MECHANISM BASED STATISTICAL REQUIREMENTS FOR FRACTURE TOUGHNESS TESTING

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A mechanism based statistical brittle fracture model is applied to determine the reliability of "brittle" fracture toughness testing. Guidelines for optimizing the number of tests needed for sufficient reliability in the results are evaluated on a theoretical basis. It is shown that brittle fracture testing, which usually is easier to perform than ductile fracture testing, requires more tests to ensure the same degree of reliability.

INTRODUCTION

The evaluation of the critical flaw size in the assessment of the structural integrity of e.g. offshore and pressure boundary components is currently based on fracture mechanics. The largest hazard in causing unstable crack growth is that of brittle cleavage fracture. Fracture mechanics testing is, however, often expensive and time consuming to perform. Therefore it is of importance to be able to optimize the number and size of test specimens needed to ensure reliability of the design parameters extracted from the results, such as lower bound curves etc. Usually it is thought that 2 to 5 full thickness tests per heat is sufficient, regardless of fracture mechanism. Much of the scatter in test results has commonly been attributed to some errors performed in the testing procedure.

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The scatter due to the material inhomogeneity and fracture mechanism has not been examined thoroughly. Recently it has been shown through mechanism based statistical evaluation that, for brittle fracture, the fracture mechanism based scatter is actually quite large (Wallin (1)).

In this paper results from the statistical evaluation are studied. The aim is to be able to tell how many and what type of tests should be performed, in view of the large scatter, to ensure a certain degree of reliability of the lower bound values or equivalent fracture toughness parameters. The required number of tests is different for ductile and brittle fracture mechanism.

It is shown that brittle fracture testing, which usually is easier to perform than ductile fracture testing, requires more tests to ensure the same degree of reliability.

PARAMETER VALIDITY

The main feature of most fracture mechanics parameters is to be able to describe materials fracture toughness with one single parameter. Such interrelated parameters are for example the plane-strain fracture toughness K_{IC}, the critical J-intergral J_{IC} and the critical crack tip opening displacement $CTOD_C$.

All the different parameters are assumed to represent the stress and strain fields ahead of a sharp crack. Because of their definitions they should all be geometry independent and show identical scatter for a constant stress state. An important factor affecting the reliability of the different parameters is the way by which they are determined. Depending on the method and the parameter chosen one will observe quite different effects regarding specimen size and crack length dependence as well as the test result scatter. Some often used toughness parameters and their characteristics as suggested by the authors are listed in Table 1.

In Table 1, K_{IC} and K_Q are the valid and the invalid fracture toughness, determined by ASTM E399, respectively. Both parameters are determined by constructing a 95-percent secant to the P-V-curve. K_m and K_i are determined by using the K_{IC} LEFM-formulas together with the load maximum and load at ductile fracture initi-

TABLE 1 - Commonly used fracture toughness parameters.

TYPE	PARAMETER	SCATTER	SIZE EFFECT	CRACK LENGTH EFFECT	RELIABILITY
LEFM	K_{IC}	medium	small	small	medium
	K_Q	small	unpredictable	medium	small
	K_m	small	unpredictable	medium	small
	K_i	small	unpredictable	large	small
EPFM	J_{IC}	medium	small	small	medium
	J_i	medium	small	small	large
	$CTOD_i$	medium	small	small	large
	J_c	large	medium	small	large
	$CTOD_c$	large	medium	small	large
	J_m	small	large/ unpredictable	large	small
	$CTOD_m$	small	large/ unpredictable	large	small
	J_u	medium/ large	medium	medium/ large	medium
	$CTOD_u$	medium/ large	medium	medium/ large	medium

ation, respectively. The parameter J_{IC} is the valid critical J-integral value determined by ASTM E813. The parameters J_i, $CTOD_i$, J_c and $CTOD_c$ are the values of the J-integral and the crack tip opening displacement at crack growth initiation, ductile and brittle respectively. J_m and $CTOD_m$ are the respective parameter values corresponding to maximum load. Finally J_u and $CTOD_u$ stands for the value of the J-integral and crack tip opening displacement at the onset of brittle fracture which has been preceeded by some amount of ductile tearing.

A summary of thickness effects connected to different parameters is presented in Fig. 1. Most of the observed size effects are due to invalid tests. The only test parameters to be regarded as valid are K_{IC}, J_c, $CTOD_c$, J_i and $CTOD_i$. The other parameters do not correspond to the initiation of crack extension. Instead they describe rather the thickness effects on specimen plasticity together with ductile crack growth. As such they cannot be regarded to represent parameters describing true initiation fracture toughness. Interesting enough, even the valid parameters seem to record thickness effects.

The effect of normalized crack length on different parameters is schematically presented in Fig. 2. It is seen that the "valid" parameters show the smallest crack length dependence.

Ordinary K_{IC}-tests according to ASTM E399 applies LEFM-formulas and allows the use of the 95 percent secant procedure. Since the 95 percent secant usually describes mainly plasticity effects, it's application does not yield an optimum description of the materials actual fracture toughness. A more realistic toughness value is obtained by calculating the J-integral or CTOD at the actual crack initiation point, ductile or brittle. This will lead to physically more realistic toughness values.

The preferable parameters to use are thus J_c, $CTOD_c$, J_i, $CTOD_i$ and with some reservations J_u and $CTOD_u$. The application of these parameters yields, however, in the case of brittle fracture, a relatively large test result scatter (1) and a rather strong specimen thickness effect (Wallin (2)). These effects can, on the other hand, be dealt with theoretically through application of the WST-model presented by Wallin et al. (3).

CLEAVAGE FRACTURE

Brittle cleavage fracture differs mechanism vise completely from ductile fracture. Cleavage fracture is initiated by a critical stress induced statistical mechanism, governed by the fracture of brittle precipitates like carbides (Curry et al. (4), Curry (5) and Rosenfield et al. (6)). As such, cleavage fracture will be affected besides by changes in the stress distribution, also by the probability of finding a weak particle (3). The specimen size will affect the toughness partly by changing the constraint at the crack tip and partly by changing the effective volume i.e. the number of weak particles at the crack tip.

The new theoretical WST-model based on carbide induced brittle fracture (3) and Wallin et al. (7) allows one to write the probability of cleavage fracture in the case of a sharp crack as (2)

$$P_f = 1 - \exp - \left(\frac{K_I - K_{min}}{K_{OB} - K_{min}}\right)^4 . \qquad (1)$$

In eqn. (1) P_f is the fracture probability, K_I is the stress intensity factor, K_{min} is a lower limiting fracture toughness and K_{OB} is a thickness and temperature dependent normalization factor. For a constant temperature one can write (2)

$$K_{OB_1} = K_{min} + (K_{OB_2} - K_{min}) \cdot \left(\frac{B_2}{B_1}\right)^{1/4} , \qquad (2)$$

where B_1 and B_2 are the respective thicknesses.

Writing eqn. (1) as

$$K_I = K_{min} + (K_{OB} - K_{min}) \cdot \left\{\ln \frac{1}{1-P_f}\right\}^{1/4} \qquad (3)$$

one can construct a so called failure probability diagram yielding a very clear description of the materials fracture toughness scatter. An example of one such diagram is presented in Fig. 3 for Welding Institute fracture toughness round robin data.

Combining eqn. (1) and eqn. (2) the thickness correction for a single toughness value becomes

$$K_{B_1} = K_{min} + (K_{B_2} - K_{min}) \cdot \left(\frac{B_2}{B_1}\right)^{1/4} . \qquad (4)$$

By applying eqn. (4) it is possible to compare fracture toughness results obtained from specimens of different thickness.

It has been proposed that constraint effects are not very pronounced when dealing with brittle cleavage fracture (2). Actually it has been demonstrated (2) that eqn. (4) is guite sufficient to describe the size effect as long as the K calculated from J-integral fulfills the reguirement $B \geq 25 \cdot J/\sigma_{flow}$.

Besides that it is possible to examine the experimental scatter with the method described above it can also be used to consider the reliability of the test results. In Fig. 4 the theoretical scatter of the experimentally determined values for the test result mean is presented as a function of the number of tests. It is seen that the scatter is quite extensive up to N = 50. At first this would suggest that a very large number of tests are required to reliably determine the mean value of K_{IC}. It is, however, possible to use a quite simple procedure for conservative estimation of the mean and lower bound values. The procedure is as follows. First the experimental value of the mean is assumed to be equal to the value corresponding to the upper 95 % -limit in Fig. 4. The real mean is then estimated to be equal to the theoretical value of the mean obtained from Fig. 4. This estimation is a conservative one because the probability of over-estimating the mean is only 2.5 %. The obtained mean can then be used together with eqn. (1) to extract a lower bound value. With this procedure it is possible to make conservative estimations doing as little as three test.

It is seen from Fig. 4 that the effect of increasing the number of tests is strongest when the number of tests is less than 5. After this one must make much more tests to clearly increase the reliability of the results. Thus this mechanism based evaluation would suggest a minimum requirement of 5 tests when the fracture mode is brittle cleavage fracture. One does not, however, have to use full thickness specimens since the thickness correction in egn. (4) yields a fully sufficient result. Instead of thickness one should then use the crack front length in egn. (4) when applying it to evaluate the critical flaw size in structures.

An important parameter in the above method is the limiting fracture toughness value (K_{min}) beneath which cleavage crack propagation becomes impossible. The value of K_{min} is in the case of cleavage fracture not very large. It has been estimated to be close to 20 MPa$\sqrt{m}$ (2). It is of course not constant but changes from one material to another and is affected by grain size, temperature and loading speed. In some cases it might even be as large as 50 MPa$\sqrt{m}$. Application of K_{min} = 20 MPa$\sqrt{m}$ yields however quite a sufficient accuracy in the calculations. The effect of K_{min} is important only when the mean fracture toughness is small.

The information in Fig. 4 can be approximated with a simple equation

$$\frac{\bar{K}_{meas}}{\bar{K}_{real}} \overset{P_{95}}{\approx} 1 \pm \frac{1}{2\sqrt{N}} \left(1 - \frac{K_{min}}{\bar{K}}\right) \qquad (5)$$

Eqn. (5) yields approximately the 95-percent reliability limits for the measured mean as a function of specimen number and K_{min}.

Macroscopic inhomogenities do of course affect the reliability of testing very strongly and if such inhomogeneties are present in an uncontrolled manner, one must perform much more testing to be able to determine the actual fracture probability distribution. In such a case more than 20 tests may be needed. The inhomogenities are fortunately usually macroscopically distributed making their elimination possible through right specimen positioning. If this is possible the above described method yields reliable results.

DUCTILE FRACTURE

Ductile fracture can, at least theoretically, be divided into two parts, initiation and propagation. Ductile fracture proceeds by a mechanism of continuous microvoid nucleation and coalesence. Therefore it is practically impossible to detect the first physical initiation point. The initiation toughness is usually taken as a point where already some amount of detectable ductile tearing has taken place.

If ductile fracture initiation would actually be defined as the point when the first void is nucleated, then also this property could be described through egn. (1). Only, K_{min}, would be very close to K_{QB}, thus leading to comparatively small scatter and statistical size effect as evident from eqn. (5). Since the ductile initiation toughness is, however, determined after some amount of ductile tearing, egn. (1) is not directly applicable. The continuous propagation of ductile fracture is affected mainly by the materials macroscopical homogeneity. If the material is sufficiently homogeneous then the ductile fracture toughness will show quite a small scatter. This is especially true when examining a whole fracture resistance curve. The scatter will become proportionally larger when taking the measuring point closer to the actual initiation point.

Microvoid coalesence is a critical strain controlled kind of mechanism. As such it is very strongly governed by maximum strain state along the crack front, i.e. crack growth will occure where the strain energy of the specimen is critical for ductile crack initiation.

Since 3-D stress analysis have shown that plane-strain state is dominant in the center of a specimen and because it is only weakly dependent on specimen thickness one would assume ductile initiation toughness to be independent of thickness as long as plane-strain state prevails in the center of the specimen. Due to this effect the ductile fracture toughness should be practically size independent as long as the requirement $B > 25 \cdot J/\sigma_{flow}$ is fulfilled.

Side grooving the specimen affects the stress distribution by raising the stress at the specimen surface. This will, however, not affect the measured initiation toughness as long as the side grooving is moderate, i.e. the K or J at the surface does not rise above the K or J at the centre of the specimen.

Assuming that $K_{min}/K > 0.5$ for ductile fracture initiation and applying eqn. (5), a total of only two tests are required to ensure the same proportional reliability as for when doing five tests for cleavage fracture.

Thus this mechanism based evaluation would suggest a minimum reguirement of 2 or 3 tests when the fracture mode is ductile fracture. Also in this case one does not have to use full thickness specimens as long as applying the right parameter and fulfilling the thickness reguirement $B > 25 \cdot J/\sigma_{flow}$.

SUMMARY AND CONCLUSIONS

Mechanism based statistical testing requirements connected with fracture toughness testing has been examined both for ductile fracture initiation as well as for brittle cleavage fracture. The use of special "valid" initiation parameters has been proposed. It has been suggested that 5 tests minimum should be performed when the fracture mode is brittle cleavage fracture while 2 or 3 tests are sufficient for ductile fracture. Furthermore it has been suggested that full thickness specimens are not required as long as the size requirement $B > 25 \cdot J/\delta_{flow}$ is fulfilled.

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SYMBOLS USED

B = specimen thickness

CTOD = crack tip opening displacement

J = J-integral

K = linear elastic stress intensity factor

K_{IC} = valid linear K_{min} = lower limiting value of K_{IC}

K_{OB} = normalizing value of K_{IC} corresponding to a fracture probability of 63 %

P_f = cumulative fracture probability

δ_{flow} = materials flow stress

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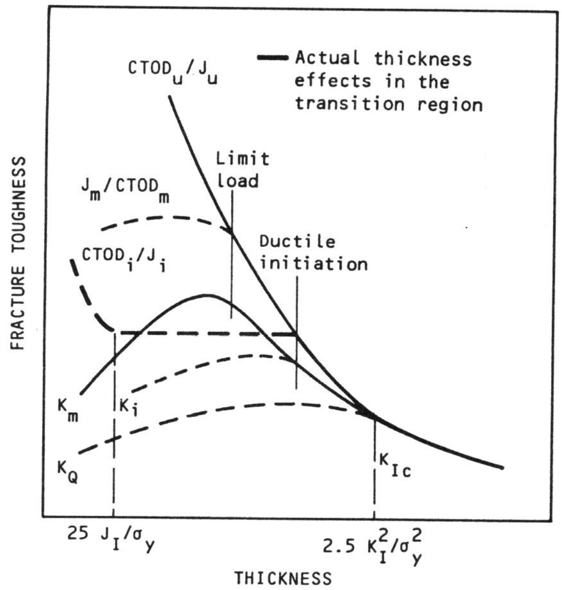

Figure 1 Thickness effects in the transition region

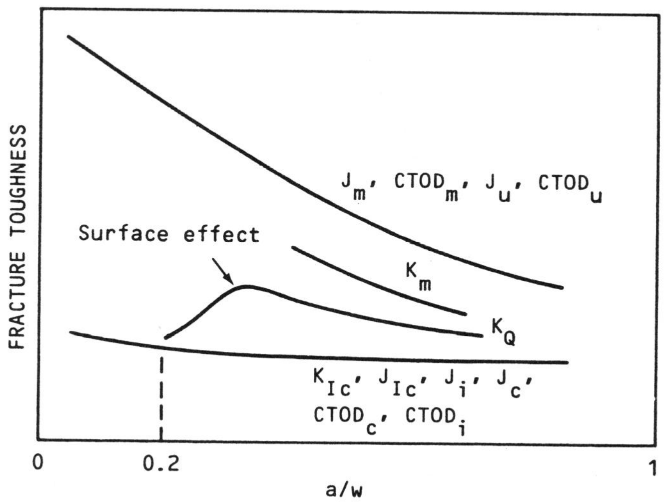

Figure 2 Schematic presentation of a/w effects

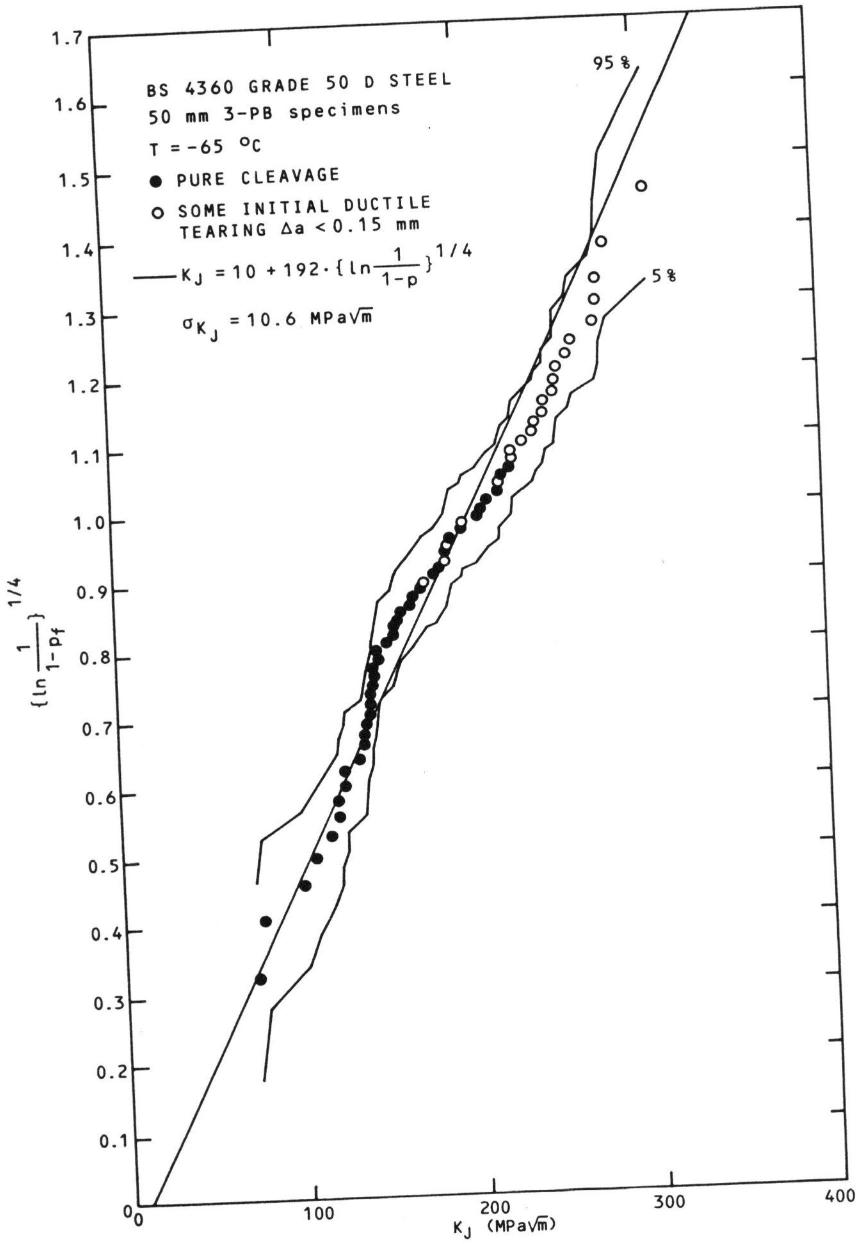

Figure 3 ECSC collaborative elastic-plastic fracture toughness testing methods control sample results

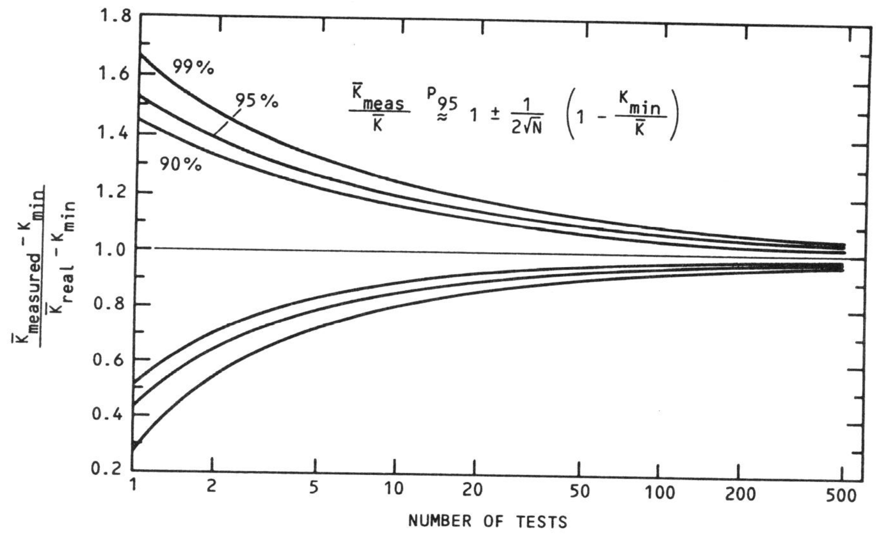

Figure 4 Theoretical scatter of experimentally determined mean as a function of the number of tests