THE EFFECT OF CRACK DEPTH AND ABSOLUTE THICKNESS ON FRACTURE TOUGHNESS OF 3PB SPECIMENS

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Dynamic fracture toughness tests have been made on prefatigued Charpy-size impact specimens in the brittle to ductile transition region of the test material. The crack depth vs. specimen width ratio were approximately 0.05, 0.1, 0.3 and 0.5. Small scale yielding correction (SSYC), T-stress and Q parameter were used for constraint correction. It was concluded that the most effective method for correction was SSYC, while T and Q were capable for qualitative correction only.

Static 3PB tests with specimen thickness varying from 5 to 300 mm were conducted in the brittle to ductile transition region of the test material. Statistical and SSYC methods were used for constraint description. The statistical method alone, gave a good description of the results, while SSYC was not overpredictive.

INTRODUCTION

Standardized fracture toughness test specimens contain a deep crack with a/W = 0.5. This type of geometry is considered to have a larger constraint and thus a smaller fracture toughness than a specimen with a more shallow crack. The shallowness of a crack starts to play an active role in three-point-bending when a/W ≤ 0.3. Due to more frequent appearance of shallow cracks in structural components, the use of standardized fracture toughness in design may be overconservative.

An other dimension that affects the fracture toughness in the transition region is specimen thickness. Increasing thickness decreases fracture toughness. This is due to inreasing constraint and a sampling effect. The more material there is in front of the crack, the more probable it is that there exists a crack initiator. The thickness effect can be effectively taken into account by a statistical analysis (Wallin (1)). In theory, the SSYC can also be used for thickness correction.

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THEORY

Taking into account the effect of a/W on fracture toughness

The ratio between crack depth and specimen width (a/W) affects the measured fracture toughness by an in-plane constraint effect. Low a/W correspond to low constraint and vice versa. Small scale yielding correction (SSYC), T-stress and Q parameter are generally used for constraint correction. A short description of the methods is as follows.

T-stress. T-stress is the second term in William's stress serie, Eq. 1.

$$\sigma_{ij}=A_{ij}(\theta)r^{-\frac{1}{2}}+B_{ij}(\theta)+C_{ij}(\theta)r^{\frac{1}{2}} \tag{1}$$

The loss of J dominance is attributed to a compressive T stress while with a tensile T stress the dominance of J is retained according to modified boundary layer formulations. In pure bending the T stress is tensile for a/W > 0.35. Geometries with compressive T stress loose J dominance at a deformation level which depends on T (Al-Ani and Hancock (2)).

Q parameter. A geometry which has lost the dominance of J is thought to be controlled by a J-Q annulus. J sets the size scale over which large stress and strain develop and close to the crack tip the stress distribution is determined by the Q parameter. Q is considered as a stress triaxiality parameter. Negative/positive Q parameter reduces/increases the hydrostatic stress. This is presented in Eq. 2 where the HRR distribution serves as the reference state. Eq. 2 is not valid for distances close to the crack tip ($r/(J/\sigma_0) < 1$) where finite strain effects dominate (O'Dowd and Shih (3)).

$$\sigma_{ij}=(\sigma_{ij})_{HRR}+Q\sigma_0\delta_{ij} \qquad , for\,|\theta|<\frac{\pi}{2} \tag{2}$$

Small scale yielding correction (SSYC). The small scale yielding correction is based on a detailed Finite Element analysis. The meshes are refined near the crack tip to infer the stress and strain distributions with high accuracy. In SSYC the effects of large scale plasticity are neglected. Thus the criterion for fracture is the microscopic criterion close to the crack tip. Due to finite strains within the crack tip the fracture criterion is taken to be at 2...4·δ from the crack tip. When SSYC is based on stress fields, it suites for fracture mechanisms which are exclusively controlled by the maximum principal stress, such as cleavage (Anderson and Dodds (3)).

Statistical aspects of the effect of specimen thickness on fracture toughness

In case of cleavage fracture, increasing the specimen thickness increases the cumulative failure probability. This is due to increased probability of existence of a critical microscopic fracture triggering site in the vicinity of the crack tip. This is presented as a Weibull type equation in Eq. 3 (1).

$$P_f = 1 - \exp - [const. \times B \times (K - K_{min})^4] \quad (3)$$

The treshold fracture toughness, K_{min}, below which fracture cannot occure is taken as being approximately 20 MPa$\sqrt{m}$ for steels.

In the case of ductile fracture, the specimen thickness should not have statistical effect on fracture toughness. During ductile fracture, the microvoid coalescence must occure along the whole specimen thickness. Thus, opposite to cleavage fracture toughness, the ductile fracture toughness depends on the mean material parameters (1).

EXPERIMENTAL

Test material

Charpy size impact specimens were cut from an ASTM A 533 B Class 1 steel plate and static bend specimens from a steel plate of RAEX 37-52 continuously cast normalised oxygen steel.

Test specimens

17 to 20 impact specimens (10·10·55 mm) of each geometry with nominal a/W values of 0.05, 0.1, 0.3 and 0.5 were manufactured. For tests in the upper shelf region a total of 5 to 6 specimens of each geometry were manufactured.

The thicknesses of fatigue precracked static SENB specimens were 5, 10, 20, 100, 200 and 300 mm, while specimen width and length were 40 mm and 200 mm, respectively. The crack length a/W was 0.5. After fatiguing 10% side-grooves were machined on both sides to the specimens of 5, 10 and 20 mm thickness. Totally 60 specimens, 10 for each thickness, were manufactured.

Test methods

Specimens with varying a/W. Specimens were tested dynamically by an inverse geometry instrumented impact hammer at -30 °C and at +80 °C, which are in the transition and upper shelf region of the brittle to ductile transition of the material. Load and energy were determined as a function of the specimen displacement. The fracture toughness parameter, J_c, at brittle or ductile crack initiation was calculated by Eq. 4.

$$J_c = \eta \frac{E_i}{B(W-a)} \tag{4}$$

where E_i is the energy value at brittle or ductile crack initiation and η is obtained by Eq. 5, which is based on a numerical fit to a number of different FEM-solutions.

$$\begin{aligned} \eta &= 1.9 - 25.124 \times (0.275 - \frac{a}{W})^2 &&, \textit{ when } 0 < \frac{a}{W} \leq 0.274 \\ \eta &= 1.859 + \frac{0.03}{1 - \frac{a}{W}} &&, \textit{ when } 0.274 < \frac{a}{W} \leq 0.9 \end{aligned} \tag{5}$$

Specimens with varying thickness. The specimens were tested at -100 °C, which is in the brittle to ductile transition region of the test material. The static tests were conducted with servohydraulic 100 kN and 2 MN material testing machines. Load, COD and displacement were measured. The displacement measuring device froze occasionally and thus displacement was not measured in every test.

The fracture toughness, J_c, was determined at cleavage crack initiation by Eq. 4 where η = 2 was used. Fracture energy in Eq. 4 was integrated from the load-displacement record. For each thickness the relation between fracture energies integrated from COD and displacement records was determined. Specimens for which displacement record was not obtained, the fracture toughness was estimated from the fracture toughness calculated from the load-COD record by using the determined relation.

The fracture toughness, J_c, was also determined using the load-COD record alone, according a procedure suggested by Kirk and Dodds (5), where E_i is replaced by the area corresponding to the plastic part of the load-COD record and η, based on COD, is determined according to Eq. 6.

$$\eta = 3.785 - 3.101\frac{a}{W} + 2.018\left(\frac{a}{W}\right)^2 \quad , \textit{ when } 0.05 \leq \frac{a}{W} \leq 0.70 \tag{6}$$

For thicknesses 200 mm and 300 mm there were difficulties with fatiguing the precrack. The precrack initiated and propagated only close to the specimen surface. Thus a multiple precracking was necessary. First precracking was conducted with loading rollers of the same length as the specimen thickness and second with sub-length rollers. This way the precrack first propagated close to the specimen surface and then in the specimen center.

In seven 200 mm thick specimens and in one 300 mm thick specimen the crack propagated only close to the specimen surface. For these specimens an effective thickness, where the fatigue crack propagated, was taken into account and a corresponding fracture energy was determined by using a method based on equal inertia on each unit thickness on the fracture surface.

RESULTS AND INERPRETATION

The effect of a/W on fracture toughness at -30°C

For tests in the transition region the initial fracture toughness (J_c) is presented as a function of ratio of crack depth vs. specimen thickness (a/W) in Fig. 1. The constraint effect is clearly visible. The fracture toughness for a/W of 0.3 and 0.5 are on the same level, but a part of J_c for a/W of 0.1 and all J_c for a/W of 0.05 show an evident loss of constraint. The ratio of highest to lowest fracture toughness is 4.9, 25.5, 6.0 and 9.5 for a/W of 0.05, 0.1, 0.3 and 0.5, respectively. In the case of small scale yielding this relative difference should, with 75 % confidence, be in the range 6...17 (1).

It seems that the change in scatter is related to changes in constraint behaviour. The results of the two deepest crack depths are roughly unaffected by constraint changes, whereas the results corresponding to a/W of 0.1 are strongly affected either by constraint or lack of it. This seems to cause the relative difference to be so high. For the shortest crack depth all specimens are affected by the loss of in-plane constraint.

One explanation for the small relative scatter for the shortest crack depth is that all specimens except one experienced ductile tearing before cleavage fracture initiation. Ductile tearing increases the cleavage fracture initiation probability in two ways. First, it leads to statistical sampling effect, which increases the cleavage fracture initiation probability. Second, ductile tearing makes the crack longer, which increases the in-plane constraint and thus increases the fracture probability. Both effects reduce the apparent fracture toughness and thus decreases the relative difference. Only the lowest result without ductile crack growth is purely a result of constraint effects.

T-stress. T-stress was determined according to Kirk et al (6). Fracture toughness (J_c) as a function of T-stress divided by yield strength is presented in Fig. 2. Between $-0.7\sigma_y \leq T \leq +0.6\sigma_y$ T-stress seems to have no effect on fracture toughness. J_c starts to rise when the compressive T stress is about $0.8\sigma_y$.

In the a/W=0.05 group ductile crack growth affects the fracture toughness. None of the results except the lowest one are applicable for T stress correction due to ductile crack growth.

It seems that T stress can be used only for qualitative constraint correction. It can be argued whether T stress can be used at all, because plastic deformation has occured in all specimens at least in some magnitude.

Q parameter. Q parameter was determined according to (3). Fracture toughness (J_c) vs. Q parameter is presented in Fig. 3. Lines are drawn between points of equal fracture probability. The slope of the lines seem to increase as the J-level increases. Thus fracture toughness is not a function of Q only, but the J-level must also be taken into account. Also the Q parameter seem to be applicable for qualitative constraint correction only.

Small scale yielding correction. Small scale yielding fracture toughness (K_{ssy}) was calculated according to a 2-D FEM analysis (4). The results are presented in Fig. 4. The effect of constraint seems to be effectively removed. Fracture toughness is approximately at equal level for all but the 0.05 a/W ratios.

The correction is excellent when one considers that the FEM-model was only 2-D and approximately five times bigger than the specimens. Also the material parameters in the analysis were not exactly the same as for the test material.

The effect of a/W on fracture toughness at 80°C

The ductile fracture toughness (J_i) results are presented in Fig. 5. The results show a clear pattern. The increase of ductile crack initiation fracture toughness accelerates as crack depth decreases. The results show quite a small scatter. An interesting point is that brittle crack propagation, after ductile tearing, occured in some specimens of low a/W. For the deepest cracks (a/W > 0.37) no cleavage fracture propagation occured.

The effect of specimen thickness (B) on fracture toughness

Fracture toughness (J_c), calculated by using the load-displacement record, vs. specimen thickness (B) is presented in Fig. 6. As in Fig. 1 an evident behaviour can be seen. The increase in fracture toughness seem to accerelate as specimen thickness decreases. The theoretical 95% probability curves have been added to the figure. The curves seem to describe the fracture toughness quite well. Only a few data points fall outside the curves.

Results calculated by using the COD based η-factor are presented in Fig. 7. It seems that results in Fig. 7 are slightly higher/lower than in Fig. 6 when the fracture toughness is bigger/smaller. Again, the 95% probability curves seem to describe the results quite well.

The results of Fig. 6 have been small scale yielding corrected in Fig. 8. The correction has been based on three dimensional FEM - analysis by Dodds (7). The correction was not applicable for the highest results of the 5, 10 and 20 mm thick specimens. Thus some results are omitted. The SSYC has brought results more to the same fracture toughness level thus decreasing, but not removing, the effect of thickness. It seems that SSYC and statistical analysis are not applicabale together. Especially for the thinnest specimens the SSYC seems to be much too strong. This implies that SSYC requires further development, before it can be applied with confidence.

Data points in Figs. 6, 7 and 8 which don't correspond to some round specimen width are due to failed precracking of the specimen. For these specimens the fracture toughness has been calculated corresponding to the thickness where crack did propagate. It seems that these results fall quite well with the other results. The scatter seems to be a little bit large but acceptable.

SUMMARY AND CONCLUSIONS

Various methods have been experimentally used to separately remove the effects of crack depth vs. specimen width ratio (a/W) and specimen thickness (B) on measured fracture toughness (J_c). It seems that small scale yielding correction (SSYC) is most effective for removing the constraint effect of a/W. The statistical size correction alone seems to suite best for taking into account the effect of B for these bend specimens.

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SYMBOLS USED

σ_{ij} = asymptotic stress field

δ_{ij} = asymptotic strain field

Θ = angle

r = distance from the crack tip

σ_0, σ_y = yield strength

P_f = cumulative failure probability

K, K_c = fracture toughness as stress intensity factor

J, J_c = fracture toughness as J-integral

B = specimen thickness

W = specimen width

a = crack length

REFERENCES

(1) Al-Ani,A.M. and Hancock,J.W.,J.Mech.Phys.Sol.39,1,1991,pp.22-43.

(2) O'Dowd,N.P. and Shih,C.F.,J.Mech.Phys.Sol,40,5,1992,pp.939-963.

(3) Anderson,T.L. and Dodds,R.H.,JTEVA,19,2,1991,pp.123-134.

(4) Wallin, K., "Defect Assessment in Components - Fundamentals and Applications", ESIS/EGF9, J. G. Blauel & K.-H. Schwalbe, Eds., Mechanical Engineering Publications, London, 1991, pp. 415-445.

(5) Kirk,M.T. and Dodds,R.H.,NUREG/CR-5969,1993,18 p.

(6) Kirk,M.T.,Koppenhofer,K.C. and Shih,C.F.,ASTM STP 1171,1993,pp. 79-103.

(7) Dodds,R.H., To be published.

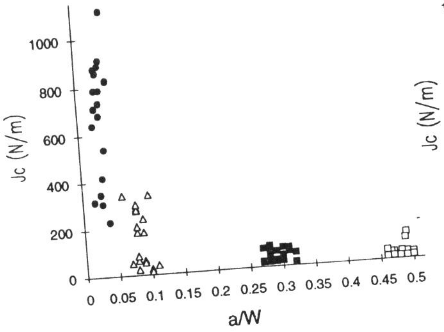

Figure 1. Fracture toughness (J_c) vs. crack depth to specimen width ratio (a/W).

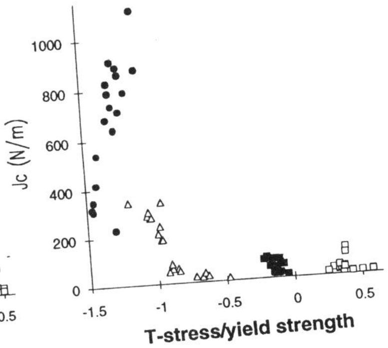

Figure 2. Fracture toughness (J_c) vs. T stress divided by yield strength (T/σ_y).

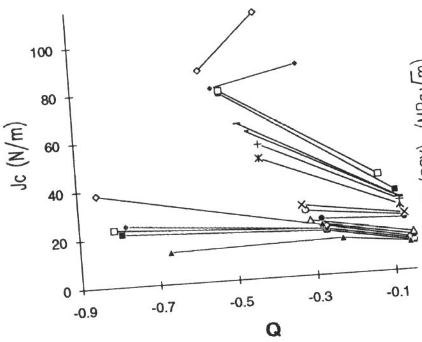

Figure 3. J_c vs. Q parameter. Lines correspond to equal fracture probability.

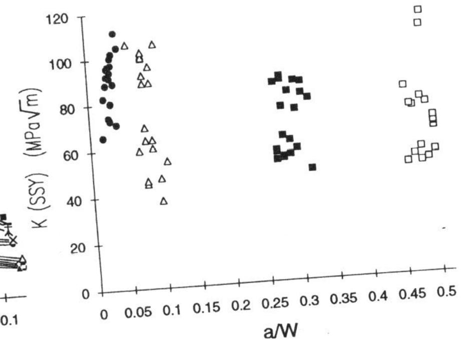

Figure 4. SSY corrected fracture toughness (K_{ssy}) vs. a/W.

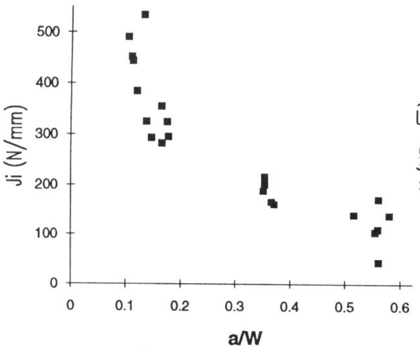

Figure 5. J_i at ductile initiation vs. a/W.

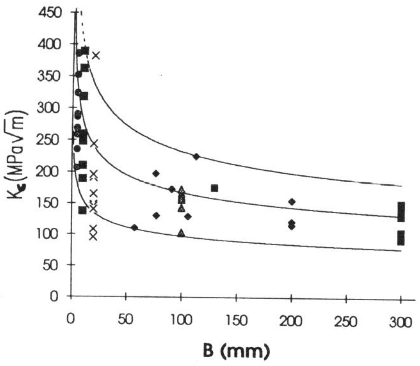

Figure 6. K_c vs. specimen thickness (B). η bases on displacement.

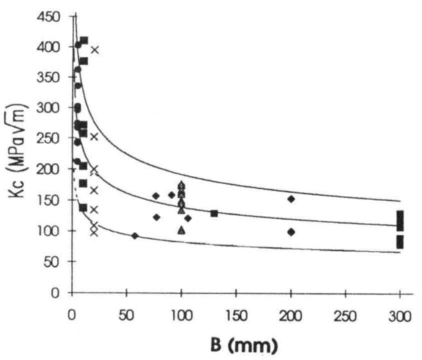

Figure 7. Fracture toughness (K_c) vs. specimen thicknees (B). η bases on COD.

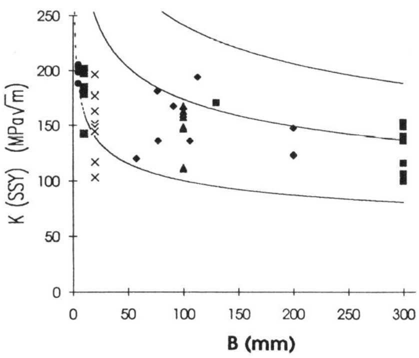

Figure 8. SSY corrected fracture (K_{ssy}) toughness vs. specimen thickness (B).