On the Applicability of a Computerized Single Specimen Technique to Evaluate J_{IC}

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ABSTRACT

The applicability of a single specimen technique based on unloading compliance is considered for low strength materials (0.2% yield strength ranges from 170 to 390 MPa) with varying work hardening capabilities (work hardening exponent n ranges from 0.2 to 0.45). The high degree of confidence in the applicability of the technique for materials characterized by intermediate n (<0.3) is evident from the excellent matching of single specimen data with those derived through multiple specimen technique. The single specimen technique predicts erratic crack lengths in materials with moderately high work hardening capabilities ($n > 0.3$). The anomalous crack length variation cannot be attributed to crack closure effect. Fractographic studies revealed that the erratic crack length predictions are related to the mechanism of crack growth, which occurs by alternating stretching and tearing process.

KEYWORDS

J - Integral; Single specimen technique; Crack closure; Crack tip blunting; Unloading compliance.

INTRODUCTION

The critical value of J integral near the onset of crack growth, J_{IC}, is the widely used parameter to characterise the fracture toughness of low strength structural materials. The multiple specimen technique for the determination of J_{IC} as per ASTM standard E - 813 (1987) requires at least five specimens. The significant costs in time, labour and material associated with multiple specimen technique have led to the development of procedures to determine complete R - curve from test records of a single specimen. Crack extension during a single specimen J-R curve can be detected by either unloading compliance (Clarke et al., 1976) or potential drop methods (Hollstein et al., 1985). Here, we consider the applicability of a single specimen technique based on elastic unloading compliance, the details of which are given elsewhere (Saxena et al., 1988). Low strength materials with varying work hardening capabilities are considered.

SINGLE SPECIMEN TECHNIQUE BASED ON UNLOADING COMPLIANCE METHOD

A sequential measurement of elastic compliance is made at regular intervals during the load displacement testing of a precracked specimen by periodically unloading and evaluating the slope of elastic portion of unloading curve. The slope gives instantaneous elastic compliance and hence the crack length. The value of J is obtained from the area under the load-displacement curve (Clarke et al., 1976). Thus, a number of J vs crack extension (Δa) data pairs are obtained which are subsequently used to establish the J-R curve.

An application software has been developed (Saxena et al., 1988) in BASIC on a micro PDP-11 computer for machine control (MTS 880 servo-hydraulic test system) as well as data acquisition, storage and analysis. Separate routines are incorporated for on-line test control and post-test data analysis. The test control routine, JICT is summarized in the flow chart shown in Fig.1. The area under load vs load-line displacement curve is continuously updated using trapezoidal quadrature numerical integration technique. Load and crack opening displacement (COD) data pairs recorded during unload/reload cycle are used to calculate compliance by linear regression analysis. The estimated compliance is related to crack length using a polynomial interpolation (Saxena and Hudak, 1978).

Post-test data analysis routine JICE (Fig.2) includes various corrections to the predicted crack length, reduction of J vs Δa data pairs to evaluate J_{IC} and validity checks as per ASTM standard E-813 (1987). Inaccuracies in the prediction of crack length may arise due to errors in load and COD measurement as well as elastic modulus estimation and also due to specimen rotation as a result of large scale plasticity. Predicted crack lengths are corrected either by adding the difference between optically measured and calculated crack length or through an effective modulus. An effective modulus is estimated by substituting the optically measured initial crack length in the compliance equation (Saxena and Hudak, 1978). The crack lengths are reestimated using the effective modulus thus derived. To account for errors due to large scale plasticity, a rotation correction (Alan Vandersluys and Futato, 1983) routine is incorporated. The corrected J and Δa values are processed to arrive at J_{IC}. The point of intersection of J-R regression line with the 0.2 mm offset line parallel to blunting line, defined as J_Q is calculated by successive convergence technique. J_Q qualifies to be J_{IC}, if the specimen thickness, B and the uncracked ligament, b_o are greater than 25 J_Q/σ_{yt}, where σ_{yt} is the average of yield and ultimate tensile strengths. Further, the slope of J-R curve, dJ/da should be less than σ_{yt}.

APPLICATION OF SINGLE SPECIMEN TECHNIQUE

An iron based solid solution Fe-0.5% Mo and pure nickel are considered under moderately high work hardening ($n > 0.3$) class of materials whereas a mild steel and an Fe-Al-Mn austenitic steel represent medium work hardening ($n < 0.3$) materials. A summary of tensile properties of the materials under consideration is given in Table I.

Standard compact tension specimens of 25.4 mm thickness were precracked as per ASTM standard E-813 (1987). Precracked specimens were side grooved to a depth of 2.5 mm on either side to minimise tunnelling of crack front. The specimens were loaded in displacement control mode at a ramp rate of 0.5 mm/min. The post-fatigue cracked specimens were broke open to measure initial and final crack lengths.

Mild Steel

Predicted crack extension was seen to match fairly well with that measured optically (Table II). The difference between the crack extension predicted by elastic compliance at the last unloading and the average physical crack extension was 13% as against the specified limit of 15% (E-813, 1987). Optical correction was incorporated to take into account the observed deviations. The corrected J- Δa plot is shown in Fig.3. The post-test analysis routine yields J_Q as 227 kJ/m^2. The conditional value J_Q is subjected to validity checks. The effective specimen thickness (23.3 mm) and uncracked ligament (22.2 mm) are much greater than 25 J_Q/σ_{yt} (16.2 mm). Further, the slope of regression line (dJ/da = 200 MPa) is less than σ_{yt} (350 MPa). J_Q thus qualifies to be J_{IC}.

J_{IC} was also evaluated for mild steel using multiple specimen technique. The analysis of J- Δa data thus derived using standard three point bend specimens of thickness 20 mm yields J_{IC} of 233 kJ/m^2, which is very close to that derived through single specimen technique (J_{IC}= 227 kJ/m^2).

Austenitic Steel

In a manner similar to that observed with mild steel, a good correlation is seen between the predicted and measured crack extension (Table II) revealing high degree of confidence in the technique. J vs Δa plot after incorporating optical correction is shown in Fig.4. J_Q of 187 kJ/m^2 satisfies validity criteria and thereby qualifies to be J_{IC}.

Fe-0.5% Mo and Nickel

In case of Fe-Mo and nickel (Figs. 5 and 6), irrespective of the difference between the predicted and the measured crack extension (Table II), no systematic trend in crack extension with J is seen. The pct difference is the lowest in case of nickel (5%) and highest in case of Fe-Mo (167%). Rotation correction (Alan Vandersluys and Futato, 1983) too fails to improve the situation in either case (Figs. 5 and 6).

J_{IC} has also been determined for Fe-Mo and nickel through multiple specimen technique using compact tension specimens of 25.4 mm thickness. J - Δa data thus derived are included in the respective plots shown in Figs.5 and 6. A linear increase in crack extension with J is seen in either case. These experiments have resulted in valid J_{IC} of 200 kJ/m^2 for Fe-Mo and J_Q of 302 kJ/m^2 for nickel since minimum size requirement is not satisfied.

DISCUSSION

It is evident from the foregoing that the prediction of crack extension by compliance technique is inaccurate in case of Fe-0.5% Mo and pure nickel. Crack length does not increase systematically with J. To bring out reasons for the apparent anomalous crack length predictions, data pertaining to Fe-Mo and mild steel are analysed. Compliance variation with J, shown in Fig.7, reveals wavy nature in case of Fe-Mo whereas the compliance increases systematically with J in case of mild steel. Crack closure or inelastic material response can be the probable reasons (Nicholas, et al., 1984) for the observed anomalous compliance variation.

Since unloading is by 10%, the compressive stresses developed on the monotonic plastic wake behind the crack tip are not of sufficient magnitude to close the crack. In all the cases, the unloading (reverse) plastic zone size, r_p is seen to be negligible as compared to the process zone size, Z_p. The ratio between r_p and Z_p varied upto 0.004, which is much less than the maximum recommended value (Clarke, et al., 1976) of 0.01 to minimise errors during unloading. r_p is estimated using the expression, $r_p = 1/6\pi\ (K_I/2\sigma_y)^2$, where K_I is the stress intensity corresponding to the unloading range. Process zone size, Z_p is estimated as $Z_p \simeq J/\sigma_y$ at the point of unloading (Clarke, et al., 1976). The linearity of load vs COD plots shown in Fig.8 provides further evidence to the non-existence of crack closure. These observations rule out the possibility of crack closure effect as the probable reason for the observed anomalous behaviour.

The inaccurate prediction of crack length can be attributed to the large scale plasticity at the crack tip. Hahn and Rosenfield (1968) based on their extensive studies have reported that the critical plastic zone size at the crack tip r^* varies with the work hardening exponent, n as $r^* \simeq n^2$, where r^* is in inches. Higher n in case of Fe-Mo and nickel thus leads to increased plastic zone size at the crack tip. The plasticity factors (Table I) estimated from load-COD plots as per the procedure suggested by Barker (1984) also indicate similar behaviour. The highest plasticity factor ($\simeq$ 0.95) is seen in case of nickel and Fe-Mo alloy whereas austenitic steel possesses minimum value (0.76). Mild steel is characterised by an intermediate value of 0.88. Nicholas et al., (1984) have studied the effect of plasticity at the crack tip on the compliance. Several tests conducted on oxygen free high conductivity (OFHC) copper have revealed unsystematic change in compliance over the entire range of stress intensity factor, K from 10 to 40 MPa $\sqrt{m}$. In a similar study on AISI 310 steel, Tobler (1983) observed that the error in inferred crack length increased significantly as J test proceeds, with as high as 55% disagreement in crack length. These errors were attributed to plasticity effect on compliance.

Extensive crack tip plasticity in case of Fe-Mo and nickel is evident from fractographic studies. Fracture surfaces were examined under ISI-100A Scanning Electron Microscope (SEM). In the stable crack growth region, steps resembling beach marks were visible in case of Fe-Mo (Fig.9a) whereas such features were absent in mild steel (Fig.9b). These features can be understood in terms of alternating stretching and tearing at the crack tip, which is evident from Fig.10. Figure 10 is a crack path profile when viewed perpendicular to the thickness direction. The J vs Δa plot shown in Fig.5 also reflects such behaviour. Alternating stretching and tearing during stable crack growth has also been observed in case of AISI 304 stainless steel (de Vries and Schaap, 1985) and Armco iron (Srinivas et al., 1987).

During blunting, compliance measurements indicate an apparent decrease in crack length. The apparent shortening of crack may be explained (Nicholas, et al., 1984) on the basis of change of three dimensional stress field at the crack tip. As a precracked sample is loaded, the crack tip region undergoes a change from a state of plane stress, where compliance is governed by modulus E, to that of plane strain where effective modulus is higher and is given by $E/(1-\nu^2)$ where ν is poisson's ratio. The inapplicability of compliance technique for crack prediction in case of low strength, moderately high work

hardening materials thus appears to be related to the error in effective modulus used in the compliance equation (Saxena and Hudak, 1978). If the present computer code is supported by a finite element method (FEM) routine which is capable of doing 3 dimensional stress analysis at each unloading and hence estimating effective modulus, it might be possible to predict accurate crack lengths in materials undergoing large scale crack tip plasticity.

CONCLUSIONS

1. The unloading compliance based on single specimen technique is applicable for low strength materials with medium work hardening capabilities ($n < 0.3$).

2. The predicted crack length in case of moderately high work hardening materials ($n > 0.3$) are erratic and do not follow a systematic trend with J.

3. The negligible reverse plastic zone size and the linearity of load vs COD plot rule out the possibility of crack closure effect leading to the anomalous crack length predictions.

4. Fractographic studies reveal that the inaccurate predictions of crack extension in moderately high work hardening materials is related to the mechanism of crack growth. Crack growth occurs by alternating stretching and tearing processes.

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Table I. Mechanical Properties of Materials Studied

Material	0.2% Proof stress(MPa)	U.T.S (MPa)	Work hardening Coeff.	J_{IC}, kJ/m^2 Single specimen	Multiple specimen	Plasticity index
Mild Steel	228	472	0.20	227	233	0.88
Austenitic Steel	390	707	0.27	187	-	0.76
Fe-0.5% Mo	250	350	0.32	-	200	0.96
Nickel	170	380	0.43	-	302	0.95

Table II. Comparison Between Predicted and Observed Crack Extension

Material	Crack extension, mm Predicted	Measured	% difference
Mild Steel	1.45	1.66	12.6
Austenitic Steel	4.57	5.23	12.6
Fe-0.5% Mo	-0.35	0.52	167
Nickel	0.71	0.75	5.3

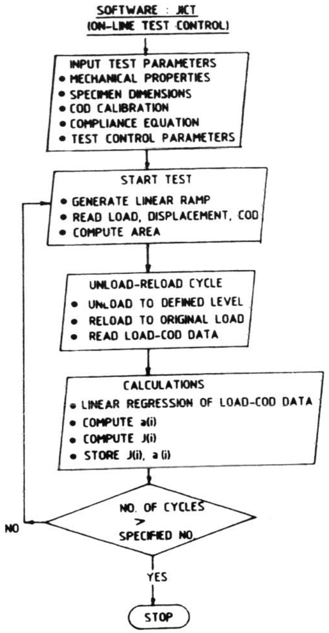


Fig.1: Flow diagram of on-line test control routine.

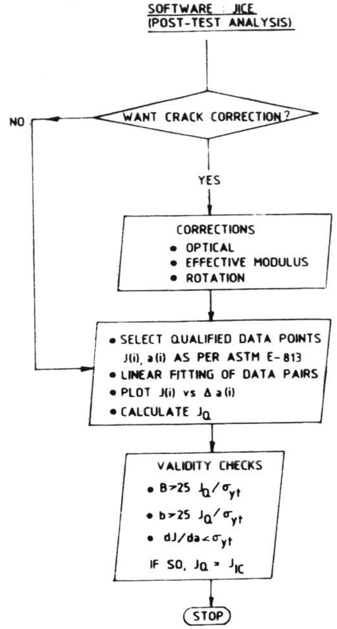


Fig.2 Flow diagram of the post-test data analysis routine.

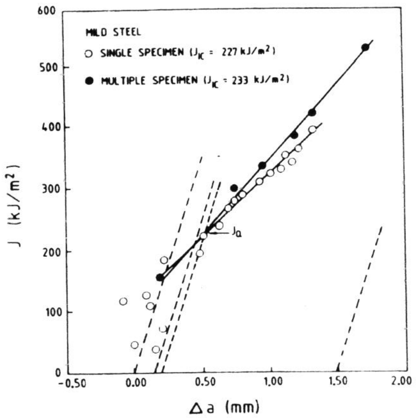


Fig.3 J-R curve for mild steel.

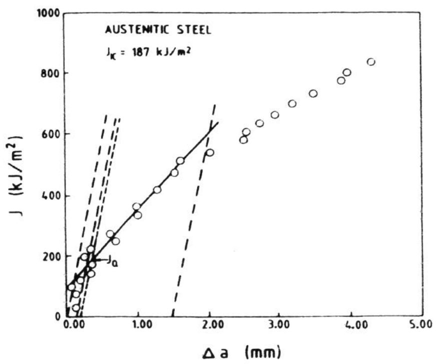


Fig.4 J-R curve for austenitic steel.

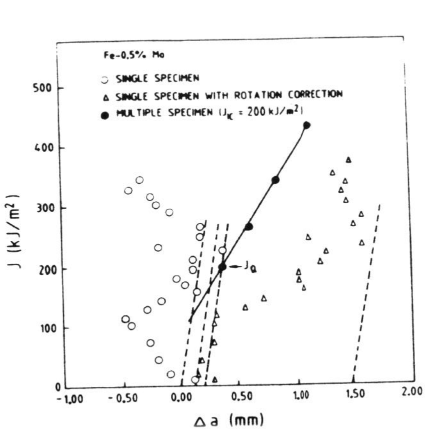


Fig.5 J-R curve for Fe-0.5% Mo alloy.

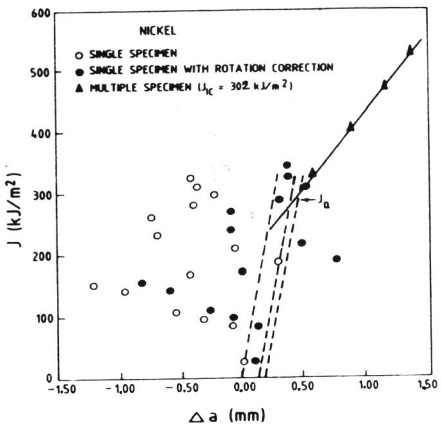


Fig.6 J-R curve for nickel.

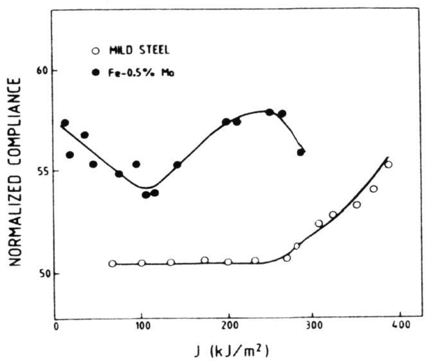


Fig.7 Compliance variation with J for mild steel and Fe-0.5% Mo.

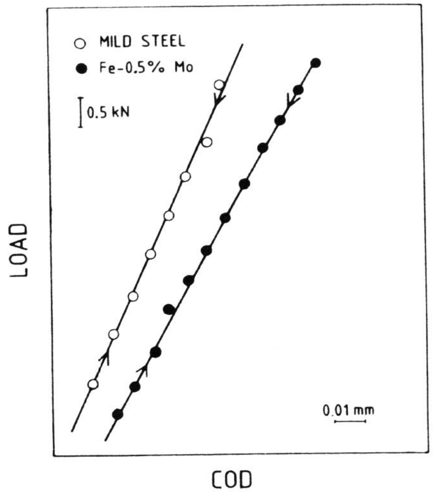
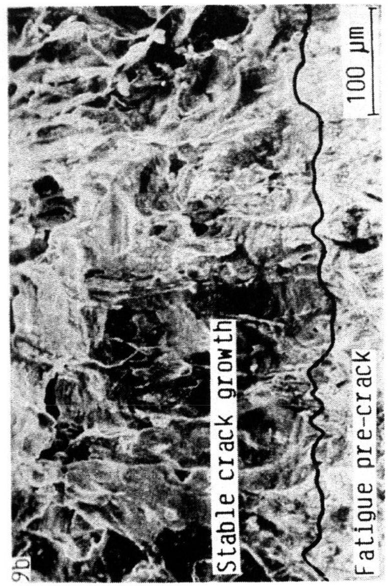


Fig.8 Load-COD plots corresponding to unloading/reloading cycle for mild steel and Fe-0.5% Mo.



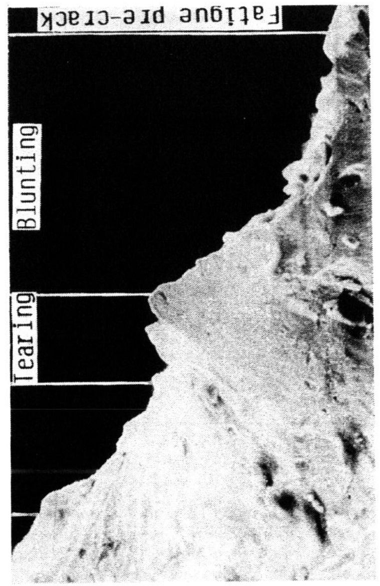


Fig.10 Crack path profile revealing alternating blunting and tearing in Fe-0.5%Mo.

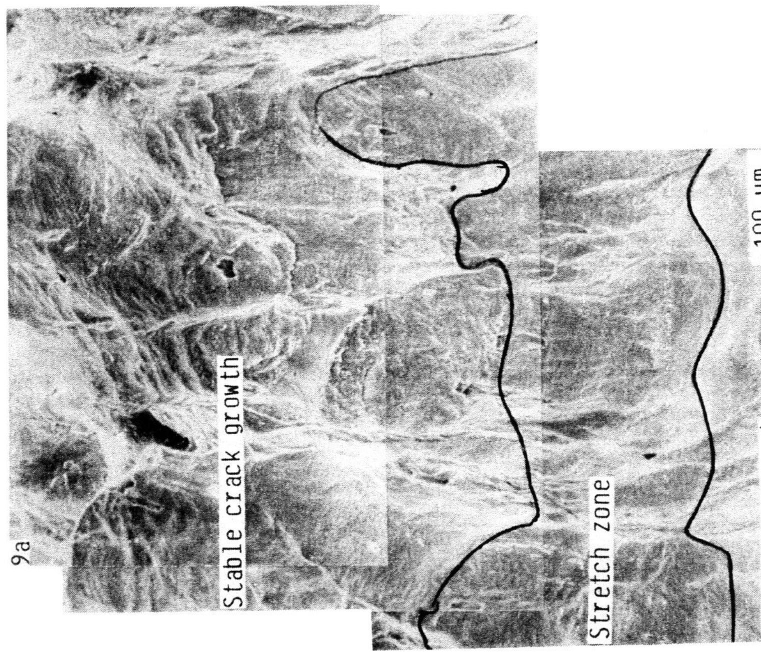


Fig.9 SEM fractographs for (a) Fe-0.5%Mo and (b) mild steel.