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Study of elastic–plastic fracture toughness determination

J. FERNÁNDEZ-SÁEZ, J. CHAO, J. DURÁN, J. M. AMO
Centro Nacional de Investigaciones Metalúrgicas, Avda Gregorio del Amo 8, 28040 Madrid, Spain

The elastic–plastic fracture toughness via J-integral and crack tip opening displacement (CTOD) has been obtained in two structural steels using several fitting equations representing the resistance curve of the material. The toughness is determined as the values corresponding to the critical stretched zone width (SZW) on the R-curves and with respect to 0.2 mm crack growth. The SZW measurements were performed by scanning electron microscopy. The various toughness values have been compared and the importance of using appropriate R-curves based on physical considerations has been pointed out. The J–CTOD relationship during the blunting process has been experimentally investigated from load–displacement records of the fracture test.

1. Introduction

It is well known that the toughness of elastic–plastic materials can be measured in terms of the critical value of the J-integral [1] or crack tip opening displacement (CTOD) [2].

The standards for J-integral [3, 4] and CTOD [4] measurement use a multi-specimen method to construct fracture resistance curves. This method involves unloading of a number of specimens with identical nominal dimensions at different load-point displacements to allow different amounts of stable crack growth.

The following step is to fit the experimental data points J (or CTOD)–Δa obtained using an equation which represents the fracture resistance curve of the material, where a is the crack depth.

The initiation fracture toughness via the J-integral, J_i, or via CTOD, δ_i is defined as the value of J or CTOD at the start of physical crack growth. This point does not coincide with $\Delta a = 0$, because an apparent growth exists motivated by the crack-tip blunting as a result of the exterior loads applied. During the blunting process, a stretched zone is formed. The stretched zone width (SZW) is equivalent to the crack extension due to crack-tip blunting. The expression relating J-integral (or CTOD) with this apparent crack growth is known as the blunting line equation. Several approaches to equate blunting lines can be found in the literature [5–7].

A topic subjected to considerable discussion is the proper evaluation of the crack initiation toughness. This value can be obtained as the intersection of the blunting line with the J–resistance curve [3, 4] or CTOD–resistance curve [4] or as the value corresponding to the critical stretched zone width (SZW) on these R-curves [4]. This is a more direct method based on the microscopic observation of the blunting phenomena.

Generally, in both procedures it is necessary to extrapolate the experimental data obtained and, therefore, the fitting of these data by an appropriate equation is of great importance.

Another (operational) definition of fracture toughness can be used. This consists of taking as material toughness the values of J or CTOD corresponding to a stable crack growth of 0.2 mm on the R-curves,

In this work an experimental investigation has been carried out on two structural steels in order to compare the different fracture toughness values obtained at the initiation and at $\Delta a = 0.2$ mm using several equations for R-curves.

The J–CTOD relationship during the crack-blunting process has also been investigated.

2. Experimental procedure

2.1. Materials and test specimens

The investigation was carried out using two structural C–Mn steels. Their chemical compositions and tensile properties are shown in Table I. Steel A is used in offshore construction and Steel B in pressure vessel technology.

The compact tension (CT) specimens were machined and fatigue precracked according to ASTM standard [3]. The specimen dimensions were thickness $B = 25$ mm, width $W = 50$ mm, and crack depth-to-width ratio $a/w = 0.6$. In order to allow straight-fronted ductile crack growth during the test, specimens were side-grooved after fatigue pre-cracking, with a standard Charpy V-notch profile cutter. The net section thickness was about 80% of initial thickness.

2.2. Fracture mechanics tests

The specimens were tested on a MTS machine of 250 kN capacity under displacement control. The load

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TABLE I (a) Chemical composition and (b) tensile properties
(a)

Steel	C	Si	Mn	Ni	Cr	Mo	Cu	P	S	Al	B
A	0.20	0.37	1.10	0.10	0.13	0.02	0.22	0.013	< 0.002	0.037	0.0004
B	0.15	0.32	1.20	0.016	0.09	0.03	0.29	0.010	< 0.022	–	–

Steel	Yield strength σ_Y (MPa)	Tensile strength σ_{UTS} (MPa)	Elongation %	*RA* %
A	345	513	34	70
B	381	501	35	58

point displacement (LPD) and crack mouth opening displacement (CMOD) were measured with clip gauges. The loading was continued to an appropriate level in the elastic–plastic region to allow some crack growth in the specimen. For each steel, six identical specimens were loaded to give different amounts of crack growth.

Heat tinting is used to mark the extent of crack growth in tested specimens. The specimens were subsequently broken open at liquid nitrogen temperature. The average crack growth was measured using the nine-point average method [3, 4].

2.3. Determination of *J*-integral and CTOD values

The *J*-integral value was obtained from the expression [4]

$$J = \frac{\eta U}{B_n(W - a_0)} \quad (1)$$

where $\eta = 2 + 0.522[1 - (a_0/W)]$, U is the area under the load versus load point displacement record up to the line at constant displacement, corresponding to the end of the test, B_n, W and a_0 are the net thickness, width and initial crack length of the specimen, respectively.

The CTOD was obtained using the expression [4]

$$\delta = \frac{K^2(1 - \nu^2)}{2E\sigma_y} + \frac{0.4(W - a_o)}{0.4W + 0.6a_o}V_p \quad (2)$$

where K, σ_y, E and ν are the stress intensity factor, yield strength, elastic modulus and Poisson ratio, respectively. V_p is the plastic component of CMOD.

2.4. Determination of *J*–CTOD relationship

Because the readings of LPD (and CMOD) are available at regular intervals during the test, *J* and CTOD values can be calculated at these points and, therefore, their relationship can be established in a totally experimental way through testing a specimen.

2.5. Measurement of stretched zone width (SZW)

The stretched zone exists between the fatigue precracked region and the stable fracture zone (tearing). The critical stretched zone width (SZW) was evaluated at the standard nine positions using calibrated photographs taken in a scanning electrical microscope (SEM) [4]. Six measurements were done at each position and therefore a total of 54 measurements along the crack front were performed. The critical stretched zone width of the specimen was determined by averaging the 54 measurements. Finally, the SZW of the set of specimens is the average of the SZW of each specimen.

3. Results and discussion

3.1. Fracture resistance curves and fracture toughness of the material

The crack initiation toughness via *J*-integral, J_i, or via CTOD, δ_i, was determined as the values of *J* or CTOD at the intersection of critical SZW with the respective *R*-curves. Also, the material toughness was evaluated at the intersection of $\Delta a = 0.2$ mm with the same curves.

Therefore, as pointed out in the Section 1, the type of equation representing the fracture resistance behaviour of the material plays an important role in determining the material toughness.

In this work, to study the best equation for *R*-curves, several approaches have been used.

(a) Correlating the experimental data with a polynominal equation

$$J(\text{CTOD}) = m_0 + \sum_{i=1}^{n} m_i(\Delta a)^i \quad (3)$$

$m_0, m_1, \ldots$, are the regression coefficients to be obtained.

In order to develop the best regression model, it is necessary to select only those variables which are relevant. In this work the method of forward selection [8] was used. This method involves adding variables to the model sequentially until the increase in the regression sum of squares (RSS) due to the inclusion of a new variable is no longer statistically significant. The significance of a variable is tested by a *F*-test [8].

(b) By making use of the ASTM power law [3]

$$J(\text{CTOD}) = A(\Delta a)^m \quad (4)$$

(c) Applying the modified power law proposed by EGF [4]

$$J(\text{CTOD}) = C(\Delta a + D)^F \quad (5)$$

(d) Generally, there are no data available for very small crack growth in the range of the critical stretched zone width. For this reason, physically based considerations on the behaviour of the R-curve in this region will be of great importance to estimate realistic values of crack initiation toughness. One equation which represents an adequate R-curve must obey at least the two properties below.

1. The value of J or CTOD must be zero with nil crack growth ($\Delta a = 0$).

2. The slope of the curve at the point $\Delta a \to 0$ must be a finite value.

In this work, the following exponential-type law accomplishing these features is proposed

$$J(\text{CTOD}) = G\,\Delta a\,[1 + H\exp(-M\Delta a)] \quad (6)$$

In all the above approaches, the fitting coefficients were estimated by the least-squares method.

The different fit equations obtained for J-integral and CTOD are given in Table II. The equation for J-integral, together with the experimental values for both materials A and B, are plotted in Figs 1 and 2, respectively. For CTOD analysis similar curves were obtained. In Table III, the results corresponding to SZW and J-integral can be seen. J_i and $J_{0.2}$ are calculated by substitution of Δa = SZW and $\Delta a = 0.2$,

TABLE II Fitting equations for fracture resistance curve (Δa in mm)

Steel	Equation type	J-integral (N mm^{-1})	CTOD (mm)
A	3	$J = -62.2 + 1526.4(\Delta a) - 837.4(\Delta a)^2$	$\delta = 0.038 + 0.130(\Delta a) - 0.554(\Delta a)^3$
	4	$J = 753.5\,(\Delta a)^{0.773}$	$\delta = 0.920\,(\Delta a)^{0.693}$
	5	$J = 716.3\,(\Delta a - 0.147)^{0.407}$	$\delta = 0.899\,(\Delta a - 0.128)^{0.416}$
	6	$J = 33.9\,\Delta a\,[1 + 37.5\exp(-0.703\,\Delta a)]$	$\delta = 0.037\,\Delta a[1 + 46.3\exp(-0.776\,\Delta a)]$
B	3	$J = 80.4 + 64.7\,\Delta a$	$\delta = 0.119 + 0.082\,\Delta a$
	4	$J = 135.7\,(\Delta a)^{0.246}$	$\delta = 0.188\,(\Delta a)^{0.214}$
	5	$J = 123.7\,(\Delta a + 0.338)^{0.472}$	$\delta = 0.156\,(\Delta a + 0.56)^{0.537}$
	6	$J = 146.7\,\Delta a\,[1 + 5.6\exp(-4.758\,\Delta a)]$	$\delta = 0.208\,\Delta a\,[1 + 6.1\exp(-0.776\,\Delta a)]$

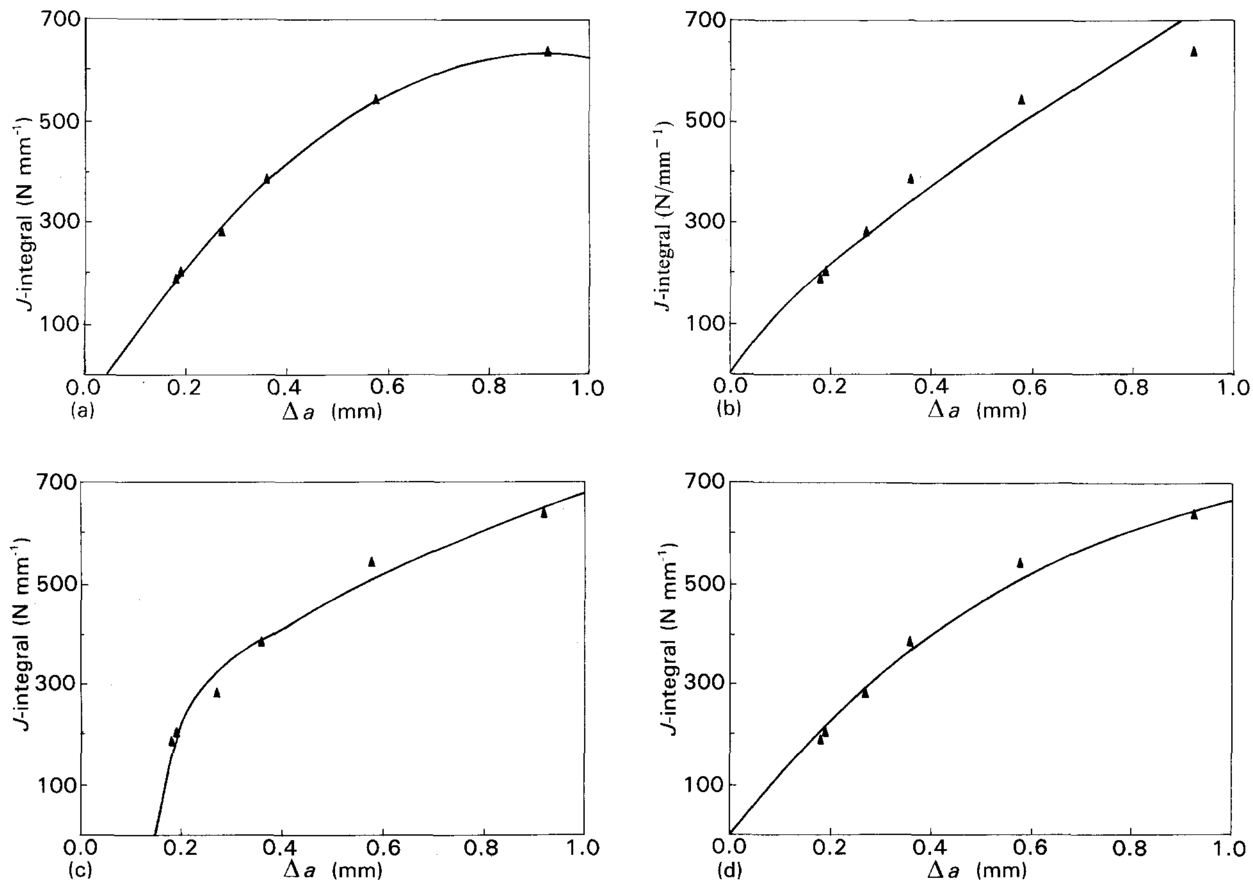

Figure 1. J–resistance curves for Material A: (a) equation type 3, (b) equation type 4, (c) equation type 5, (d) equation type 6; (experimental J values).

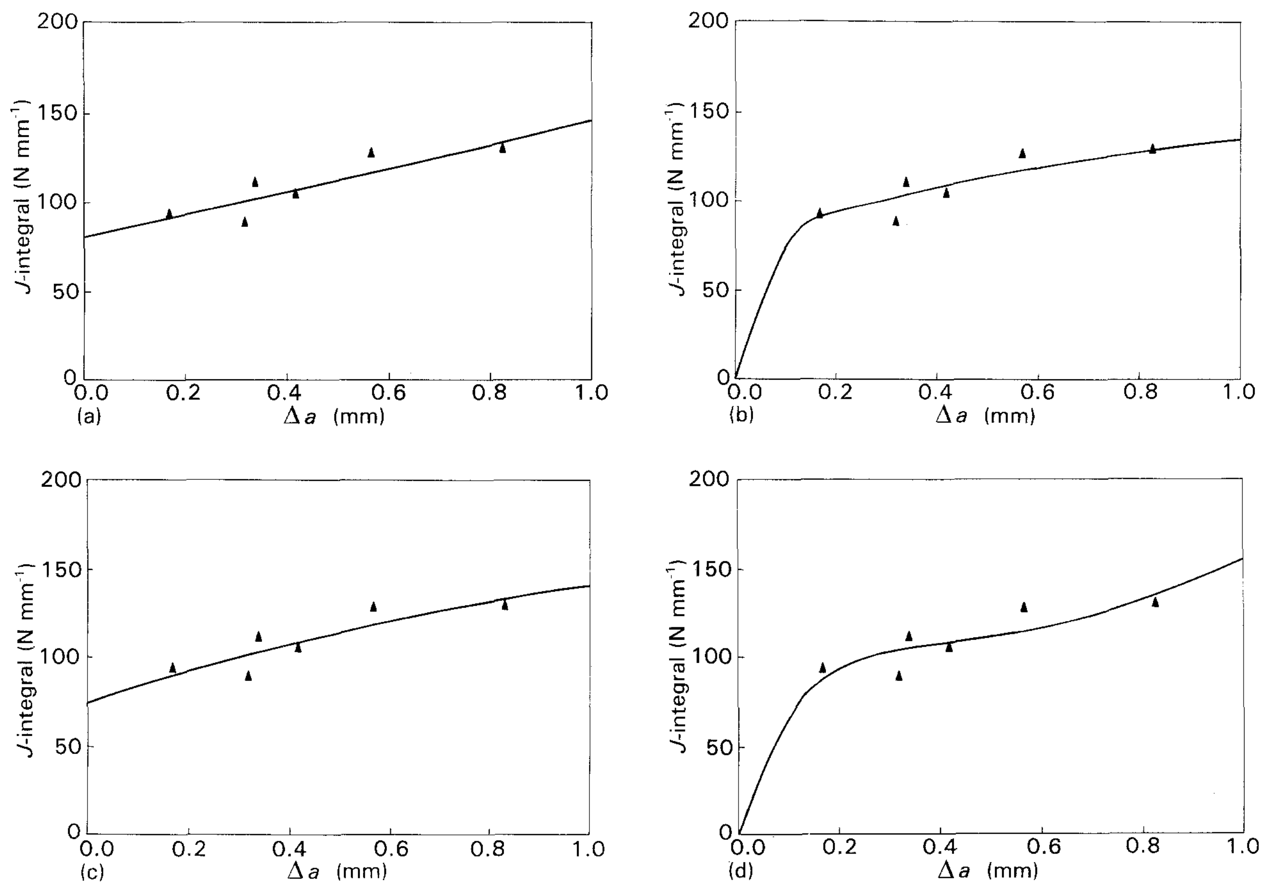

Figure 2. J–resistance curves for Material B: (a) equation type 3, (b) equation type 4, (c) equation type 5, (d) equation type 6; (experimental CTOD values).

TABLE III J-integral fracture toughness results

Steel	Equation type	SZW (mm)	J_i ($N mm^{-1}$)	$J_{0.2}$ ($N mm^{-1}$)	J_i/SZW	R-slope
A	3	0.102	85	210	833	1356
	4	0.102	129	217	1265	978
	5	0.102	–	217	–	–
	6	0.102	124	228	1219	1134
B	3	0.055	84	93	64	1513
	4	0.055	67	91	295	1207
	5	0.055	81	92	96	1459
	6	0.055	43	93	608	774

respectively, in the different fitting Equations 4–6. The "experimental blunting slope" is evaluated as J_i/SZW and the slope of the R-curve at the initiation point (R-Slope in the table) is the value of the derivative function with respect to Δa of the corresponding fitting equation for Δa = SZW.

From the results in Table III, the following comments can be made.

(a) Quite different J_i values are obtained depending on the fitting equation used.

(b) For $J_{0.2}$, however, the differences are negligible.

(c) Comparing the values of the "experimental blunting slope" (J_i/SZW) and the slope of the R-curve (R-slope) a good agreement is observed with the results of Equation 6. However, the rest of the equations give higher differences between these two calculated slopes. This finding supports the choice of Equation 6 as an adequate representation of the fracture resistance behaviour of the steels tested.

(d) The crack initiation toughness values calculated using the ASTM equation (Equation 4) and the EGF equation (Equation 5), when it is possible, are higher than the values obtained with exponential-type law (Equation 6). This could indicate that these methods would give unrealistic and too optimistic toughness values.

The results corresponding to CTOD for both materials are given in Table IV. The same comments as for the J-integral can be applied here. Furthermore, it is now also possible to calculate the "blunting angle" as $\Theta = \tan^{-1}$ (δ_i/2SZW). In the case of the exponential-type law proposed in this work, this angle is less than 45° which is in agreement with the studies of Pandey *et al.* [9, 10].

TABLE IV CTOD fracture toughness results

Steel	Equation type	SZW (mm)	δ_i (mm)	$\delta_{0.2}$ (mm)	δ_i/SZW	R-slope	$\theta°$	J_i/δ_i($N\,mm^{-2}$)
A	3	0.102	0.170	0.294	1.667	1.284	39.9	500
	4	0.102	0.189	0.302	1.853	1.286	42.8	683
	5	0.102	–	0.301	–	–	–	–
	6	0.102	0.166	0.302	1.630	1.504	39.2	747
B	3	0.055	0.123	0.135	2.216	0.082	47.9	683
	4	0.055	0.101	0.133	1.820	0.390	42.3	663
	5	0.055	0.120	0.134	2.162	0.105	47.2	675
	6	0.055	0.065	0.135	1.169	0.902	30.3	661

3.2. J–CTOD relationship

To evaluate the J–CTOD relationship, CMOD and load readings were taken at regular intervals with load point displacement, and J and CTOD were calculated using Equations 1 and 2, respectively. For each specimen, the experimental data were fitted with the linear equation

$$J = N + P \cdot \text{CTOD} \quad (7)$$

The values of calculated CTOD exceeding 2SZW of the specimen were eliminated for regression analysis and, therefore, the J–CTOD relationship was obtained during the blunting process and not during the stable crack-growth process.

The parameter N is about 1% of the $P \cdot$CTOD value and, therefore, can be considered negligible. Then, we can write

$$J = P \cdot \text{CTOD} \quad (8)$$

The mean and standard deviation of parameter P for the six specimens tested are

for Material A: $\bar{P} = 700.3$, $\sigma_p = 30.8$

for Material B: $\bar{P} = 704.2$, $\sigma_p = 46.7$

The standard deviation for P indicates a small scatter in the six specimens of each steel tested. Moreover, the P mean value is close to the J_i/δ_i relationship obtained with different R-curve equations (see Table IV).

Furthermore, as Equation 8, is possible to be determined for each specimen, it allows the estimation of a J value at crack initiation with a single specimen, if the value of δ_i is available for this specimen, i.e.

$$J_i = P \cdot \delta_i \quad (9)$$

The CTOD crack initiation can be determined from a single specimen by measurement of the stretched zone depth (SZD) [9, 10] and, therefore, this permits, together with Equation 9, the evaluation of the crack initiation toughness in terms of J integral from the test of a single specimen.

4. Conclusions

1. To obtain the initiation toughness we must take into account physical considerations about the appropriate equations to fit experimental data. The exponential-type law proposed in this work gives toughness results which are consistent with the experimental blunting slopes and microcopic analysis of Pandey *et al.* [9. 10]. The methods proposed by ASTM [3] and EGF [4] can give unconservative values of material initiation toughness.

2. The EGF method for toughness determination is not applicable in all situations because of the fitted equation of R curves give not real values at Δa = SZW.

3. The values of J-integral and CTOD corresponding to a physical crack growth of 0.2 mm are practically the same obtained for the different fitting equations. This is due to the fact that to obtain this value, it is not necessary to extrapolate experimental data and in this region all equations basically coincide.

4. An experimental method to evaluate the J–CTOD relationship during the blunting process can be obtained from the load–LPD and load–CMOD records.

5. The experimental relationship of J–CTOD together with measurement of SZW and SZD can be a suitable single-specimen method to obtain initiation fracture toughness in terms of J-integral.

References

1. J. A. BEGLEY and J. D. LANDES, in "Fracture Toughness", ASTM STP 514 (American Society for Testing and Materials, Philadelphia, PA, 1974) p. 170.
2. J. F. KNOTT, "Fundamentals of Fracture Mechanics" (Butterworths, London, 1973).
3. "Standard Test Method for J_{Ic}, A Measure of Fracture Toughness", ASTM E813-87 (American Society for Testing and Materials, Philadelphia, PA, 1987).
4. "EGF Recommendations for Determining the Fracture Resistance of Ductile Materials", EGF p1-90. European Group on Fracture (December, 1989).
5. J. MILLS, *J. Test. Eval. JTEVA* **9** (1981) 56.
6. K. H. SCHWALBE, *Int. J. Fract.* **9** (1973) 381.
7. O. KOLEDNIK and H. P. STUWE, *ibid.* **33** (1987) R63.
8. R. MOSKOVIC and P. L. WINDLE, *Eng. Fract. Mech.* **31** (1988) 221.
9. R. K. PANDEY, A. N. KUMAR and P. SUNDARAM, *J. Mater. Sci.* **26** (1991) 6237.
10. R. K. PANDEY, P. SUNDARAM and A. N. KUMAR, *Int. J. Fract.* **47** (1991) R29.

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