THE EVALUATION OF FRACTURE TOUGHNESS ON SENB SPECIMENS WITH SHALLOW CRACKS

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The aim of this paper is to present a part of an experimental program being carried out to study size and geometry effects on CTOD and J resistance curves. The material selected for this investigation was the high strength low alloy (HSLA) steel, called NIONICRAL 70A produced by Steel works Jesenice in Slovenia. The experiments were performed on various single edge notch bend (SENB) specimens with different crack depth to specimen width ratios (a/W). The unloading compliance technique to determine the crack growth during the test was used.

INTRODUCTION

Fracture mechanics offers two parameters for the description of cracked body behaviour in elastic-plastic regime: The critical J-integral value (J_{Ic}) and the critical crack tip opening displacement (CTOD). Both parameters are generally accepted as a measure of fracture toughness of engineering materials.

The notch depth of the standard CTOD or J-integral specimens has a significant influence on measured fracture toughness results and should be carefully considered when laboratory test results are related to the service behaviour of the cracked component. Typically, laboratory specimens with deep cracks are tested in order to provide maximum constraint (stress triaxiality) at the crack tip and hence determine conservative estimates of material toughness. Therefore it is questionable to use the J_{Ic} and CTOD values obtained from deep cracked specimens to assess the significance of the shallow surface defects in terms of structural integrity.

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Materials and Specimens

The material selected for this investigation was the high strength low alloy (HSLA) steel produced by Steelworks Jesenice, Slovenia. This steel, called NIONICRAL 70A, is an economically interesting material for the manufacture of complex load bearing structures. Therefore, the way how it behaves in the presence of shallow surface cracks, which cannot be avoided in various weld joints, is very important.

The engineering stress-strain curve obtained from a standard 6 mm diameter longitudinal tensile test conducted at room temperature and a slow loading rate shows that the NIONICRAL steel has the following mechanical properties: Yield strength $\sigma_y = 718$ MPa, ultimate tensile strength 778 MPa, elongation at fracture ≈ 22%, ultimate stress to yield stress ratio of 1.08 and a strain hardening exponent of 0.06.

Three-point-bend (SENB-single edge notch bend) specimens with a cross section 18x36x160 and 36x36x160 were cut out from plates of 40x200x500 so that the crack was propagating in the direction of plate thickness. All specimens were fatigued up to a series of values of crack-depth to specimen width ratio - R= a/W: approx. 0.1, 0.2, 0.3, and 0.6.

Experimental Procedures

The unloading compliance technique was used to measure the crack length and all specimens were instrumented so that the crack growth could be correlated with the J-integral and crack tip opening displacement, CTOD. The details of the experimental procedures are fully described in Refs. (1,2,4).

According to ASTM E762 and BS 5763 both parameters, J-integral and crack tip opening displacement are regarded as the sum of small scale yielding and a fully plastic contribution (1,2):

$$J_{(i)} = \frac{K_{(i)}(1-\nu^2)}{E} + J_{pl(i)} \qquad (1)$$

$$J_{pl(i)} = \left[J_{pl(i-1)} + \frac{2}{b_i} \frac{A_{pl(i)} - A_{pl(i-1)}}{B} \right] \left[1 - \frac{a_i - a_{i-1}}{b_i} \right]$$

Most CTOD based studies have used the BS 5762 (1) CTOD-CMOD correlation to analyze the behaviour of shallow crack specimens:

$$\delta_i = \frac{K_{(i)}(1-\nu^2)}{2\,E\,\sigma_y} + \frac{0.6\,\Delta a_i + 0.4\,(W - a_i)}{0.6\,(a_o + \Delta a_i) + 0.4W + z}\,V_p \qquad (2)$$

Crack length and crack extension were calculated using the specimen compliance C_i:

$$C_i = \frac{\Delta\delta_{xi}}{\Delta F_i} \qquad \text{and} \qquad U_x = \left[\sqrt{\frac{4EBC_i}{S}} + 1\right]^{-1} \qquad (3)$$

$$\frac{a_i}{W} = 0.999748 - 3.9504\,U_x + U_x^2 - 3.21408\,U_x^3 + 51.51564\,U_x^4 - 113.031\,U_x^5$$

J - integral and crack tip opening displacement δ are correlated with the equation:

$$J = m\,\sigma_y\,\delta \qquad (4)$$

where the parameter **m** is described as a constraint factor based on the degree of through thickness constraint.

Blunting Line. The slope of the blunting line was determined from tensile data using the EGF procedure (4):

$$J_{Bl} = \frac{\sigma_o}{0.4\,d_n}\,\Delta a \qquad \text{and} \qquad \delta_{Bl} = \frac{\sigma_o}{0.4\,d_n\,\sigma_y}\,\Delta a \qquad (5)$$

The factor d_n is evaluated from:

$$d_n = \frac{1.185\,E}{\pi\,\sigma_o\,(1+n)(1-\nu^2)}\left[\frac{2\,\sigma_o}{\sqrt{3}}\;\frac{1+\nu}{E}\;\frac{1+n}{n^{n/(1+n)}}\right]^{(1+n)} \qquad (6)$$

The quatities σ_o and n are obtained by a power law fit to the stress-strain curve.

Results and Discussion

After marking the extension of ductile crack growth and breaking the specimen, crack growth Δa was measured on nine places along the thickness. The average crack length (initial a_o and final a_f) and average crack extension Δa were compared to the calculated values according to the compliance method and the difference is less than acceptable.

It is quite obvious that a much higher load is needed for crack opening (CMOD) and load line displacement (Lld) on specimens with shallow cracks (Figure 1). Further we can see that for the same Lld the CMOD is greater for deep cracked specimens (Figure 2).

The results presented in Figures 3 to 5 clearly indicate that the initiation of ductile tearing values, J_i and δ_i (or theirs engineering approximations $J_{0.2BI}$ and $\delta_{0.2BI}$) increase considerably with the use of shallow cracked specimens.

The influence of specimen geometry on J-resistance curves is shown in Fig. 3 and 4. It is evident that there is no significant difference between rectangular 18x36 mm and square 36x36 mm specimens.

Also the correlation between J-integral and crack tip displacement has been investigated. According to the equantion (4) the correlation factor **m** increases with the decreasing R ratio (Figure 6).

CONCLUSIONS

The effect of crack depth to specimen width ratio a_o/W on CTOD and J-resistance curves of HSLA steel NIONICRAL 70A was studied on SENB specimens with a rectangular (18x36) and square (36x36) cross section. The analyses of the experimental results led to the following conclusions:

- High capability of plastic deformation and high resistance against crack propagation - high fracture toughness are characteristic of HSLA steel NIONICRAL.
- Laboratory tests reveal that SENB specimens with shallow cracks ($a_o/W<0.2$) exhibit significantly larger (critical) CTOD and J-integral values than specimens with deep cracks.
- The unloading compliance technique might become inappropriate with the decreasing a/W ratio, because the specimen compliance becomes increasingly difficult to measure.

The summarized results of this investigation once again confirm that the shallow crack specimens lose crack tip constraint when the yielded region at the crack tip extends to the free surface behind the crack. This loss of constraint requires that shallow crack specimens undergo considerably more crack tip blunting and plastic zone development than the deep crack specimens to develop the same opening mode stress in the vicinity of the crack tip.

SYMBOLS USED

$A_{pl(i)}$ = area as shown in Figure 1 (kNmm)
B, W, S = thickness, width and span of SENB specimen (mm)
E = modulus of elasticity (MPa)
V_p = plastic component of the mouth opening displ. (mm)
$\Delta\delta_{xi}$ = increment of crack mouth opening displacement (mm)
ν = Poisson's ratio

REFERENCES

(1) ASTM E1152: "Standard test method for determining J-R curves ", 1987.

(2) ASTM E813: "Standard test method for J_{Ic}, a measure of fracture toughness", 1987.

(3) BS 5762: "Methods for Crack Opening Displacement (COD) Testing", British Standards Institution, 1979

(4) EGF Recomendations for Determining the Fracture Resistance of Ductile Materials", EGF P1-90, European Group on Fracture

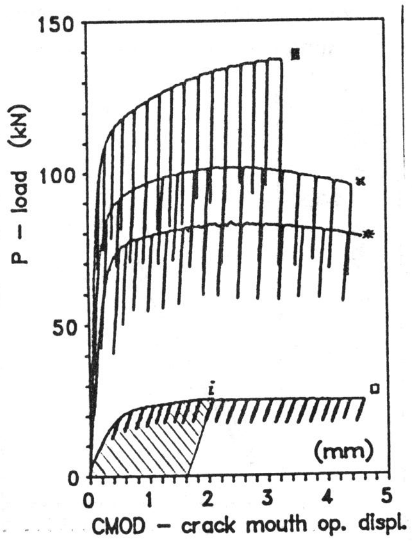

Figure 1 Load-crack mouth opening displacement plot

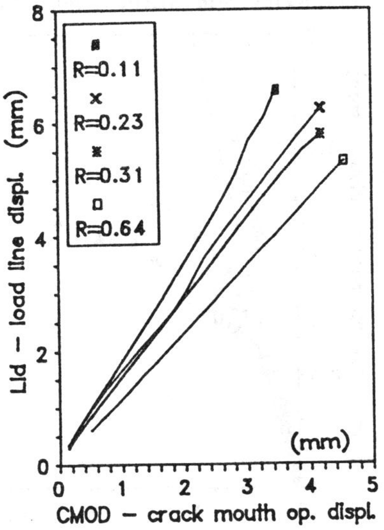

Figure 2 Load line displ.- crack mouth opening displacement plot

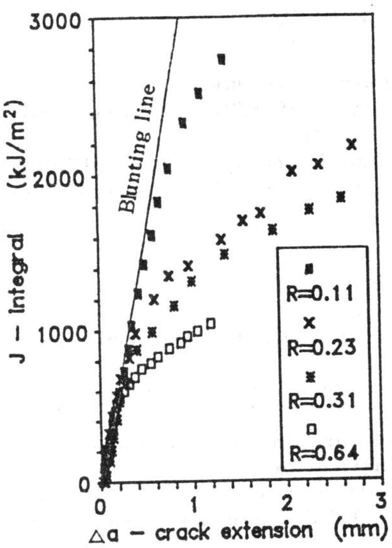

Figure 3 J - R curves for 18x36x160 mm SENB specimen

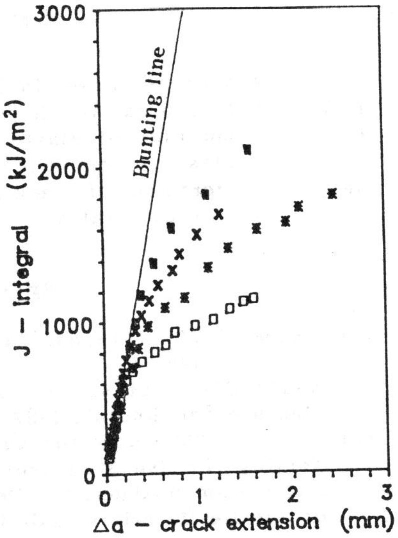

Figure 4 J - R curves for 36x36x160 mm SENB specimens

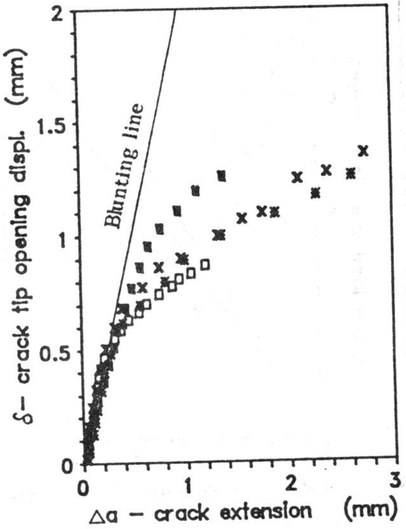

Figure 5 δ - R curves

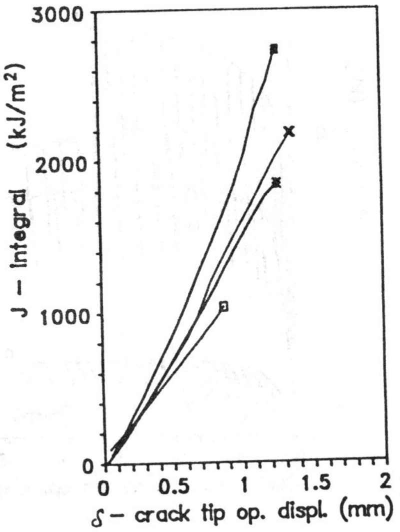

Figure 6 J integral - crack tip opening displacement correlation