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 \(K_{\text{max}}/K_Q\) 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
\[
r_Y = 0.4 \left( K_Q / YS \right)^2
\]
and \(a = a_0 + r_Y\) should be reintroduced and the crack length criterion replaced by a limitation on ligament size as a function of \(r_Y\).
(c) The \(K_{\text{max}}/K_Q\) 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
\[
a_c = K_{IC}^2 / \pi \sigma^2 \left(1 + 1.26(\sigma/YS)^2\right)
\]

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 (BST 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 KQ 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) KQ 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) KQ 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 KQ 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 KQ 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 (KQ/YS)^2, where YS is 0.2% proof stress.
TABLE I MATERIAL PROPERTIES

<table>
<thead>
<tr>
<th>Material</th>
<th>0.2% Proof Stress YS MPa</th>
<th>Tensile Strength UTS MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Titanium 1114-680</td>
<td>1024</td>
<td>1103</td>
</tr>
<tr>
<td>Steel Em26</td>
<td>1303</td>
<td>1435</td>
</tr>
<tr>
<td>Aluminium 2219-T851</td>
<td>348</td>
<td>448</td>
</tr>
</tbody>
</table>

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., $a = 2.5 \left( \frac{K_Q}{YS} \right)^2$ 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 fracture occurs under purely elastic strain, with no deviation from linearity of the load displacement record must be a valid measure of $K_Q$. 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 $\frac{K_{max}}{K_Q}$ ratios of greater than 1.10 often exhibit lower $K_Q$ values than the above defined value of $K_{TC}$ 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 $K_{TC}$ values. The expression used was:

$$ r_y = \left( \frac{K_Q}{YS} \right)^2 / 2 \pi $$

(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,

$$ a = a_o + 0.4 \left( \frac{K_Q}{YS} \right)^2 $$

(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 % 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, (V. Pries, 1982). The main point here is that the plasticity correction would not be viable at ligament sizes less than $0.4 \left( \frac{K_Q}{YS} \right)^2$, 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
responsible for the variation in $K_{\text{max}}/K_Q$ ratio with test piece dimensions. The higher $K_{\text{max}}$ 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 $K_{\text{max}}/K_Q$ 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 $K_{\text{max}}/K_Q$ 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,

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

and

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

where $\sigma$ 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:

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

$$K/K_{IC} = (1/(1 + 1.26 (\sigma/YS)^2))^{0.5}$$  (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.
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 \(a = a_0 + 0.4 \left(\frac{K_Q}{YS}\right)^2\), 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 \(\left(\frac{K_Q}{YS}\right)^2\).

\(K_{\text{max}}\) values vary with both thickness and crack length. The ratio \(K_{\text{max}}/K_Q\) exhibits a consistent correlation with the expression \((B + 0.4 \left(\frac{K_Q}{YS}\right)^2)/B\), (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 \(K_{IC} = K_Q^1\).

**REFERENCES**


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