DIRECT MEASUREMENT OF J INTEGRAL - EXPERIENCE AND PROSPECTIVE

S. Sedmak*, B. Petrovski*, T. Adžiev**, A. Sedmak***, J. Gočev**

The direct measurement of J integral was applied originally to the edge cracked tensile panel, whereas later its application has been extended to surface cracked tensile and bending panels, and pressure vessels. Special attention has been paid to the weldments, because of their heterogeneity and significant influence of residual stresses and geometry imperfections. The influence of residual stresses and geometry imperfection was investigated on wide panels and pressure vessels in a stress relieved or as-welded state, with concave or convex angular distortion, with different matching of weld and base metal and with different crack position and magnitude. In this paper the experience gathered so-far and prospective of J integral direct measurement is analysed and presented.

INTRODUCTION

Introduced a decade ago by Read (1), direct measurement represents an efficient way of J integral evaluation, because no additional assumption to the original expression is necessary. The direct measurement was applied originally to the edge cracked tensile panel, and later it has been extended to the surface cracked tensile and bending panels, and to pressure vessels as well, King et al (2), Berge et al (3), Adžiev et al (4), Sedmak et al (5), Sedmak et al (6). The surface cracks introduced problems regarding three dimensional effects, which were estimated to be within 20%, (2). The four point bending panels required somewhat modified procedure for J integral evaluation because of different boundary conditions, Sedmak et al (7). Pressure vessels were the most complicated because of special sealing system, needed for strain gauges inside vessel, as shown in (6).

*Faculty of Technology and Metallurgy, Karnegijeva 4, 11000 Belgrade, Yugoslavia
**Faculty of Mechanical Engineering, Karpos bb, 91000 Skopje, Macedonia
***Faculty of Mechanical Engineering, 27. Marta 80, 11000 Belgrade, Yugoslavia

Special attention has been paid to the weldments, because of their heterogeneity and significant influence of residual stresses and geometry imperfections. Using the finite element method, it has been shown that the heterogeneity influence to the measured J integral values is negligible for all conventional undermatching and overmatching weldments, Savović (8), Sedmaks (9). It was also shown that the modified J integral, comprising the additional line integral, can be used when heterogeneity influence is not negligible, (8).

Influence of residual stress and geometry imperfections was analysed in a number of papers, e.g. (4), (7), (9), Read (10). Although some conclusions were made, this topic is far from being over, mainly due to the limited experimental evidence.

Some applications required modifications of the original procedure, like pressure vessels due to biaxial stress state, as shown by Radaković (11), material behaviour which is better described as strain hardening than as ideally plastic, (11), and bending panels, as already mentioned, (7). Therefore, the aim of this paper is to analyse experience gathered so far, and to comment on prospective of the direct measurement of J integral. Special attention will be focused to the influence of residual stresses and geometry imperfections, as well as to the matching effect.

EXPERIENCE

Effects of residual stresses and geometry imperfections are analysed first in (10), where ASTM A537 Class 1 steel was used and later in (4), (6), (7) and (9), with two HSLA steels, E460 and Sumiten SP80. In (10) four wide tensile plates, coded as WMAW-60, HAZAW-60, WMSR-60 and WMAW-30, were tested in different conditions as indicated by their codes: cracks were positioned in weld metal (WM) or heat affected zone (HAZ), test temperature was either -60°C or -30°C, and plates were in as-welded (AW) state or stress relieved (SR). Bending stresses, caused by clamping of the specimens with angular distortions, were estimated from strain gage measurement. Based on results for small specimen (J_{Ic}) and wide plates (J_c), including direct measurement of J integral, it was concluded that the effect of bending stresses was small comparing to the residual stress effect, except for the specimens with extremely low J values at failure. It was also concluded that the residual stress effect was significant and somewhat unexpected. Namely, as confirmed also by metallographic examinations, residual stress influence was more due to hydrostatic pressure effect than due to superposition with a loading stress, Read (12).

Similar experiments were carried out later in the scope of joint Yugoslav-USA research project "Fracture mechanics of weldments". Two steels were tested, Sumiten 80P (SM 80P), 16 mm thick, and E460, 20 mm thick. In the later case two surface cracked pressure vessels, four tensile and three bending panels were tested under different conditions, Tab. 1. In all cases cracks were positioned in HAZ of the overmatched welded joint, produced by submerged arc welding of HSLA steel E460, (4), (6) and (7). It was concluded that the effect of residual stresses was significant, as already estimated by Read. Nevertheless, conclusions about geometry imperfections were not in agreement with those given by Read, because it was shown that this effect was not negligible, although certainly not as important as the residual stresses, (4).

Table 1. J integral direct measurement - E460

	PV1	PV2	TP1	TP2	TP3	TP4	BP1	BP2	BP3
state	AW	SR	SR	SR	AW	AW	AW	SR	SR
GI	0	+	-	+	-	+	0	-	+

GI geometry imperfection, 0 no GI, + positive effect of GI, - negative effect of GI

The other series of experiments was performed on Sumiten SP80, (5), (9) and (13). One full-scale pressure vessel and four groups of tensile panels were tested, all in AW state and without significant geometry imperfections. Influence of crack position and size was followed, Tab. 2, as well as matching effect (every group consisted of base metal (BM), under-, normal- and overmatched specimens). Typical results are shown as J integral vs remote strain for the small crack in WM (TP1), Fig. 2. Several important conclusions emerged regarding matching and crack size effects, valid for both crack positions - MW and HAZ. As clearly indicated by the shape of curve in Fig. 2, overmatching has a beneficial effect in reducing crack driving force, whereas undermatching and normalmatching (which was actually also undermatching, although less pronounced) increased crack driving force significantly. Anyhow, one should notice the effect of large crack (not shown here), which negate the matching effect just described, (13). Therefore, one can conclude that the overmatching can protect a weldment against small cracks, regardless of their position, but not against large cracks. Finally, probably the most important feature of these results is the striking resemblance of J and CMOD behaviour, indicating their linear relationship, as shown in Fig. 3 and 4 for the tensile panels (base metal and two undermatched weldments), with small cracks in weld center, Read et al (14). This was also the case for all four group of specimens, (13), and in all other experiments, as shown by the relationship between J and CMOD, obtained for TP3, TP4, BP1, BP2 and BP3 specimens (defined previously in Tab. 1), Fig. 5.

Table 2. J integral direct measurement - Sumiten SP80

specimen	TP1	TP2	TP3	TP4
crack position	WM	WM	HAZ	HAZ
crack size	S	L	S	L

CONCLUSIONS AND PROSPECTIVES

The experience gathered so far leads to the following main conclusions:

- There is a linear relationship between J and CMOD, suggesting a possibility of using the latter one instead of the former one.
- There is a significant influence of residual stresses which still can not be quantified.
- The influence of geometry imperfection is neither significant nor negligible.
- Overmatching has a beneficial effect on weldment crack resistance, but only for small cracks.
- Direct measurement of J integral is applicable for all cases analysed, but further testing is needed, specially regarding residual stresses effects.

REFERENCES

(1) Read, D.T., "Experimental Method for Direct Evaluation of J-Contour Integral", STP 791, ASTM, Philadelphia, USA, 1983, pp. II-199-208.

(2) King, R.B. et al: "J integral analysis of surface cracks in pipeline steel plates", STP 803, ASTM, Philadelphia, USA, 1983, pp. I-444-457.

(3) Read, D.T., "J-integral values for small cracks in steel panels", ASTM STP 945, Philadelphia, 1988, pp. 151-163.

(4) Adžiev, T., "The contribution to analysis of residual stresses effect to the fracture resistance of cracked welded structure" (in macedonian), D.Sc. thesis, Faculty of Mechanical Engineering, University of Skopje, 1988.

(5) Sedmak, S. and Petrovski, B., "Application of direct measurement of J integral on a pressure vessel with axial crack", STP 945, ASTM, Philadelphia, USA, 1988, pp. 730-740.

(6) Sedmak, S., Adžiev, T., Petrovski, B. and Sedmak, A., "J integral as a measure of crack driving force in full-scale pressure vessel test", Proc. of ICF 7, Houston, 1989, pp. 447-454.

(7) Sedmak, S., Adžiev, T., Sedmak, A. and Gočev, J., "Experimental and numerical analysis of cracked welded joints", Proc. of ICM 7, Hague, 1995, pp. 291-292

(8) Savović, N., "Theoretical, experimental and numerical analysis of elastic plastic fracture mechanics parameters" (in serbian), D.Sc. thesis, Faculty of Mechanical Engineering, University of Belgrade, 1994.

(9) Sedmak, S. and Sedmak, A., "An analysis of surface crack growth in full-scale pressure vessels", STP 1131, ASTM, Philadelphia, 1992, pp. I-850.

(10) Read, D.T., "Fracture toughness of weldments: elastic-plastic fracture analysis", Proc. of the 1984 Pressure Vessels and Piping Conference and Exhibition, San Antonio, 1984, pp. 75-90.

(11) Radaković, Z., "Application of resistance curves to the residual strength estimation of a pressure vessel" (in serbian), M.Sc. thesis, Faculty of Mechanical Engineering, University of Belgrade, 1995.

(12) Read, D.T., "Fracture toughness of weldments: wide plate tests", Proc. of the 1984 Pressure Vessels and Piping Conference and Exhibition, San Antonio, 1984, pp. 27-43.

(13) Read, D.T. and Petrovski, B., "Elastic-plastic fracture at surface flaws in HSLA weldments" (in serbian), Proc. of the Third Fracture Mechanics Summer School, Aranđelovac, 1984, TMF-GOŠA, pp. 119-139.

(14) Read, D.T. McHenry, H.I. and Petrovski, B., "Elastic-plastic models of surface cracks in tensile panels", *Experimental Mechanics*, June 1989, pp. 226-230.

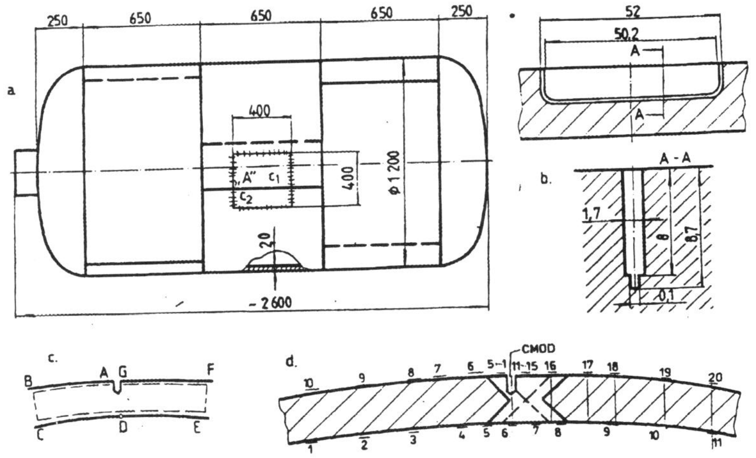

Fig. 1. Direct measurement of J integral on pressure vessel with axial crack

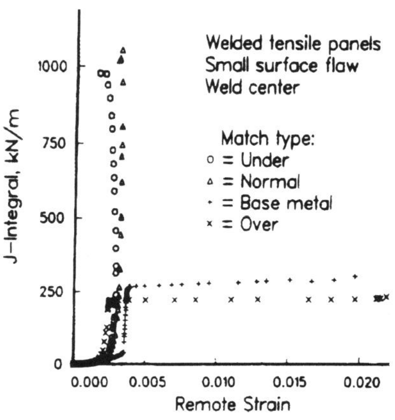

Fig. 2. J vs remote strain (13)

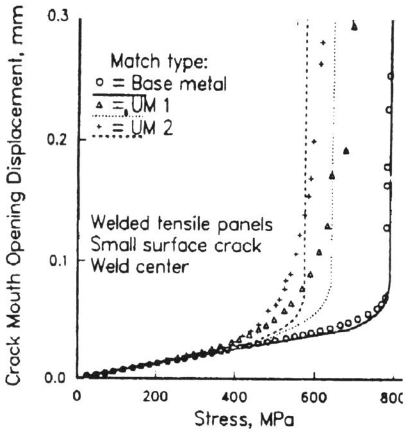

Fig. 3. CMOD vs stress (14)

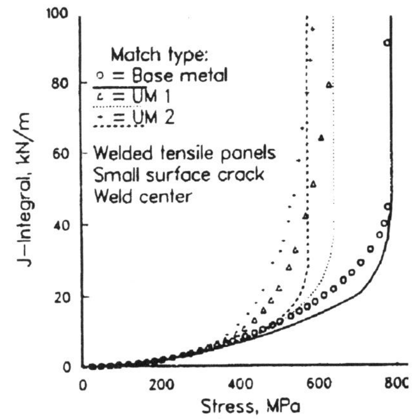

Fig. 4. J vs stress (14)

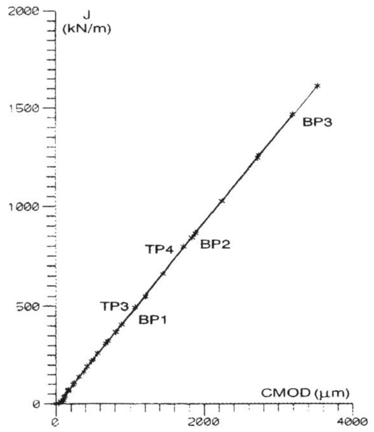

Fig. 5. J vs. CMOD relation