Finite element simulation of cracked weldments - the effect of under- and overmatching

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Keywords

Finite element, crack, simulation, undermatching welded joint, overmatching welded joint, J integral, weldment heterogeneity

1. Introduction

Having in mind weldment susceptibility to cracking, it is necessary to evaluate its fracture mechanics parameters as precisely as possible. Heterogeneity of weldment often causes difficulties in evaluation of elastic-plastic fracture mechanics parameters, such as J integral and crack opening displacement (COD). The J integral, as defined by Rice [1], 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 [1] 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.

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 as shown in. Toward this end 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 Savovic, [2]. The modified *J* integral is evaluated by the finite element method for both undermatching and overmatching welded joints.

2. 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 [3], and only the results for undermatching and overmatching specimens are given here, Figure 1 and 2. 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.

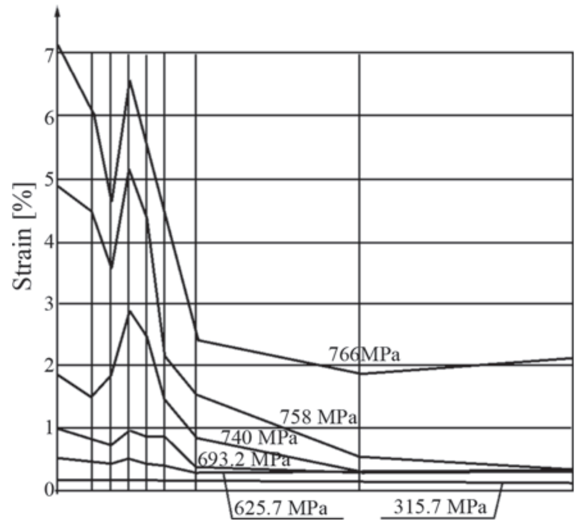

Figure 1. Strain distribution along undermatched welded joint.

The results in Figure 1 and 2 indicate an uneven strain distribution in both weldments. For UM specimen, Figure 1, 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, Figure 1. For OM specimen,

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strains are shown for the remote stress up to 601 MPa, Figure 2. 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.

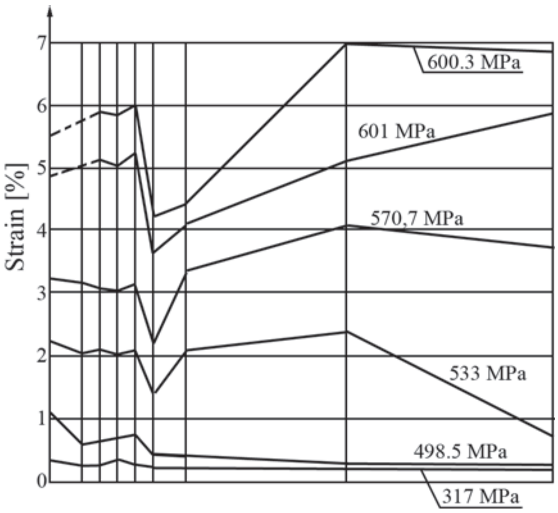

Figure 2. Strain distribution along overmatched welded joint.

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

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

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

Numerical results, compared with the experimental ones, are shown in Figure 3 and 4 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.

Table 2. Iteration procedure for UM joint tensile properties.

Combination	R_{eh}, H' [MPa]			
	BM	WM	CGHAZ	FGHAZ
1	778.5	626.28	675.40	595.18
2	758.5	626.24	675.32	595.20
3	758.5	585.26	675.30	595.23
4	758.5	585.26	775.10	595.23
5	758.5	585.26	775.60	595.23
6	758.5	585.26	750.60	595.23
7	758.5	585.26	760.30	595.23

Table 3. Iteration procedure for OM joint tensile properties.

Combination	R_{eh}, H' [MPa]			
	BM	WM	CGHAZ	FGHAZ
1	534.12	453.28	575.40	500.28
2	534.12	483.24	575.40	500.28
3	534.12	483.18	575.33	500.28

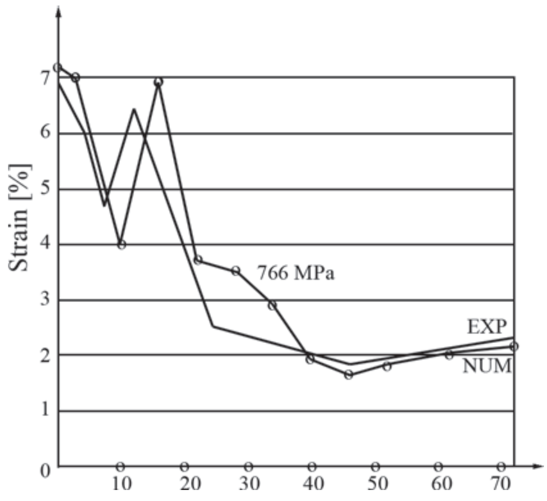

Figure 3. Strain distribution along UM welded joint (FEM and experiment).

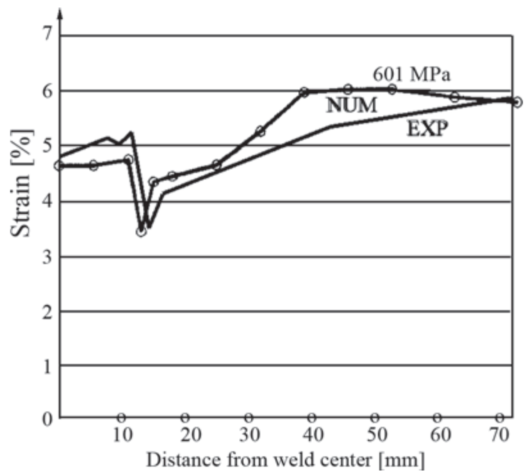

Figure 4. Strain distribution along OM welded joint (FEM and experiment).

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4. The modified J integral for 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, Figure 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, Figure 1-4. This is also in accordance with the well-known structural heterogeneity of HAZ: fine grain normalized region and coarse grain overheated region.

The *J* integral can be evaluated along path Γ_1 encompassing the crack and not crossing the interface:

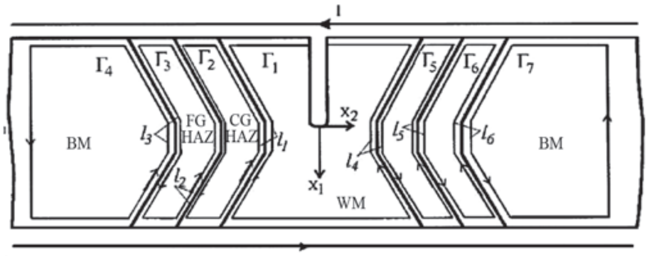

Figure 5. Integration paths for weldment.

$$J_{\Gamma_1} = \int_{\Gamma_1} (Wn_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds = G \quad (1)$$

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. For six closed paths, Γ_2-Γ_7, Figure 5, crack driving force G=0:

$$\int_{\Gamma_a} (Wn_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds = 0, \qquad a = 2,3,4,5,6,7 \quad (2)$$

The *J* integral along paths Γ_2-Γ_7 reduces to zero because these paths do not encompass any discontinuity. Using equations (1) and (2) one can write:

$$J = \int_{\Gamma} (Wn_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds - \sum_{a=1}^{6} \int_{\ell_a} (Wn_1 - \sigma^{ij} n_j \frac{\partial u^i}{\partial x^1}) ds \quad (3)$$

where l_a denote the closed contour around material interface. The expression (3) defines the modified *J* integral for a weldment, represented by four regions of different material properties. The modified J integral is path independent, as shown in [2], 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 com-plete 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.

5. Numerical procedure and results

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, Figure 6, in accordance with ESIS recommendations [4]. Both integral terms in eqn (5) were numerically evaluated on different paths (J1-J3), Figure 7. 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.

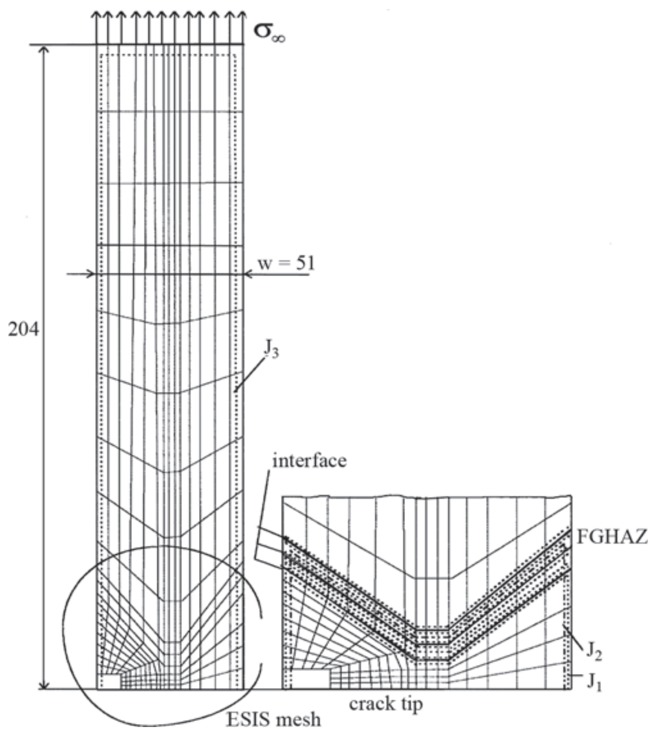

Figure 6. Finite element mesh with some details.

Data for mechanical properties (yield stress R_{eh} and hardening coefficient H') of weldment regions are given in Table 2 (combination 7) for UM plate and in Table 3 (combination 2) for OM plate. The calculation is performed on Pentium PC. The results are given in Table 4 (UM plate) and Table 5 (OM plate), showing the average value of *J* integral for six inner paths, Jave, close to the crack tip and not intersecting material boundaries (each two paths crossing three rings of elements around the crack tip, Figure 6), 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 - Figure 7), and the values of second integral term in the modified *J* integral along the boundaries between WM and CG HAZ (J4, Figure 7), between CG HAZ and FG HAZ (J5, Figure 7), and between FG HAZ and BM (J6, Figure 7).

Table 4. Results for UM plate.

J1	J2	J3	J4	J5	J6	J_{AVE}
41.3	42.3	44.7	-0.8	0.3	-0.4	39.7
72.6	71.2	79.2	-3.0	2.7	-1.0	68.3
100.5	95.6	107.0	-5.6	5.8	-4.2	92.6
133.1	124.8	139.4	-8.2	9.1	-7.3	122.4
136.3	127.6	142.6	-8.5	9.5	-7.6	125.4
160.8	149.4	166.6	-11.3	12.1	-10.1	148.4
202.7	187.2	206.0	-16.3	16.5	-14.3	188.8
220.5	202.7	222.6	-18.4	18.9	-16.8	206.3
223.5	205.2	225.4	-18.7	19.3	-17.2	209.2
247.4	225.5	247.7	-21.4	23.0	-21.0	232.6

As can be seen from Table 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%, [5]. On the other hand, if values of the modified *J* integral

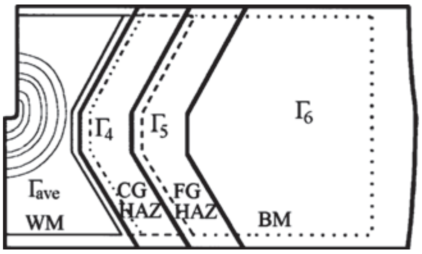

Figure 7. Integration paths.

Table 5. Results for OM plate.

J1	J2	J3	J4	J5	J6	J_{AVE}
31.37	32.1	34.2	-0.69	0.29	-0.3	29.71
64.51	62.7	69.1	-2.93	2.67	-1.1	59.91
89.11	85.7	93.9	-3.9	4.09	-1.6	81.99
122.1	116	126	-6.32	6.25	-2.5	114.2
151.2	143	153	-8.55	8.42	-3.6	142.5
169.1	159	169	-10.1	9.91	-4.4	160.4
195.7	183	193	-12.5	12.5	-5.7	186.4
212.1	197	208	-13.5	14.1	-6.3	203.2
221.7	206	217	-14.4	15.1	-6.8	212.3
245.4	227	238	-16.7	17.7	-8.1	235.6

Table 6. Results for UM plate - modified *J*.

J_{ave}	JW1	JW2	JW3
39.715	40.516	41.829	44.58
68.318	69.605	70.889	77.861
92.567	94.899	95.83	103.016
122.44	124.905	125.686	132.995
125.372	127.807	128.61	135.983
148.362	149.486	150.18	157.324
188.772	186.343	187.365	191.85
206.276	202.139	203.194	206.298
209.22	204.787	205.844	208.772
232.632	225.968	227.167	228.326

Table 7. Results for OM plate - modified *J*.

J_{ave}	JW1	JW2	JW3
29.708	30.685	31.687	34.054
59.911	61.58	62.44	67.784
81.986	85.208	85.846	92.523
114.212	115.794	116.234	123.37
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	207.36	206.671	210.621

(defined by eqn. (3) and denoted here as JW), shown in Table 6 (UM weldment) and Table 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 (Table 4 and 5) and JW1-3 (Table 6 and 7) is as follows:

$$JW1 = J1 + J4 \quad (4)$$

$$JW2 = J2 + J4 + J5 \quad (5)$$

$$JW3 = J3 + J4 + J5 + J6 \quad (6)$$

Speaking in engineering terms the effect of weldment heterogeneity is ruther negligible than significant. 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. This is especially 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 even 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 Table 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 (Tables 2 and 4).

6. Conclusions

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

• Numerical simulation of uncracked tensile panel experiment can be used to estimate material properties (yield stress and hardening coefficent) in HAZ, which are otherwise extremely difficult to evaluate even by testing of microspecimens.

• The effect of weldment heterogeneity 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.

• The effect of weldment heterogeneity is not significant for most of the common weldments, but can become significant for dissimilar weldments, like ferrite-austenite joints.

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