THE ROLE OF WELDMENT INTERFACES IN FRACTURE MECHANICS PARAMETERS EVALUATION

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ABSTRACT

The role of weldment interfaces in fracture mechanics parameters evaluation has been investigated. The J integral was used as the elastic-plastic fracture mechanics parameter, and direct measurement was used for its evaluation. Theoretical and numerical analysis have been used in order to investigate the J integral path dependency problem caused by material heterogeneity, i.e. weldment interfaces. It is shown theoretically that the J integral is not path independent for a generally shaped weldment, but that its path independence can be recovered if the modified J integral is used, comprising the original J integral and line integrals along weldment interfaces. This is confirmed by the finite element analysis applied to the undermatching and overmatching welded joints, used previously for J integral direct measurement.

KEYWORDS

Weldment interface, J integral, path dependency, base metal, weld metal, coarse grain heat affected zone, fine grain heat affected zone, finite element method, overmatching, undermatching

INTRODUCTION

The J integral, as defined by Rice (1968), has been used extensively as the fracture mechanics parameter during last three decades. Its popularity follows from the fact that the original introduction of J integral was well established within the basic laws of continuum mechanics. It was proved by Rice (1968) that the J integral is path independent (what has enabled its simple evaluation), that it has a physical meaning, i.e. it can be identified with crack driving force, and that it describes stress and strain fields around crack, making it a valid fracture mechanics parameter. Anyhow, as stated in the Rice's original paper, J integral is valid only for two-dimensional plane (non-linear) elasticity in absence of volume and thermal forces, and for the homogeneous material, at least in crack direction. Its application beyond these limitations has been questionable, but still not unsuccessful. As for the example, the J integral was successfully applied in the elastic-plastic fracture mechanics without any modifications of the original expression. On the other hand, the introduction of J integral within the basic laws of continuum mechanics enabled its modifications for some problems out of the scope of original definition, like three-dimensional problems, thermal and inertial forces effects.

In this paper, the influence of weldment heterogeneity is of primary interest and will be analyzed both theoretically and numerically. Theoretical analysis is applied in order to show that the J integral is not path independent for a generally shaped weldment. Anyhow, its path independence can be recovered if the modified J integral is introduced, comprising the original J integral and line integrals along weldment interfaces. Toward this end first the modified J integral for a general bi-material body is defined, following Smelser and Gurtin (1977), and than the modified J integral for multi-material body, representing welded joint with four different material regions (base metal - BM, weld metal - WM, coarse grain heat affected zone - CGHAZ and fine grain heat affected zone - FGHAZ), is defined following Savović (1994). The modified J integral is evaluated by the finite element method for both under and overmatching welded joints used previously for J integral direct measurement, Read and Petrovski (1986).

Direct measurement of J integral has been introduced by Read (1983) as a convenient technique for J integral evaluation. Since the J integral is evaluated using strain measurements along the outer body contour, which are then used for direct integration, no assumptions regarding crack length and specimen geometry is necessary. Only limitations are those already existing for J integral itself, including material homogeneity. Although one can argue that integration paths not crossing material interface can be used to alleviate this problem, it should be noted that direct measurement of J integral uses outer path which inevitably crosses all material interfaces. Thus, an analysis of material interface effect to the J integral direct measurement is essential.

It was stated already by Rice (1968) that the J integral is valid fracture mechanics parameter for a body homogeneous at least in a crack growth direction. Having weldments in mind one can conclude that the shape of material interface is of crucial importance in this respect. Indeed, as shown by Bleackley al (1986), there was no problem with J integral path dependence for the "I" shaped welded joints, but problems arose when "X" shaped joints were analyzed. Solution suggested by Luxmoore et al (1986), was to evaluated the J integral using only the paths not crossing the material interface. This is not generally acceptable, as explained in the case of J integral direct measurement, when material interfaces have to be crossed by integration path.

Probably the most intriguing part of this analysis is determination of weldment elastic-plastic characteristics in different regions. Standard experimental procedure can be applied to the BM and usually to the WM, but the HAZ is too small to provide even micro-specimens. Therefore, simulated welding cycles are often used to prepare the adequate specimens. Anyhow, as explained later, different approach is used here, based on fitting the results of numerical simulation of experimental data, Savović and Sedmak (1994). In this way it was also proved that two different regions of HAZ are sufficient to describe weldment behaviour correctly.

THE MODIFIED J INTEGRAL FOR BI-MATERIAL BODY

Let us consider the bi-material cracked body with the interface between two different materials, as shown in Fig. 1. The J integral can be evaluated along path Γ_1 encompassing the crack and not crossing the interface:

$$J_{\Gamma_1} = \int_{\Gamma_1} (W n_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds = G \qquad (1)$$

where W denotes strain energy density, n_j unit normal to Γ_1, σ^{ij} stress tensor, u^i displacement vector, x^i Descartes coordinates (x^1 along crack) and G crack driving force.

One should notice that the path Γ_1 can be separated into three parts, Γ'_1, Γ''_1 and l_1, where the last one is along the material interface, Fig. 1.

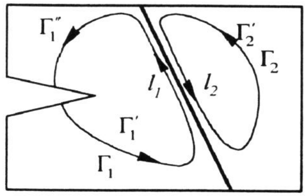

Figure 1. Basic definitions for bi-material body

On the other side, if one chooses closed integration path Γ_2, being completely in the other part of bi-material body, Fig. 1, than analogous expression can be written

$$J_{\Gamma_2} = \int_{\Gamma_2} (W n_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds = 0 \qquad (2)$$

except that J integral in this case equals zero because there is no crack and the energy release rate is zero for the closed path Γ_2. One should notice that the path Γ_2 can be separated into two parts, Γ'_2 and l_2, where the last one is also along the material interface, but at the opposite side compared to l_1, Fig. 1. Now, by combining eqns (1)-(2) one can get:

$$G = J_{\Gamma 1} + J_{\Gamma 2} = J_{\Gamma} + J_l \qquad (3)$$

where it was taken into account that the path Γ comprises paths Γ'_1, Γ''_1 and Γ'_2, while the path l comprises paths l_1 and l_2, Fig. 1. Therefore, it can be concluded that in order to regain path independence of J integral for the bi-material body, the line integral along material interface has to be added. In the special case, when the interface is parallel to the crack direction, additional line integral is zero.

MATERIAL CHARACTERISATION OF WELDMENT HETEROGENEITY

Elastic-plastic numerical analysis of the modified J integral requires precise knowledge of material properties, such as stress-strain curve, i.e. yield stress and hardening coefficient. If weldment is analyzed at least four regions with different material properties can be identified: BM, WM, CGHAZ and FGHAZ. There is no problem to obtain stress-strain curve for the BM and usually no problem with WM, but both regions of HAZ are too small to be properly tested. Anyhow, as already mentioned different approach was used here, because some experimental evidence was at disposal. Namely, before direct measurement of J integral was performed, the uncracked tensile welded wide plates, otherwise the same as the cracked ones, had been tested in order to obtain strain distribution along welded joint. More details can be found in (Savović and Sedmak, 1994), and only the results for undermatching and overmatching specimens are given here, Fig. 2 and 3. The tensile properties (tensile strength - R_m and yield stress - R_{eh}) obtained by standard testing for BM and WM of both undermatching (UM) and overmatching (OM) joints are given in Tab. 1. The UM joint was made by submerged arc welding (SAW) of SM60 (Sumitomo Steel - Japan), using wire US80B and flux MF38 (Kobe Steel -Japan), while the overmatching joint was made in the same way, but with SM80P (Sumitomo Steel - Japan) as the BM.

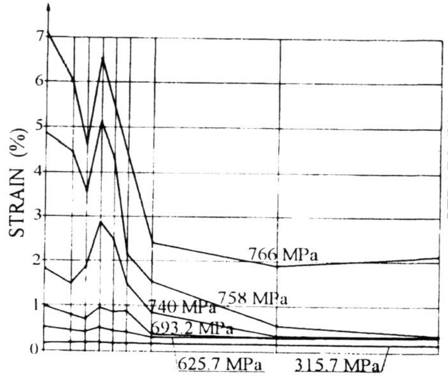

Fig. 2. Strain distribution along undermatched welded joint

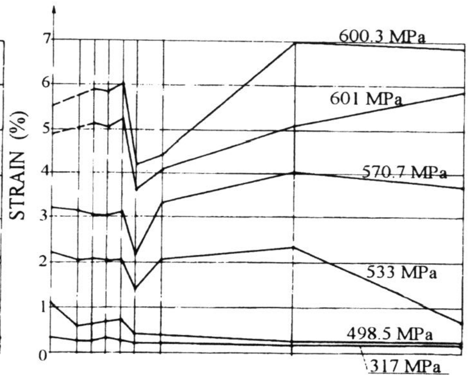

Fig. 3. Strain distribution along overmatched welded joint

Table 1. Tensile properties of UM and OM welded wide plates

Material	BM-SM80P	BM-SM60	WM-UM	WM-OM
R_{eh} (MPa)	778	534	626	453
R_m (MPa)	>806	601	768	>601

The results in Fig. 2 and 3 indicate an uneven strain distribution in both weldments. For UM specimen, Fig. 2, the largest strain is found in WM, the smallest in BM, while HAZ is characterized by two extremes, local minimum in coarse grain HAZ (CGHAZ) and local maximum in fine grain HAZ (FGHAZ). Results for UM specimen are given for the remote stress up to 766 MPa, Fig. 2. For OM specimen, strains are shown for the remote stress up to 601 MPa, Fig. 4. It should be noted that the strain in BM becomes larger than the strain in WM only when the remote stress exceeds 533 MPa, while local minimum and maximum in HAZ appear once again. Such a behaviour suggests lower yield stress of WM compared to BM. Having in mind that the weldment is OM, one can conclude that the hardening is more expressed in WM than in BM.

Numerical results

The finite element method has been used to simulate the strain distributions obtained experimentally for UW and OW tensile specimens. The specimens were analyzed as two-dimensional plane stress problem, which was solved for the remote stresses 766 MPa (UM) and 601 (OM), using modified version of software published by Owen and Hinton (1980). The heat affected zone was divided into two regions, FGHAZ and CGHAZ, in order to take into account two local strain extremes, obtained by the experiment, Fig. 2 and 3. Tensile properties of CGHAZ and FGHAZ, needed for the calculation (yield stress R_{eh} and hardening coefficient H'), were varied until numerical strain distributions matched closely enough the experimental ones. Seven and three different combinations of tensile properties were used to match the UW and OW specimen strain distribution, respectively, as shown in Tab. 2 and 3. Since the tensile properties in any combination were defined according to the previously obtained results, this procedure can be regarded as the iterative one. For the first iteration yield stresses for BM and WM were taken

from Tab. 1, and hardening coefficients were taken from the slope of σ-ε curves, while for CGHAZ and FGHAZ they were estimated. As shown in Tab. 2 and 3, yield stresses and hardening coefficients had to be varied even for BM and WM.

Table 2. Iteration procedure for UM joint tensile properties evaluation

Combination	R_{eh}, H' (MPa)			
	BM	WM	CGHAZ	FGHAZ
1	778, 500	626, 2800	675, 4000	595, 1800
2	758, 500	626, 2400	675, 3200	595, 2000
3	758, 500	585, 2600	675, 3000	595, 2300
4	758, 500	585, 2600	775, 1000	595, 2300
5	758, 500	585, 2600	775, 600	595, 2300
6	758, 500	585, 2600	750, 600	595, 2300
7	758, 500	585, 2600	760, 300	595, 2300

Table 3. Iteration procedure for OM joint tensile properties evaluation

Combination	R_{eh}, H' (MPa)			
	BM	WM	CGHAZ	FGHAZ
1	534, 1200	453, 2800	575, 4000	500, 2800
2	534, 1200	483, 2400	575, 4000	500, 2800
3	534, 1200	483, 1800	575, 3300	500, 2800

Numerical results, compared with the experimental ones, are shown in Fig. 4 and 5 for the UM and OM specimens, respectively. These results indicate combination No. 7 for UM and No. 2 for OM specimen as the closest numerical matching of the experimental results. One should notice that a general behaviour with two local extremes can be described closely enough by BM, WM and two different regions in HAZ.

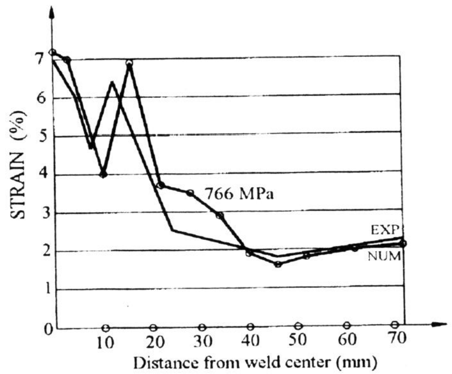

Fig. 4. Strain distribution along UM welded joint (FEM and experiment)

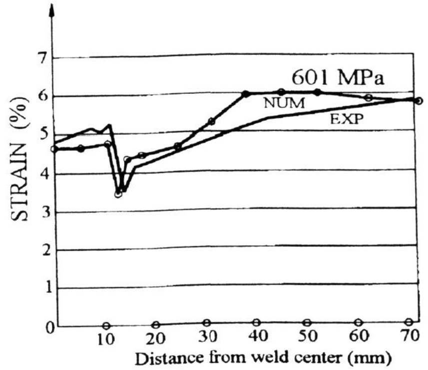

Fig. 5. Strain distribution along OM welded joint (FEM and experiment)

THE MODIFIED J INTEGRAL FOR MULTI-MATERIAL BODY (WELDMENT)

The modified J integral for a weldment will be introduced as for a multi-material body, represented by four regions of different material properties, Fig. 6: BM, WM and two regions in HAZ - one with fine grain structure (FG) and the other one with coarse grain structure (CG). Such a representation follows the uneven strain distribution along weldment, with two extremes in HAZ, Fig. 2-5. This is also in accordance with the well-known structural heterogeneity of HAZ: fine grain normalized region and coarse grain overheated region.

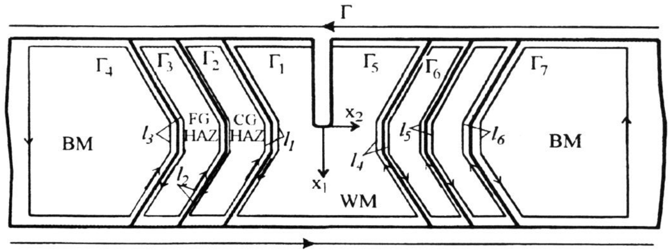

Fig. 6. Integration paths for multi-material body

Applying the same procedure as for the bi-material body, the J integral can be evaluated along path Γ_1 encompassing the crack and not crossing the interface, i.e. eqn (1) is still valid, while eqn (2) has to be written for six closed paths, Γ_2-Γ_7, Fig. 6:

$$\int_{\Gamma_a} (W n_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds = 0, \qquad a = 2,3,4,5,6,7 \tag{4}$$

The J integral along paths Γ_2 - Γ_7 reduces to zero because these paths do not encompass any discontinuity. Using equations (1) and (4) one can write:

$$J = \int_{\Gamma} (W n_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds - \sum_{a=1}^{6} \int_{\ell_a} (W n_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds \tag{5}$$

where l_a denote the closed contour around material interface. The expression (5) defines the modified J integral for a weldment, represented by four region of different material properties. The modified J integral is path independent, as shown by Savović (1994), and has the following physical meaning: the first integral term represents the force acting on both the crack tip and material interfaces (discontinuities of stress and strain), whereas the second one eliminates the force on the boundaries. Thus, the complete integral expression represent only the force acting on the crack tip, and can be identified with the energy release rate due to the unit crack growth.

NUMERICAL PROCEDURE AND RESULTS

Numerical analysis of elastic-plastic material behaviour is performed using modified version of programme by Fawkes and Owen (1984) for elastic-plastic analysis of two-dimensional problems by the finite element method. Collapsed isoparametric eight-noded element around the crack tip are used, producing r^{-1} singularity. The finite element mesh around crack tip, Fig. 7, was generated in accordance with the ESIS recommendation, ESIS (1991).

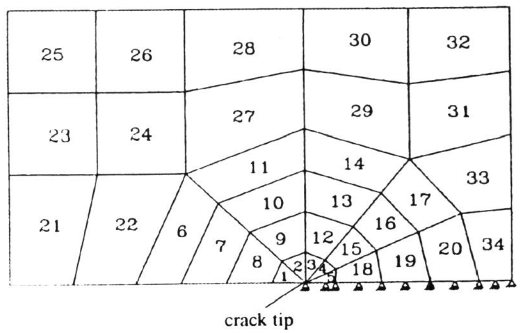

Fig. 7. The finite element mesh around crack tip

In order to check a weldment heterogeneity influence on the J integral value, obtained by the direct measurement on a surface cracked tensile panel, its cross-section through the maximum crack depth was analyzed by the finite element method, using a mesh consisting of 297 eight noded elements and 822 nodes, Fig. 8. Both integral terms in eqn (5) were numerically evaluated on different paths (J1-J3), Fig. 8. The plane strain with an edge crack was assumed. Such an approach gives conservative results, but this has no relevance for the analysis performed in this paper.

Data for mechanical properties (yield stress R_{eh} and hardening coefficient H') of weldment regions are given in Tab. 2 (combination 7) for UM plate and in Tab. 3 (combination 2) for OM plate. The calculation is performed on Pentium PC.

The results are given in Tab. 4 (UM plate) and Tab. 5 (OM plate), showing the average value of J integral for six inner paths, J_{ave}, close to the crack tip and not intersecting material boundaries (each two paths crossing three rings of elements around the crack tip, Fig. 7), the values of first integral term in the modified J integral for the remote paths intersecting the material boundaries (J1, J2 and outer path J3 - Fig. 8), and the values of second integral term in the modified J integral along the boundaries between WM and CG HAZ (J4, Fig. 9), between CG HAZ and FG HAZ (J5, Fig. 9), and between FG HAZ and BM (J6, Fig. 9).

Table 4. Results for UM plate

J1	J2	J3	J4	J5	J6	J_{AVE}
41.3062	42.2782	44.6796	-0.79005	0.34121	-0.3501	39.7158
72.6046	71.2274	79.2382	-2.99886	2.66134	-1.0395	68.3186
100.481	95.6042	106.957	-5.58250	5.80860	-4.1670	92.5672
133.131	124.831	139.410	-8.22616	9.08108	-7.2702	122.440
136.271	127.582	142.554	-8.46372	9.49186	-7.5983	125.372
160.795	149.400	166.615	-11.3089	12.0884	-10.070	148.362
202.666	187.190	206.002	-16.3222	16.4976	-14.327	188.772
220.514	202.676	222.586	-18.3749	18.8937	-16.806	206.276
223.504	205.236	225.386	-18.7163	19.3246	-17.222	209.220
247.370	225.526	247.658	-21.4016	23.0434	-20.973	232.632

Table 5. Results for OM plate

J1	J2	J3	J4	J5	J6	J_{AVE}
31.3748	32.0882	34.2002	-0.68967	0.28851	-0.25512	29.7088
64.5078	62.6990	69.1252	-2.92714	2.66912	-1.08319	59.9118
89.1068	85.6501	93.8878	-3.89848	4.09360	-1.55944	81.9860
122.111	116.304	125.953	-6.31730	6.24786	-2.51278	114.212
151.237	142.926	153.065	-8.54770	8.41536	-3.58438	142.463
169.063	159.063	169.334	-10.1065	9.90650	-4.38634	160.431
195.653	182.752	193.113	-12.4677	12.4879	-5.67176	186.387
212.058	197.401	207.956	-13.4919	14.0746	-6.31892	203.184
221.718	205.938	216.686	-14.3573	15.0908	-6.79846	212.314
245.412	226.866	237.576	-16.6522	17.7209	-8.06864	235.620

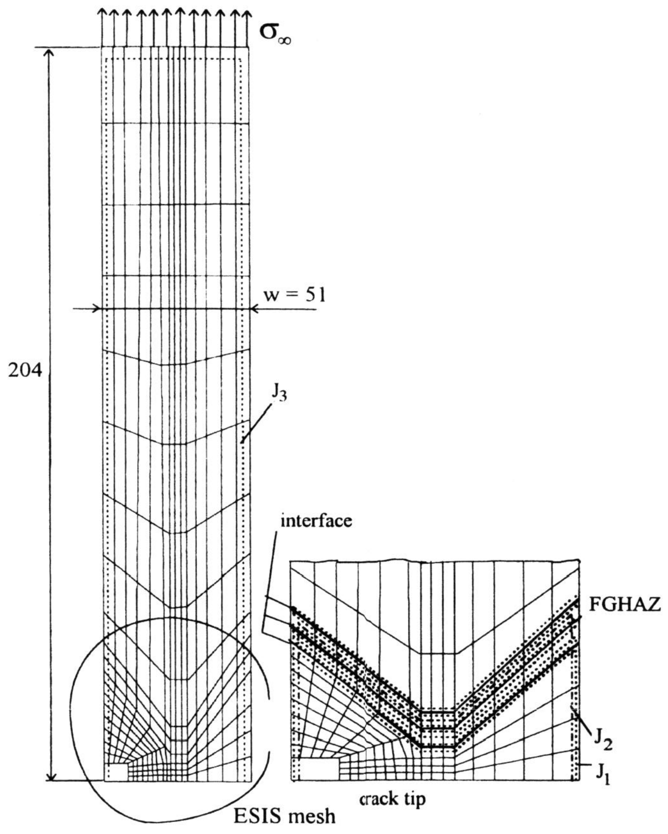

Fig. 8. Finite element mesh with some details

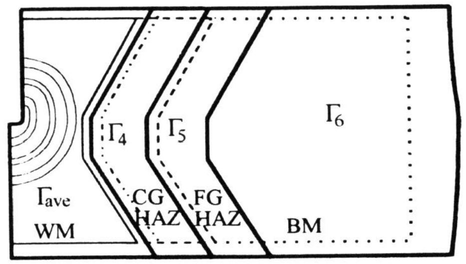

Fig. 9. Integration paths

DISCUSSION

As can be seen from Tab. 4 and 5 the finite element results confirm theoretical analysis of material interface effect on the J integral value. Namely, for both UM and OM weldments and for all load levels, the Rice's J integral is path dependent because its values for different paths differ out of the limits of numerical error. The largest difference (J1 and J2) is cca 9%, while the numerical error can be estimated to cca 2.5%, Laćarac and Sedmak, (1996). On the other hand, if values of the modified J integral (defined by eqn (5) and denoted here as JW), shown in Tab. 6 (UM weldment) and Tab. 7 (OM weldment), are analyzed, one can see an excellent agreement between JW1, JW2 and JW3, as well as a good agreement (within the limits of numerical error) between these values and J_{ave}. The relations between J1-J6 (Tab. 4 and 5) and JW1-3 (Tab. 6 and 7) is as follows:

$$JW1=J1+J4 \quad (6)$$

$$JW2=J2+J4+J5 \quad (7)$$

$$JW3=J3+J4+J5+J6 \quad (8)$$

Table 6. Results for UM plate - modified J integral

J_{ave}	JW1	JW2	JW3
39.7158	40.5161	41.8293	44.5808
68.3186	69.6057	70.8898	77.8611
92.5672	94.8991	95.8303	103.016
122.440	124.905	125.686	132.995
125.372	127.807	128.610	135.983
148.362	149.486	150.180	157.324
188.772	186.343	187.365	191.850
206.276	202.139	203.194	206.298
209.220	204.787	205.844	208.772
232.632	225.968	227.167	228.326

Table 7. Results for OM plate - modified J integral

J_{ave}	JW1	JW2	JW3
29.7088	30.6851	31.6870	34.0548
59.9118	61.5806	62.4409	67.7840
81.9860	85.2083	85.8461	92.5234
114.212	115.794	116.234	123.370
142.463	142.689	142.793	149.348
160.431	158.956	158.863	164.748
186.387	183.186	182.773	187.462
203.184	198.566	197.983	202.219
212.314	207.360	206.671	210.621
235.620	228.759	227.934	230.576

Speaking in engineering terms the effect of material interfaces is neither significant nor negligible. Having in mind the shape of weldment and differences in properties one can hardly think of more critical situation when similar materials are welded. Anyhow, dissimilar materials (e.g. ferrite and martensite or austenite steels) would produce much larger differences between the J integral for the outer contour and the modified J integral (i.e. crack driving force). Therefore, in such cases J integral direct measurement has to be followed (or preceded) by a numerical analysis in order to correct the experimental values. This is specially important if directly measured J integral is used as the J-R curve for the undermatched dissimilar weldments, because large overestimation can be obtain.

On the other hand, from the results of OM weldment one can conclude that the differences are much smaller and therefore negligible. As a matter of fact the J integral for outer contour is within 1% of J_{ave}. Anyhow, this is not a general rule for OM weldments, because the example used here is not exactly the overmatching weldment. Namely, although tensile strength is larger in WM than in BM, the yield stress is lower. From the results in Tab. 3 and 5 it seems that the yield stress influence is more important than the hardening coefficient (at least for the loading applied here, which are much higher than in real structures), because they resemble strongly the results for UM weldment (Tab. 2 and 4). Thus, from the point of view of numerical simulation the OM specimen used in this paper is actually slightly UM weldment, and the interface effect on the directly measured J integral values can be neglected. Nevertheless, in a general case, for a weldment with overmatching both in tensile strength and yield stress, the interface effect probably would be the same as for the UM weldment.

One should notice that from the results shown here it looks like HAZ effect can be neglected because its two regions (fine and coarse grains) seem to neutralize each other. Having also in mind difficulties regarding HAZ properties evaluation it is tempting to neglect its influence on J integral. More experimental and numerical evidence is needed for such a conclusion, but for directly measured J integral values obtained on weldments with HAZ separable into CG and FG regions, this is a reasonable engineering assumption.

More detailed analysis regarding HAZ heterogeneity could be performed. As shown by Kirk and Dods (1992) seven different regions of HAZ can be identified if hardness measument is applied as a criterion. On the other hand, the results presented here do not indicate such a necessity, at least not for the steel used. There was an attempt to define experimentally (using tensile microspecimens) HAZ structure of a similar HSLA steel, Gočev (1996), but it failed to provide anything new except already introduced FG and CGHAZ. Therefore, at least for HSLA steels it seems that four different regions in a welded joint are enough to describe its behaviour.

Regarding the finite element analysis it can be said that the mesh used here is adequate because much finer mesh, used in the meantime by the same author, has produced practically the same results.

Finally, one should notice that only one practically important case of the cracked weldment is analyzed here (central crack in WM). Some other important cases, like weldment with crack along diffusion zone are left for the future analysis. In this case diffusion zone separates crack faces and different materials produce asymmetrical deformation, making also CTOD difficult to define and evaluate.

CONCLUSIONS

From the results and their discussion the following conclusions can be made:

- Directly measured J integral for weldments is generally not equal to the crack driving force because of path dependence problem caused by material interfaces between BM, HAZ and WM.
- The effect of material interfaces can be evaluated using the modified J integral, i.e. the additional line integral, obtained by theoretical analysis in order to regain the J integral path independence.
- Speaking in engineering terms this effect is neither significant nor negligible.
- More evidence is needed, but probably this effect is the most pronounced for the "X" shaped weldments and dissimilar materials.

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