J INTEGRAL AND FINAL STRETCH ZONE FOR A CRACK IN HAZ OF UNDERMATCHED AND OVERMATCHED WELDMENTS

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Overmatched weld metal is generally required for its beneficial effect on strength and crack resistance of steel weldments. In order to avoid cold cracks in the welded joints of HSLA steel with yield strength above 700 MPa, slightly undermatched weld metal is recommended. The contribution of asymmetrically strained parts of welded joints with the crack tip positioned in HAZ to J integral value will differ in overmatched and undermatched weldments, as it is shown by J integral direct evaluation method, applied to the tensile panel with surface crack. Performed experimental analysis with J-R curves revealed significant influence of matching effect on the crack behaviour in weldments in two considered cases. Final stretch zone has been analyzed for closer insight in crack behaviour for both kinds of weldments.

INTRODUCTION

Safety of welded structure is depended on strength and crack resistance of welded joints. Generally accepted approach in welded joint design requires higher strength level in WM compared to BM (overmatching effect - OM), due to beneficial effect on its strength and crack resistance. However, in order to avoid cold cracks in weldments of HSLA steel with yield strength over 700 MPa, slightly undermatched WM is recommended.

The analysis of cracks, positioned in HAZ, is connected with different straining behaviour of BM and WM in both, overmatched and undermatched weldments. The application of J integral direct evaluation method, introduced by Read (1), has offered the possibility to analyze crack behaviour in a weldment of heterogeneous structure and mechanical properties in real structure (2), (3). Using this method and fractographic analysis of specimens with the crack positioned in HAZ a better understanding of critical crack behaviour could be achieved, as well as crack response in overmatched and undermatched weldments under load. This is the aim of this paper.

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THE APPLICATION OF J INTEGRAL DIRECT EVALUATION METHOD TO HETEROGENEOUS STRUCTURE

Welded tensile panel with surface crack, which tip is positioned in HAZ, is selected for J integral direct evaluation. Crack behaviour in that case is similar to the crack behaviour in a real structure, e.g. pressure vessel, due to similar constraint effect. The value of J integral is calculated from measured strains along properly selected path, stresses in remote sections and crack mouth opening displacement (CMOD). Thus, the specimen has to be instrumented, as it is shown in Fig. 1a. No further requirements have to be specified for validity of J integral evaluation, since the direct method is applied and J-R curve can be extended beyond yield point according to ASTM 1152.

Based on J integral definition, given by Rice (4)

$$J = \int_{\Gamma} W dy - \vec{T}\frac{\partial \vec{u}}{\partial x} ds \qquad (1)$$

and according to Read's approach (1) convenient form of J integral path is selected (Fig. 1c) and individual contributing values specified. For this purpose J integral path has to be divided in four segments: CD and DE on the smooth specimen side, AB and GF on cracked side (Fig. 1c), due to asymmetrical strain distribution (Fig. 1e, f), since mismatched weld metal is dispositioned in DEFG part of specimen. The contributions of individual segments to value of J integral are given in the form:

$$J = SW_{DC} - ST_{CB} + SW_{BA} + SW_{GF} - ST_{FE} + SW_{ED} \qquad (2)$$

The contribution of strain energy density, SW, is evaluated as:

$$SW = \int W dy \qquad W = \int \sigma_{yy} d\varepsilon_{yy} \qquad (3)$$

using the approximate relations given in Fig. 1d and corresponding ε_{yy} values from Fig. 1e, f, in limits for integral path segments.

Components of traction vector T in remote sections BC and EF are $T_y = \sigma_{yy}$, $T_{xy} = \sigma_{xy} = 0$, since the effect of crack tip singularity is negligible there. The specimen thickness w corresponds to arc element ds and the factor $(\partial u/\partial x)$*ds is approximated by u(C) - u(B) (1). Displacements u(C) and u(B) can be calculated from strain distributions:

$$u(C) = \int_{D}^{C} \varepsilon_{yy} dy \qquad u(B) = \int_{A}^{B} \varepsilon_{yy} dy + \alpha * CMOD \qquad (4)$$

$$u(E) = \int_{D}^{E} \varepsilon_{yy} dy \qquad u(F) = \int_{G}^{F} \varepsilon_{yy} dy + (1 - \alpha) * CMOD \qquad (4a)$$

with α, factor of asymmetry in CMOD value. (For symmetrical case $\alpha = 1/2$). So, the contribution to J integral is, e.g. for BC part:

$$ST_{CB} = \sigma_{yy} * [u(C) - u(B)] \qquad (5)$$

EXPERIMENTAL RESULTS

Undermatched weldment was produced by submerged-arc welding (SAW) of Sumiten 80P steel (SM80P) of Sumitomo, Japan, with US80B wire under flux MF-38, Kobe Steel, Japan. Using Sumiten 60 (SM60) steel with same consumables overmatched weldment was obtained. Tensile properties of BM and WM are given in Table 1.

Table 1. Tensile properties of base metal and weld metal of undermatched and overmatched welded joints

Material	Yield strength, Y.S. MPa	Ultimate tensile strength, U.T.S. MPa	Reduction of cross-section %
Steel Sumiten 80P (SM80P)	795	841	76
Steel Sumiten 60 (SM60)	579	621	79
Weld metal SM80P+US80B	585	771	67
Weld metal SM60+US80B	571	713	67

Figure 2 presents J-R curves for overmatched and undermatched weldments with crack tip positioned in HAZ, obtained in this experiment by unloading compliance method, for small (16x2,5 mm) and large (24x5 mm) cracks. For comparison, J-R curves for BM SM80P steel are also presented in Fig. 2.

Development of CMOD during loading can be followed in Fig. 3, as presented versus strain in remote section (average of strain gauges 8 and 17 readings).

ANALYSIS OF TEST RESULTS AND DISCUSSION

First approach in complex crack significance and matching effect analysis for tensile properties, presented in Fig.4, is related to symmetrical case for cracks positioned in the center of weld metal (5). In the case of undermatched metal, small crack has negligible influence on stress and strain, whereas large crack reduces deformability, and only slightly strength. In the case of OM welded joint, the cracks of both sizes did not affect tensile panel behaviour, exhibiting crack protective overmatching effect. That means that for UM weldment plastic yielding is limited to the crack region, and for OM weldment general yielding may be expected even in a presence of crack of significant size.

Next evidence of overmatching crack protective effect is visible in Fig. 3. For small crack in HAZ of OM weldment, as well as in BM, CMOD can reach limited value, and after that general yielding spread in specimen; for UM weldment, CMOD continue to grow again after certain amount of strain in remote section. In the case of large crack, CMOD is steadily growing for both BM and UM weldment up to the test end. Protective effect of OM weld metal is expressed by limited strain development in remote section at constant CMOD value, followed by final growth in CMOD.

Individual contribution of J integral path segments can be analyzed from data given in Table 2. Having in mind that specimen part DEFG contains weld metal, different responses could be expected for two kinds of weldments, according to matching effect. For this purpose contributions on DEFG and ABCD parts are separated in the form:

$$J_{ABCD} = SW_{AB} + SW_{CD} - ST_{BC} \quad I \qquad J_{DEFG} = SW_{DE} + SW_{FG} - ST_{EF} \quad II \qquad (6)$$

Table 2. Individual contribution of contour segments to J integral for crack in HAZ of undermatched and overmatched weldment

Specimen designation	UM-5		UM-6	OM-5		OM-6
Flow strength, MPa	678		678	596		596
Scan number	46	80	34	38	88	42
Applied stress, MPa	678	753	640	523	588	524
CMOD, mm	0.117	0.888	2.95	0.25	2.91	1.18
SW_{DC}, kN/m	84	602	102	215	1297	613
SW_{ED}, kN/m	177	283	69	150	550	339
SW smooth side, kN/m	261	885	171	365	1847	952
SW_{BA}, kN/m	- 53	- 532	- 28	-120	- 375	-288
SW_{GF}, kN/m	-109	- 602	- 21	-125	-1202	-109
SW cracked side, kN/m	-162	-1134	- 49	-245	-1577	-397
ST_{CB}, kN/m	- 2	- 239	- 64	22	84	- 38
ST_{FE}, kN/m	43	- 742	- 89	- 40	- 603	-116
ST total, kN/m	41	- 981	-153	- 18	- 519	-154
J integral, kN/m	58	732	275	138	789	709

For UM-5 weldment with small crack in HAZ at low stress (scan 46) part I and II differ only slightly (33/25 kN/m), but for high stress level the difference is significant (309/423 kN/m), and the contribution to J integral value from lower strength side, e.g. weld metal, side is clearly higher. In the OM-5 weldment at lower stress (scan 38) again the difference is not important (73/65 kN/m) but at high stress lower strength side (ABCD, side of base metal only in this case) contributed with 838 kN/m in J integral value and weld metal side contribution was even negative (- 49 kN/m), in total J integral value of 789 kN/m. This can be explained by traction of lower strength part induced by extensive plastic strain in base metal. As already been mentioned, the factor α, introduced in Eq. 4, can be, most probably, evaluated from differences in contributing parts in total J integral value. Anyhow, this requires further investigation.

FINAL STRETCH ZONE ANALYSIS

Closer insight in crack behaviour can be obtained by final stretch zone evaluation, that is performed for both OM and UM weldments (Fig. 5-9). In order to undertake measurements to establish stretch zone width (SZW) with the required accuracy (10), it is necessary to image the fracture surface using a technique which has both high resolution and depth focus. This requirements are satisfied in the electron microscope. In this investigation JEOL 35 is used.

For final stretch zone measurement fracture surface was tilted at an angle of about 45° with respect to incident beam about an axis parallel to the machined notch root. Five measurement were taken within 1/4 to 3/4 range of notch width 2c.

Stretch zone has not been revealed on both end parts of the notch in OM weldment specimen (Fig. 1a) and fracture by cleavage (C) was found after fatigue pre-crack (F) in this region (Fig. 6). There was some variation in the stretch zone across crack front in the measuring range (Fig. 7), with least value about 40 μm and the highest one of 100 μm. The average value of 5 measurements along the range was 60 μm.

The variations in SZW were much more expressed in UM weldment, with an average value of 110 μm (Fig. 8). Some ductile islands (D) have also been found in the stretch zone of UM weldment (Fig. 9).

Extremely complex crack behaviour in heat affected zone (HAZ) requires better understanding of contributing effects: mismatching, strain distribution and J integral evaluation, microstructure and its effect on final stretch zone.

ACKNOWLEDGEMENT

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REFERENCES

(1) Read, D.T., Experimental Method for Direct Evaluation of J-contour Integral, Fracture Mechanics Fourteenth Symposium, Vol.II, Testing and Application, STP791, ASTM Philadelphia, 1983, pp.199-213.

(2) Sedmak, S. and Petrovski, B., Application of Direct Measurement of J integral on a Pressure Vessel with Axial Notch, Fracture Mechanics Eighteenth Symposium, STP945, ASTM Philadelphia, 1987, pp.730-740.

(3) Božić, B., Sedmak, S., Petrovski, B. and Sedmak, A., Crack Growth Resistance of Weldment Constituents in a real Structure, Bulletin T.CI de l'Academie serbe des Science et des Arts, Classe des Science technique, No.25, pp.21-42.

(4) Rice, J.R., Journal of Applied Mechanics, Trans. ASME, June 1968, pp.379-386.

(5) Miyamoto, H., Kobayashi, H. and Ohtsuka, N., Standard Method of Test for Elastic-Plastic Fracture Toughness J_C Recommended in Japan, ICM 4, Pergamon Press, Oxford, 1982, Vol.2, pp.747-753.

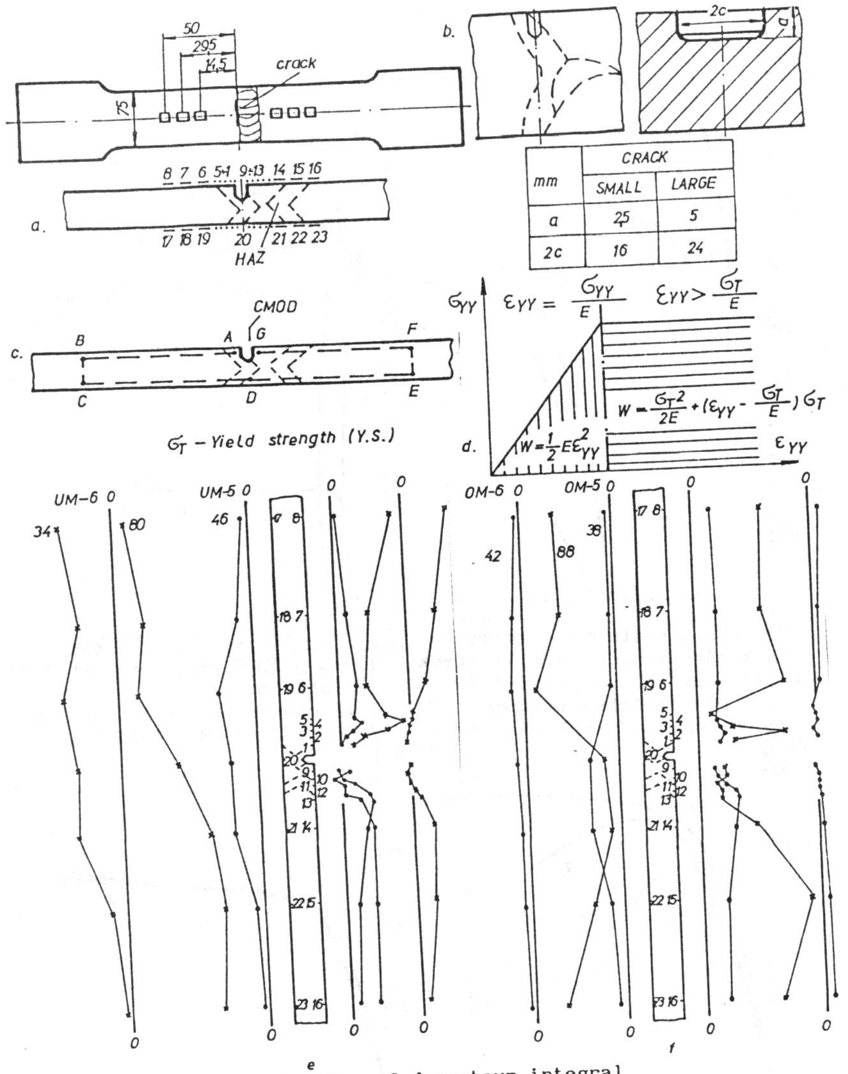

Figure 1 Direct evaluation of J-contour integral
a. Shape, dimensions and instrumentation of welded tensile panel with crack tip positioned in the heat-affected-zone
b. Crack disposition and size
c. J integral contour
d. Simplified σ_{yy}-ε_{yy} relationship
e. Strain distribution for undermatched weldment
f. Strain distribution for overmatched weldment

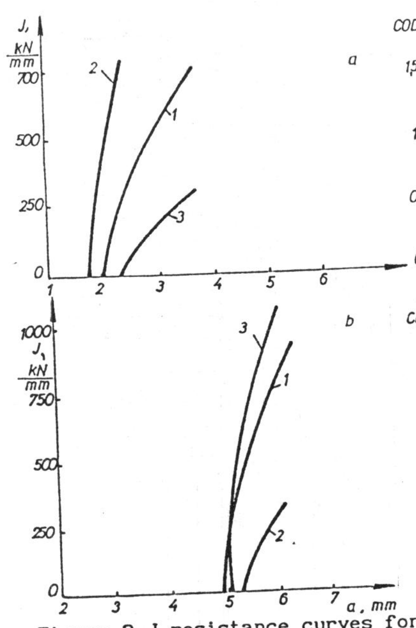

Figure 2 J resistance curves for crack tip in HAZ a.-Small crack (16x2.5 mm) b.-Large crack (24x5 mm) 1 -Overmatched weldment 2 - Undermatched weldment 3-Base metal

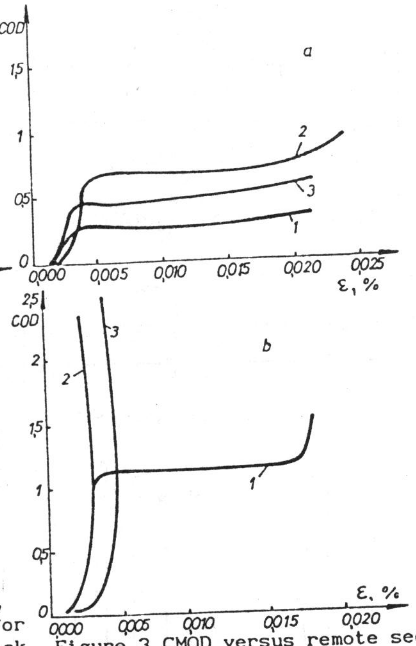

Figure 3 CMOD versus remote section strain for small (a) and large cracks (b) in BM, and in HAZ of UM and OM weldment.

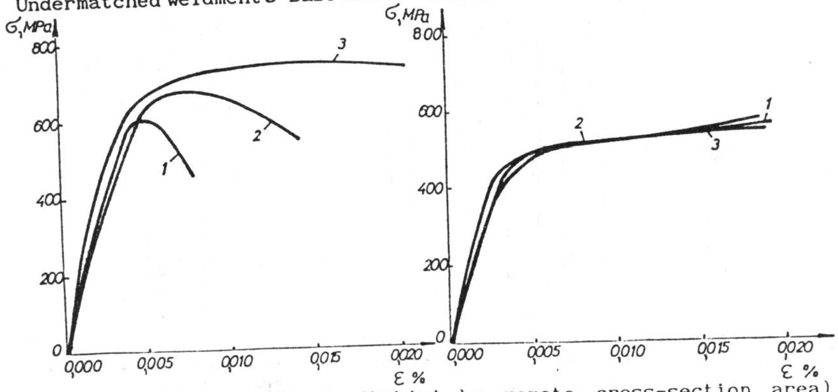

Figure 4 Stress σ (load divided by remote cross-section area) versus average strain ε (elongation measured by three LVDT's on 230 mm) for overmatched and undermatched weldments, obtained by tensile panels with crack in the middle of weld metal.

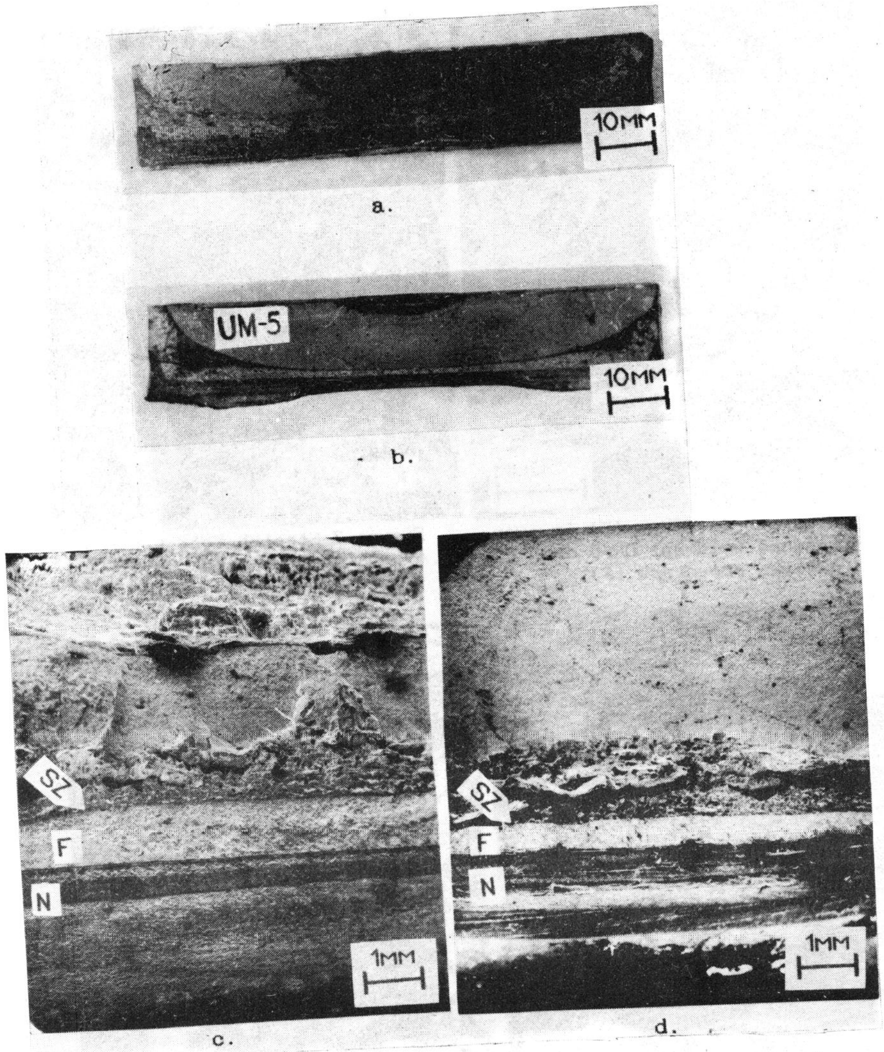

Figure 5 Surface cracks in tensile panels: a, c -large crack in overmatched weldment OM-6; b, d -small crack in undermatched weldment UM-5. (N -notch, F -fatigue pre-crack, SZ -stretch zone).

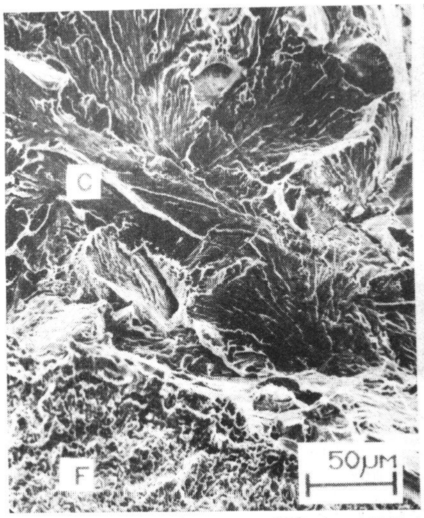

Figure 6 Cleavage (C) in over-matched weldment OM-6 next to fatigue pre-crack (F).

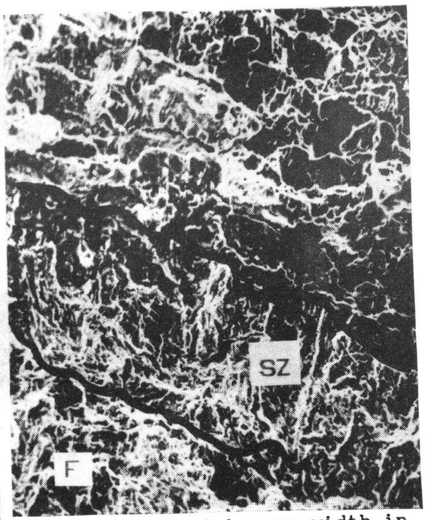

Figure 7 Stretch zone width in overmatched weldment OM-6.

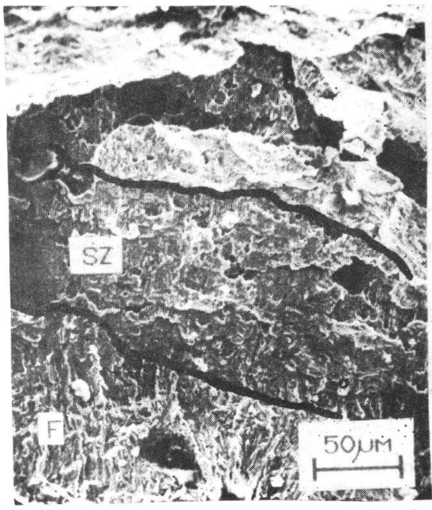

Figure 8 Stretch zone width in undermatched weldment UM-5.

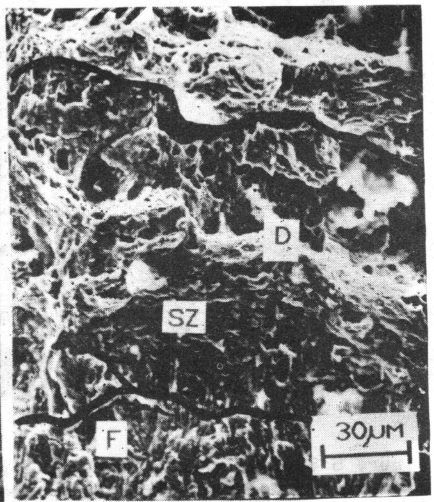

Figure 9 The portion of stretch zone with ductile islands (D) in undermatched weldment UM-5.