WIDTH INFLUENCE ON R-CURVES OBTAINED WITH THIN SHEET TEST-PIECES BEARING BLUNT CENTRAL NOTCHES

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ABSTRACT

Crack growth resistance curves obtained from 2 series of central notch AISI 4340 steel samples, quenched and tempered at 250°C, have been compared. One series was characterized by a 76.2 mm width and a notch length/width ratio of 0.3, the other by a 25.4 mm width and a notch length/width ratio of 0.4. Notch root radius (\( r \)) was varied between 0 (fatigue pre-crack) and 0.8 mm. Specimen thickness was 1.6 mm for both series. \( K_{IC} \) vs \( \Delta \sigma \alpha \) curves show that the behavior of the two types of samples is similar, provided that the net section stress is somewhat smaller than the yield stress. Also, the \( K_{IC} \alpha \) vs \( J_{IC} \) series of data are clustered around the same interpolating lines as \( \Delta \sigma \ll \sigma_0 \), \( K_{IC} \alpha \ll \sigma_0 \). It has been seen to vary between 0.93 and 0.99, according to the specimen width, and can be conservatively set at 0.9 for standardization purposes.

KEYWORDS

Blunt central notch specimen; blunt notch R-curves - geometry dependance - condition of validity; blunt notch plastic zone size; effective crack growth from blunt notches; effective radius; \( K_{IC} \) - \( \alpha \) relationship; \( J_{IC} \) - \( \alpha \) relationship.

INTRODUCTION

Up to now, no research program dealing with R-curves determination using blunt notch thin sheet specimens has been referred to in the literature. In fact researchers who have dealt with plane stress ruptures have focussed their attention on the resistance to the onset and propagation of fracture from fatigue pre-crack or very severe stress concentrations; as a result of these studies ASTM Standard E561-81 has been developed, as well as proposals to modify it (Wheeler and co-workers, 1982).

In the framework of a broad plan of experiments aimed to the AISI 4340 steel fracture resistance characterization under various heat treatment and loading node conditions (Firrao and De Benedetti, 1977; Firrao and colleagues, 1979, 1982) researches have been undertaken to verify the applicability of the above referred standards also in experiments where ruptures originated from a blunt notch.
To evaluate the effective half-crack length, \( d_{eff} \) (physical half-crack length, \( d \), or plastic zone dimension) second lines were drawn from the origin \( P \) on the experimental load-displacement diagrams to increasing load points, and their slopes measured to derive \( d_{eff} \) by the following formular:

\[
\frac{1}{d_{eff}} = \frac{2}{d} \left( \frac{b}{\sin \left( \frac{\theta}{2} \right)} \right)^{1/2} \left( \frac{\pi^2}{w} \right)^{1/2} \cdot \frac{\cos \left( \frac{n-\theta}{2} \right)}{\cos \left( \frac{n-\theta}{2} \right)}
\]

where 

\[ L = \frac{1}{1 + \nu} \left[ \frac{\sin \left( \frac{\pi \rho}{2} \right)}{\sinh \left( \frac{\pi \rho}{2} \right)} \right] \]

\[ \psi = \frac{1 + \nu}{1 - \nu} \]

\[ \rho = \frac{1 + \nu}{2}\left( \frac{1 - \nu}{\psi} \right) \]

\[ L_{eff} = \frac{L}{\rho} \]

and \( v \) are the Young's and Poisson's moduli respectively; \( 2\nu \) is the central slot opening measured between 2 points at an initial distance \( 2Y \) (13 mm, one from the other); \( \rho \) is the cross section stress.

No method encompassing first the determination of \( d_{eff} \) and second, the plastic zone size correction by Irwin's formula (1960) E838A is employed to determine \( d_{eff} \) values, since it has already been seen that such a procedure yields erratic results when notches have blunt ends.

Eq. 1 was also employed to derive \( d_{eff} \) values by the partial unloading compliance procedure already described by Pirrao and Ferrario (1982).

Effective stress intensity factors, \( K_{eff} \), have been calculated inserting \( d_{eff} \) values into the following formula, \( K_{eff} \) suggested in ASTM Standard E838-81:

\[
K_{eff} = \frac{\sqrt{2}}{1 - \nu} \left[ \frac{1.77 - 0.177 \left( \frac{d_{eff}}{d} \right) + 1.77 \left( \frac{d_{eff}}{d} \right)^2}{1 + \nu} \right]
\]

Eq. 2 has been also used to compute \( J \)-integral values; in fact, \( K \) values obtained inserting into it \( d_{eff} \) have been subsequently used in the followin, equation (Landes, Walker, 2nd Clarke, 1979):

\[
J = K^2/2E + A[B_{eff}w+d]\]

where \( A \) is the area between the load displacement curve and the secant line drawn from the origin to the particular point to which a given value of the load and of \( d_{eff} \) is associated.

RESULTS AND DISCUSSION

Tensile and hardness properties of AISI 4340 steel, quenched and tempered at 250°C, are: \( \sigma_{uts} = 1780 \) and \( \sigma = 1430 \) N/mm²; \( e_f = 70 \); HRC = 49.

The geometry of employed specimens is shown in Fig. 1. They were fabricated from 1.6 mm thick steel sheets from the same stock from which large samples had been obtained. Furthermore, they underwent a heat-treatment identical to that previously used by Pirrao and Ferrario (1982), namely oil-quinch from 870°C and 2h temper at 250°C. In the same reference, the specimen fabrication and test procedure have been detailed.
depend only on the applied stress intensity factor, but also on the root radius \( \rho \). At constant \( K_{\text{eff}} \), it decreases as the notch is progressively blunter.

The \( K \)-curve pertaining to the sample with \( \rho = 0 \) and the ones related to specimens with notch-end radius of 0.07 mm ca. almost coincide. What once more indicates that there is a limiting value of \( \rho \) below which a mechanical notch behaves like a fatigue crack (Chipperfield and Knott, 1973; Pirraro and co-workers, 1979, 1982; Pirraro and Ferrario, 1982; Pirraro and Roberti, 1984).

A point-to-point comparison between \( R \)-curves obtained with samples of different widths was not possible at all values of notch root radii since the electrical discharge machining of notches did not allow to obtain identical values of \( \rho \) in the case of the sharpest ones. Fig. 3 illustrates such a comparison at two different \( \rho \) levels.

It can be seen that, when \( \rho \) is very small, experimental points pertaining to specimens of different widths lie on a unique \( R \)-curve. When the notch root radius increases, 25 mm wide test-pieces enter a region close to general yielding at lower levels of \( \Delta \sigma \) with the different position of arrows signifying that \( \sigma_0 \) reaches 0.98 \( \sigma_f \). From there on \( R \)-curves depart one from the other.

To identify the values of the stress intensity factor applied at fracture nucleation from notches, \( K_1 \), it is useful to consider \( \sigma_0 = 2 \Delta \sigma \text{phys} \).

\[ \sigma_0 = 2 \Delta \sigma \text{phys} \]

Fig. 1. Test-piece geometry; \( \phi = 25.4 \) mm, \( 2\theta = 0.4 \), \( l = 64 \) mm. Notch orientation: LT.

Fig. 2. Variation of effective stress intensity factors with the effective half-crack growth.

- \( \rho = 0 \)
- \( \rho = 0.035 \)
- \( \rho = 0.085 \)
- \( \rho = 0.115 \)
- \( \rho = 0.180 \)

Fig. 3. Comparison of \( R \)-curves pertaining to samples with different width and similar notch root.

Fig. 4. Variation of gross section nominal stress as a function of the physical crack length.
samples. The provision that at individual points of the $J=K$ diagrams both $\theta$ and $\beta$ be larger than 15°-$J_0/\theta_0$ was also satisfied. It can thus be concluded that the validity of the $J$-theory has to be ascertained on the basis of more restrictive limitations based on the maximum value of $\sigma_0$.

Values of $J$ have been reported in Fig. 7 as a function of $\rho$. There, the solid line represents again the interpolation of data pertaining to 76.2 mm wide specimens.

The plot verifies that present results yielded by specimens with $\rho \leq 0.115$ mm agree with those determined with wider samples. Instead, no concordance arises when fracture nucleation occurs in a completely plasticized net section as is the case of test-pieces with $\rho = 0.33$ or 0.78 mm.

The $J$ values that, for both types of specimens, are clustered around a straight line passing through the origin of the $J-\rho$ field. All have been reported in Fig. 8 and the equation of the line calculated as $J = 0.928 - 0.29 \rho$. Since each line has a very small intercept and was obtained with data pertaining to specimens of different width $\rho$, it is possible to state that it is the $J-\rho$ type already verified in previous researches (Fitzro and co-workers, 1982; Roberti and colleagues, 1981), with $A$ being again a material constant for the steel thickness and the metallurgical condition employed; together with the horizontal segment drawn at the $J \_\text{ freezing}$ level averaging fatigue pre-cracked test-pieces data, it allows to compute a $\rho_{\text{off}}$ value of 0.05 mm ca., below which mechanical notches can be a safe, suitable alternative to fatigue cracks.

As regards, the conditions of validity of fracture toughness results, it has been seen that with 25.4 mm wide samples $K$ and $\sigma_c$ values are acceptable

Fig. 7. Critical values of $J$-integrals applied at fracture in blunt

Fig. 8. Overall plot of valid $J$ values pertaining to different $W$ values.

Fig. 5. Stress intensity factors applied at onset of fracture in notched samples.

Fig. 6. Variation of applied $J$ integrals as a function of physical half crack growth.
as long as $\sigma_n$ is almost equal to $\sigma_1$; in the case of 76.2 mm wide specimens, the limit is lowered at 0.93 $\sigma_1$. With a conservative approach to the problem and taking into account the whole series of data here discussed, it can be concluded that the limit of 0.9 $\sigma_n$, set forth by Wheeler and co-workers (1982) for the validity of A1 alloy sharp crack tension $R$-curve, can be applied also to blunt notch high-strength steel specimens.

CONCLUSIONS

$R$-curves measured in terms of either effective stress intensity factors or $J$-integrals applied to 1.6 mm thick, quenched and tempered AISI 4340 steel specimens, with central blunt notches, have been found to be independent of test-piece width as long as the net section nominal stress does not go beyond 0.9 $\sigma_1$; it can be conservatively set at 0.9.

In the field of validity of results, the existence of relationships of the $K_i = K_{eq}$ and $J = J_{eq}$ type has been confirmed. Since $A$ and $A'$ have been determined as being independent of specimen width, they can be considered as being material characteristics for the steel here used, at the here employed thickness.

Finally, the existence of a minimum value of the notch-end radius below which a blunt notch behaves like a fatigue pre-crack has been ascertained.

REFERENCES


