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The Effect of Specimen Geometry on Fracture Toughness Transition Behaviour

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ABSTRACT This report concerns fracture toughness tests performed on A533B-1 pressure vessel steel. A total of 76 specimens were tested within the lower transition regime using compact tension specimens with thicknesses (B) in the range 25 to 127 mm and with width to thickness ratios (W/B) of 2 or 1.2. All specimens failed by cleavage fracture without prior ductile crack extension.

Statistical analysis of the results has indicated that mean values of the K_{IC} parameter, as defined in existing UK and US national testing standards, are size dependent. A possible explanation for the results has been advanced in terms of the inability of small specimens to sample the full range of *valid* K_{IC} values at a given temperature, due to specimen size restrictions imposed by the standards. The same effect was also observed in terms of an alternative linear elastic parameter, K_{LE}.

As a comparative exercise, mean values of toughness at the point of failure were also computed using *all* results for a given specimen size regardless of whether failure was entirely elastic or not. The resulting mean toughness values were found not to be size dependent. These results are considered to have important implications for the status of K_{IC} as a material property.

Introduction

According to testing Standards in the United Kingdom **(1)** and the United States of America **(2)** valid measurements of the fracture toughness parameter K_{IC} can only be made providing that test specimen dimensions satisfy the relationship

$$a, B \geqslant 2.5(K_{IC}/\sigma_y)^2 \quad (1)$$

where

a = specimen crack length
B = specimen thickness
σ_y = material yield stress

The minimum specimen sizes needed to satisfy equation (1) were based largely upon the experimental work of Brown and Srawley **(3)**. The importance, and inconvenience, of the resulting size criteria have prompted numerous subsequent workers **(4)–(10)** to investigate the size dependence of K_{IC} data. As a result of these studies, arguments have been proffered both for **(9)**

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and against **(5)(7)(10)** the use of specimens smaller than those defined by equation (1). Nonetheless, the original criteria remain unchanged.

The initial objective of the present experimental programme was to study the effect of W/B ratio on K_{IC} values. The impetus behind the work was practical; smaller W/B ratios would help conserve material when characterising the longitudinal fracture properties of thick section weldments. In the event however, a more general question concerning the size dependence of K_{IC} values assumed greater importance. An outline summary of the programme and its results is presented below; more complete details, including full statistical analyses, are presented elsewhere **(11)**.

Material and specimen geometries

The material used for the experimental programme was a 160 mm thick plate of A533B-1 steel. The chemical composition of the plate is given in Table 1. A large number of tensile data were obtained throughout the temperature range of interest, tests having been performed according to either the ASTM E8 or BSI 18 standard test methods. Tensile tests exhibited neither sharp yield points nor discontinuous stress–strain curves. Consequently, yield stress values have been approximated by using 0.2 percent proof stress ($\sigma_{0.2}$) levels (i.e., stress levels at 0.2 percent strain measured over a standard gauge length). Eyeline bounds to $\sigma_{0.2}$ values are presented, for each of the principal test temperatures, in Table 2.

All fracture toughness test specimens were manufactured as either standard (CT) or 'squat' (SCT) compact tension specimens with a/W ratios in the range 0.5–0.55. Standard compact tension specimens (CT; $W/B = 2.0$) were tested in four thicknesses and squat compact tension specimens in three thicknesses. The complete test matrix is given in Table 3. Relative positions of specimens within the plate are shown in Fig. 1.

Table 1 Chemical composition by product analysis (wt percent)

C	*Mn*	*Mo*	*Ni*	*Si*	*Cr*	*S*	*P*	*Cu*	*Sn*	*Co*
0.19	1.25	0.49	0.68	0.21	0.13	0.013	0.017	0.07	0.011	0.009

Table 2 Bounds to 0.2 percent proof stress values at principal test temperatures

Test temperature (°C)	*Lower bound* $\sigma_{0.2}$ (*MPa*)	*Upper bound* $\sigma_{0.2}$ (*MPa*)
−65	445	505
−75	460	525
−85	480	545

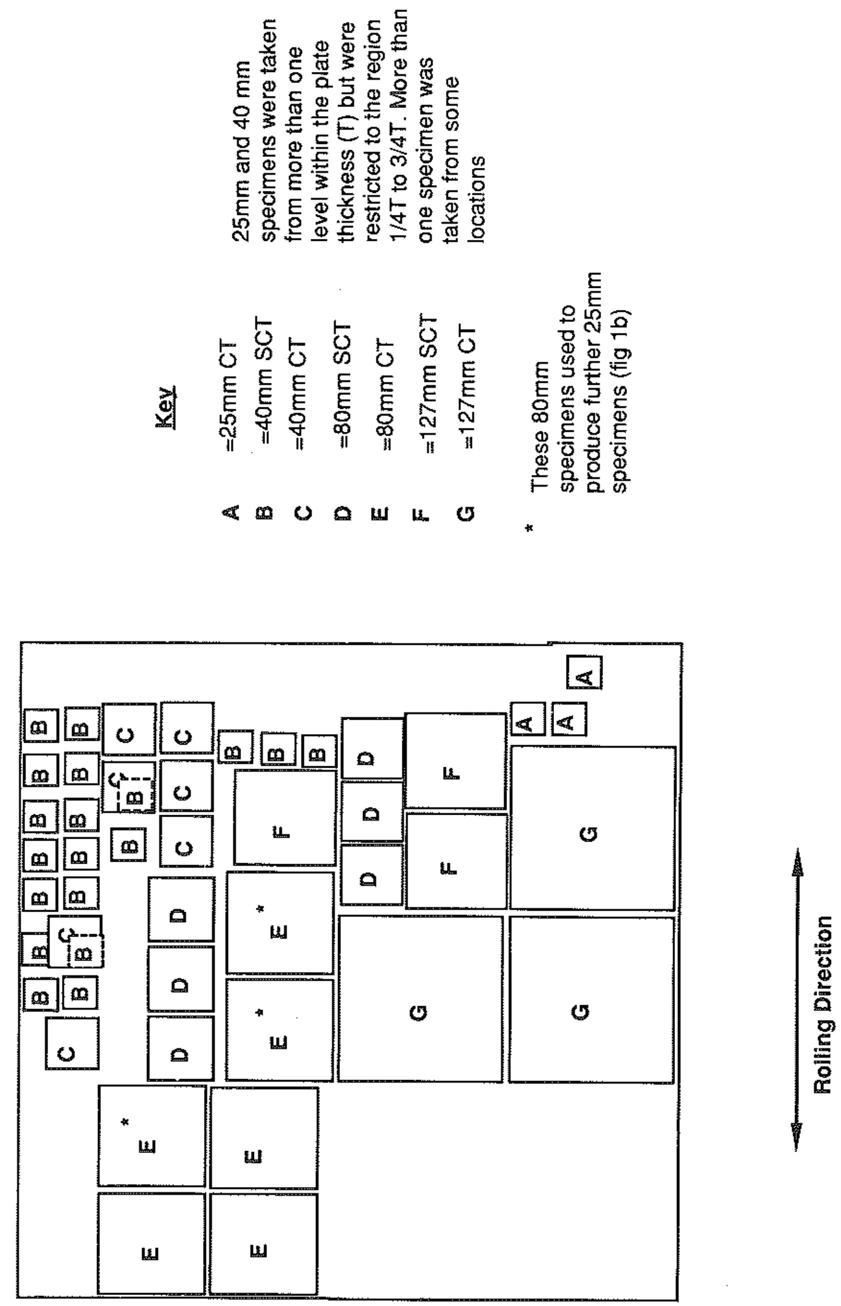


Fig 1 Relative positions of different sized specimens within the A533B-1 plate

Table 3 Test matrix (nominal specimen dimensions)

Specimen type	*Thickness* B *(mm)*	*Crack length* a *(mm)*	*Width* W *(mm)*	*Number of specimens*
25CT	25	25	50	21
40SCT	40	25	50	27
40CT	40	40	80	13
80SCT	80	50	100	6
80CT	80	80	160	6
127SCT	127	75	150	3
127CT	127	127	254	3

Test programme and experimental details

In order to identify the end of the lower shelf and onset of the lower transition regime for the material under test, 25 mm CT were tested across an extended temperature range (−130 to −65°C). Subsequent tests on 40 mm thick specimens (both standard and squat) were confined to three temperatures within that region (−85, −75, or −65°C), and tests on the largest specimen sizes ($B = 80$ and 127 mm) were all performed at −65°C. As test results became available and the size independence of K_{IC} results was called into question, additional 25 mm specimens were extracted from some of the 80 mm CT and tested at −85°C and −65°C.

All fatigue pre-cracking and fracture toughness testing was performed in accordance with ASTM E-399-87. Test specimens all failed by cleavage fracture within the lower shelf/lower transition regimes, i.e., without the intervention of prior ductile crack extension. Only two specimens exhibited any significant plasticity prior to failure (judged as $\Delta_{max}/\Delta_Q > 1.5$ in the present case; where Δ_{max} = specimen displacement at failure and Δ_Q = displacement at the intersection of the specimen load–displacement curve and a 5 percent linear offset line to the initial elastic loading response), and for these cases fracture toughness values were calculated in terms of the J integral and then converted to K values using the expression

$$K_{Jc} = \{E \cdot J_c/(1 - \nu^2)\}^{0.5} \quad (2)$$

where Young's modulus, E, and Poisson's ratio, ν, are taken as 2.06×10^5 MPa and 0.3, respectively. All other K values were calculated directly, using the K expression in ASTM E 399-87. Full details of experimental technique are presented in reference **(11)**.

Results

Within the present paper three different categories of results were identified.

(1) K_{IC}: those results which met all of the criteria of ASTM E399, with the exception of W/B ratio (squat compact tension specimens only).

(2) K_{LE}: those tests for which failure occurred at or before the 5 percent secant offset load–specimen deflection line (including K_{IC} results).

(3) K_{max}: *all* results, regardless of the level of plasticity (including K_{IC} and K_{LE} results).

All individual fracture toughness values are presented in reference **(11)**.

Statistical analyses

Separate statistical analyses were performed for each of the different categories of results described above. Comparisons between data samples were made by testing the hypothesis:

the population means of two different data samples are the same when tested at the 5 percent level,

where the overall population from which the samples were taken was assumed to be normally distributed. Analyses of K_{IC} and K_{LE} results are considered in this section. Analysis of K_{max} results was less extensive and is discussed below. Full details of the statistical tests themselves are presented in reference **(11)**.

Temperature effects

Not all tests on different sized specimens were performed at the same test temperatures. However, within the range −85 to −65°C mean K_{IC} and K_{LE} values were found to be temperature independent, i.e., showed no statistically significant variations as a function of test temperature. Consequently, in all subsequent comparisons specimens of a given size and W/B ratio tested within the range −85 to −65°C were considered as samples from a single population.

Geometry effects

(a) Influence of specimen geometry on the parameter K_{IC}. No K_{IC} data were obtained for 80 mm squat specimens. For 40 mm thick specimens a significant difference (at the 5 percent level) between K_{IC} population means of squat and standard compact tension specimens was predicted. The opposite result was obtained for 127 mm thick specimens, i.e., a 95 percent confidence that K_{IC} population means were the same.

(b) Influence of specimen geometry on the parameter K_{LE}. All comparisons showed a 95 percent confidence that population means of squat and standard specimens were the same.

Size effects

Building on the assumption of the independence of fracture toughness values to W/B ratio, the influence of specimen size (thickness and crack length) on mean K_{IC} and K_{LE} values was examined. For the purposes of comparison, the effects of thickness and crack length were considered as being non-synergistic and assessed independently (i.e., the influence of one dimension was assessed whilst assuming the other dimension had no effect). Results of the comparisons are summarised below.

(a) Thickness effects.

(1) *Influence of thickness on the parameter* K_{IC}

Results of the statistical comparisons can be summarised by the expression

$$B25_{K_{IC}} \equiv B40_{K_{IC}} < B80_{K_{IC}} \equiv B127_{K_{IC}}$$

where $BN_{K_{IC}}$ refers to the K_{IC} population mean for a specimen of thickness equal to N mm. Values of K_{IC} are presented as a function of specimen thickness in Fig. 2(a) which also shows lines representing the thickness criterion $B = 2.5\,(K_{IC}/\sigma_y)^2$, defined using upper bound values of σ_y at -85°C and -65°C.

(2) *Influence of thickness on the parameter* K_{LE}

Results of statistical comparisons show the same trend as that observed for the parameter K_{IC}, i.e.

$$B25_{K_{LE}} \equiv B40_{K_{LE}} < B80_{K_{LE}} \equiv B127_{K_{LE}}$$

where $BN_{K_{LE}}$ refers to the K_{LE} population mean for a specimen of thickness equal to N mm. K_{LE} results are plotted as a function of specimen thickness in Fig. 3(a) together with upper bound K_{IC} values defined by equation (1).

(b) Crack length effects.

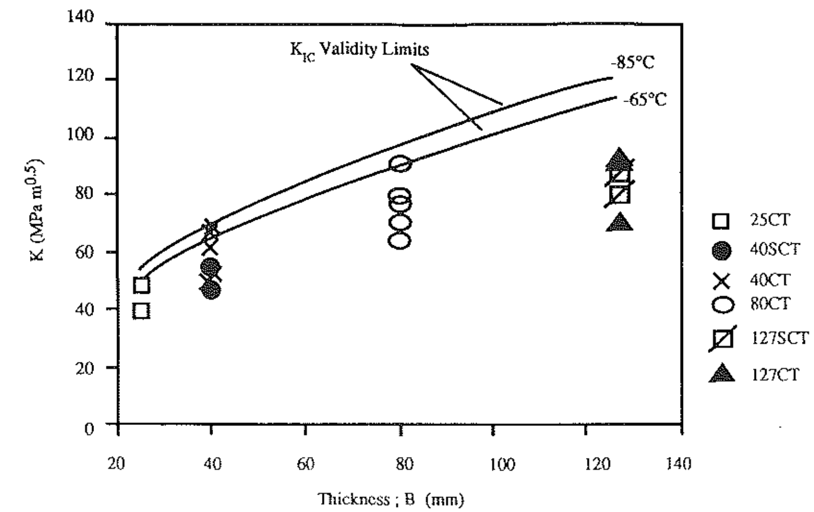
Statistical comparisons were made between specimens of different nominal crack lengths, although no distinction was drawn between specimens of crack lengths 75 mm (127 mm thick squat compact tension specimens) and 80 mm (80 mm standard compact tension specimens), respectively. Justification for this approach is provided in reference **(11)**.

(1) *Influence of crack length on the parameter* K_{IC}

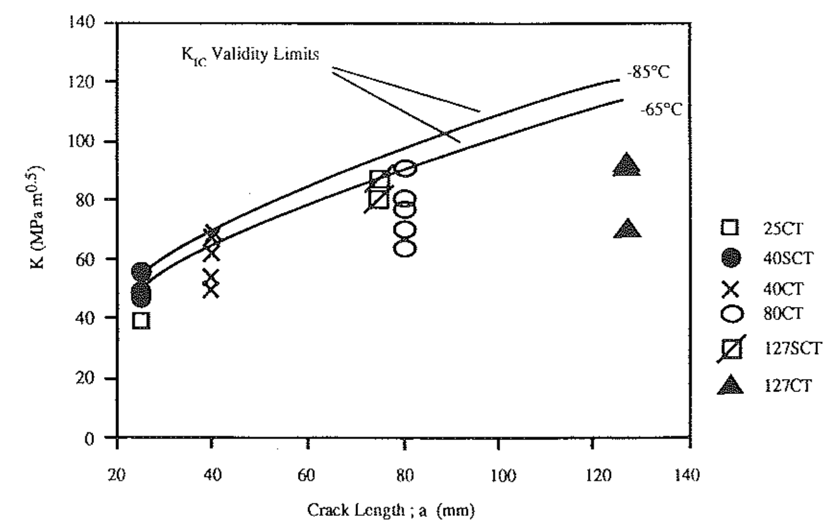
No K_{IC} results were obtained for 80 mm thick squat compact tension specimens and hence there are no data corresponding to a nominal crack length of 50 mm. Comparisons of population means for the remaining samples can be summarised by the expression

$$a25_{K_{IC}} < a40_{K_{IC}} < a75/80_{K_{IC}} \equiv a127_{K_{IC}}$$

where $aN_{K_{IC}}$ refers to the K_{IC} population mean for a specimen of nominal crack length equal to N mm. Variations in K_{IC} as a function of crack length and the validity bounds of equation (1) for -85°C and -65°C are presented in Fig. 2(b).

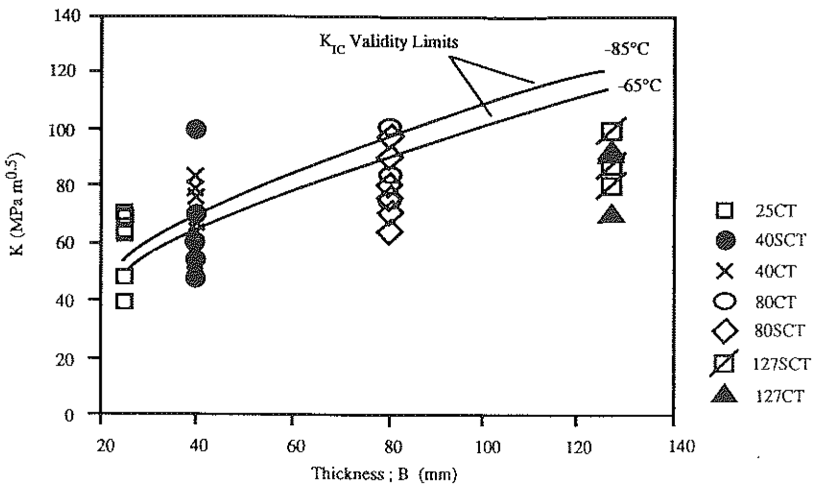


(a) K_{IC} as a function of specimen thickness (B)

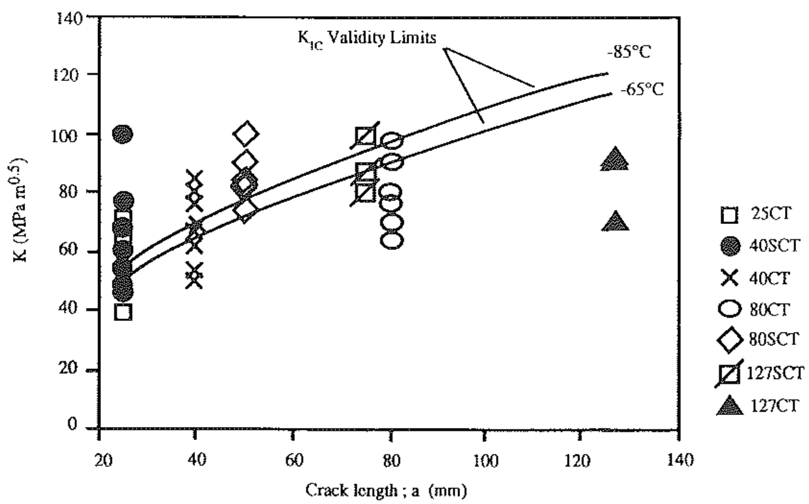


(b) K_{IC} as a function of specimen crack length (a)

Fig 2 Variations in K_{IC} values with changes in specimen dimensions



(a) K_{LE} as a function of specimen thickness (B)



(b) K_{LE} as a function of specimen crack length (a)

Fig 3 Variations in K_{LE} values with changes in specimen dimensions

(2) *Influence of crack length on the parameter* K_{LE}
In terms of the parameter K_{LE} no simple relationship exists between the population means of specimens of different crack lengths. So, for example, the mean value for specimens with $a = 40$ mm is significantly lower than that for specimens with $a = 50$ mm, but the same as that for

specimens with $a = 127$ mm. K_{LE} results are plotted as a function of specimen crack length in Figure 3(b). Once again the validity bounds of equation (1) are included for the temperatures -85°C and -65°C.

Discussion

In terms of the initial programme objective, statistical comparisons suggest that, apart from a single exception, no significant differences exist between mean values of either K_{IC}, or K_{LE} obtained using standard or 'squat' compact tension specimens of the same thickness. However, statistically significant increases in mean K_{IC} and K_{LE} values have been observed with increasing specimen thickness and crack length. Indeed, the single observed difference between mean K_{IC} values for squat and standard specimens now appears to be due to this latter phenomenon. Such findings are contrary to the whole concept of a size independent fracture parameter such as K_{IC}, and deserve detailed consideration.

The K_{IC} concept refers to a unique, single valued (for homogeneous material tested at a single temperature), material property which characterises the onset of unstable crack advance under linear elastic loading conditions. The purpose of K_{IC} testing standards is to turn the K_{IC} concept into a tangible, measurable, quantity by prescribing conditions which promote plane strain and restrict plasticity in test specimens. Differences can thus arise between the K_{IC} concept, and K_{IC} values as defined by testing standards and it is perhaps not surprising that many experimental programmes **(4)–(9)** have found measured K_{IC} values to vary with specimen size. One explanation put forward to describe such size dependency is the resistance curve effect **(4)–(6)(8)**, whereby K_{IC} values are associated with a fixed proportion of crack extension, e.g., 2 percent of initial crack length. Whilst this argument provides a possible explanation for size dependent K_{IC} values it does imply that K_{IC} always coincides with the same amount of notional growth. This is not the case for data obtained in the present study where, for example, specimens failed at varying proximities to the 5 percent secant offset line. (A change in specimen compliance of 5 percent is equivalent to a notional increase in crack length of 2 percent. Intersection of specimen load–displacement curves with the 5 percent offset line therefore corresponds to 2 percent growth, *providing* plasticity effects are negligible).

An alternative explanation for size dependence in K_{IC} values is use of the very criteria designed to assure size independence (equation (1)). The restrictions arising from the criteria are not a problem providing K_{IC} is single valued, i.e., specimens either can, or cannot, measure K_{IC}. Unfortunately, real materials are rarely homogeneous so that, at a specific temperature, a *distribution* of fracture toughness values over a finite toughness range is inevitable. If a unique, size independent distribution of *true* K_{IC} values is assumed, then imposition of the criteria of equation (1) can restrict the proportion of this distribution which can be sampled by small specimens, as illustrated schematically in

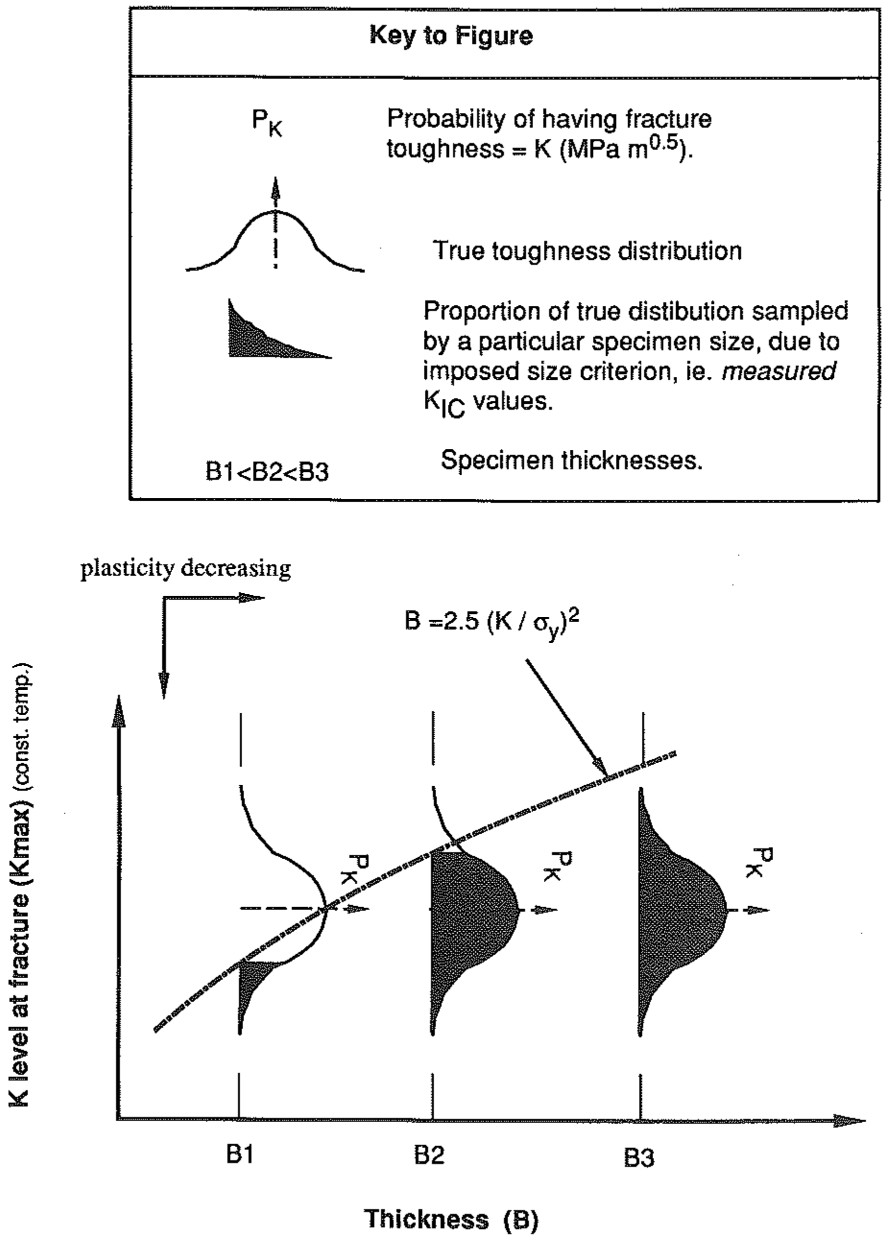


Fig 4 Schematic diagram showing potential variations in *measured* K_{IC} values caused by imposition of specimen size restrictions

Fig. 4. Resulting mean values of measured K_{IC} must therefore be size dependent. It should be noted that this is a general argument which can be used to explain, but does not depend upon, the results of the present experimental programme. Nonetheless, it is now examined within the context of the present test results.

The above argument implies that removal of the size criteria of equation (1) should remove the size dependence of measured K_{IC} values. In fact, the present results have shown that the fracture parameter K_{LE} is also size dependent even though it is not restricted by equation (1). The common feature between K_{IC} and K_{LE} is that they both refer to strictly linear elastic failures, i.e., failures at or before the 5 percent offset line. Deviations from linear elastic behaviour occur when specimen plastic zone size grows to an appreciable proportion of specimen thickness, crack length or remaining ligament. Since plastic zone size is always constant for a given K level, then its relative influence on specimen behaviour must decrease as specimen dimensions increase. Consequently, small specimens deviate from linear elastic behaviour at lower K values than larger specimens thus explaining the persistence of size dependency in linear elastic mean K_{LE} values.

One completely unrestricted parameter measured in the present study is the value of fracture toughness at final fracture; here termed K_{max}. Since K_{max} is uninfluenced by any direct or indirect size criteria, the model illustrated in Fig. 4 predicts that mean values of it should be size independent. Using data at $-65°C$ only (mean K_{max} values are temperature dependent within the range -85 to $-65°C$) a statistical comparison **(11)** did indeed show that, within a 95 percent confidence limit, mean K_{max} values are constant with both specimen thickness and crack length. The basic data are shown as a function of specimen thickness and crack length in Figs 5(a) and 5(b), respectively. Eyeline bounds to the data are included in the figures where for the sake of clarity no distinction has been drawn between the various specimen geometries. Mean fracture toughness in the lower shelf regime (mean $K_{max} \approx 80$ MPa$\sqrt{m}$) therefore appears to be independent of size and geometry providing that all specimen failures are considered.

In summary, the results of the present experimental programme have highlighted deficiencies in the definition of K_{IC} according to ASTM E399 and BS 5447. For the A533B-1 steel studied, the mean level of 'valid' K_{IC} values was shown to increase with both specimen thickness and crack length. A similar effect was observed for the mean level of another linear elastic fracture toughness parameter (K_{LE}) which was not restricted by the size criteria B, $a \geqslant 2.5 (K/\sigma_y)^2$. No size dependence was observed for mean values of K_{max}; where K_{max} includes all specimen failures regardless of the level of specimen plasticity. The specimen matrix used to provide these results was not specifically designed for a generic investigation of size effects on K_{IC} values. As a consequence the test data are limited in certain respects, particularly with regard to the randomisation of specimen sizes throughout the plate. Nonetheless, the

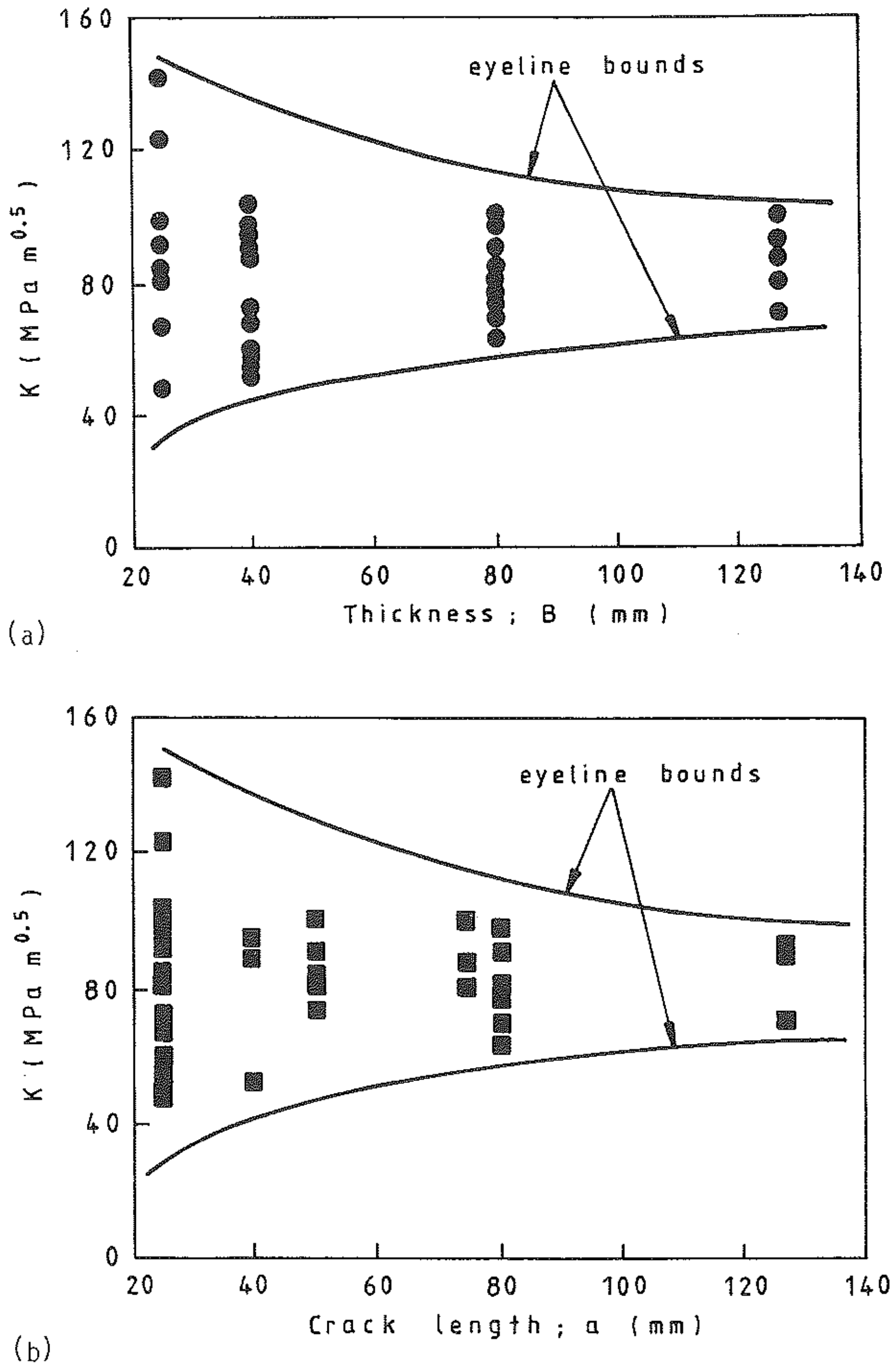


Fig 5 Vibrations in K_{max} values with changes in specimen dimensions.
(a) K_{max} as a function of specimen thickness (B)
(b) K_{max} as a function of specimen crack length (a)

nature of the results calls the efficiency of current test standards into question and clearly raises the need for further work in this area.

Conclusions

(1) Assuming no systematic variation in fracture toughness values with plate position (Fig. 1), then mean values of K_{IC} for the low alloy A533B-1 pressure vessel steel examined in the present study are dependent upon specimen size.

(2) Similar results are observed for the fracture toughness parameter (K_{LE}), where failures are restricted to linear elastic conditions, but not subject to limitations on specimen size; $a, B \geqslant 2.5\,(K_{IC}/\sigma_y)^2$.

(3) A possible explanation for these size dependencies has been advanced in terms of a distribution of toughness values whose maximum range lies above the limits imposed by a requirement for strictly linear elastic specimen response. However, further work to substantiate this explanation is required.

(4) Any variations in mean K_{IC} values between squat and standard compact tension specimens are probably due to the causes noted in (3) above. No statistically significant differences have been observed between the two specimen types in terms of the linear elastic parameter K_{LE}.

(5) Within the lower shelf/lower transition regimes, mean values of K_{max} (fracture toughness values at failure, regardless of the level of plasticity) are size independent.

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