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A Simple J-integral Approach for Fracture Toughness Assessment on Invalid Test Data of Standard CT Specimens

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Abstract: High strength materials are prone to failure in presence of flaws/cracks and this is expressed through the fracture toughness of the material. In fracture base design, the structure should be designed such that for a detectable minimum/or design allowable flaw size the structure under given service condition, the stress intensity factor (K) at the crack tip should always be less than K_{Ic}, the plane strain fracture toughness. In view of the sensitiveness of the parameter to the material conditions in terms of heat treatment, grain size, etc. it has become generally necessary to confirm the achieved K_{Ic} with respect to what is required by the design. It has been found extremely difficult and impractical to follow standard tests for K_{Ic} determination especially at various stages of fabrication/quality control, in view of involved procedures, for testing and to meet the validity conditions of the test. In fracture toughness testing, the Compact Tension (CT) specimen is recommended as one of the standard specimens. Many times the test becomes invalid as per ASTM E 399 standard. Since fracture toughness testing is a costly affair, it is preferable to minimize the number of repeat tests. A simple J-integral method is adopted for assessing the fracture toughness from the invalid test data of standard CT specimens.

Key words: Fracture toughness, CT specimens, maraging steel, HSLA steel, titanium alloy, J-integral

Introduction

The safety of the structural component in the absence of cracks can be assured if the stress under service loads is less than the yield strength or 0.2% proof stress (σ_{ys})/ultimate tensile strength (σ_{ult}) of the material, where as in the presence of cracks, the crack-tip stress intensity factor (K) should be less than the fracture toughness (K_{Ic}) of the material. Structural components generally contain crack-like defects which are either inherent in the material or introduced during the fabrication process. These cracks usually have sharp edges and are sensitive to initiation of crack growth and fracture. Thus, the fracture toughness of the material used in the structure is a key input for failure assessment.

Material properties such as fracture toughness are variable and a consumer/client may wish to satisfy him-self that the properties of a particular batch of material or component are adequate. This

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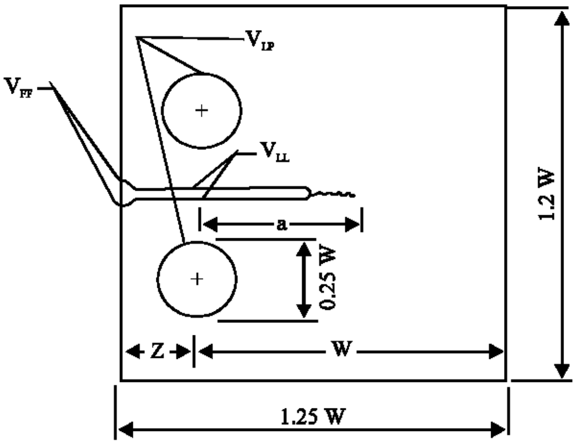

Fig. 1: Standard CT specimen and the crack mouth opening displacement location (front face displacement), V_{FF}

is normally achieved by testing limited number of samples and assessing the results against a preset criterion to decide whether the material is acceptable. Selection of suitable criterion for choosing fracture toughness value for use in crack assessment or for accepting/rejecting a material is essential to minimize the "consumer's risk" (risk of accepting bad material) and "producer's risk" (risk of rejecting good material).

Fracture Toughness (K_{Ic}) Evaluation

In fracture toughness testing, the Compact Tension (CT) specimen (Fig. 1) is recommended as one of the standard specimens by the ASTM E24 task group. The load-displacement curves in general are not perfectly elastic but exhibit different degrees of non-linearity (Fig. 3). After considerable experimentation, ASTM E 399 standard (1992) suggested the load P_Q at a 5% secant offset to define K_Q as the critical stress intensity factor at which the crack reaches an effective length, a_{eff}, equal to 2% greater than the initial crack length a_0. To establish that valid plane strain fracture toughness K_{Ic} has been determined, it is necessary to calculate the ratio P_{max}/P_Q where P_{max} is the maximum load sustained by the specimen. If

$$P_{max}/P_Q>1, \tag{1}$$

Then the test is invalid because it is possible that K_Q is not representative of the plane strain fracture toughness (K_{Ic}). If this ratio does not exceed 1.1, we proceed to calculate $2.5(K_Q/\sigma_{ys})^2$, in which, σ_{ys} is the 0.2% proof-stress or yield strength of the material. If

$$2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2 < \text{B (specimen thickness) and } a_0 \text{ (initial crack length)} \tag{2}$$

Then the plane strain fracture toughness,

$$K_{Ic} = K_Q. \tag{3}$$

Otherwise, the test is not a valid K_{Ic} test.

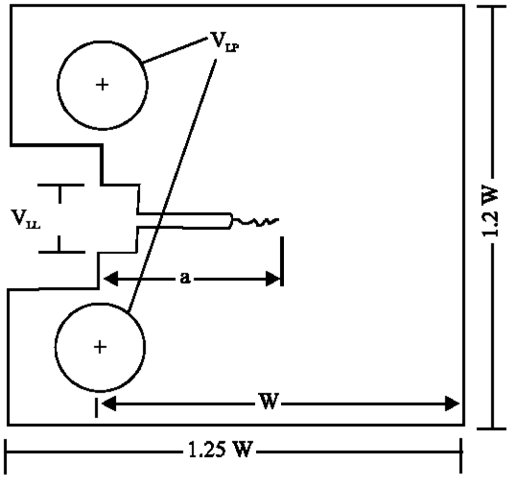

Fig. 2: Modified CT specimen showing crack opening displacement measurement locations using the load points, V_{LP} and load line displacement, V_{LL}

To satisfy the requirement of conditions in Eq. (2), it is necessary to use a larger specimen, the size of which can be estimated on the basis of the evaluated K_Q.

The available material from the actual hardware of the structural components may not always have sufficient thickness to make standard CT specimens for testing. If K_Q is invalid, the strength ratio, R, is a useful comparative measure of the toughness of the material when the specimens tested are of the same size and that size is insufficient to produce a valid K_{Ic}. The strength ratio, R, for the CT specimen is (ASTM, 1992).

$$R = \frac{2P_{max}(2W + a_0)}{B(W - a_0)^2 \sigma_{ys}} \qquad (4)$$

Here, W is the width of the CT specimen

The above validity conditions when met in the actual specimen ensure that a truly plane strain condition is existing at the crack-tip. If, however, any one of the validity conditions is not met, the test is termed “invalid” and the test is to be discarded. A retest is advised after incorporating suitable changes in the geometry of the specimen. It is quite often possible that due to the above strict validity conditions, the borderline cases are also termed as invalid and reasonably valid data is discarded just because the validity conditions are not meeting by a whisker. Fracture toughness testing is very expensive as it involves fabrication of very complex specimen like Compact Tension (CT) specimen and the equally complicated test procedure that involves fatigue pre-cracking under precisely controlled loading conditions, fracture testing, crack length measurement, etc. All this makes the test very specialized and losing the valuable data, time and material as well as the number for retests should be minimized under all circumstances.

Generation of J-Resistance Curve

For the case of elastic-plastic behavior, the fracture toughness is best characterized by the J-resistance curve. For fracture toughness evaluation, the ASTM standard E 1820 (2001) specifies a

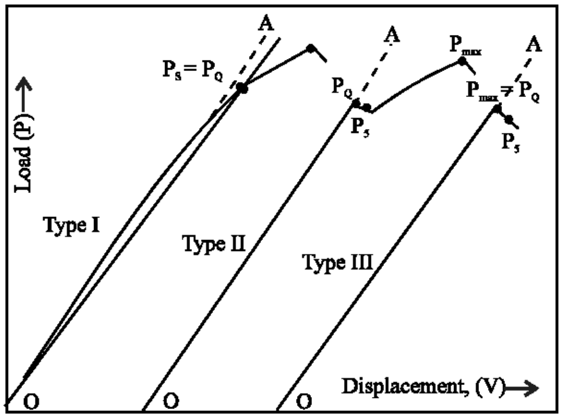

Fig. 3: Principal types of load, (P) versus crack opening displacement, (V_{FF}) curves in standard K_{Ic} test

fairly elaborate procedure to establish the J-resistance curve and thereupon evaluate the J_{Ic} value. The procedure calls for generating load versus load-line displacement curve when a fatigue pre-cracked specimen is incrementally loaded under displacement control. The crack extension occurring during the incremental loading can be obtained by different techniques like, heat tinting multiple specimens, unloading compliance and potential difference method. The unloading compliance method is most widely used because of its simplicity, accuracy and above all the need for just a single specimen to get the J_{Ic} value.

The experimental determination of J-resistance curve requires that the displacement be measured at the load point (V_{LP}, Fig. 2). Because of practical difficulty in measuring V_{LP}, the ASTM standard (2001) proposed that the displacement be measured at the load line (V_{LL}, Fig. 2) with the assumption that the latter is an adequate approximation for V_{LP}. Therefore the CT specimen of E399 standard is modified by enlarging the notch area to accommodate the clip gauge in the load line (Fig. 2). This necessitated the increase in the spacing of loading pin holes. Many investigators later have suggested that this extra machining of the specimen is not required and that the crack mouth opening displacement (CMOD) value (V_{FF}, Fig. 1) is sufficient to develop the J-resistance curve.

Objective of the Present Study

The objective of the present study is to analyze the fracture toughness data recorded in a standard K_{Ic} test. This research presents a simple J-integral method to assess the fracture toughness from the invalid test data of CT specimens made of different high strength materials.

Load-line Displacement Evaluation for Compact Tension Specimens

Newman (1979) and Orange (1982) have presented analytical results at different displacement measurement locations in CT specimens for developing J-resistance curves. It is noted that the crack front face opening displacement, V_{FF} provides an approximation to the load point displacement V_{LP}. After examining the extensive experimental data, Orange has proposed the following empirical expression for V_{LL} in terms of V_{FF}:

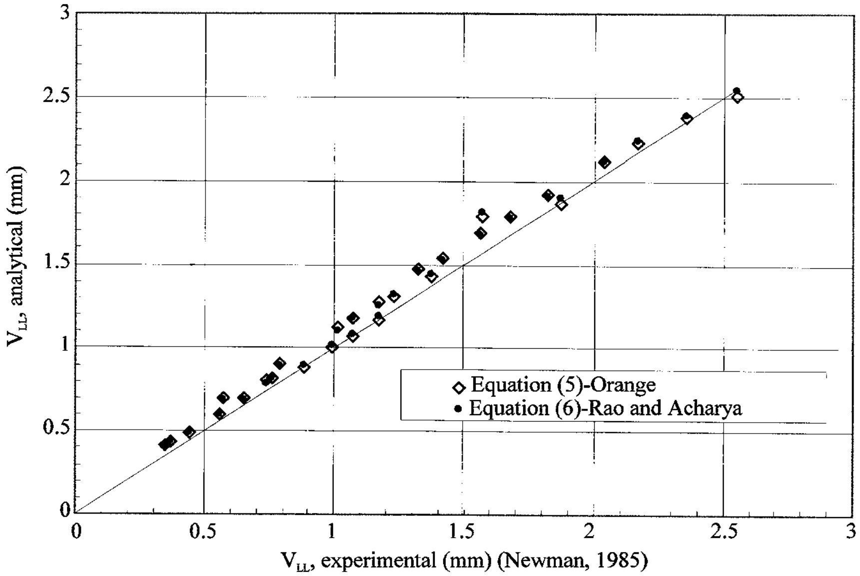

Fig. 4: Comparison of experimental values of load line displacement (V_{LL}) with those obtained from Eq. 5 and 6 for AA7075-T651 Aluminum alloy

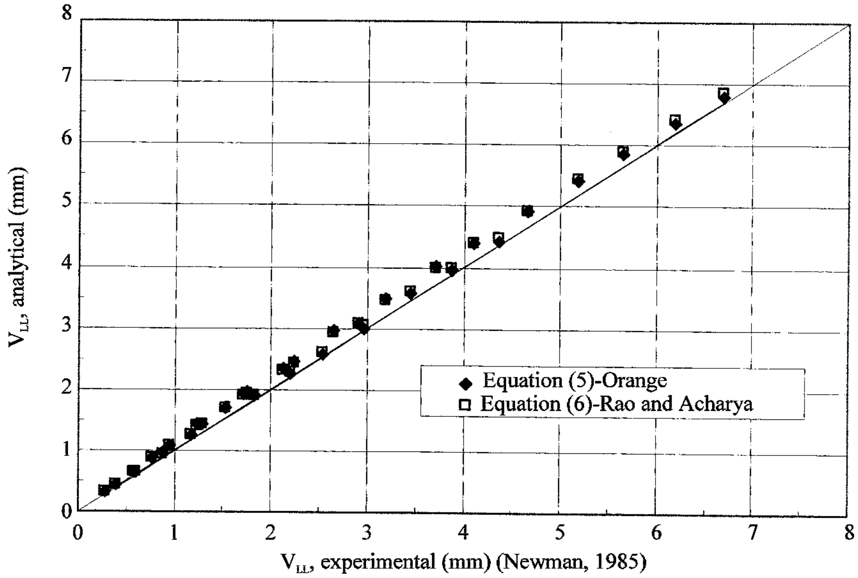

Fig. 5: Comparison of experimental values of load line displacement (V_{LL}) with those obtained from Eq. 5 and 6 for AA2024-T351Aluminum alloy

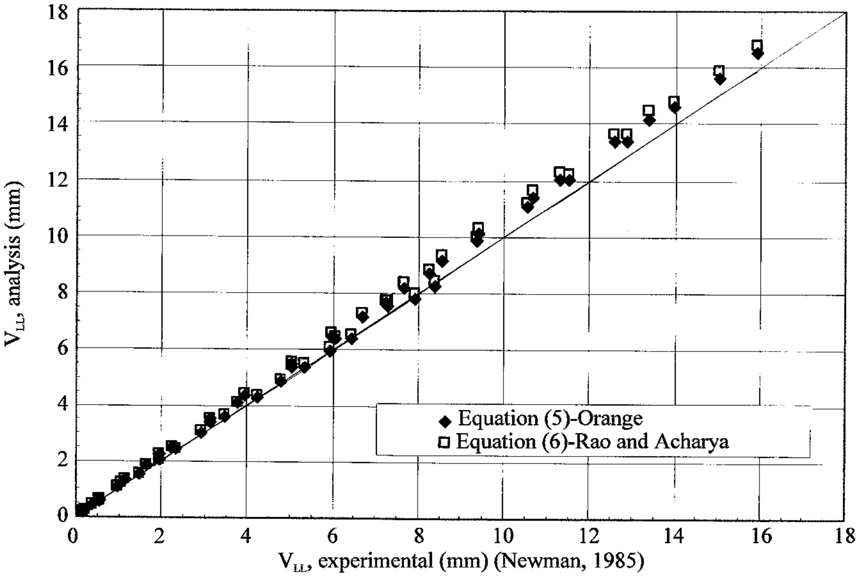

Fig. 6: Comparison of experimental values of load line displacement (V_{LL}) with those obtained from Eq. (5) and (6) for AISI 304 Steel

$$V_{LL} = 0.773\ V_{FF} \tag{5}$$

Equation (5) was found to be accurate to within 1% in the range: $0.35 \le (a/W) \le 0.80$. Finite Element Analysis (FEA) results of Neale (1975) indicate a factor of 0.77 to relate V_{FF} to V_{LL}. Hiser and Loss (1985) have examined the variability and applicability of displacements measured at various locations on CT specimens. They found that the average deviation of J_{Ic} values evaluated using V_{FF} from the standard J_{Ic} values evaluated from V_{LL} was 8% and the maximum deviation was 16%. Finally, they concluded that V_{FF} could be used to generate the J-resistance curve equivalent to that determined using V_{LL}. Landes (1980) suggested a proportionality factor of 0.727 between V_{LL} and V_{FF} that is valid in the range: $0.5 \le a/w \le 0.75$

Rao and Acharya (1986, 1992) have presented a relation between V_{LL} and V_{FF} as:

$$V_{LL} = \frac{\sqrt{\left\{\left(a^2 + W^2\right)/2\right\}}}{Z + \sqrt{\left\{\left(a^2 + W^2\right)/2\right\}}}\ V_{FF} \tag{6}$$

Here, Z is the distance from the load line to the point of the front-face displacement measurement (Fig. 1).

The recorded load-line displacement values (Newman, 1985) of compact tension specimens having different W/B ratios (16, 8 and 4) made of three materials (namely AA2024-T351, AA7075-T651 and AISI 304 steel) are compared with those obtained from Eq. (5) and (6). For all the three specimen configurations, results obtained from Eq. (5) and (6) correlate well with the experimental results of V_{LL}

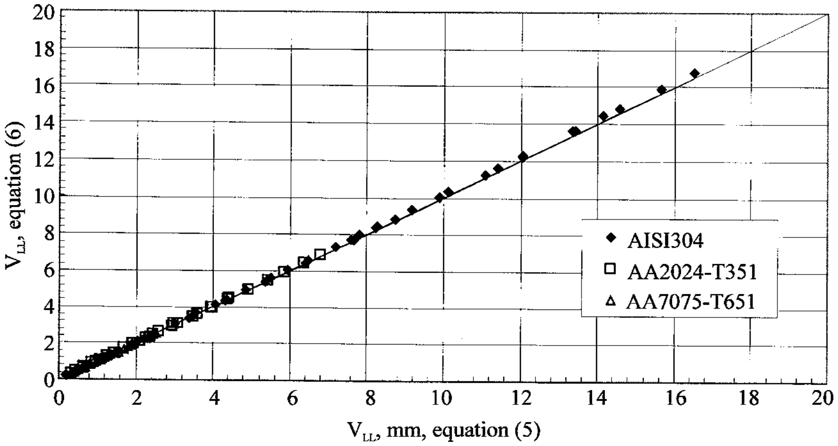

Fig. 7: Comparison of load -line displacement (V_{LL}) from the recorded front-face displacement (V_{FF}) of standard CT specimens of three materials

Fig. (4-6). The results of Eq. 6 deviate from the test values by a maximum of 8.6% and on average by 4.4%. The results of Eq. (5) and (6) shown in Fig. 7 for all the three materials, match within -3 to 1.4%.

A Simple Procedure for Generation of J-Resistance Curve from Test Data of Standard CT Specimens

This section provides a simple procedure for generating J-resistance curve from the recorded front-face displacement (V_{FF}) of the standard CT specimen that is generally used for K_{Ic} evaluation. While generating J-resistance curve, Eq. (6) is used to estimate the load line displacement (V_{LL}) values from the measured front-face displacement (V_{FF}) values of the standard CT specimen (Fig. 1).

For any point i on the load (P) versus V_{FF} curve, the crack length a_i can be obtained from Sexena and Hudak (1978).

$$a_i / W = 1.0010 - 4.6695\,\xi_i + 18.460\,\xi_i^2 - 236.82\,\xi_i^3 + 1214.9\,\xi_i^4 - 2143.6\,\xi_i^5 \qquad (7)$$

Where

$$\xi_i = \left\{1 + \sqrt{(EBV_{FFi} / P_i)}\right\}^{-1}, \qquad (8)$$

Here P_i and V_{FF} are, respectively the load and front face displacement at the point (i) and E is the Young's modulus.

Crack extension, da, due to increase in load is given by

$$da = a_i - a_0 \qquad (9)$$

Here a_0 is the initial crack length.

To account for various uncertainties in testing, Modulus E can be replaced by an effective modulus E_M given by

$$E_M = \frac{P_o}{B\,V_{FF}}\left(1+\frac{0.25}{x_o}\right)\left(\frac{1+x_o}{1-x_o}\right)^2\left\{\begin{matrix}1.6137+12.678x_o-14.231x_o^2\\ -16.610x_o^3+35.050x_o^4-14.494x_o^5\end{matrix}\right\} \qquad (10)$$

Where $x_0 = \frac{a_o}{W}, P_0$ is the load corresponding to V_{FF}in the linear portion of the experimental P versus V_{FF} curve. The test is considered valid if the difference between E_M and E does not differ by more than 10%.

Equation (7) gives the crack length (a) corresponding to any point on P versus V_{FF} curve. Using the value of a in Eq. (6) V_{LL} can be calculated. Thus, P versus V_{LL} curve can be generated from the experimental P versus V_{FF} curve of the standard CT specimen.

The area (A) under P versus V_{FF} curve at selected points is used to evaluate the J-integral value (Rice *et al.*, 1973):

$$J = 2A/\{B(W\text{-}a)\} \qquad (11)$$

Using the values of J and da from Eq. (9) and (11), the J-resistance curve is generated and J_{IQ} is evaluated as per the ASTM standard E1820 (ASTM, 2000). The fracture toughness (K_{JQ}) corresponding to J_{IQ} is obtained from

$$\left.\begin{array}{ll} K_{JQ} = \sqrt{\dfrac{J_{IQ}\,E}{\left(1-\nu^2\right)}}, & \text{for plane-strain condition (thick specimen)} \\ \quad\;\; = \sqrt{J_{IQ}\,E}, & \text{for plane stress condition (thin specimen)} \end{array}\right\} \qquad (12)$$

Here J_{IQ} is the value of J-integral at the intersection of 0.2 mm exclusion line and J-resistance curve and ν is the Poisson's ratio.

Results and Discussion

Following the procedure given in the preceding section, J-resistance curves were generated from the load (P) versus front-face displacement (V_{FF}) curves of the standard CT specimens. Fracture toughness assessments were carried out considering the test data of three materials, namely, M250 maraging steel (parent and weld-metal), high strength low-alloy (HSLA) steel and Ti-6Al-4V alloy. Fig. 8 shows the load P versus V_{FF} curve from the recorded data of a M250 grade maraging steel CT specimen. The corresponding load P versus V_{LL} curve is also shown in Fig. 8. The load P versus V_{FF} curve is of type I (as per ASTM E 399, Fig. 3), exhibiting smooth curve from linear portion to the maximum load point (without any pop-in). As expected, the load P versus V_{LL} curve is shifted to the left of the load P versus V_{FF} curve. Figure 9 shows the J-resistance curve developed from the load P versus V_{FF} recorded data. Table 1 gives the fracture analysis results for the three materials.

Table 2 shows the comparison between the initial measured crack length, a_0 and the crack length, $a_{0\text{-}e}$ estimated using Eq. (7). The $a_{0\text{-}e}$ is calculated at the point of deviation from linearity on the P-V_{LL} curve and initial measured crack length is from the broken halves of the test specimen measured under

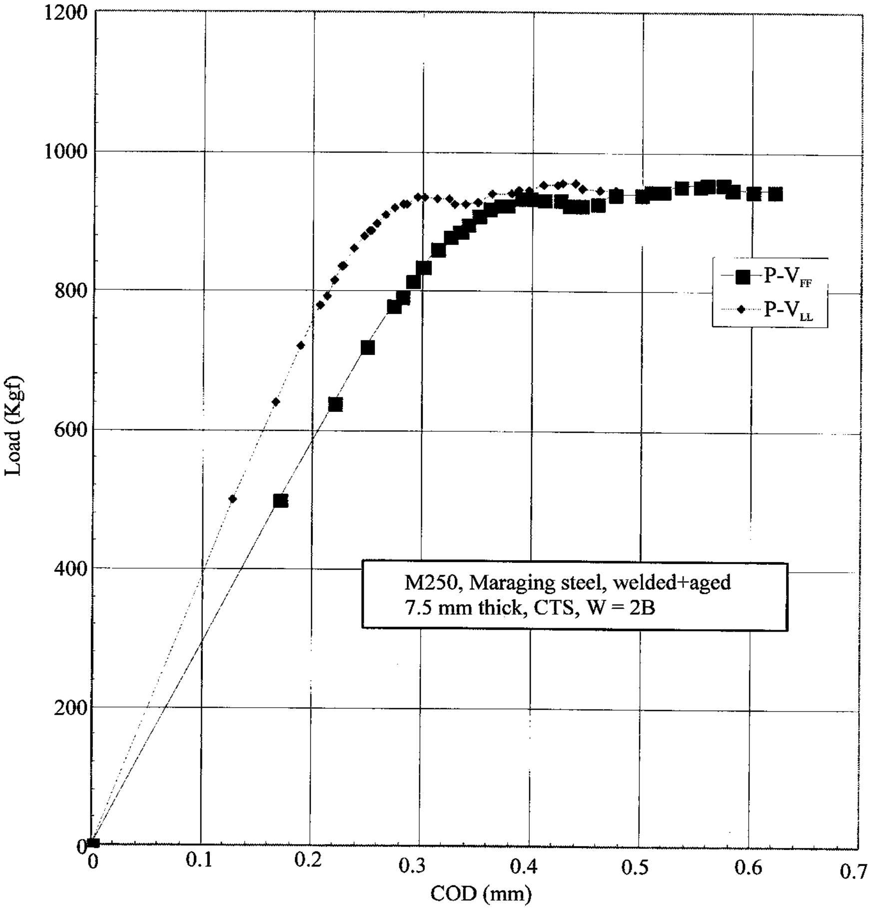

Fig. 8: Typical Load vs COD (P-V_{FF}) curve from plane strain fracture toughness test for M250 maraging steel and the corresponding P-V_{LL} curve developed from it

Table 1: Fracture analysis results of different materials

B (mm)	a_0 (mm)	σ_{ys} (MPa)	σ_{ult} (MPa)	$\frac{P_{max}}{P_Q}$	K_Q or K_{ic} (MPa√m)	$2.5\left(\frac{K_Q}{\sigma_{ys}}\right)^2$	Test validity	Strength ratio, R	J_{IQ} or J_{ic} (KJ/m^2)	K_{JQ} (MPa √m)	RE (%)
M250 grade maraging steel *, E = 186.3 GPa, υ = 0.3											
7.61	7.57	1775	1812	1.09	101.9	8.23	Invalid	1.07	57.25	104.4	2.5
7.60	7.41	1827	1866	1.08	91.70	6.30	Valid	0.90	42.43	90.3	-1.5
7.60	7.65	1827	1866	1.07	91.85	6.32	Valid	0.92	45.00	93.5	1.8
M250 grade maraging steel *, Weld metal, E = 186.3 GPa, υ = 0.3											
7.58	7.30	1509	1564	1.13	88.00	8.50	Invalid	1.10	46.55	90.3	2.6
7.59	7.34	1589	1641	1.13	85.60	7.26	Invalid	1.02	39.70	86.1	0.6
7.55	7.11	1619	1651	1.20	76.60	5.40	Invalid	0.92	31.18	76.6	0.0
7.55	7.35	1619	1651	1.10	85.60	6.99	Valid	0.98	42.05	87.9	2.7
Ti-6Al-4V alloy , E = 121.5 GPa, υ = 0.3											
20.03	20.00	893	950	1.04	73.7	17.02	Valid	0.89	36.3	71.2	-3.3
19.96	19.89	893	950	1.03	82.2	21.21	Invalid	0.98	43.85	78.5	-4.5
19.96	20.14	893	950	1.07	84.4	22.36	Invalid	1.05	48.25	81.5	-3.4
19.93	19.74	896	960	1.02	74.4	17.25	Valid	0.86	36.87	72.5	-2.5
19.70	19.86	896	960	1.03	72.8	16.51	Valid	0.86	35.12	70.7	-2.9
18.42	18.95	896	960	1.03	71.6	15.96	Valid	0.89	31.80	68.5	-4.3

Table 1: Continue

HSLA Steel *, E = 214.9 GPa, υ = 0.3											
12.52	12.64	1267	1422	1.15	92.5	13.32	Invalid	1.02	34.00	90.2	-2.5
7.54	7.11	1435	1533	1.21	77.8	7.35	Invalid	1.08	31.66	81.1	4.2
7.52	7.29	1435	1533	1.17	80.8	7.93	Invalid	1.09	35.00	85.3	5.6
7.55	7.36	1354	1450	1.16	76.9	8.06	Invalid	1.10	32.58	82.8	7.7
7.55	7.28	1354	1450	1.16	81.8	9.11	Invalid	1.16	33.92	84.4	3.2

Note: * Thin specimens; + Thick specimens; Width (W) = 2B, for all specimens; andRE % = $\{(K_{JQ}-K_Q)/K_Q\}*100$

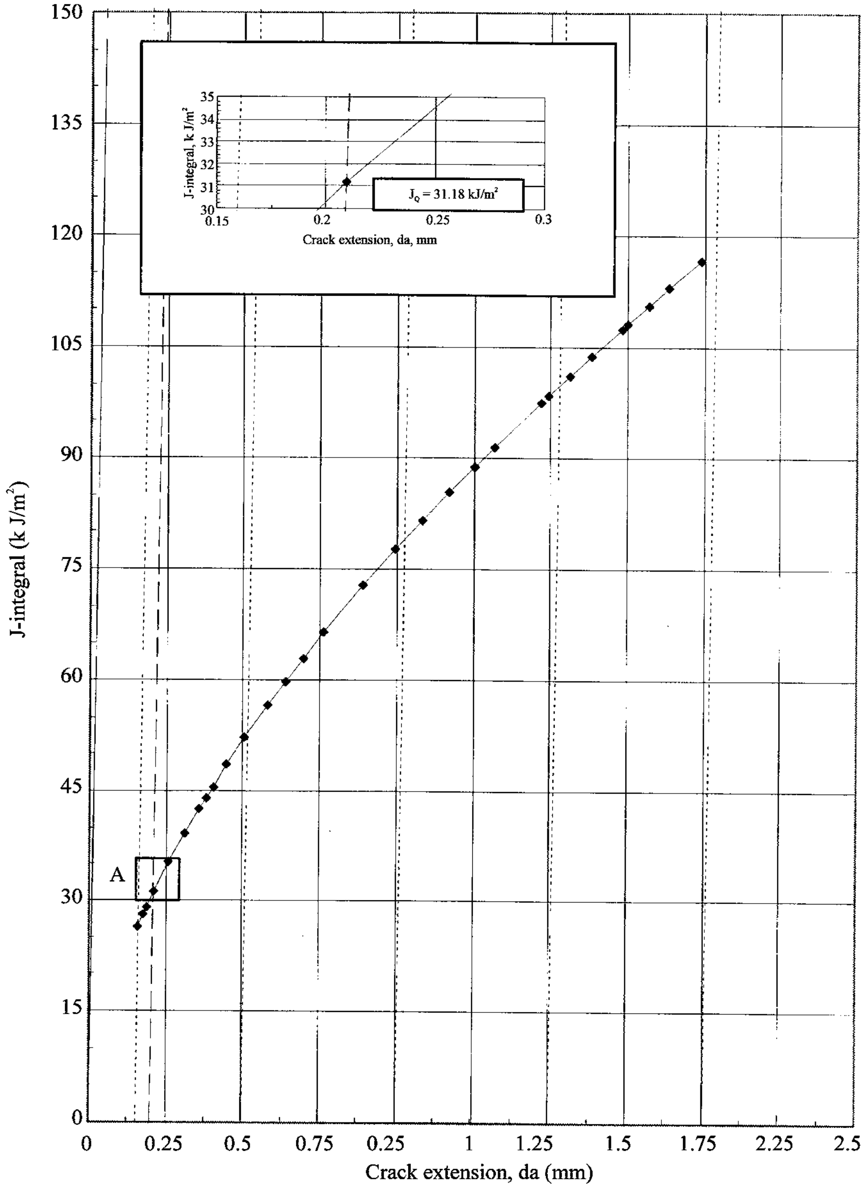

Fig. 9: J-da curve developed from the recorded P-V$_{FF}$ curve for M250 grade maraging steel. Inset shows the magnified view of the box A

Table 2: Comparison of the initial measured crack length (a_p) and the initial crack length (a_{o-e}) estimated using Eq. (7)

a_p (mm)	a_{o-e} (mm)	K_{JQ}/K_Q	da at P_Q	
			(mm)	% of a_p
M250 grade maraging steel (Parent metal)				
7.573	7.571	1.02	0.170	2.2
7.407	7.406	0.99	0.199	2.7
7.646	7.644	1.02	0.190	2.5
M250 grade maraging steel (Weld metal)				
7.302	7.511	1.03	0.131	1.8
7.342	7.354	1.01	0.178	2.4
7.109	7.104	1.00	0.162	2.3
7.346	7.391	1.03	0.155	2.1
Ti-6Al-4V alloy				
20.00	19.99	0.97	0.373	1.9
19.89	19.88	0.96	0.410	2.1
20.14	20.13	0.97	0.370	1.8
19.741	19.739	0.97	0.38	1.9
19.856	19.853	0.97	0.37	1.9
18.95	18.94	0.96	0.39	2.1
HSLA Steel				
12.64	12.637	0.98	0.30	2.4
7.11	7.111	1.04	0.17	2.4
7.29	7.29	1.06	0.14	1.9
7.36	7.359	1.08	0.12	1.6
7.28	7.28	1.03	0.19	2.6

a low power microscope at multiple locations as defined in the standard E399. The correlation is excellent, the deviation being within ±5%. The discrepancy in values of K_{JQ} and K_Q may be due to the following reasons.

The K_{Ic} evaluation is based on the load P_Q at 2% crack extension, whereas da values in Table 2 show slightly higher or lower values than 2% crack extension. The value of K_{JQ} is dependent on the relation (1) for thick and thin specimens. Most of the results demand higher thickness specimens for obtaining the valid K_{Ic} value. Hence, 7.5 mm thick specimens in the present study are considered as thin specimens. The fracture analysis results of K_{JQ} are found to be within ±5% of the K_Q values.

Concluding Remarks

The J-resistance curve can be generated from the load versus crack mouth opening displacement data of standard CT specimens. There is no need to incorporate additional machining in the CT specimens to provide for V_{LL} recording. The J-integral approach will be useful for fracture toughness assessment. The method, however, is applicable to the cases in which the load versus the CMOD curve is of type I and shows gradual curvature from linear to the maximum load point. The K_{JQ} value evaluated from this approach can be used as an indication of fracture toughness of the material provided the value does not differ by more than ±10% from the experimentally evaluated plane strain fracture toughness for that material. Based on such a condition, the procedure described herein can be used for material qualification purposes thus minimizing the number of retests.

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