APPLICATION OF THE J CONCEPT TO VERY SMALL TENSION SPECIMENS OF AUSTENITIC STAINLESS STEELS

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ABSTRACT

Research of a relevant fracture criterion in the elasto-plastic, the limited plastic and the fully plastic regime in tension is performed with subsized specimens of two austenitic stainless steels with the Double Edge Notched and the Center Cracked configurations and with a wide range of shape factors, including small cracks. From the possible alternatives, the limit load, PDY or PL, the Crack Opening Displacement, COD or CTOD and the J integral, it is shown that the J concept is the most appropriate one to describe crack growth resistance. However J is to be determined by the multiple specimen technique or by an experimental integration with averaging on the free face of the specimen and not generally by an estimation procedure. But J is doubtfully path independent and no longer describes the deformation field at the crack tip.

KEYWORDS

Ductile fracture, Austenitic stainless steels, Toughness, J contour integral.

INTRODUCTION

To evaluate the toughness of metals with specimens not satisfying size requirements of the ASTM standard E 399 for linear elastic behavior, one can use the ASTM standard E 813 – 1981 to determine J_{0.2} with specimen of bend type and of required dimensions, that contain deep initial cracks or the British standard 5762 – 1979 to measure the Crack Opening Displacement at initiation, δ_1 with bend specimens that contain deep initial cracks and without required dimension. A versatile criterion is the limit load or the collapse load for the fully plastic regime without crack growth. Bending is preferred to tension because it is said that more constraint occurs at the crack tip (Mc Meeking and Parks, 1979) and deep cracks are used because there is more confidence in the estimation procedures. Moreover constraint increases with strain hardening. However, some structures under concern have not the required dimensions, have small cracks and are tension loaded.

The purpose of this paper is to present the main results of a research of relevant parameters to describe toughness of two austenitic stainless steels with specimens exhibiting the above limitations.
AUSTENITIC STEELS AND EXPERIMENTAL PROCEDURE

9.8 mm thick rolled plates of two austenitic steels in the water-quenched condition from 1050°C were tested in the transverse direction with respect to rolling. Chemical composition and tension test results are given in Table 1.

Table 1: Chemical Weight per cent Analysis and Mechanical Properties of the Steels.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z2 CND 17-13</td>
<td>0.010</td>
<td>0.40</td>
<td>1.55</td>
<td>0.003</td>
<td>0.009</td>
<td>13.75</td>
<td>16.89</td>
<td>2.52</td>
<td>0.02</td>
</tr>
<tr>
<td>Z1 NCDU 25-20</td>
<td>0.013</td>
<td>0.85</td>
<td>1.10</td>
<td>0.002</td>
<td>0.014</td>
<td>25.22</td>
<td>20.17</td>
<td>4.26</td>
<td>1.50</td>
</tr>
</tbody>
</table>

\[ \sigma = \alpha (\sigma / \sigma_0)^p \]

with \( \sigma_0 = 210 \text{ MPa}, \ v = 10^{-3} \)

Strain and stress

\[
\text{Strain interval} = 0.05 - 0.15 - 0.30, \quad \text{nominal} = 0.05 - 0.30
\]

Hollomon law, \( \epsilon = \alpha (\sigma / \sigma_0)^p \)

DEN and CC specimens of two widths, \( w = 40 \text{ mm} \) and \( w = 80 \text{ mm} \) with a gauge length of 2 \( w \) and with notches of root diameter 0.2 mm giving shape factors \( a / w = 0.0, 0.2, 0.5, 0.5, 0.65 \) and 0.8 and with fatigue cracks with \( a / w = 0.5 \) were tested at a tensile speed of 0.6 mm/min. During testing, recording was done of load, elongation for an external gauge length of 1.5 \( w \) through an inductive transducer and elongation for a gauge length of 40 \( w \) externally for DEN and of 13.5 \( w \) axially for CCP with a double cantilever clip gage. Moreover, many photographs were taken on a face on which a grid pattern formed by adjacent 2 mm diameter circles was deposited. These photos were intended to determine crack shape evolution (blunting or crack tip opening), crack growth and the deformation of the specimen everywhere.

Finally, to determine crack growth resistance curves, the unloading method and the heat-tinting technic were applied.

RESULTS AND DISCUSSION

Elastic behaviour

The elastic compliance of the CCP is in a very good agreement with the value given by Sflis and Liebowitz (1972). On the other hand, for the DEN compliance shows an unexplained erratic scatter about the value given by Bowie (1964). In the latter case, parasitic bending may be advocated. So the unloading method to determine crack growth has been disregarded, though nice re-
with $h_1$ and $h_2$ depending on geometry ans stress state.

The plane stress state is considered here and, in this case,
\[ P_0 = 2B(h - a)G \]

By identifying, we get:

- For ZD CND 17-13: $J = 623 K (0.5) \Delta$ with $J, N, mm^{-1}, a, mm; n=4.76$
- For ZD NCDU 25-20: $J = 748 K (0.5) \Delta$ with $n=5.23$

The results are shown on figure 2 for the CCP specimen $w = 40 mm$ of the ZD CND 17-13. The Sumpter and Turner approximation always overestimates the true value. For deep cracks the other estimations give the same value. For the other lengths, estimations are overestimations with the Shih estimation being higher for mean cracks and lower for short cracks than the Rice estimation. For other geometries and steel, the same trend is observed. However, the discrepancy from the reference value is bigger for the ZD NCDU 25-20 steel, for the DENS specimen and for the width 40 mm. For the Shih estimation, more accuracy could be obtained with a Ramberg-Osgood relation.

Another estimation of the J integral is obtained from the grid pattern observed at different load for displacements. From the displacements, total or incremental strains $e_x$, $e_y$, and $e_x$ are obtained, with the hypothesis $e_x = e_y = 0$ and $e_{xy} = -1/2(e_{xx} + e_{yy})$, i.e., neglecting contraction from the strain components, the equivalent strain is deduced. To deduce the stress components with the hypothesis $e_x = e_y = e_{xy} = 0$, the incremental and the deformation theories have been considered. However, the first one has been disregarded because giving oscillating results due to the precision on strain increments. So the results presented here are an estimation.

For all crack lengths, it is seen that J shows a scatter band of about 20% around the mean value when the integration path length varies. For short cracks, the mean value is equal to the reference value. For mean crack lengths (a/w ≈ 0.5), the mean value overestimates for CCP and underestimates for DENS, as shown on figure 1, and the discrepancy increases with crack length. None explanation has been found.

This method also allows to test if the HRR strain field occurs at the crack tip, i.e., if for $n+1/n$ (J, $\theta$, m). In fact, $h = n+1/n$ varies with $\theta$, $w$ and J and varies in the steel. So for $w = 40 mm$, $h$ varies between 0.6 and 0.7 (0.7 for $\theta = 0.6$; 0.7 for $\theta = 45^\circ$, and 0.9 for $\theta = 90^\circ$). For $w = 40 mm$, $h$ varies between 0.4 and 0.8. These values are to be compared to the theoretical ones, 0.69 to 0.82. An example is given on figure 4. It is shown that the consider- ing the theoretical one is large. So it is not excluded that HRR field occurs. Such a conclusion has already been drawn by Hodgkinson (1980) for a CT specimen of 316 L steel.

The last criterion considered is the COD. This parameter has been obtained experimentally by the conventional 90° angle intercept method from the crack tip. A linear or a bilinear relation with $J$ is obtained and in the relation
\[ V = J = a \sqrt{\theta} \]  
CTOD

$m$ increases with the crack length for the two geometries. $m$ shows more scatter for the DENS, 0.8 m < 0.01, than for the CCP, 1.22 m < 1.85. These values are comparable to the values 1.15 - 2.2 for CCP and SMT, as compiled by Paranjpe and Banerjee (1979) from experimental and calculated values of the literature.

Finally, crack growth resistance curves have been determined with $w = 40 mm$ specimens with $a/w = 0.5$. The results given on figure 5 show that the two steels have the same resistance. And this resistance determined with CCP is the same as the resistance determined with TBP and CT specimens of 316L steel by other authors (Tanaka and Harrison (1978), Bamford and Bush (1979), Hodgkinson (1980)). One 316 L steel investigated by Balladon, Héritier and Rabbe (1983) is very clean and its resistance is very high. So, this result tends to confirm the idea that J can be the relevant fracture toughness parameter for very small specimens. However, it is noticed on figure 5 that crack growth is higher with DENS, which is very striking because more triaxiality is built-up in this specimen.

CONCLUSION

In small tension specimens of austenitic stainless steels with high strain hardening, the net section stress criterion cannot be retained for rupture. As to the J integral, it is seen that the Rice and Shih estimates are in agreement with the reference V value for deep cracks; otherwise, V is the one parameter. The J measured on the specimen surface is another estimation which is correct for short cracks and less correct otherwise. The discrepancy is attributed to experimental precision. Moreover, J describes the strain field and gives for CCP correct crack growth resistance. This is strangely not true with DENS. So J is considered to fulfill partially requirements of the relevant fracture toughness. Finally the J - COD relation has been established.

ACKNOWLEDGMENTS

The work described in this paper formed part a submission by one of the authors (J.P. Chavaillard) for the degree of Ph.D. The provision of facilities by the Commissariat à l'Energie Atomique is gratefully acknowledged.

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Fig. 1. Relationship between load and crack length (ultimate load for a/w = 0; current load for a/w ≠ 0; +, ultimate load for initial crack length for a/w ≠ 0).

Fig. 2. V or J estimates versus load point displacement for the CCP with w = 40 mm. Z2 CND 17-13 steel.
Fig. 3. $V$ derived from the pseudo-potential and $J$ calculated by contour integration for CCP and DENS specimens of $w = 80$ mm and $a/w = 0.5$

(- - -): DENS; (- - -): CCP

[Note: gives scatterband for several integration paths]

Fig. 4. Strain $\epsilon_{yy}$ for $\theta = 0^\circ$ versus distance to crack tip for CCP and DENS of Z1 NCDU 25-20 with $a/w = 0.5$.}

Fig. 5. Crack growth resistance curves for austenitic stainless steels

(•, •, •): present study; (BIR): Balladon, Heritier and Rabbe; (BB): Bumford and Bush; (H): Hodkinson; (TH): Tanaka and Harrison.)