REAPPRAISAL OF FRACTURE TOUGHNESS TESTING AND ASSESSMENT PROCEDURES

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ABSTRACT

Current plane strain fracture toughness standards specify that both the crack length a and the thickness B should be greater than 2.5 $(K_Q/YS)^2$ and that the K_{max}/K_Q ratio should be less than 1.10. Some existing data have been reanalysed in an attempt to resolve a number of questions revealed through experience in using the standards. Application of the criteria tend to result in data which are conservative with respect to K_{IC} values from large test pieces. They are also unduly restrictive with regard to the minimum permissible thickness.

It is suggested that:-

(a) The thickness criterion should be either reduced or removed.

(b) Either the term 'invalid' should be replaced by 'conservative' or a plasticity correction of the form $r_y = 0.4\ (K_Q/YS)^2$ and $a = a_o + r_y$ should be reintroduced and the crack length criterion replaced by a limitation on ligament size as a function of r_y.

(c) The K_{max}/K_Q criterion should be removed.

K_{IC} values calculated with the above modifications are independent of test piece geometry. The equivalent critical defect size calculation is of the form

$$a_c = K_{IC}^2/\pi\sigma^2(1 + 1.26\ (\sigma/YS)^2)$$

KEYWORDS

Fracture properties; fracture mechanics; fracture tests, fracture toughness; fracture.

INTRODUCTION

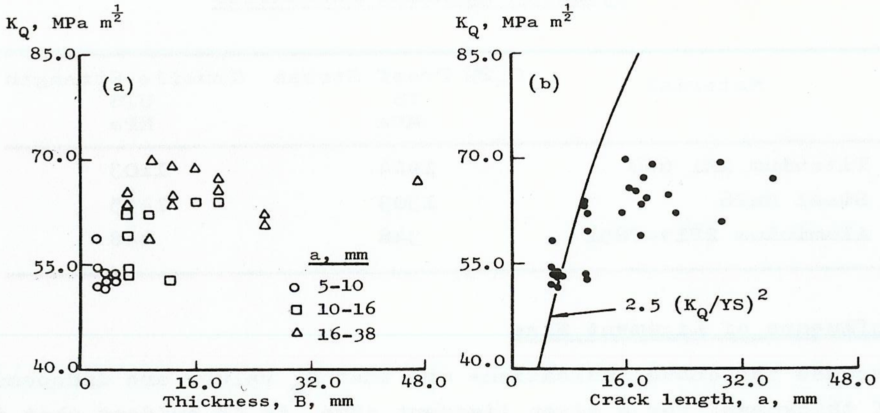
Originally the inclusion of a minimum thickness criterion in linear elastic fracture mechanics (LEFM) test procedures was based on the observation that fracture toughness values tended to increase as the thickness of test pieces was reduced. The 5% offset procedure (BSI 1977) had not been adopted at that time and the fracture toughness values on which this observation was based were measured at pop-in or maximum load. Subsequently May (1970) reported that K_Q values using the offset procedure could be higher for thinner test pieces, whilst Jones and Brown (1970) observed that, depending on the width of the test piece (W) K_Q values could either increase or decrease with thickness (B). However, reanalysis of the actual test records from the former indicates that the results on which the above conclusion was based must be discounted because of calibration errors discovered since. The values reported by Jones and Brown are somewhat at variance with the data for three alloys reported below and for much other data not reported. Data was also obtained from test pieces in which both B and W were varied in proportion and the occurrence of size effects was attributed to the influence of B although the governing factor could equally have been W or a. In fact, as observed by Kaufman and Nelson (1973) K_Q values for the aluminium alloy 2219-T851 are independent of thickness and only the crack and ligament dimensions have any effect.

Some of the above data (Kaufman, 1974) and other data (Wilkinson and Walker, 1971) have been reappraised and suggestions made regarding alternative criteria to those in existing standards.

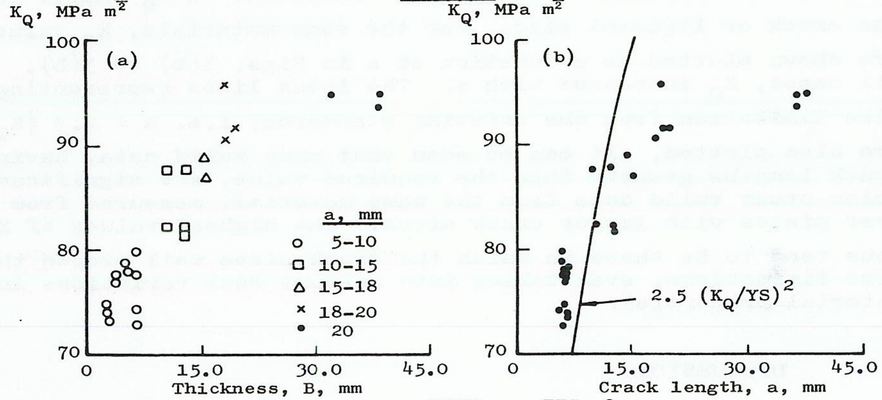
PRESENTATION OF RESULTS

Influence of Thickness

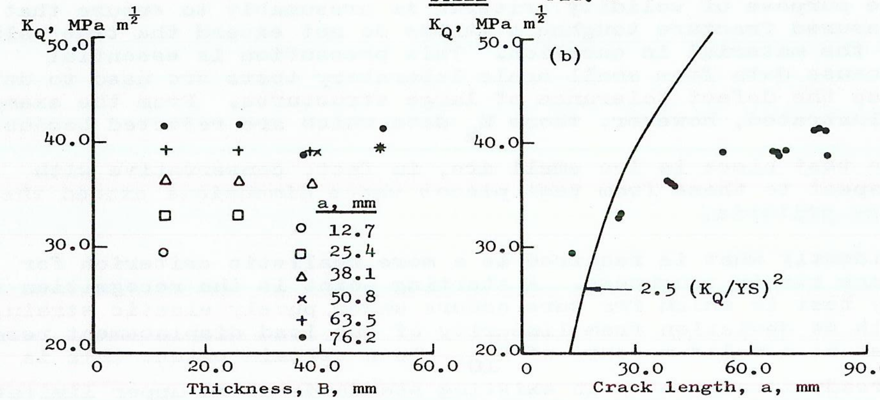
In order to separate the influence of thickness from the influence of crack size, data from restricted ranges of ligament size have been examined separately. A typical example of the relationships obtained is given in Figs. 1(a) to 3(a) where K_Q values for the materials listed in Table 1 are shown plotted as a function of thickness B for restricted crack sizes, a. It can be seen that the K_Q values in a given range do not vary significantly with thickness. The minimum thickness in these three cases extended to below the present criterion $2.5\ (K_Q/YS)^2$, where YS is 0.2% proof stress.



TITANIUM FIG. 1



STEEL FIG. 2



ALUMINIUM

Fig. 3 Influence of Test Piece Dimensions on K_Q Values

TABLE 1 MATERIAL PROPERTIES

Material	0.2% Proof Stress YS MPa	Tensile Strength UTS MPa
Titanium 1M1 680	1024	1103
Steel En26	1303	1455
Aluminium 2219-T851	348	448

Influence of Ligament Size

Because the above indications are that K_Q values are independent of thickness, for a given ligament size, it is evident that the only factor which has a significant influence on K_Q values is the crack or ligament size. For the same materials, K_Q values are shown plotted as a function of a in Figs. 1(b) to 3(b). In all cases, K_Q increases with a. The locus lines representing the size limitation from the existing standards, i.e. $a = 2.5\ (K_Q/YS)^2$ are also plotted. It can be seen that many valid data, having crack lengths greater than the required value, are significantly below other valid data from the same material, measured from test pieces with larger crack sizes. The highest values of K_Q thus tend to be those in which the crack sizes well exceed the size limitations, even taking into account real variations in material properties.

DISCUSSION

The purpose of validity criteria is presumably to ensure that measured fracture toughness values do not exceed the true value of the material in question. This precaution is essential because data from small scale laboratory tests are used to determine the defect tolerance of large structures. From the examples illustrated, however, those K_Q data which are rejected because the test piece is too small are, in fact, conservative with respect to those from test pieces whose dimensions exceed the size criteria.

Evidently what is required is a more realistic criterion for plane strain toughness. A starting point is the recognition that any test in which fra ture occurs under purely elastic strain, with no deviation from linearity of the load displacement record must be a valid measure of K_{IC}. To a certain extent this is already incorporated in existing standards as an upper limitation on the ratio K_{max}/K_Q of 1.10. However, analysis of the previous data indicates that tests with K_{max}/K_Q ratios of greater than 1.10 often exhibit lower K_Q values than the above defined value of K_{IC} when the ratio is unity, Fig. 4. Here again, therefore, compliance with the K_{max}/K_Q criterion results in the rejection of conservative values.

Originally it was recommended that a plastic zone size correction factor be added to the original crack length a_o in an iterative procedure for the determination of K_{IC} values. The expression used was:-

$$r_y = (K_Q/YS)^2/2\pi \qquad (1)$$

In subsequent test procedures and standards this recommendation was omitted, presumably in order to simplify fracture analysis. However, it is clear from the above data that test pieces with small crack sizes exhibit low K_Q values. A plastic zone correction should increase these values more for smaller test pieces than for larger ones. Modified K_Q' values for the three materials illustrated have, therefore, been recalculated using a single empirically determined plastic zone correction,

$$a = a_o + 0.4\ (K_Q/YS)^2 \qquad (2)$$

together with the compliance functions (Y) given in ASTM E399:83. The K_Q' values, in Fig. 5 are independent of crack length and significantly higher than the original K_Q values calculated without a plastic zone correction. The data from the test pieces with small crack lengths are in line with those from the largest test pieces, many of which exhibited linear elastic failure. The increased scatter at small crack lengths is probably a feature of inaccuracies in measuring a_o which tends to be compounded in the calculation. In many of the tests the nominal stress exceeded the uniaxial yield stress.

At very small ligament sizes when r_y is greater than (W-a), failure is governed by the tensile properties and the 5% offset load is related to the yield stress rather than the fracture toughness of the material. This situation predominates in the fracture of low strength high toughness materials where fracture is by a fully ductile shear mechanism. The development of such shear crack growth by void initiation has been shown to be a function of the nominal stress, (Priest, 1982). The main point here is that the plasticity correction would not be viable at ligament sizes less than $0.4\ (K_Q/YS)^2$, independent of the crack length.

Since the conservatism in K_Q values appears to be the result of omitting a plastic zone correction, this factor could also be

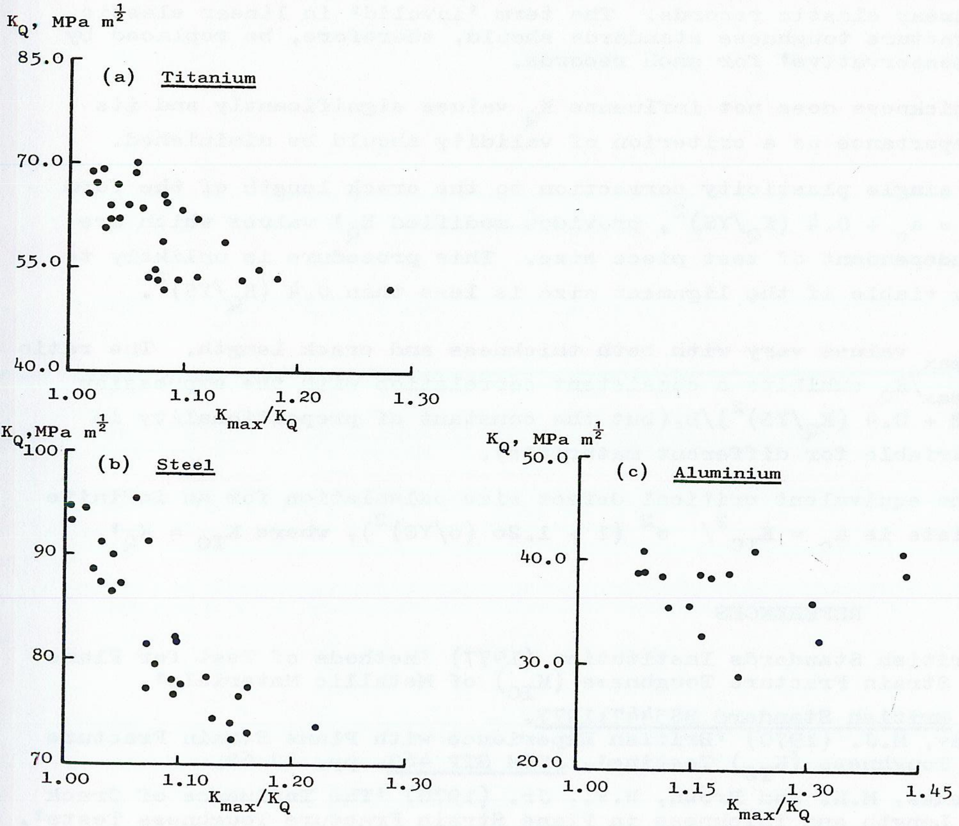


Fig. 4 K_Q As a Function of K_{max}/K_Q

responsible for the variation in K_{max}/K_Q ratio with test piece dimensions. The higher K_{max} values result from an additional fracture resistance as a result of shear deformation accompanying crack extension, as indicated by R curves in, e.g. J integral tests. The shear lip size is independent of test piece thickness and should, therefore, have a more pronounced effect on thinner test pieces. Such a relationship between the K_{max}/K_Q ratio and thickness is illustrated by the correlation with the expression $(B + 0.4\ (K_Q/YS)^2)/B$ in Fig. 6. The scatter in some of the data is probably again the result of inaccuracies in determining crack length and also material variation. The different slopes for the three materials represent differing R curves which are not necessarily related to the fracture toughness. The strong dependence of K_{max}/K_Q ratio on B, indicates that the ratio is not a suitable criterion for confirming validity, since K_Q is independent of B.

In view of the independence of K_Q' values of both crack length and thickness it is reasonable to equate this value to K_{IC} for the purpose of defect tolerance calculations. Using the above relationships for the analysis of defects in an infinite plate,

$$K_{IC} = \sigma\ (\pi\ (a + r_y))^{0.5} \qquad (3)$$

and

$$a_c = K_{IC}^{\ 2}/\pi\sigma^2\ (1 + 1.26\ (\sigma/YS)^2) \qquad (4)$$

where σ is applied stress.

At low values of stress if a safety factor of two is included, the latter relationship is in line with the defect tolerance calculations in at least one current method (BSI, 1980) which gives:-

$$a_c = K_{IC}^{\ 2}/2\pi\sigma^2 \qquad (5)$$

At values of stress approaching YS, however, the relationship is more conservative. However, this is counterbalanced by the higher values of K_Q' calculated with the plastic zone correction. In this type of analysis

$$K/K_{IC} = (1/(1 + 1.26\ (\sigma/YS)^2))^{0.5} \qquad (6)$$

and K is the apparent stress intensity factor, without plasticity correction, equal to failure to K_Q.

In current fracture assessment procedures, the criteria of failure may differ between structure and test piece. In contrast in the proposed method the criteria of failure are the same, being either an indication of non-linear deformation equivalent to 5% change in elastic crack opening compliance, in line with the test procedures

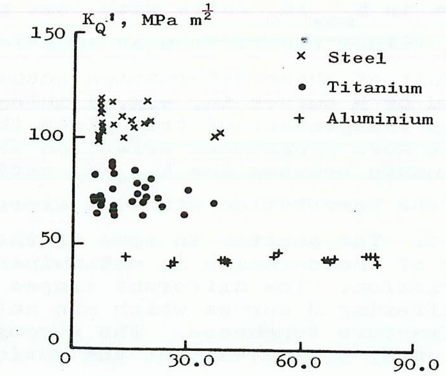


Fig. 5 Modified K_Q' Values as a Function of Crack Length

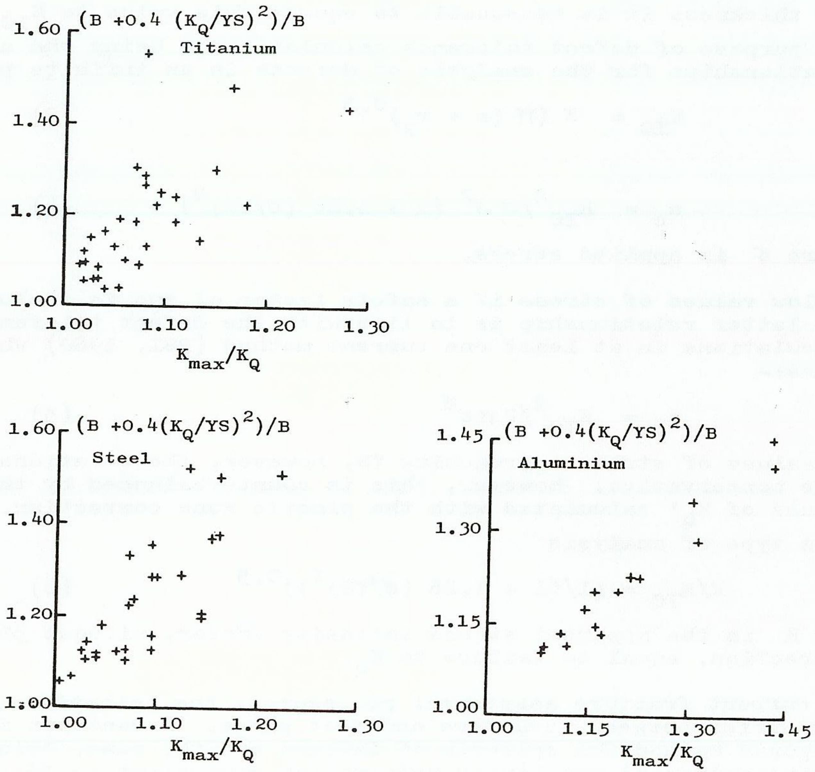


Fig. 6 Influence of Thickness on K_{max}/K_Q Ratio

for plane strain fracture toughness, or the achievement of yield stress.

CONCLUSIONS

K_Q values from tests exhibiting non-linear load-displacement behaviour are conservative with respect to values obtained from linear elastic records. The term 'invalid' in linear elastic fracture toughness standards should, therefore, be replaced by 'conservative' for such records.

Thickness does not influence K_Q values significantly and its importance as a criterion of validity should be diminished.

A single plasticity correction to the crack length of the form $a = a_o + 0.4\ (K_Q/YS)^2$, provides modified K_Q' values which are independent of test piece size. This procedure is unlikely to be viable if the ligament size is less than $0.4\ (K_Q/YS)^2$.

K_{max} values vary with both thickness and crack length. The ratio K_{max}/K_Q exhibits a consistent correlation with the expression $(B + 0.4\ (K_Q/YS)^2)/B$, (but the constant of proportionality is variable for different materials).

The equivalent critical defect size calculation for an infinite plate is $a_c = K_{IC}^{\ 2}/\ \sigma^2\ (1 + 1.26\ (\sigma/YS)^2)$, where $K_{IC} = K_Q'$.

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