J INTEGRAL DIRECT MEASUREMENT ON SURFACE CRACKED WELDED PLATES IN BENDING

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The experimental investigation of surface welded plates are presented. Plates are made of microalloyed steel TStE460, welded by SAW, with dimensions 600×300×20 mm. The four point bending and J integral direct measurement was used in order to simulate behaviour of a cracked welded full-scale structures such as pipelines and pressure vessels. CMOD was also measured and compared with J integral. Three bending panels are tested, one in as-welded condition, whereas the other two were post-weld-heat-treated. Results are given in a form of the following diagrams: J vs. ε, CMOD vs. ε, J vs. CMOD and J-R curves. Besides the residual stress effect, influence of the geometry imperfections was obvious. The finite element method is used in order to analyze the path dependency problem of the J integral for weldments.

INTRODUCTION

The wide plates tensile and bending testing have been recently used in order to simulate a full-scale structure behaviour as closely as possible (1-2). Structures with a simple geometry like pipelines and pressure vessels are well represented by such experiments, providing the same thickness and welding procedure for the wide plate (3). So far, the bending tests were performed only for plates with an edge crack, whereas significant experience with tensile testing of surface cracked plates exists. Having in mind the importance of bending stresses in some full-scale structures prone to surface cracks, it is reasonable to perform bending testing of surface cracked wide plates. It should be also noted that bending testing requires significantly lower machine capacity, that can be very important for wide and thick plates made of high strength steels, requiring sometimes maximum force which exceeds the capacity of a standard testing machine. Therefore, as an extension of tensile testing, bending is applied for surface cracked wide plates equipped with CMOD and strain gauges in order to enable direct measurement of J integral, as introduced by Read (4) and modified here according to differences between bending and tensile loading.

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On the other hand, since the direct measurement of J integral is performed on the outer contour (path along strain gauges, Fig. 1d), encompassing weldment regions of different material properties (base metal - BM, heat affected zone - HAZ and weld metal - WM), numerical simulation of the experiment was necessary in order to investigate path dependency of J integral. Namely, as noticed by Rice in his original paper, J integral is path independent not only for homogeneous material, but also for heterogeneous one, if the boundaries between regions of different material properties are parallel to the crack. Therefore, X, Y and any other weldment different from I shape should be carefully analyzed when J integral is evaluated.

EXPERIMENT

The surface cracked welded plates (dimensions 600×300×20 mm) are used for four point bending, with distances between loading points 200 mm and between supports 400 mm, Fig. 1a. Plates were produced of microalloyed steel TStE460, by submerged arc welding (SAW) using EPP2 wire and OP40TT flux. Tensile properties of BM and weldments in AW state are given in Table 1. Three bending plates were tested out, one of them (BP1) in as-welded condition (AW), while the remaining two were post-weld-heat-treated (PWHT) at 580°C for two hours for stress relieving. The crack, 9 mm deep and 52 mm long, Fig. 1b-c, was made by electrical-discharge machine with crack tip (radius 0.1-0.15 mm) positioned in the HAZ, Fig. 1d. After specimen preparation an angular distortion (1°) was noticed, as shown in Fig. 2. The same geometry imperfection was previously noticed for the tensile panels, Fig. 2.

Table 1 - Tensile properties of TStE460 steel and its SAW weldment (AW state)

	R_{eH} (MPa)	R_m (MPa)	$A_{5.65}$ (%)
Base Metal	460	625	24.5
Weld Metal	482	670	18.5

J integral was evaluated using direct measurement technique (4), employing series of strain gauges, Fig. 1d, and CMOD clip gauge, Fig. 1e. The procedure for J integral evaluation was modified in order to take into account differences between bending and tensile loading. Namely, as explained in (4), on the contours BC and EF (Fig. 1e) J integral reduces to the traction-bending term $T_y dv/dx$, where T_y denotes the traction force and v the displacement component normal to the crack plane. It should be noticed that the traction force T_y is constant in tension, whereas it changes from maximum negative value at the loaded side to the maximum positive value at the unloaded side in bending, requiring somewhat different integration procedure. Otherwise, J integral evaluation procedure was the same as for the tensile loading, including elastic-perfectly plastic material behaviour.

The J-resistance curve (J-Δa) is used for a comparison of crack behaviour in bending and tensile testing. Single specimen compliance technique is used for both bending (BP1 and BP3, whereas technical difficulties disabled crack growth evaluation for BP2) and tensile plates (TP3 and TP4 - both in AW condition). The experimental results are shown in Figures 3-6, as J versus ε, CMOD versus ε, J versus CMOD and J versus Δa, respectively, where ε denotes the remote strain, obtained as the average of the absolute values of the readings in points B, C, F and E, Fig. 1e. Together with the bending test results, tensile test results are shown in Fig. 5-6.

NUMERICAL INVESTIGATION

The finite element method (FEM) is used in order to analyze the influence of material heterogeneity on J integral evaluated on the outer plate contour. The finite element mesh consisted of 148 eight-noded isoparametric elements and 531 nodes. The crack tip was modeled by the collapsed elements, arranged in a ring in accordance with ESIS recommendations (6). Having in mind relatively small differences between tensile properties of BM and WM (Table 1), negligible influence of heterogeneity was anticipated. Therefore, the J integral value for the outer contour was here only compared to its average value calculated for 6 inner contours, whereas the more detailed analysis of J integral path dependency problem is given elsewhere (6). The outer contour was positioned as close as possible to the path used for direct measurement of J integral, whereas 6 inner contours (not intersecting the boundary between different materials) were positioned in the first three element rings around the crack tip.

Table 2 - J integral for inner and outer contours - FEM results

F (kN) - applied force	39.0	62.4	80.4
J_{inn} - average value of 6 paths	17.2	58.5	315.5
J_{out} - value for the outer path	16.7	57.3	313.3

The results of FEM analysis indeed show negligible difference between J integral values for the outer contour and the average values for 6 inner contours, Table 2, verifying its use as the valid fracture mechanics parameter in this case. It should be noted that modified J integral (6) should be used as a valid fracture mechanics parameter if the difference between J integral values become significant in other cases.

DISCUSSION

As shown in Fig. 3 and 4, the general shape of J-ε and CMOD-ε is similar, what is a consequence of the linearity between J and CMOD, Fig. 5. As expected from previous experience (3,7) the values for J and CMOD are higher for BP1 (AW) than for BP2 and BP3 (PWHT), what is attributed to the residual stress effect (difference between BP1 in AW state and BP2 & BP3 in PWHT state) and to the influence of geometry imperfections (difference between BP2 and BP3). The influence of geometry imperfections, i.e. angular distortions, Fig. 2, was also noticed in the case of tensile panel and pressure vessel testing (3,7). As one can see from Fig. 2 & 6, the concave angular distortion (TP3) is beneficial to the crack growth resistance, whereas the convex distortion (TP4) reduces it. One should notice that, contrary to the expected behaviour, but in accordance with previous experience (3,7), these two effects do not vanish with higher plasticity, Fig. 3-4. More detailed discussion of both residual stress and geometry imperfection effects is given elsewhere, e.g. (7).

The influence of crack tip position was neglected in this investigation because all specimens behaved in the same way regarding crack growth. As shown by metallographic investigation crack tip was positioned in subcritical HAZ, and crack growth was parallel to the metallographic HAZ boundary, irrespective of the sample state (AW or PWHT), (7). It was also noticed that the microstructure of HAZ was not affected by PWHT. More detailed analysis of the metallographic investigation, including microhardness measurement and impact toughness testing is given in (7).

CONCLUSIONS

The results presented in this paper indicate clearly the soundness of the surface cracked bending plate testing. Further testings are necessary in order to investigate constraint effects in bending, as well as the influence of residual stresses, geometry imperfections and crack tip position.

Residual stresses and geometry imperfections have significant influence on crack growth behaviour, which is not vanishing (at least not clearly) even at high plasticity. Anyhow, these influences are more or less the same as for tensile testing.

Having in mind the linearity between CMOD and J integral, CMOD evaluation can replace more expensive measurement of J integral in some cases.

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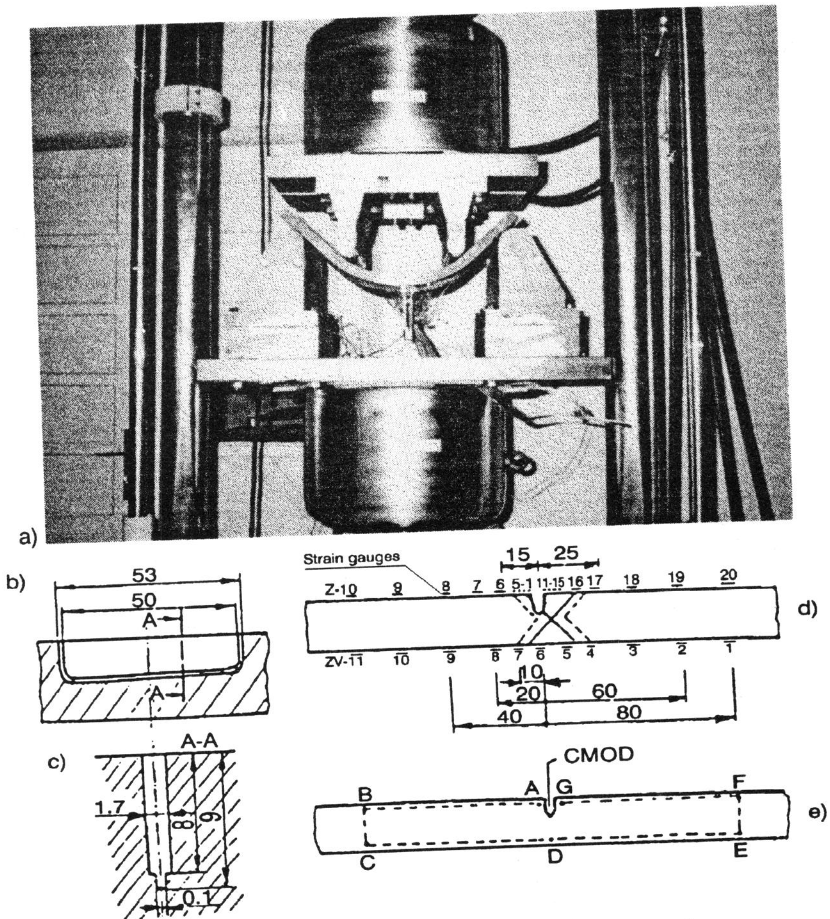

Figure 1 Surface cracked welded plate with instrumentation

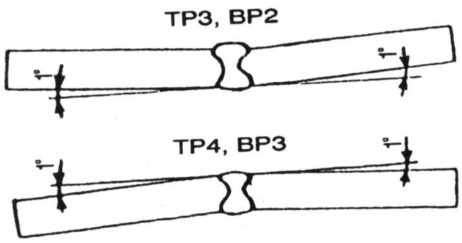

Figure 2 Angular distortions

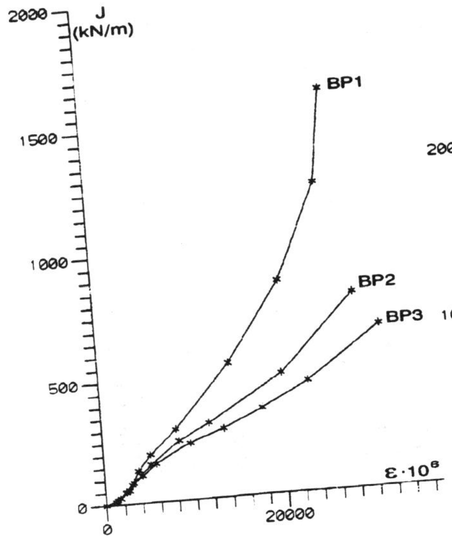

Figure 3 J versus ε

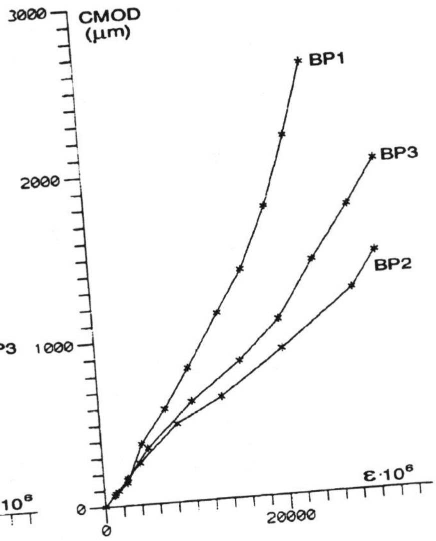

Figure 4 CMOD versus ε

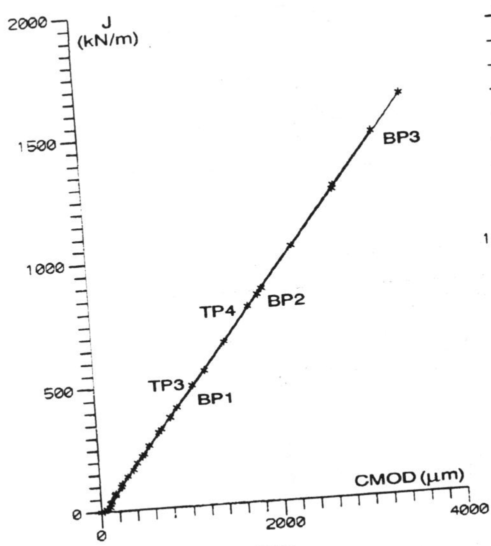

Figure 5 J versus CMOD

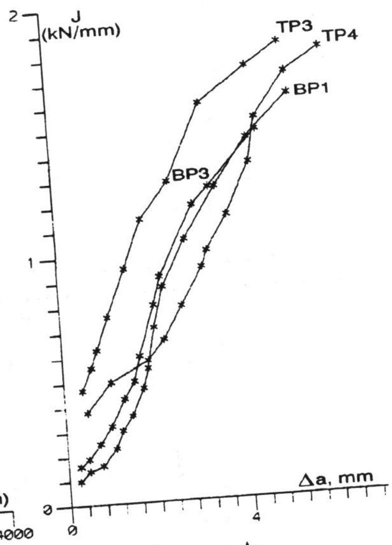

Figure 6 J versus Δa