ON THE BLUNTING LINE AND INITIATION TO TEARING FOR TWO STEELS

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ABSTRACT

A small selection of toughness data on two steels of different strengths and yield to ultimate ratios, is analysed in terms of various measures of initiation toughness. The relationship between J and COD, the definition of the blunting line and the effect on initiation of a range of geometries is studied. The often used requirement, $50\ J_{IC}/\sigma_{fl}$, above which initiation toughness is independent of size was found sufficient for the lower strength steel, marginally adequate for the ligament size but insufficient with respect to thickness of the high strength steel.

KEY WORDS

Toughness; J-contour integral; COD, Test methods; Fracture

INTRODUCTION

In steels the initiation of separation from a pre-existing sharp crack seems to occur at a vlue of the J-integral or alterntively of the crack opening displacement, J_i or δ_i respectively. Thereafter, a resistance curve (R-curve) of toughness versus crack growth is found. The R-curve is reviewed in many books and papers, e.g. Turner (1979). Only behaviour above the fracture mode transition is considered here. On the micro scale there is evidence that the local toughness is not increasing (Knott, 1973; Garwood and others, 1975; Rice and others, 1980). A single value of toughness, more or less representative of initiation can be measured through a standardised J test (ASTM: E813, 1981) or COD test (BSI: BS 5762, 1979), although the latter allows some flexibility on whether a toughness is selected close to initiation or close to maximum load, according to the circumstance of interest. A number of studies have been reported (Clarke and others, 1980; Gibson and Druce, 1983) that examine the extent to which a single measure of toughness is geometry independent. A further contribution to such studies was made recently by Etemad (1983) using HY130 steel and by Wei (1982) on BS 4360-50D steel.

The object of the present paper is to look at the toughness of these two steels near iniation. The R-curve results of both of these studies and instability results of Etemad (1983) will be discussed elsewhere.

THE MATERIALS AND TEST DATA

The properties of the two steels are detailed in Table 1. Conventional three-point bend tests were made using a screw driven testing machine with clip gauge and displacement transducers to measure both crack mouth opening and cross head displacement, the latter being corrected later for extraneous

TABLE 1 Properties of HY130 and BS4360-50D Steels

	50D	HY130
0.2% yield strength, *MPa*	340 - 355	896 - 902
Tensile strength, *MPa*	490 - 620	970 - 983
Percentage elongation	18	21 - 23

HY130 Weight% : 0.10C, 0.74Mn, 0.37 Si, 0.006P, 0.002 S, 4.94Ni, 0.53Cr, 0.53Mo

50D Weight% : 0.18C, 1.50Mn, 0.30Si, 0.04P, 0.05S, 0.07V

displacements to estimate J from work. The multiple test-piece method was used to generate R-curves for a variety of bend configurations and sizes. The results were analysed by several different formulae for J and COD. For the present purpose certain sets of results on both steels are selected and re-examined. The values of COD used here are according to BSI:BS5762 (1979) with the rotational factor $r = 0.4$

$$\delta = \delta_{el} + \delta_{pl} = \frac{K^2}{2\sigma_y E'} + \frac{0.4\ (W - a)\ V_p}{0.4\ \ W + 0.6\ a + Z} \qquad (1)$$

where K is the stress intensity factor, E is Young's modulus, E' is $E/(1 - \nu^2)$, σ_y is the yield stress, W is the test piece width, a is the crack length, V is the clip gauge displacement with suffix p for plastic and Z is the height of the knife edges on which the clip gauge is mounted.

The values of J were based on the well-kncwn relationship

$$J = \eta U/Bb \qquad (2)$$

where η is a geometric factor, U is work, B is the test-piece thickness and b the ligament width $(W - a)$. This in most cases was corrected for small amounts of crack growth according to the method in ASTM: E813 (1981), which for deep notch bending; where $\eta = 2$, reduces to

$$J_1 = J_o\ (1 - \frac{\Delta a}{b}), \qquad (3)$$

where J_o is based on Eqn. 2, $J_o = \eta_o\ (U + dU)/Bb_o$.

A second rather different formula, suggested by Sumpter & Turner (1976) was also used:

$$J_2 = \frac{K^2}{E'} + \frac{2Q_L\ (W - a_f)}{B(W - a_o)^2}\ \frac{(V_{gt} - \gamma\ V_{ge})\ W}{a + r\ (W - a_f) + Z} \qquad (4)$$

where a_f is the final crack length including growth, a_i is the initial crack length, Q_L is the limit load. Suffixes gt and ge on V refer to the total elastic components respectively. Also, $\gamma = h(a_f/W)/h(a_i/W)$, where $h(a/W) = -\ 43.0 + 403.0\ (a/W) - 1073.2\ (a/W)^2 + 1162.8\ (a/W)^3$. The tests on HY=30 were made at room temperature. The 50D steel was tested over a range of temperatures, from just above the static ductile transition, - 50°C, to room temperature. However, within this range the R-curves were not affected by temperature, so that test data for a variety of test temperatures are used here. The variation of toughness due to crack orientation was significant and is shown in Table 3.

ANALYSIS OF RESULTS

For HY130, the value of the rotational factor, r, was investigated by simultaneous measurements of clip gauge and load point displacements. This allowed direct determination of COD, including the effect of slow crack growth, rather than reliance on a constant r value as prescribed by BSI (1979). These experimentally determined values, r_f, were found using the final ligament, Table 2. A mean value of $r = 0.45 \pm 0.09$ was obtained with no clear grends against a/W or b/W. The value at no growth, $r = 0.36$, can be compared to a value of 0.40 in BSI (1979) and 0.39 from elastic-plastic finite element computations in plane strain with $a/W = 0.5$ (Turner, 1984). Note that use of r_f instead of $r = 0.4$ had little effect on the value of COD for HY130, because the elastic component of COD calculated from Eqn. (1) was comparable to the plastic part.

Since J and COD were measured separately on both steels, it was possible to use a relationship of the form $J = mf\delta$ to find the factor m. This relationship is not unique, except in certain simplified cases such as the Dugdale-BSC line plasticity model (Rice, 1968). The stress f is usually taken as the yield stress, σ_y, but the flow stress, σ_{fl}, is used for blunting line analysis with $\Delta a = \delta/2$ (i.e. semi-circular tip or one with 45° flanks) and $m = 1$ to give $J = 2\sigma_{fl}\Delta a$ (ASTM, 1981).

TABLE 2 r and m values for HY130

Δa mm	J_1 KN/mm	$(V/q)_f$	W/b_f	a_f/W	r_f	δ mm for r_f	m r_f	δ mm for $r = 0.40$	m $r = 0.40$
3.57	0.47	0.81	2.4	0.59	0.41	0.38	1.37	0.38	1.37
2.11	0.41	0.82	2.3	0.56	0.48	0.33	1.38	0.30	1.52
1.83	0.35	0.86	2.4	0.58	0.54	0.27	1.44	0.24	1.62
1.36	0.32	0.84	2.3	0.57	0.51	0.25	1.47	0.22	1.67
1.01	0.32	0.76	2.2	0.54	0.37	0.20	1.78	0.21	1.69
0.00	0.14	0.73	2.0	0.50	0.36	0.08	1.94	0.09	1.73
Average					0.45		1.56		1.60

SENB, $2B = W = 50mm$, $z/W = 0.05$, $a/W = 0.50$, $s/W = 4.0$

From Geometry $r_f = (W/b_f)\ (\ (V/q)_f - (1/W)\ (a_f + Z)\ )$

For HY=30, direct measurements of blunting was not made; instead *COD* values, calculated using Eqn. 1 with r_f and $r = 0.4$, were related to corresponding J_i values to find m. These show an average value of $m \simeq 1.60$ with $f = \sigma_y$ or $m = 1.54$ with $f = \sigma_{fl}$. The latter gives a blunting line of $J = 0.08\sigma_{fl}\Delta a$, which is 35% steeper than the prescribed ASTM line.

However, there is very little rise in the R-curve in the present tests so that $3.08\ \sigma_{fl}\Delta a$ gives a J_{Ic} value only 5% lower than the value obtained from using the ASTM blunting line.

For 50D steel, m values are given in Table 3, using $J = m\sigma_y\delta$ with *COD* from Eqn. (1) and J from either Eqn. (3), i.e. J_1, or (4), i.e. J_2, for three circumstances: i) no visible crack other than the stretch zone; 2) crack growth of about $0.2mm$ without a clear "thumbnail" pattern; 3) crack growth for which a thumbnail of tear seemed defined with about $0.3mm$ of growth. The value of m varied somewhat according to the formula used for J. The grand mean of m based on J_1, were 2.09 ± 0.1 and based on J_2, 1.66 ± 0.01.

TABLE 3 m Factors for BS4360 - 50D Steel

Fracture Surface Appearance	W/B	Orientation	J_1 kN/mm	J_2 kN/mm	m using J_1	m using J_2
Stretch Zone only	1	TS	0.09	0.21	2.35	1.70
	1	TS	0.23	0.22	1.71	1.61
	2	LS	0.12	0.10	1.04	1.70
	2	TS	0.33	0.21	2.46	1.57
	2	LT	0.26	0.19	2.40	1.69
Average m	-	-	-	-	2.19	1.65
Very small Amount of Δa	2	LS	0.22	0.15	2.52	1.68
	2	LS	-	0.25	-	1.68
	2	TS	0.15	0.14	1.78	1.70
	1	LT	0.25	0.20	2.10	1.68
	2	TS	0.30	0.25	1.98	1.64
	2	TS	0.27	0.28	1.55	1.61
Average m	-	-	-	-	1.99	1.67
Small Amount of Δa	2	TS	0.46	0.37	2.08	1.68
	2	TS	0.29	0.26	1.88	1.69
	2	TS	0.42	0.28	2.44	1.61
	2	LT	0.26	0.21	1.92	1.61
Average m	-	-	-	-	2.08	1.65

SENB, $W = 46mm$, $a/W = 0.5$, $S/W = 4.0$

These m values imply blunting lines of $4.18\sigma_y$ and $3.32\sigma_y$ based on J_1 and J_2 respectively, which reduce to 3.43 and 2.72 if based on σ_{f1} instead of σ_y.

The ASTM (1981) blunting line, $J/\Delta a = 2\sigma_{f1}$, does not fit the present data well. Some R-curve results that clearly showed slow growth, fell nearly on the $2\sigma_{f1}$ line, implying the need for an apparently steeper line. One R-curve is shown in Fig. 1. The blunting data fit $J/\Delta a = 3.32\sigma_{f1}$ or $4.05\sigma_y$. The former is in fair agreement with $2m$ based on J_1. These blunting data give a 25% lower J_{Ic} value than the prescribed ASTM blunting line. Note, however, that four of the six test points on Fig. 1 would be excluded by the present ASTM procedure so that the implied J_{Ic} value is not valid by that standard.

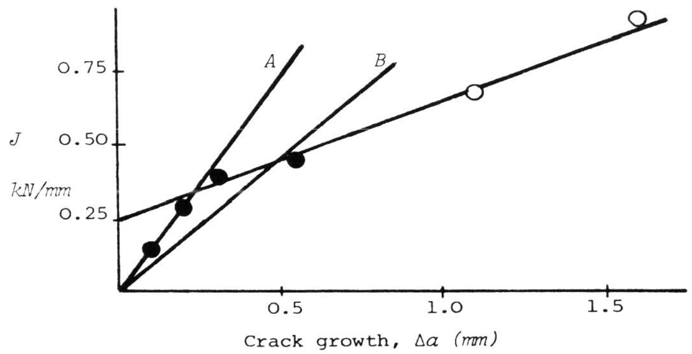

Fig. 1. BS 4360-50D R-curve. SENB, $2B = W = 46mm$, TS.
● disqualified by the ASTM (1981), ○ valid test point;
A is $J=3.32\sigma_{f1}\ \Delta a$, B is $J=2\ f1\ \Delta a$

The choice between $f=\sigma_y$ or σ_{f1} is not clear, although, it seems inconsistent to use σ_{f1} in the blunting line analysis and σ_y in the J-*COD* relationship, if the crack opening stretch of the former is identified with the *COD* of the latter. Although the properties of the two steels are quite different, all the bend data discussed here for both steels (using J_1) give a mean value of $m = 1.63 \pm 0.09$ based on σ_{f1}, where as mean value of $m = 1.85 \pm 0.25$ based on σ_y. The correlation between J - *COD* relationship and the blunting line analysis seems slightly better using σ_{f1} rather than σ_y.

INITIATION AND SIZE REQUIREMENTS

J_i values at initiation are compared with the corresponding J_{Ic} values obtained from methods prescribed in ASTM: E813 (1981), in Figs. 2 to 4. J_i values were found from test-pieces, which upon being broken open showed no crack growth, and are thus lower bound values, possibly just pre-initiation. For HY130 these values were supplemented with J_i values found by extrapolation of R-curves to $\Delta a = 0$. For 50D steel due to the uncertainty in the value of J_{Ic} arising predominately from the choice of blunting line discussed earlier only J_i values are reported in Figs. 2 to 4.

Fig. 2 shows the variation of initiation toughness, J_i and J_{Ic}, with specimen width, or equivalently ligament size, at constant thickness and ao/W. An independent value of initiation toughness is achieved for $W > 25mm$ (if the rather low value of the final point at $W = 66mm$ for HY130 is attributed to scatter) for both steels.

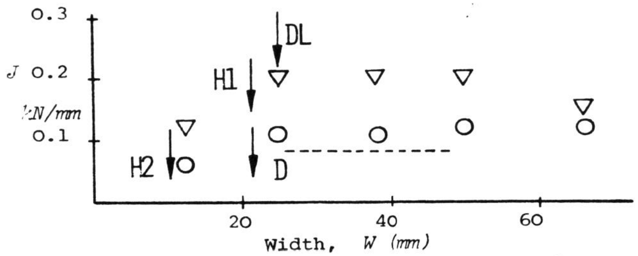

Fig. 2, Effect of W on initiation toughness of two steels. SENB, $a/W=0.5$, $S/W=4$. DL is the "DEMONSTRATED LIMIT". For HY130; *TL*;
○ J_i, ▽ J_{Ic}, $H1=50J_{Ic}/\sigma_{f1}$, $H2$ $50J_i/\sigma_{f1}$ and $B=50mm$. For *50D*; ----J_i, $D=50J_i/\sigma_{f1}$, *LT* and $B=24mm$.

Figure 3 shows a variation of the initiation toughness, J_i and J_{Ic}, with specimen thickness at constant width and a_o/W. An independent value of initiation is achieved for $B > 25mm$ for both steels, but an increase in toughness for the smallest of the three thicknesses of HY130 (i.e. $B = 12.5mm$) were $B < b$. This is in agreement with the established trend, e.g. Druce (1981), of increasing toughness with decreasing thickness, reflecting a change from plane strain to plane stress conditions, (i.e. from $B > b$ to $B < b$).

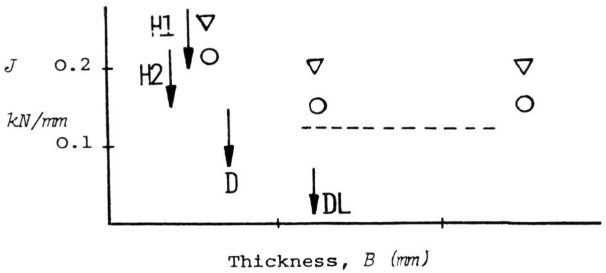

Fig. 3. Effect of B on initiation toughness of two steels Legends as in Fig. 1 except : HY130; *TS*, $W=50mm$ and for 50D; $W=46mm$.

Figure 4 shows the variation of initiation toughness with increasing absolute size of specimen. An independent value of J_i or J_{Ic} was not achieved, although perhaps approach for $B = W > 25mm$, as expected from Figs. 2 and 3. Note, however, that the constant dimension (B in Fig. 2; W in Fig. 3) is greater than $25mm$ in both cases.

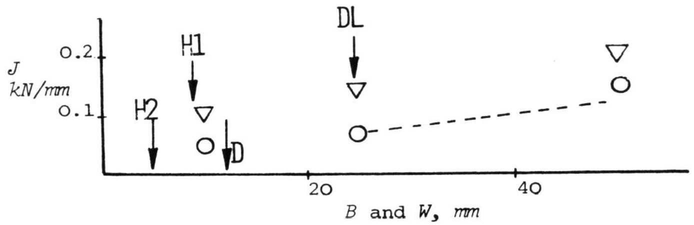

Fig. 4. Effect of scaling on initiation toughness of two steels. Legends as in Fig. 2 except: HY130; *TS*, $B/W=1$ and for 50D; $B/W=1$.

The value of initiation toughness as shown here slightly increase with increased size. Results of Druce (1981) do not show a particular trend with absolute size.

The size requirement (namely a, b and $B > \alpha\ J/\sigma_{f1}$) for geometry independent initiation toughness value is tested here for these two steels. The value for α suggested by Landes and Begley (1972) and later adopted by ASTM (1981) was *25*. Note that *50* is used here for conservatisim. The constant α found here appears in the column "<u>Demonstrated Limit</u>" Table 4. Also, in Table 4 the column "<u>Statement</u>" shows whether these demonstrated limits relate to the ASTM standard. "<u>YES</u>" means adequate, "<u>NO</u>" inadequate, and "<u>MAY BE</u>", that the ASTM expression allows a smaller size than demonstrated here, the demonstrated limit being inconclusive.

TABLE 4 — <u>Size Requirements</u>

Steel	$X \geq 50$	Y/σ_{f1}	Statement	Demonstrated Limit (α)
	X	Y		
HY130	B	J_i	No	150
	B	J_{Ic}	No	120
	b	J_i	No	102
	b	J_{Ic}	May be	60
BS4360 - 50D	B	J_i	May be	70
	B	J_{Ic}	Yes	50
	b	J_i	May be	55
	b	J_{Ic}	Yes	35

For HY130 the results in Table 4 imply that minimum specimen ligament and thickness requirements of $50J/\sigma_{f1}$ are not sufficient to ensure geometry independent J_i or J_{Ic} values, although the ligament independent value of J_{Ic} was within the reach of these requirements. Note that the size requirements are the same for geometry independent J_i or J_{Ic} values, the value of α differs in the Demonstrated Limit Column due to the differences in the value of J. For 50D, although the range of testing was insufficient to derive definite expressions for size independent initiation toughness values; the results here suggest that $50\ J_{Ic}/\sigma_{f1}$ is not invalidated. Note that because of the uncertainty over the blunting line, an assumption of $J_{Ic} = 1.5\ J_i$ was made. Furthermore, the documented values of α for 50D were lower than those for HY130, reflecting that despite $J_{Ic}/\sigma_{f1} = 0.21$ for HY130 but $J_{Ic}/\sigma_{f1} = 0.43$ for 50D the same absolute size was obtained for geometry independent initiation toughness values.

CONCLUSIONS

J data for initiation of ductile crack growth on a variety of configurations of three-point bend pieces show a two-fold spread of results in each of two steels.

The value of the factor m, relating J to $\sigma_{f1}\delta$ was found to be 1.63 ± 0.09 for both steels, implying a blunting line of $J = 3.26\ \sigma_{f1}\Delta a$, which is 39% steeper than the prescribed ASTM value. Using this steeper line, the J_{Ic} value for HY=30 would be reduced by 5% where as for 50D it would be by 24%.

For HY=30, initiation to tearing was found to be affected predominantly by thickness. Furthermore, $50\ J_{Ic}/\sigma_{f1}$ was found marginally adequate for the ligament size and insufficient for thickness. The same expression in terms of J_i was found inadequate in respect to thickness as well as the ligament width. The results for 50D showed $50\ J_{ic}/\sigma_{f1}$ to be satisfactory for thickness and ligament, but $50\ J_i/\sigma_{f1}$ only marginally adequate for ligament width.

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