Fracture Toughness Testing in the Ductile–Brittle Transition Region

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ABSTRACT

Fracture to"ghness testing in the ductile-brittle transition regime is often problematic. In this region both constraint effects as well as ductile tearing will affect the brittle fracture probability. This causes the scatter to grow very large in the transition region. Up till now there has not existed any kind of reliable means of how to validate such data. In this paper a new method for validation is presented.

Based on a theoretical cleavage fracture model, it is possible to evaluate the effect of ductile tearing on the cleavage fracture probability. When combining this model with the knowledge from finite element calculations of the plastic zone, it is not only possible to evaluate a minimum specimen size to obtain valid brittle fracture toughness results, but it is also possible to change the invalid results into valid results. It is also possible to describe the fracture probability of large specimens and structures from the results obtained with "invalid size" specimens.

INTRODUCTION

The standardization of fracture toughness testing is presently undergoing rapid development. Many testing standards already exists and presently several new standards are being developed together with revision of the existing ones.

The most problematic toughness range se^ms to be the transition region where it is practically impossible to measure valid K_{IC} results and yet the final fracture is cleavage fracture. Presently only the British CTOD-test standard BS 5762 is applicable in this toughness region. The CTOD-standard does, however, in the present form contain weaknesses that deteriorates it's applicability in the transition region.

In this paper the effect of ligament size on cleavage fracture toughness in the elastic-plastic regime is examined. The large scale yielding effect of the ligament is combined with statistical cleavage fracture theory so that also the effect of prior ductile tearing is included. The examination is performed within the framework of a statistical micromechanism based model for cleavage fracture (WST-model) [1]. As a result a new specimen ligament size requirement for elastic-plastic cleavage fracture toughness testing with bend type specimens is obtained. Additionally a simple correction function to validate invalid test results with insufficient ligament size and prior ductile tearing is presented.

DUCTILE CRACK GROWTH CORRECTION (DCG)

The WST-model for cleavage fracture has been presented elsewhere [1-3]. Macroscopically it yields a Weibull type expression with the exponent equal to 4 (eq. 1).

$$P = 1 - \exp\left\{-\left(\frac{K-K_{min}}{K_o-K_{min}}\right)^4\right\} . \tag{1}$$

In eq. 1 P is the cumulative fracture probability, K_o is a temperature and specimen size dependent normalization parameter corresponding to 63.2 % fracture probability and K_{min} is a lower limiting fracture toughness.

The basic assumptions for the DCG-correction are presented schematically in Fig. 1. The distance parameter β defines the cleavage fracture process zone size. In the derivation it is assumed that there exists a specific ductile fracture initiation toughness K_i and that the lower limiting fracture toughness K_{min} is zero. The sampling volume is presented as having a wedge shape with an active angle θ. The value of the angle and even the exact shape of the sampling volume is arbitrary. It is only used to show that the stress and strain distributions have an angular dependence.

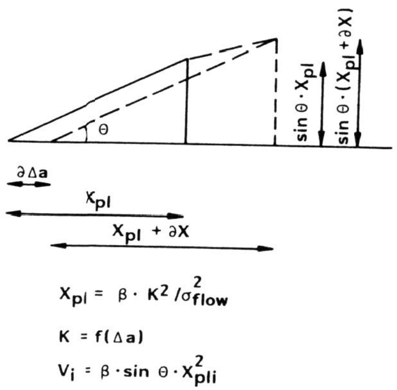

Fig. 1. Schematic presentation of basic assumptions regarding ductile crack growth correction.

The volume increment due to both increase in loading parameter as well as crack growth is, when written as a function of crack growth and neglecting second order terms

$$\partial V = \frac{V_i}{K_i^4}\left\{4\cdot f(\Delta a)^3\cdot f'(\Delta a)+2\cdot f(\Delta a)^2\cdot\sigma_{flow}^2/\beta\right\}\cdot\partial\Delta a . \tag{2}$$

Considering the form of eq. 1 we can write

$$P = 1 - \exp - \left(\frac{V}{V_o}\right) . \tag{3}$$

Combining eq. 2 and 3 the crack growth correction becomes

$$\log\frac{1}{1-P} = \frac{f(\Delta a)^4}{K_o^4} + \frac{2\cdot\sigma_{flow}^2}{K_o^4\cdot\beta}\cdot\int_0^{\Delta a} f(\Delta a)^2\cdot\partial\Delta a \tag{4}$$

for $K > K_i$.

If the ductile crack growth is independent of K the crack growth correction is much simplified. It can be written as

$$\left(\log\frac{1}{1-P}\right)^{1/4} = \left(\frac{K_i}{K_o}\right)\cdot\left(1+\frac{2\cdot\Delta a\cdot\sigma_{flow}^2}{K_i^2\cdot\beta}\right)^{1/4} . \tag{5}$$

When the crack growth is small ≈ 1 mm and/or the R-curve is relatively flat, eq. 5 can be used to approximate eq. 4. When accounting for specimen thickness and a lower limiting fracture toughness the approximate correction finally becomes

$$\left(\log\frac{1}{1-P}\right)^{1/4} = \left(\frac{K-K_{min}}{K_o-K_{min}}\right)\cdot\left(\frac{B}{B_o}\right)^{1/4}\cdot\left(1+\frac{2\cdot\Delta a\cdot\sigma_{flow}^2}{K^2\cdot\beta}\right)^{1/4} . \tag{6}$$

EFFECT OF LIGAMENT SIZE

Brittle cleavage fracture is a critical stress controlled local fracture process. The possible cleavage fracture initiators are randomly distributed and this causes cleavage fracture to be a statistical event. A prerequisite for cleavage fracture is local plasticity at the site of fracture initiation. Therefore the process zone for cleavage fracture must be smaller than or equal to the plastic zone size. Because cleavage fracture is stress controlled, the probability of cleavage fracture initiation is largest close to the stress maximum. A somewhat refined version of the WST-model [4] indicate that with a 95 % probability, cleavage fracture will initiate closer than approximately 3-5 times the distance to the stress maximum. This can be taken as an effective process zone for cleavage fracture initiation. Outside this region cleavage fracture is still in theory possible within the plastic zone, but the probability of fracture as compared to the fracture probability closer to the stres maximum is essentially negligible.

The J-integral or K_J describes cleavage fracture initiation as long as it describes the stresses within the process zone with an adequate accuracy. McMeeking and Parks [5] showed with their FEM calculations that at increasing J-levels the stresses start to deviate from the small scale yielding calculations. They plotted their results in the form of the normalized distance $x/(J/\sigma_o)$ to be able to make the comparison with the small scale yielding results. With increasing J the stresses deviated from the small scale yielding results at smaller values of normalized distance. When the process zone is defined with the normalized distance it is possible to determine the ligament size and J-level at which the stresses no longer describe the proces zone correctly. If the cleavage fracture initiation process zone extends to approximately 3-5 times the distance of the stress maximum the McMeeking and Parks results would indicate that the size restriction should be $b \geq 35 - 60 \cdot (J/\sigma_o)$.

Besides having a ligament size restriction it is equally interesting to know what happens to the stresses at higher load levels. In order to investigate this the McMeeking and Parks results where replotted in coordinates where the distance is normalized with the ligament and not by J. The thus obtained results are presented in Fig. 2. It is seen that the stress distribution above a certain load level saturates and become independent of J, and depends only on ligament size. This means that beyond a certain critical J-value the effective J from a cleavage fracture point of view becomes constant.

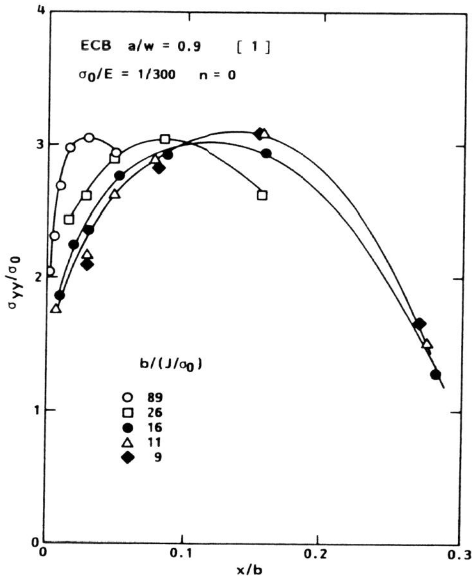

Fig. 2. Stress distribution in front of crack for large scale yielding [5].

The effect of large scale yielding can also be investigated by reanalysing the FEM calculations by Mudry and coworkers [6]. They apply a local cleavage fracture model based on Weibull statistics combined with large scale yielding FEM calculations of a CT-specimen The results are interpreted in the form of an effective Weibull stress which for small scale yielding is defined as $\sigma_w \sim (K_I^4 \cdot B)^{1/m}$, where B is the specimen thickness and m is the Weibull inhomogeneity factor. Apparently they determine a J-validity criteria as the load level where the large scale yielding σ_w deviates more than 5 % from the theoretical small scale yielding result. Another possibility of how to analyse their results is to make use of the

theoretical small scale yielding definition of σ_w and to turn the large scale yielding results directly into an effective K_I value. One reanalysed result for a CT-specimen is presented in Fig. 3. Here the same behaviour as in Fig. 2 is visible. First, at low K_j levels the effective K_{jeff} is equal to the measured K_j, but above a certain level K_{jeff} saturates and becomes in the end constant. The saturation level corresponds to a maximum J_{max} that yields a size criterion of approximately $b = 50 \cdot (J_{max}/\sigma_{flow})$. This is well in accordance with the assumption of a cleavage fracture initiation process zone having a size of 3 - 5 times the distance to the stress maximum which led to a size criterion of $b \geq 35 - 60 \cdot (J/\sigma_o)$.

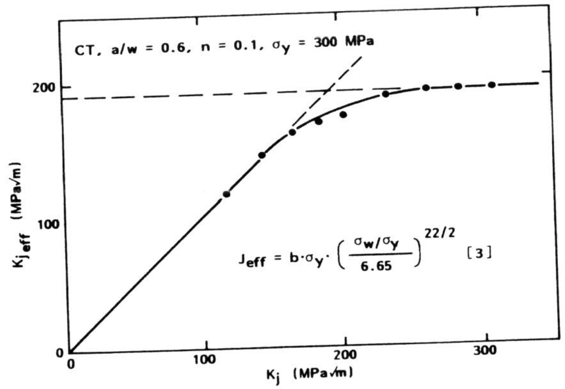

Fig. 3. Relation between K_j and K_{jeff} [6].

With the foregoing discussions in mind, the following assumptions regarding the effect of ligament size on cleavage fracture toughness are proposed:

- The J-integral (or K_j) describes the cleavage fracture initiation event as long as $b \geq 50 \cdot (J/\sigma_{flow})$.
- At higher load levels the effective load parameter J_{eff} is constant and equal to $J_{max} = b \cdot \sigma_{flow}/50$.
- When J_{eff} reaches J_{max} ductile tearing will preceed cleavage fracture initiation.

Next an attempt is made to verify the theoretical assumptions also experimentally.

EXPERIMENTAL

The experimental part consisted of 105 K_{Jc} tests with identical specimens. The specimens were 25 mm thick CT-specimens with 20 % side-grooves and a relative crack length of 0.6. The material was a 2 1/4 Cr 1 Mo steel taken from a large hydrogenating vessel that had been in service for more than 20 years. The material had a room temperature yield stress ($\sigma_{0.2}$) of 300 MPa and an ultimate stress (σ_u) of 532 MPa. The specimens were extracted both from the outer as well as inner quarter thickness location and their orientation were LS.

All specimens were tested at room temperature and the value of the J-integral at cleavage fracture initiation as well as the amount of ductile tearing were recorded.

RESULTS AND DISCUSSION

The J_c values ranged from 44 kJ/m^2 to >1000 kJ/m^2 and the amount of ductile tearing varied between 0 and 6 mm. Ten specimens had to be unloaded before cleavage fracture because the clip gage reached it's limit. These specimens were not included in the analysis itself, but only in the total number of tests. The median toughness for the outer surface location was 320 kJ/m^2 and for the inner surface location it was 315 kJ/m^2. This indicates that the toughness distributions for the two locations are identical and therefore they can be analysed together.

Eq. 6 implies that if K_{jeff} is constant, the result will be a linear function of ductile crack growth. The present results are shown in Fig. 4. After a ductile crack growth of approximately 0.6 mm the fracture behaviour is exactly as predicted through eq. 6. This confirms the assumption of a constant effective load parameter. The next step is to try to determine the value of K_{jmax}.

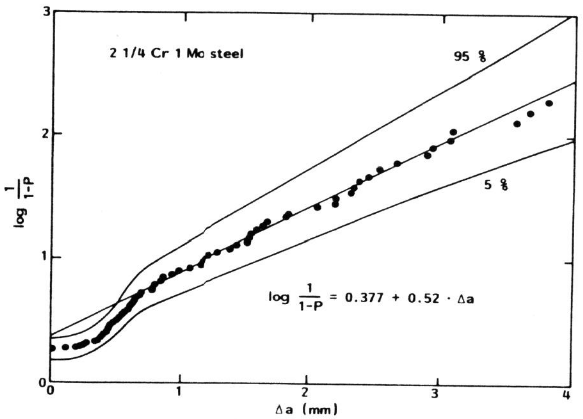

Fig. 4. Fracture probability versus ductile crack growth with confidence limits for rank estimate.

If one considers only specimens without ductile tearing K_{jeff} should be equal to K_j and eq. 1 can be applied. The present results showing no ductile tearing are presented in Fig. 5. The experimental results describe eq. 1 rather well when considering the confidence of the rank analysis. The results yield that $K_{min} \approx 20$ MPa√m and $K_o = 260$ MPa√m. When this information is combined with the information in Fig. 4 one obtains that $K_{jmax} \approx 208$ MPa√m, which corresponds to $\alpha \approx 44$ and $\beta \approx 0.0058 = 5.3 \cdot U_{max}$.

Above the data was analysed separately for ductile crack growth and fracture toughness, but the analysis can also be performed on the combined data. It is possible to use eq. 6 and to apply K_{jeff} instead of K_j. K_{jeff}

is then either equal to K_j or K_{max} depending on the value of K_j. A best fit of all the data yields $K_{min} \approx 20$ MPa√m, $K_o \approx 244$ MPa√m, $K_{jmax} \approx 169$ MPa√m ($\alpha \approx 65$) and $\beta \approx 0.0037 = 3.4 \cdot U_{max}$.

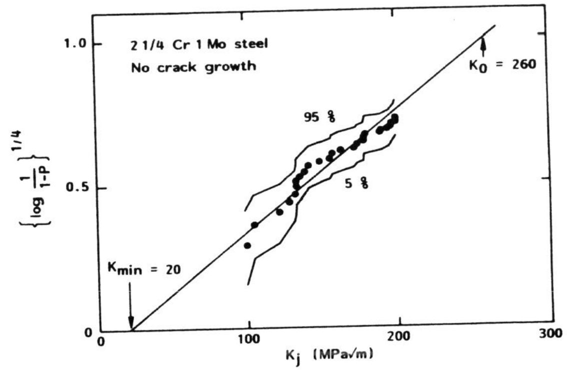

Fig. 5. Fracture probability versus fracture toughness with confidence limits for rank estimate.

It is seen that the experimental estimates of both the size requirement (α) as well as the cleavage fracture initiation process zone size (β) are comparatively close to the theoretical assumptions.

Based on the above it was desided to fix α as 50, β as $3.5 \cdot U_{max}$ and K_{min} as 20 MPa√m. Thus the only parameter to fit is the normalization toughness K_o.

The results of the analysis of the present material are presented in Fig. 6. In the figure the 90 % confidence limits of the rank based probabilities are included. The data is seen to be well described through the simplified crack growth correction. The standard deviation of the estimates of rank probabilities is 0.03.

Based on Monte Carlo simulation the theoretical expectance value together with the 90 % confidence limits for the standard deviation of the estimates of rank probabilities were determined as a function of number of tests N. The result describes the theoretical accuracy of a fit that is based on rank probabilities. The results of the simulation are presented in Fig. 7 together with the result of the present analysis. Also included are analysis results for several other data sets found in the litterature [7-12].

Considering the fact that eq. 6 is theoretically correct only for macroscopically homogeneous materials, the present results are more than satisfactory. On the whole the results are quite promising and they would indicate that the statistical crack growth correction presented here is realistic. It also seems that "macroscopical" inhomogeneities in the base material does not have a very pronounced effect on the fracture toughness distribution.

The exact values for α and β can not be reliably determined here and it is not known how they will change from one material to another, but it is felt that one can with sufficient accuracy apply $\alpha = 50$ and $\beta = 3.5 \cdot U_{max}$.

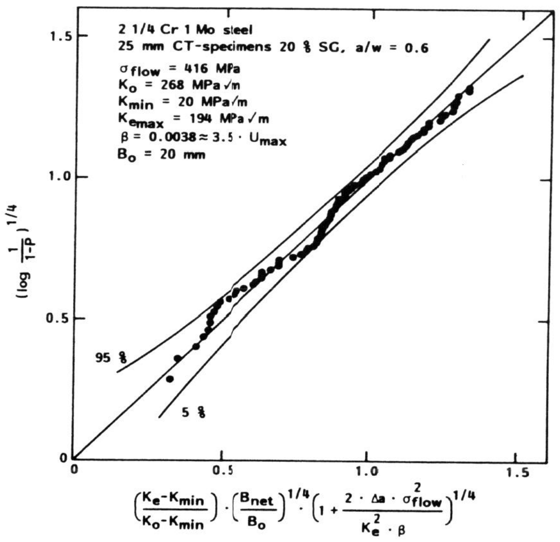

Fig. 6. Crack growth correction analysis for 105 specimens.

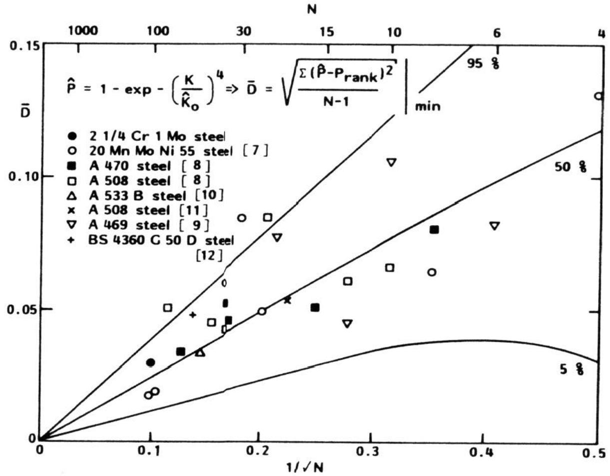

Fig. 7. Theoretical 90 % confidence limits for the standard deviation of the estimates of rank probabilities as a function of number of tests N.

The fact that eq. 6 yields a correct description of the brittle fracture probability has widespread effects regarding fracture toughness testing in the ductile/brittle transition temperature region. It means that it is possible to use quite small specimens for the tests, the results of which can then be transformed to represent the behaviour of a large specimen or a structural detail. The correction for a single test can be expressed as

$$K_{large} = K_{min} + (K_{Jeff}-K_{min}) \cdot \left(\frac{B}{B_{large}}\right)^{1/4} \cdot \left(1+\frac{2\cdot\Delta a\cdot\sigma_{flow}^2}{K_{Jeff}^2\cdot\beta}\right)^{1/4} \qquad (7)$$

where K_{large} and B_{large} correspond to the corrected result.

SUMMARY AND CONCLUSIONS

In this work a new ligament size criterion for cleavage fracture toughness testing with bend specimens has been presented. The conclusions regarding the effect of ligament size and ductile tearing on cleavage fracture toughness are as follows:

- The J-integral (or K_J) describes the cleavage fracture initiation event as long as $b \geq 50 \cdot (J/\sigma_{flow})$.
- At higher load levels the effective load parameter J_{eff} is constant and equal to $J_{max} = b \cdot \sigma_{flow}/50$.
- When J_{eff} reaches J_{max} ductile tearing will preceed cleavage fracture initiation.
- Even in a case where the ligament size restriction is violated and cleavage fracture is preceeded by ductile tearing, the result can be corrected to correspond to a valid result with a simple correction formula.

ACKNOWLEDGEMENTS

This work is a part of the Structural Reliability in Nuclear Power Plants program performed at the Technical Research Centre of Finland (VTT) and financed by the Ministry of Trade and Industry in Finland. Additional financing by the Finnish Academy is acknowledged.

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