ELASTIC-PLASTIC FRACTURE MECHANICS ANALYSES OF BEND SPECIMENS WITH SHALLOW AND DEEP CRACKS

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The effect of crack depth to specimen width ratio on elastic-plastic resistance curves and fracture toughness of a HSLA steel was studied. The experiments were performed on various single edge notch bend specimens (SENB) with different crack depth to specimen width ratios (a/W). The unloading compliance and the DC potential drop methods to determine the crack growth during the test were used.

INTRODUCTION

The notch depth of standard fracture specimen has a significant influence on measured fracture toughness results and should be carefully considered when laboratory test results obtained from deep cracked specimens are related to the service behaviour of cracked components.

Resistance Curves are curves where a certain parameter, in our case the J-integral or CTOD, is plotted over the crack extension Δa. The steep, straight line originating from zero corresponds to the process of crack tip blunting and the second flatter curve describes the stable crack extension (Fig. 3). At the intersection of the two lines, the process of stable crack is initiated (J_0, $CTOD_0$), but the values $J_{0.2BL}$ and $CTOD_{0.2BL}$ are usually used to determine an engineering measure of initiation of crack growth (1).

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MATERIALS AND SPECIMENS

The material selected for this investigation was a high strength low alloy (HSLA) steel. This steel 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.

Table 1 indicates its chemical composition and mechanical properties. The engineering stress-strain curve obtained from a standard 6 mm diameter longitudinal tensile test conducted at room temperature and a slow loading rate is shown in Fig. 1. Because of the addition of micro-alloyed elements this steel has very high yield point with a yield stress to ultimate tensile strength ratio of 0.92 and low strain hardening exponent of 0.06. The same figure is also showing an estimation of sufficient accuracy for the strain hardenig exponent evaluation. If modulus of elasticity (E), yield stress ($R_{p0.2}$), ultimate tensile strength (R_m) and elongation at maximum load (e_u) are known, the hardening exponent can be determined by:

$$n = \frac{\log \dfrac{R_m (1 + e_u)}{R_{p0.2}}}{\log \dfrac{\ln (1 + e_u)}{e_{0.2}}} \qquad (1)$$

TABLE 1 - Chemical Composition (weigth percent) and mechanical Properties of HSLA Steel tested

C	Si	Mn	P	S	Cr	Ni	Al	Mo
0.09	0.27	0.25	0.015	0.004	1.12	2.63	0.02	0.025

Modulus of elasticity E (MPa)	Yield Strength 0.2 percent offset $R_{p0.2}$ (MPa)	Ultimate Tensile Strength R_m (MPa)	Ultimate strain e_u (%)	Elongation at fracture A (%)
≈198 000	718	778	7.45	22.4

with

$$e_{0.2} = \frac{R_{p0.2}}{E} + 0.002$$

Once the hardening exponent is determined, the fictive yield stress folows from:

$$\sigma_o = R_{p0.2} \cdot 10^{\frac{n}{n-1} \log \frac{E\, e_{0.2}}{R_{p0.2}}} \qquad (2)$$

Standard three-point-bend (SENB - single edge notch bend) specimens with rectangular cross-section of 18x36 mm were extracted in the longitudinal orientation with trough-thickness notches and then fatigue-cracked to crack depth ratios of approximatelly 0.1, 0.2, 0.3, 0.5 and 0.6 and they were all instrumented so that the crack growth could be correlated with the J-integral and CTOD.

EXPERIMENTAL PROCEDURES

In the first part of the experimental program the unloading compliance technique was used to determine the J-integral and the CTOD values at the onset of ductile tearing. Prefatigued specimens were monotonically loaded and during the test partial unloadings up to 25% of the actual load were performed to measure the specimen compliance. After marking the extention of ductile crack growth (secondary fatigue) and breaking the specimen, initial crack length and crack growth Δa were measured on nine places along the thickness. The average crack length was compared to the calculated values according to the compliance or DC potential drop method. The difference should be less than 10%.

The value of J-integral was estimated at each unloading point (j) from the area under the load versus load-line displacement record (A_{pl}) using the following expressions (1), (2) :

$$J = J_{el} + J_{pl} \qquad (3)$$

J_{el} - elastic component of J
J_{pl} - plastic component of J

$$J_{el(j)} = \frac{K^2_{I(j)}(1-\nu^2)}{E} \qquad (4)$$

$$J_{pl(j)} = \left[J_{pl(j-1)} + \left(\frac{\eta_p}{b}\right)_{(j)} \frac{A_{pl(j)} - A_{pl(j-1)}}{B_N} \right] \left[1 - \left(\frac{\gamma_p}{b}\right)_{(j)} (a_{(j)} - a_{(j-1)}) \right] \quad (5)$$

where K_I is the linear elastic stress intensity factor, ν is Poisson's ratio, B_N is specimen net thickness and b is the remaining ligament (b = W - a).

The value of plastic eta factor η_p is well established for perfectly plastic materials. For deeply cracked three-point bend specimens (a/W ≥ 0.5), current standards use $\eta_p = 2$ and $\gamma_p = 1$. For the shallow crack 3PB specimens, η_p is dependent on the a/W ratio and γ_p is related to η_p by (3)

$$\gamma_p = \eta_p - 1 - \frac{b}{W} \frac{1}{\eta_p} \frac{d\eta_p}{d(a/W)} \quad (6)$$

Sumpter (4) derived the η_p equantion from limit load analyses of SENB specimens. He has proposed the following relation expressed by a polynomial as

$$\eta_p = 0.32 + 12\left(\frac{a}{W}\right) - 49.5\left(\frac{a}{W}\right)^2 + 99.8\left(\frac{a}{W}\right)^3 \quad \text{for } \frac{a}{W} < 0.282 \quad (7)$$

$$\eta_p = 2 \quad \text{for } \frac{a}{W} > 0.282$$

Table 2 presents the η_p and γ_p values for shallow crack case with no material hardening.

TABLE 2 - Variation of η_p and γ_p with Crack Depth Ratio a/W

a/W	0.05	0.10	0.15	0.20	0.25	0.282	0.50
η_p	0.808	1.125	1.343	1.538	1.786	2.0	2.0
γ_p	-9.352	-3.951	-2.116	-1.633	-1.719	1.0	1.0

Most CTOD based studies have used the BS 5762 (5) CTOD-CMOD correlation to analyze the behaviour of shallow crack specimens. CTOD is regarded as the sum of small scale yielding and a fully plastic contribution:

$$CTOD = \delta_{ssy} + \delta_{fpl} = \frac{K_I^2(1-\nu^2)}{2\,E\,R_{p0.2}} + \frac{r_p\, b_0}{r_p\, b_0 + a_0 + z} V_{pl} \qquad (8)$$

V_{pl} is the plastic contribution to the CMOD (Fig. 2), z is the knife edge height and r_p characterizes the plastic rotation factor, defined as the distance from the crack tip to the hinge point divided by the ligament length. The standard value of r_p for deep cracked specimens is 0.4 (5).

When the crack grows the center of rotation moves forward, but the location at which the CTOD has to be taken remains at the original fatigue crack tip. Therefore Eq. 8 is modified to take into account the crack growth Δa:

$$CTOD^m = \frac{K_I^2(1-\nu^2)}{2\,E\,R_{p0.2}} + \frac{r_p\, b + a - a_0}{r_p\, b + a + z} V_{pl} \qquad (9)$$

Crack length determination. Crack length and crack extension were calculated using the specimen compliance $C_{(j)}$ measured during a partial unloading of specimen (1), (2), (Fig. 2):

$$\Delta a = a_j - a_o \qquad (10)$$

$$a_j = W\,(0.999748 - 3.9504\,U_x + 2.9821\,U_x^2 - 3.21408\,U_x^3 + 51.51564\,U_x^4 - 113.031\,U_x^5 \qquad (11)$$

where U_x is given by:

$$U_x = \left[\sqrt{\frac{4\,E B_e W C_{(j)}}{S}} + 1\right]^{-1} \qquad (12)$$

S is specimen span and B_e is effective thickness for compliance based crack extension measurements: $B_e = B - (B - B_N)^2/B$.

The DC potential drop method uses Johnson's equantion for the crack length determination (6):

$$a = \frac{2W}{\pi} \arccos \frac{\cos \frac{\pi y}{2W}}{\cosh\left[\frac{U}{U_o} \operatorname{arccosh}\left(\cosh \frac{\pi y}{2W} \Big/ \cos \frac{\pi a_o}{2W}\right)\right]} \qquad (13)$$

where U_o and a_o denote the initial values of potential and crack length, U and a are the actual values of both quatities and y is half gage span ower which U is measured.

Blunting line. The slope of blunting line was determined from tensile test results (Eq. 1 and 2) using the EGF (ESIS) procedure (7):

$$J_{Bl} = \frac{\sigma_o}{0.4\, d_n} \Delta a \quad (14)$$

$$CTOD_{Bl} = \frac{\sigma_o}{0.8\, d_n R_{p0.2}} \Delta a \quad (15)$$

The factor d_n was evaluated from:

$$d_n = \frac{1.185\ E}{\pi \sigma_o (1+n)(1-\nu^2)} \left[\frac{2\sigma_o}{\sqrt{3}} \frac{1+\nu}{E} \frac{1+n}{n^{n/(1+n)}} \right]^{(1+n)} \quad (16)$$

δ_5 Measurements. In the second part of the investigation the DC potential drop method was applied on shallow cracked SENB specimens with a crack depth ratio of 0.1 and deep cracked specimens with a crack depth ratio of 0.5. Now, CTOD was directly measured on the specimen's side surface at the original fatigue crack tip by a special clip gage over a gage span of 5 mm. Therefore it was termed δ_5 by GKSS research center (Geestacht, Germany) which developed this testing procedure (8).

DISCUSSION

Since the η_p factor is reduced rapidly for crack less than 0.282 a/W (Table 2), it seems that J-integral should be reduced dramatically, too. However, when the Sumpter η_p is used in Eq. 5, only a slight reduction in the J-R values results as shown in Fig. 3 for shallow crack specimen with a/W = 0.20. The reason for this is that the γ_p factor (Eq. 6) is beetwen -4 to -2 (Table 2) rather than +1, the value used in ASTM E 1152 calculation. The second term is now greater than 1, which results in an elevation of the calculated J, especially after a considerable ductile crack extension has occured.

Figur 4 shows the complete set of J - R curves calculated the Sumpter η_p equantions (Eq. 7) and the incremental method of Eq. 3 to 5. These results show that J-R curves of shallow cracked specimens are elevated in comparison with the J-R curves of the more deeply cracked standard three-point bend specimens.

A major difficulty for CTOD testing is assesing the plastic rotation factor for specimens with a/W ratio less than 0.2. Naturally, Eq. 8 and Eq. 9 will yield correct results only when the "right" values of r_p are inserted. δ_5 measurements can be used to determine the plastic rotation factor r_p experimentally in two ways :

- by the double clip gage method

$$r_p = \frac{\delta_{5pl}(a+z) - V_{pl}(a-a_0)}{b\,(V_{pl} - \delta_{5pl})} \tag{17}$$

- by substituting CTOD values in the BS formula by δ_5

$$r_p = \frac{(a_0 + z)\,(\delta_5 - \delta_{ssy})}{b_0\,(V_{pl} - \delta_5 + \delta_{ssy})} \qquad \text{from CTOD} = \delta_5 \tag{18}$$

$$r_p = \frac{(a + z)\,(\delta_5 - \delta_{ssy}) - V_{pl}(a - a_0)}{b\,(V_{pl} - \delta_5 + \delta_{ssy})} \qquad \text{from CTOD}^m = \delta_5 \tag{19}$$

The results of this r_p factor evaluation are presented in Fig. 5 for shallow crack specimen with a/W = 0.11. Equantion 17 yields a slightly higher r_p value than Eq. 19 because total δ_5 values were inserted instead of plastic component δ_{5pl}. Equantion 18 does not give very reasonable results, probably because of the crack growth Δa is not taken into account. Figure 6 shows that the BS estimation procedure overpredicts the experimental δ_5 values. With adjusting the plastic rotation factor r_p = 0.20 to 0.25 for shallow cracked specimens, we get a very good agreement between the two values.

The use of deep or shallow cracked fracture specimens should be carefully considered with their respective application areas. The use of laboratory test results obtained from deep notched specimens will certaintly be conservative for the design of cracked components, where crack-like defects are in the form of shallow surface cracks.

CONCLUSIONS

The effect of crack depth to specimen width ratio a/W on elastic-plastic resistance curves and fracture toughness of HSLA steel was studied. The plastic rotation factor r_p was experimentally determined using the CTOD equantion of the BS standard in combination with δ_5 clip gage measurements. The analyses of the experimental results lead to the following conclusions:

- The HSLA steel presented in this paper has shown a very good toughness level.
- The boundary value of crack depth ratio between shallow crack behaviour and deep crack behaviour seems to lie between 0.1 and 0.3 (Fig. 4).
- The J-integral and CTOD values at the initiation of ductile tearing, and especially their engineering approximations $J_{0.2BL}$ and $CTOD_{0.2BL}$, increase with the use of shallow cracked specimens.
- The δ_5 measurements are consistent with the calculated CTOD values according to the BS 5762 standard for shallow cracked specimens if the r_p of 0.20 to 0.30 is used. The standard value 0.4 (5) is apparently not adequate for all materials and crack lengths. Therefore it is very important to have a reasonably accurate estimate of r_p.
- The application of δ_5 measurements on the shallow and deep cracked bend specimens offers a simple and quick toughness estimation technique without a need for knowing the material yield strength and any plastic rotation factor corrections.

REFERENCES

(1) ASTM E813: "Standard Test Method for J_{IC}, A Measure of Fracture Toughness", 1989.

(2) ASTM E1152: "Standard Test Method for Determining J-R Curves", 1989.

(3) Ernst, H., Paris, P. C., and Landes, J.D. : "Estimation on J-Integral and Tearing Modulus T from Single Specimen Test Record", Fracture Mechanics (13th Symposium.), ASTM STP 743, Philadelphia, 1981, pp. 476-502.

(4) Sumpter, J. D. G.: "J_c Determination for Shallow Notch Welded Bend Specimens", Fatigue and Fracture of Engineering Materials and Structures, Vol. 10, No. 6, 1987, pp. 479-493.

(5) BS 5762: "Methods for COD Testing", British Standards Institution, 1979.

(6) Johnson, H. H. "Calibrating the Electric Potential Method for Studying Slow Crack Growth", Materials Research and Standards, Vol. 5, No. 9, 1965, pp.442-445.

(7) "EGF Recomendations for Determining the Fracture Resistance of Ductile Materials", EGF P1-1990, European Group on Fracture.

(8) "On the Experimental Determation of CTOD Based R-Curves". Workshop on CTOD Methodology, Geesthacht, Germany, 1985.

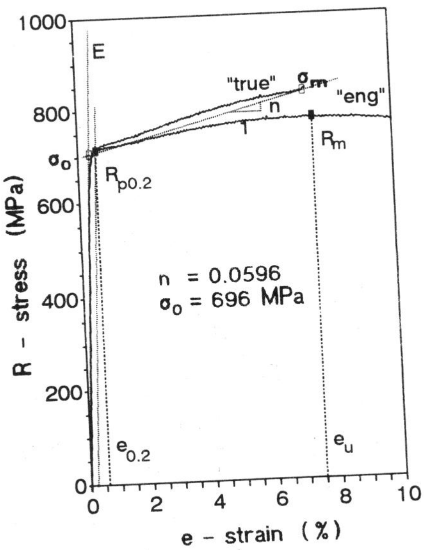

Figure 1 The engineering and the true stress-strain curve

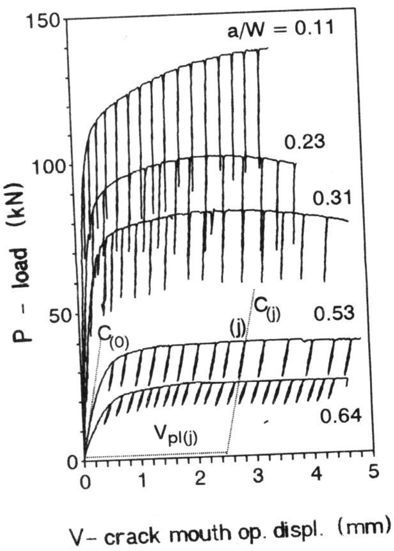

Figure 2 Load versus crack mouth opening displ. records

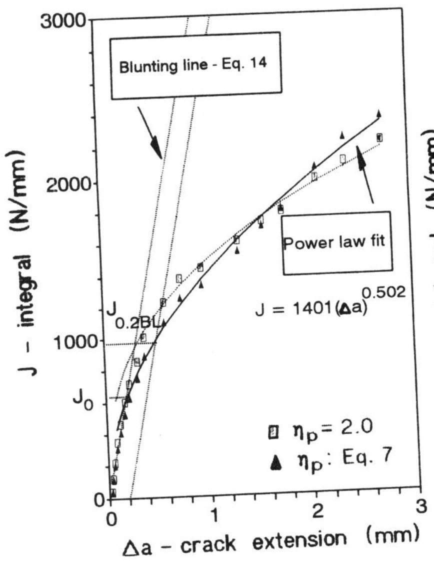

Figure 3 Influence of η_p factor on J-R curve for a/W = 0.20

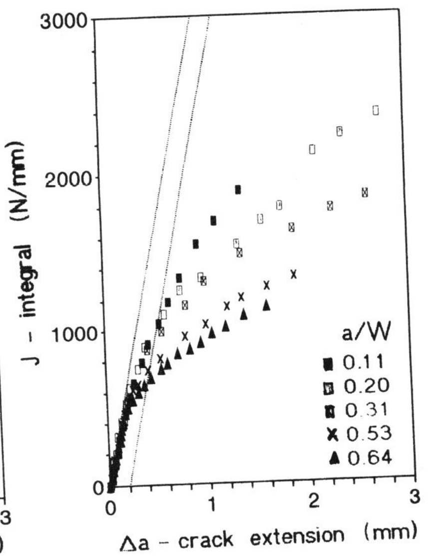

Figure 4 J-R curves for SENB specimens with different a/W

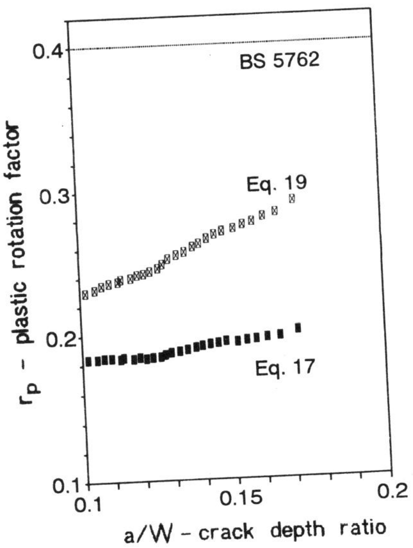

Figure 5 Plastic rotation factor for specimen with a/W = 0.11

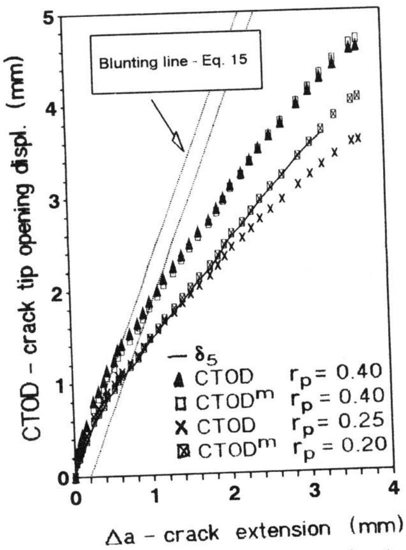

Figure 6 Influence of r_p factor on CTOD-R curves for a/W=0.11