimens of low carbon steel to the same temperature cycle (24 hours at 950°F) as used in the nitriding process produced an increase in fracture energy as indicated by tests on standard Charpy specimens. It is quite possible that this temperature cycle would adversely alter the properties of some materials.

Although it does not yield W/A values so low as does the nitrided Charpy specimen, the 1.27 cm (1/2 inch) square, triple-notched specimen appears to be a good compromise when nitriding is precluded because of adverse thermal effects. The three notches of 0.008 cm or smaller root radius are easily cut by broaching and can be further sharpened if desired by pressing a hardened knife edge into the notch root. This specimen is of larger-than-standard Charpy cross section and may require some modification of the test machine to accommodate it, but side-notching a standard Charpy specimen considerably reduces the fracture area and increases the ratio of shear lip to flat fracture area. Early, rather qualitative tests with this specimen appeared encouraging, but to date no further effort has been made to optimize its dimension.

In summary, it would appear that the impact test may be a useful source of upper-limit fracture toughness values where available section thickness does not permit valid fracture toughness testing under the ASTM criteria. For impact W/A data to be applicable to K_c estimation the following conditions must be met:

1. A sensitive, rigid impact test machine must be used to minimize energy absorption by vibration and machine friction.
2. All possible corrections must be made for broken specimen kinetic energy, windage, and so forth, particularly at low energy values.
3. The contribution of shear lip formation to the measured impact fracture energy must be removed either by an extrapolation process based on multiple specimen widths or by modification of the specimen by nitriding, side notching, or other means either to eliminate shear lip formation or to reduce it to an insignificant portion of the fracture surface.

Impact fracture testing is not recommended as a replacement for valid static fracture toughness testing, but rather for those cases in which nothing else is available for estimating fracture toughness.

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