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WELDING TECHNOLOGY SELECTION EFFECT ON FRACTURE-TOUGHNESS PARAMETERS OF BI-MATERIAL WELDED JOINTS

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Preliminary notes

Nowadays, heterogeneous welded joints in metallic constructions are more and more frequently used so that these welded joints are the subject of a large number of investigations. In the present paper, welded joints consisting of micro alloy steel and austenitic steel realized with various filler metals and welding technologies are presented. The conducted testing was aimed at establishing the effect of the type of filler metal and heat input on the total impact energy, crack-initiation and crack-propagation energy as well as on the fracture toughness at plane-strain state of ferritic-austenitic welded joints. Optimum welding technology providing the highest welded-joint safety and extending operation life of construction has been defined.

Keywords: *heterogeneous welded joints, crack initiation energy, crack propagation energy, fracture mechanics*

Utjecaj izbora tehnologije zavarivanja na parametre žilavosti loma zavarenih spojeva od bimaterijala

Prethodno priopćenje

Danas je sve učestalija primjena raznorodnih spojeva u metalnim konstrukcijama, pa su ovi zavareni spojevi predmet velikog broja istraživanja. U ovom su radu ispitivani spojevi mikrolegiranog i austenitnog čelika ostvareni s različitim dodatnim materijalima i tehnologijama zavarivanja. Istraživanja koja su provedena imala su za cilj utvrditi utjecaj vrste dodatnog materijala i unijete količine topline na ukupnu energiju udara, energiju stvaranja i energiju rasta pukotine, kao i na žilavost loma pri ravnoj deformaciji feritno-austenitnih zavarenih spojeva. Definirana je optimalna tehnologija zavarivanja koja osigurava najveću sigurnost zavarenog spoja i produžava radni vijek konstrukcije.

Ključne riječi: *heterogeni zavareni spojevi, energija stvaranja pukotine, energija rasta pukotine, mehanika loma*

1
Introduction

Welded joints between micro alloy ferritic or micro alloy ferritic-pearlitic steel and high alloy austenitic steel are more and more used in power producing, chemical and some other plants.

It is known from practice that the danger from the appearance of cold cracks in HAZ of ferritic-pearlitic and thus micro alloy steels as well can be reduced by using filler metal that gives weld metal of austenitic structure. This can be explained by the much higher hydrogen solubility in austenitic weld metal than in the HAZ of ferritic-pearlitic (martensite or bainite) structure, so that even after the welded joint has been completely cooled down, the entire hydrogen input in the weld metal remains in it during welding and it is not diffused in HAZ [1]. In that case, the concentration of hydrogen in HAZ is insufficient to cause the appearance of these cracks, even in the presence of brittle structures and high stress.

However, the practice has shown that in the cases when weld metal has austenitic structure cracks appear in HAZ, which means that the critical amount of hydrogen needed for appearance of cold cracks nevertheless penetrates HAZ. That is why, in the case of austenitic weld metal as well, the content of hydrogen should be taken into consideration when calculating the preheating temperature. According to the data from literature [2], the input in the weld metal can be up to 5 ml of hydrogen/100 g of weld metal in case of MIG/MAG welding process with solid wire.

In each welded construction, there are critical places that present the main problem in its safety assessment. Welded-joint safety assessment requires establishment of the most unfavourable exploitation factors in critical places, which presents a problem for the local safety of the welded joint. In the analysis of the welded joint capacity to withstand impact loading without fracture, the impact toughness results are used, while in the analysis of the crack growth in the welded joint the fracture-mechanics methods are used.

The determination of impact energy is important when analysing the material propensity to brittle fracture. Impact tests are conducted to determine the total energy (impact toughness), as well as crack-initiation and crack-propagation energy components in the welded-joint critical parts. The plane-strain fracture-toughness, K_{Ic}, testing was conducted in order to determine the critical stress-intensity factor, K_{Ic}, i.e. to assess the behaviour of the welded-joint components, weld metal and HAZ in presence of the crack–type defect, the most dangerous of all defects in construction materials, and especially in welded joints [3].

2
Experimental part

Two different base metals were used for this study : *micro alloy steel* S500 NL1, with the trade name NIOMOL 490K, 16 mm thick (designated as M), and *high alloy steel* X6CrNiMoTi 17 12 2 according to EN 10088 (Č4574 according to SRPS EN 10088–1), 12 mm thick (designated as V). Tab. 1 shows chemical composition, and Tab. 2 mechanical properties of base metals.

Table 1 Chemical composition of base metals [4], wt. %

	C	Si	Mn	P	S	Cr	Ni	Cu	Al	Mo	Ti	V	Nb
M	0,10	0,38	0,64	0,014	0,02	0,76	0,10	–	–	0,33	–	0,02	–
V	0,04	0,35	1,73	0,031	0,004	17,9	11,6	0,18	0,061	2,16	0,38	0,079	0,016

Table 2 Mechanical properties of base metals [4]

Base metal	Yield stress, $R_{p0,2}$ / MPa	Tensile strength, R_m / MPa	Elongation, A / %	Contraction, Z / %
M	497	584	20	65
V	321	596	37	53

Three electrode wires were used as welding filler metals [5]:

1. MIG 29/9 – electrode wire for MIG/MAG welding, diameter ∅1,2 mm. Resulting welded plate was marked with number 1.
2. MIG 18/8/6 – electrode wire for MIG/MAG welding, diameter ∅1,2 mm, which was used for welding of the plates marked with numbers 2 and 3 for various heat inputs.
3. VAC 60 – electrode wire VAC 60 for MIG/MAG welding coated with Cu layer to prevent corrosion, used for welding of unalloyed steel with tensile strength below 530 MPa. Wire diameter was ∅1,2 mm.

Chemical composition of the used electrode wires is given in Tab. 3, and mechanical properties in Tab. 4.

Table 3 Chemical composition of filler metals [5], wt. %

	C	Si	Mn	Cr	Ni
MIG 29/9	<0,4	0,5	1,5	30,0	9
MIG 18/8/6	0,8	<1,0	7	18,5	9
VAC 60	0,8	0,9	1,0	<0,25	<0,025

Table 4 Mechanical properties of pure weld metal from selected filler metals [5]

	$R_{p0,2}$ / MPa	R_m / MPa	A_5 / %	KV / J
MIG 29/9	> 540	740÷850	>18	> 30 (at 20 °C)
MIG 18/8/6	> 380	560÷660	35	> 40 (at 20 °C)
VAC 60	410÷490	510÷590	22÷30	> 47 (at –24 °C)

Filler metals MIG 29/9 and MIG 18/8/6 were selected based on the recommendations from the literature [6]. In the process of selection of these metals, care was taken that these should have different values of yield stress and tensile strength as compared to base metals. As the third filler metal, VAC 60 was used to determine whether low-carbon filler metal can be applied in welding of heterogeneous steels.

All four test-plates were butt-welded. Welding was performed using semi-automatic arc welding process MIG/MAG. Different number of welding passes was caused by welding speed, current voltage and amperage, as well as by heat input during welding. The root pass was ground and re-welded only to obtain fine root through-weld. The ambient temperature was 15÷18 °C.

Analysing the diagram of continuous cooling of micro alloyed steel, one can conclude that, to obtain pure martensitic structure in HAZ, extremely high cooling rates are necessary, which is impossible to be realized in welding conditions [7]. This enables welding of micro alloy steel without preheating. However, very often, in practice, moisture condenses on the components to be welded, especially in case of outdoor welding. It should be removed before welding begins, which is achieved by preheating. Experience shows that preheating temperature of 60 °C is sufficient for moisture removal.

Based on the above, adopted are preheating temperature of 60 °C and interpass temperature of 60±10 °C. Fig. 1 shows the shape and dimensions of Y groove.

The plates were preheated and the interpass temperatures were maintained by oxygen and acetylene flame heating. Preheating and interpass temperatures were controlled using contact thermometer. Welding of all plates was performed in shielded atmosphere Ar + 2 % O_2 with the shielding gas flow of 12 l/min. Addition of 2 % of O_2 is necessary as oxygen reduces the drops of liquid metal in the arc, thus stabilizing electric arc and preventing formation of non-metallic inclusions.

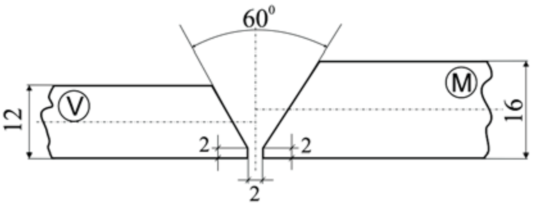

Figure 1 Shape and dimensions of Y groove

The flow is controlled by a ball rotameter. Welding was performed by forward welding technology. In all plates, the root pass was welded first, from the inside of the groove, after which the defects in this pass were removed by grinding. After that, filler-metal passes were welded. Alternating with welding, certain parts of previously welded pass were ground to remove defects and form a groove for welding the following pass. Presence of the defects was visually controlled. When the groove filling was finished, from the back of the welded joint on the root side, the defects were removed by grinding and the groove for repeated welding of the root pass was formed. When the welding was finished, the plates were cooled to room temperature in still air. By examination on Röntgen apparatus, no crack-type defects were observed.

Plate No. 1 was welded with filler metal MIG 29/9, at an average value of heat input of 7,35 kJ/cm. Plates No. 2 and 3 were welded with the same filler metal, MIG 18/8/6, at different average values of heat input: 8,88 kJ/cm for plate No. 1 and 6,87 kJ/cm for plate No. 3. In this case, the obtained values of energy input are limit values for the selected welding procedure and filler metal. Plate No. 4 was welded with filler metal VAC 60 at an average value of heat input of 8,03 kJ/cm.

3
Testing results
3.1
Impact energy determination

Testing by impact loading of the notched specimen can provide an explanation of the crack tip material behaviour, assuming that the specimen material is sufficiently homogenous at plane stress condition. Determination of the period of operation before fracture under certain testing conditions most frequently serves for regular control of the material quality and homogeneity, as well as for its processing. This testing procedure can determine the propensity to brittleness increase during exploitation (aging). Impact tests were performed on the specimens whose geometry and appearance are defined by EN 10045-1 standard [8]. Position of the notch in relation to the welded joint was defined by EN 875 standard [9]. The notch was made by milling, so that no modification of the material state during processing was possible.

Impact energy was determined by instrumented Charpy pendulum impact test, with impact loading range of 150/300 J and at room temperature. For this test, standard Charpy V-notched specimens were used. The results obtained are shown in Tab. 5 for the specimens with notches in weld metal (WM). Typical diagrams force–time and energy-time obtained by testing of the specimens with notches in WM are shown in Fig. 2.

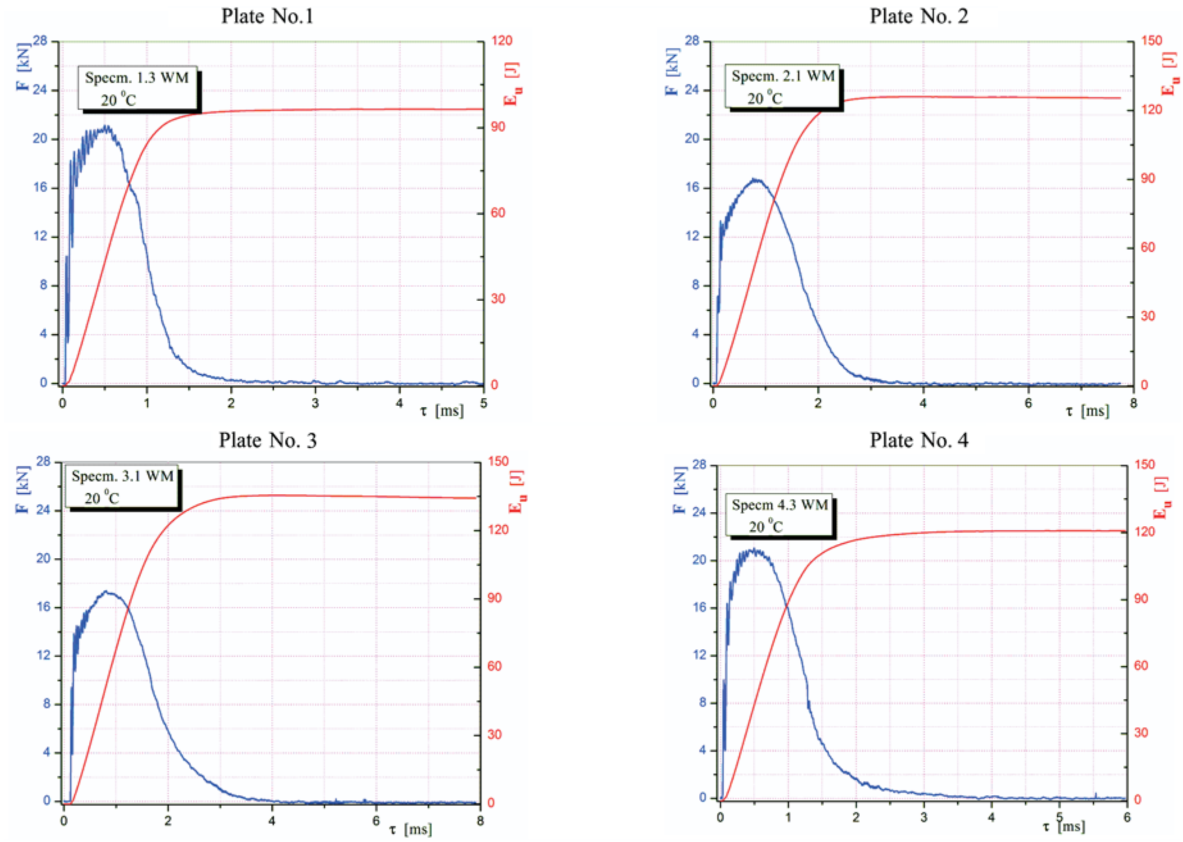

Figure 2 Diagrams obtained by impact tests on specimens from plates No. 1, 2, 3 and 4 with a notch in weld metal

Table 5 Impact energy of specimens with notch in weld metal

Plate no.	Total impact energy, E_{tot} / J	Crack initiation energy, E_I / J	Crack propagation energy, E_P / J
1	103	43	60
2	131	55	76
3	135	58	77
4	95	35	60

Test results for the specimens with a notch in heat-affected zone (HAZ) are shown in Tab. 6. Typical diagrams force–time and energy–time obtained by testing of the specimens with a notch in HAZ are shown in Fig. 3.

Table 6 Impact energy of specimens with notches in HAZ on micro alloy steel side

Plate no.	Total impact energy, E_{tot} / J	Crack initiation energy, E_I / J	Crack propagation energy, E_P / J
1	211	68	143
2	204	63	141
3	203	68	135
4	234	67	167

3.2
Determination of the plane strain fracture toughness K_{Ic}

Cracked specimens testing indicates local behaviour of the material around crack tip assuming that the material around the crack tip is sufficiently homogenous, which means that the results of the local behaviour can be treated globally, i.e. directly applied to corresponding construction. The effect of the structure heterogeneity and mechanical properties of welded joints is reflected in position of the fatigue-crack tip and properties of the area through which the fracture develops [3,10] in the first place.

The plane-strain fracture toughness, K_{Ic}, testing was conducted to determine the critical stress intensity factor K_{Ic}, that is, to assess the behaviour of welded joint components, weld metal and HAZ in the presence of the crack-type defect, as the most dangerous defect in construction materials, and especially in welded joints [3]. Testing was conducted at room temperature.

Two types of specimens were tested, depending on the location of the fatigue-crack tip, as follows:

- I group–specimens with fatigue-crack tip in weld metal,
- II group–specimens with fatigue-crack tip in HAZ on micro alloy steel side.

To determine K_{Ic}, three-point-bend (TPB) specimens were used. Their geometry is defined by BS 7448 Part 1 standard [11] and presented in Fig. 4.

Location of the notch tip in the areas of welded joint (WM and HAZ) is defined by BS 7448, part 2 standard [12]. As defined by BS 7448 Part 1 and BS 7448 Part 2 standards, testing started with preparation of the specimen, i.e. creation of a fatigue crack. Approximately 50 % of the final fatigue-crack length was prepared at maximum fatigue force $F_{max} = 0{,}4 \cdot F_L$. In this case, the minimum force was $F_{min} = 0{,}1 \cdot F_{max}$. Creation of the fatigue crack was performed on the high frequency pulsator AMSLER.

The requirement related to the plane-strain condition was not fulfilled according to (1):

$$B \geq 2{,}5 \cdot \left(\frac{K_{Ic}}{R_{p0,2}}\right)^2. \tag{1}$$

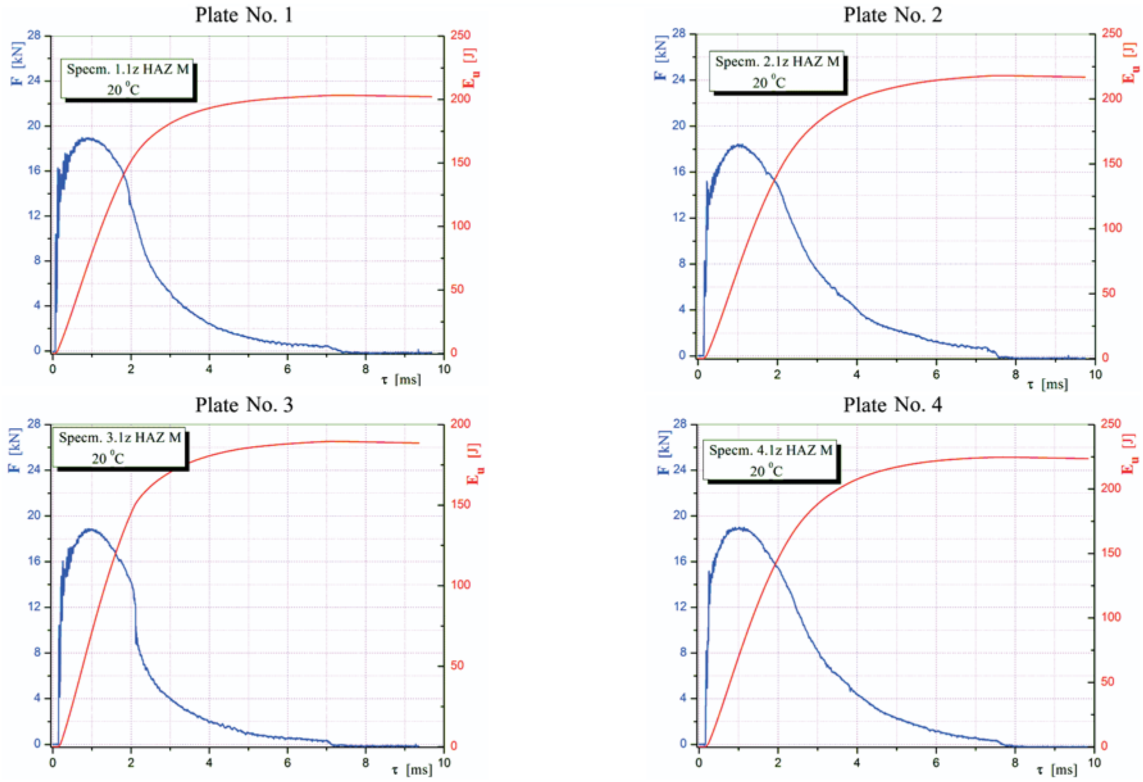

Figure 3 Diagrams of impact tests on specimens with notches in HAZ

In that case, instead of the linear-elastic fracture mechanics (LEFM) defined by BS 7448 Part 1 standard [11], the elastic-plastic fracture mechanics (EPFM) defined by ASTM E1820 standard [13] was applied. The aim of application of the elastic-plastic fracture mechanics is to determine the critical stress intensity value factor, K_{Ic}, indirectly, using critical J–integral, J_{Ic}, that is, to monitor the crack development under conditions of strong plasticity. At stable crack growth, the behaviour of elastic-plastic material, to which the welded joint components also belong, can be presented by a diagram J–Δa where Δa is crack increase.

Based on the results obtained, J–Δa curve is constructed, on which the regression line is constructed. From the constructed regression line, the critical J–integral, J_{Ic}, is obtained. Knowing the value of critical J_{Ic} integral, the value of critical stress intensity factor or the plane-strain fracture toughness, K_{Ic}, can be calculated using the dependence (2):

$$K_{Ic} = \sqrt{\frac{J_{Ic}\cdot E}{1-\nu^{2}}} \qquad (2)$$

where: E – elasticity modulus; ν – Poisson's ratio.

Table 7 K_{Ic} values for specimens with notch in weld metal

Plate no.	Critical J–integral, J_{Ic} / kJ/m^2	Critical stress intensity factor, K_{Ic} / MPa·m$^{1/2}$	Critical crack length, a_c / mm
1	45,8	101,6	53,9
2	69,5	125,1	93,4
3	75,6	130,5	100,9
4	39,8	94,7	50,8

Using fundamental fracture mechanics formula

$$K_{Ic} = \sigma\cdot\sqrt{\pi\cdot a_c} \qquad (3)$$

and introducing the value of conventional yield stress , $R_{p0,2} = \sigma$, approximate values for critical crack length, a_c, can be calculated.

Critical stress-intensity factor value, K_{Ic}, was determined using the method of a single specimen, by successive loading and unloading. Based on the data gathered from the tearing machine, (force provider and COD provider), the diagrams force F – Crack Mouth Opening Displacement (CMOD) δ were constructed. These diagrams are the foundation for determination of the critical value of J–integral, J_{Ic}. Calculated values of critical stress-intensity factor, K_{Ic}, and critical crack length, a_c, are given in Tab. 7 for the specimens with a notch in weld metal. Characteristic diagrams F–δ and J–Δa for the specimens with a notch in WM are given in Fig. 5.

Calculated values of critical stress-intensity factor, K_{Ic}, and critical crack length, a_c, are given in Tab. 8. for the specimens with notches in HAZ. Characteristic diagrams F–δ, and J–Δa for the specimens with notches in HAZ are shown in Fig. 6.

Table 8 Fatigue crack length of the specimens with notch in HAZ

Plate no.	Critical J–integral, J_{Ic} / kJ/m^2	Critical stress intensity factor, K_{Ic} / MPa·m$^{1/2}$	Critical crack length, a_c / mm
1	42,1	97,4	49,6
2	61,4	117,6	82,5
3	69,5	125,1	92,7
4	60,4	116,6	77,1

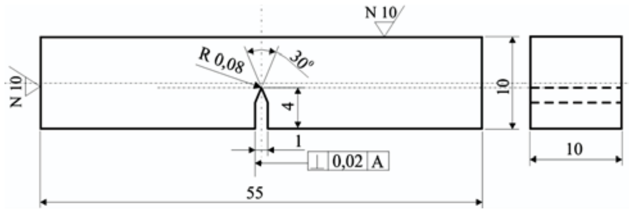

Figure 4 Specimen for fracture mechanics testing

4
Discussion

By analysing the values obtained for total impact energy of the specimens with notches in WM, one can see that selection of filler metal and welding technology affect the obtained by measurement. Total impact energy is highest in the specimen from plate No. 3, and it amounts to

Plate No. 1

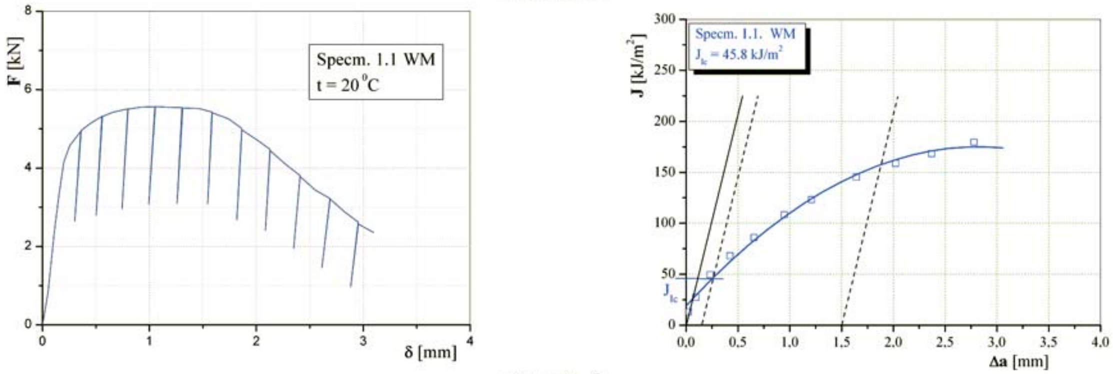

Plate No. 2

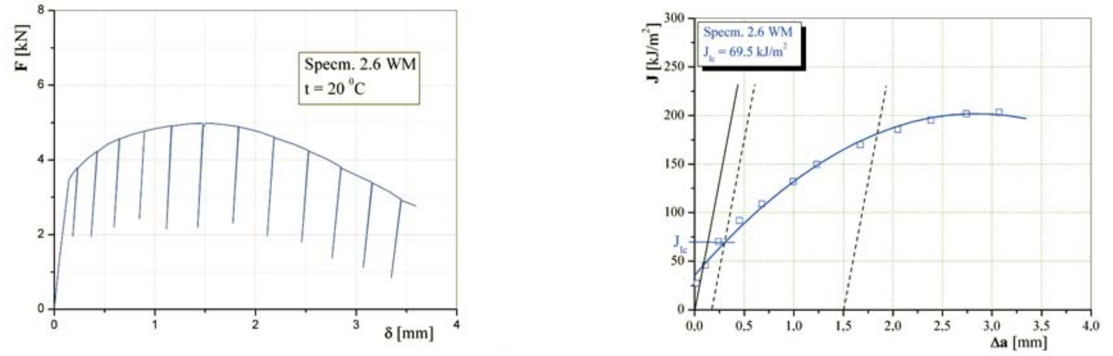

Plate No. 3

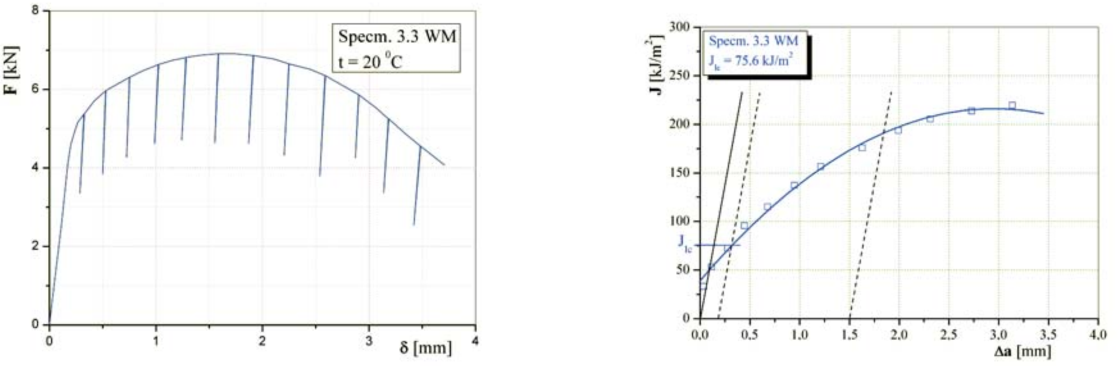

Plate No. 4

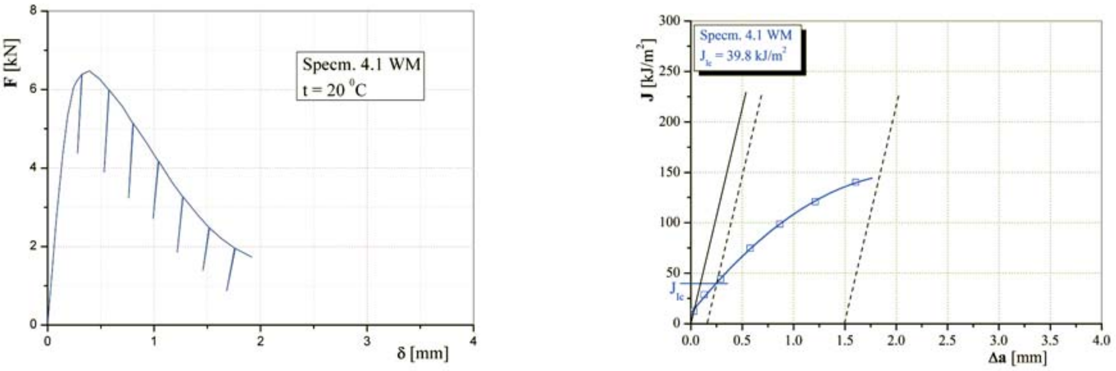

Figure 5 Diagram (a) F–δ and (b) J–Δa for specimens with notch in weld metal

Plate No. 1

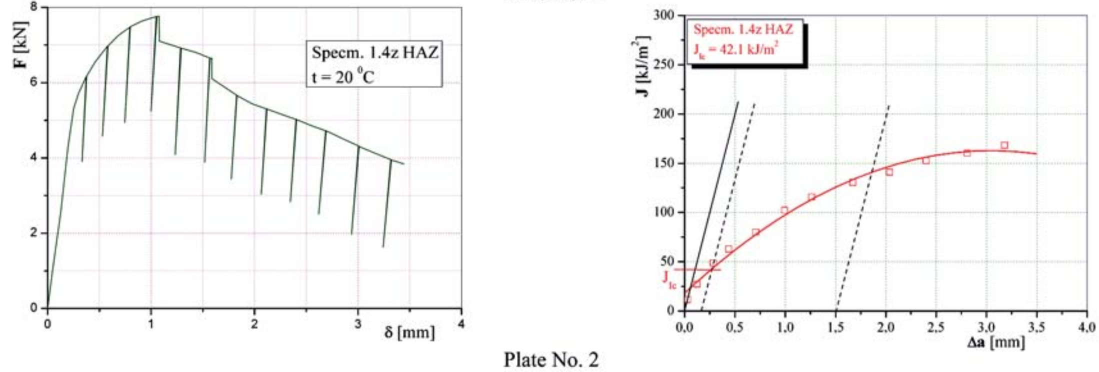

Plate No. 2

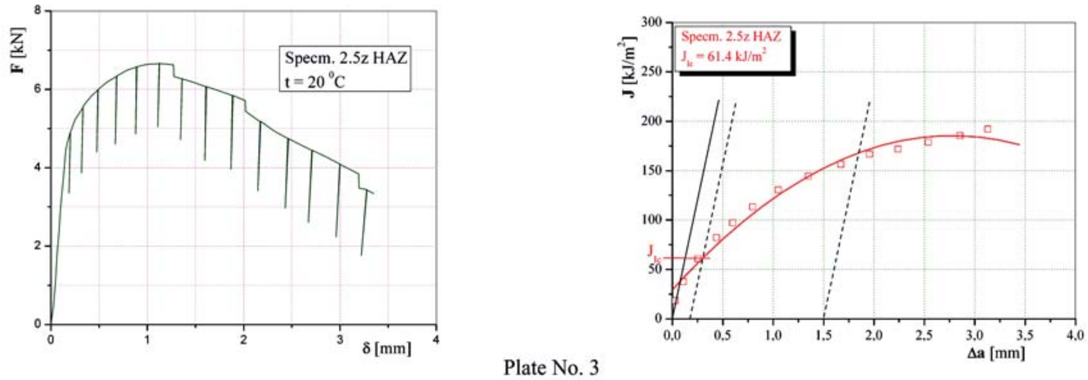

Plate No. 3

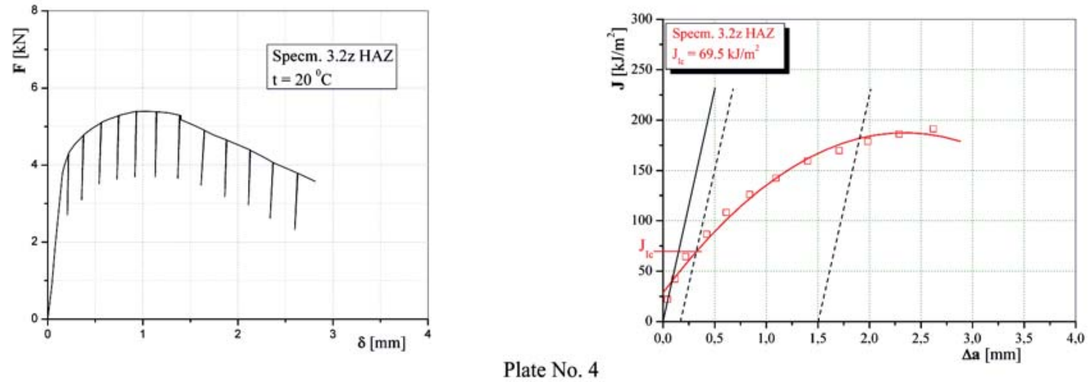

Plate No. 4

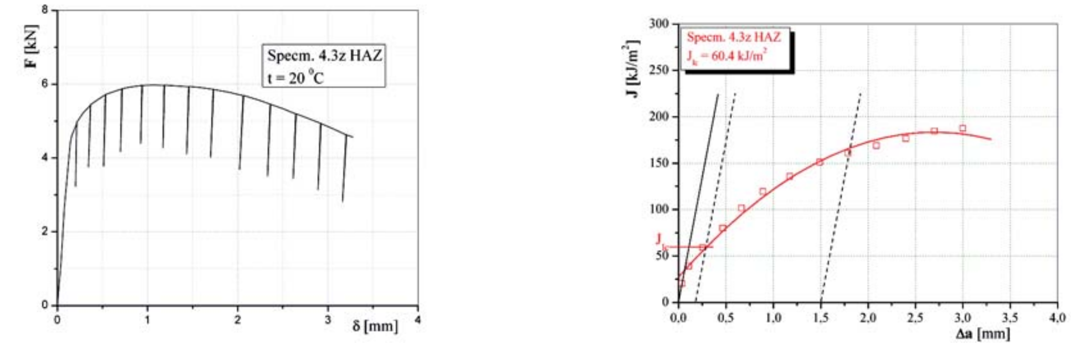

Figure 6 Diagram (a) F–δ and (b) J–Δa for specimens with notch in HAZ

135 J. Lower total impact energy, that is 131 J, was obtained in plate No. 2. Somewhat higher decrease of total impact energy is noticeable with two other test plates. In plate No.1, total energy is 103 J, while in plate No. 4 it is the lowest, 95 J.

The highest crack-initiation energy of 58 J has the plate No. 3. Plate No. 2 has almost identical crack-initiation energy - of 55 J. Somewhat lower crack-initiation energy, 43 J, is obtained in plate No.1, and the lowest, 35 J, in plate No. 4. The highest crack-propagation energy of 77 J has plate No. 3. Plate No. 2 has almost identical crack-propagation energy – 76 J. Somewhat lower crack-propagation energies of 60 J are obtained in plates No. 4 and No. 1.

As for the plates Nos. 1, 2 and 3 the austenitic filler metal, characterised by good plasticity and toughness, was used, the highest impact energy values were obtained in these plates. Contrary to that, for welding of plate No. 4, micro-alloy filler metal was used, resulting in the lowest value of total impact energy and its components.

The values obtained for total impact energy of the specimens with notch in HAZ are somewhat higher than the values of impact energy obtained for the specimens with notch in WM. Total impact energy is highest in plate No. 4, amounting to 234 J. Lower total impact energy, 211 J, has been obtained in plate No. 1. Plates Nos. 2 and 3 have the lowest total impact energies, and they are 204 J and 203 J respectively.

Crack initiation energy in HAZ has rather uniform values ranging from 63 to 68 J, which was expected due to the fact that there was the same base metal (micro alloyed steel). The highest crack propagation energy of 167 J has the plate No. 4. Almost identical crack propagation energies are obtained in plates No. 1 (143 J) and No. 2 (141 J). Plate No. 3 has the lowest crack impact energy of 135 J.

The fracture toughness K_{Ic} values of the specimens with notch in weld metal are between 94,7 $\mathrm{MPa\cdot m^{1/2}}$ in plate No. 4, and 130,5 $\mathrm{MPa\cdot m^{1/2}}$ in plate No. 3. The plates Nos. 2 and 3, welded using the same filler metal from 125,1 to 130,5 $\mathrm{MPa\cdot m^{1/2}}$, show the highest weld-metal fracture toughness value.

The values obtained for fracture toughness, K_{Ic}, of the specimens with notch in HAZ on the micro-alloy steel side, given in Tab. 8, range from 97,4 $\mathrm{MPa\cdot m^{1/2}}$ to 125,1 $\mathrm{MPa\cdot m^{1/2}}$. The lowest value of fracture toughness in the specimen with notch in HAZ of the weld is observed in plate No. 1, and it is 97,4 $\mathrm{MPa\cdot m^{1/2}}$. Somewhat higher value of fracture toughness in HAZ is observed in plate No. 4, amounting to 116,6 $\mathrm{MPa\cdot m^{1/2}}$. The highest value of fracture toughness in HAZ is shown in the plates Nos. 2 and 3. For plate No. 2, the obtained fracture toughness value is 117,6 $\mathrm{MPa\cdot m^{1/2}}$, and for the plate No. 3, the obtained value is 125,1 $\mathrm{MPa\cdot m^{1/2}}$.

The values obtained for critical crack length directly depend on the values obtained for fracture toughness at plane strain, K_{Ic}. The higher the value of fracture toughness, K_{Ic}, the higher the values obtained for critical crack length, a_{c}. Another important parameter on which critical crack length depends is permissible stress. It is obvious that permissible stress, which is lower than conventional yield stress, will provide higher values of critical crack length. It means that tested material in exploitation may have a crack up to specified length, with no danger of occurrence of brittle fracture. Therefore, to be certain to detect a crack before it reaches critical length, one should use appropriate non-destructive testing procedures. It should be noted that calculated values of critical crack length, a_{c}, refer to plane-strain conditions, and that these should be adjusted according to actual thickness of the construction material for each particular case.

5
Conclusion

Based on the presented results of testing of heterogeneous welded joints made of austenitic and micro alloyed steel, the following conclusions can be drawn:

- For welding of these basic metals, austenitic and micro alloy filler metals can be used. Welded joints obtained from austenitic filler metals demonstrate better toughness at room temperature, i.e. the highest total impact energy values, as well as crack initiation and propagation energies have been achieved.
- The resulting values of the critical stress intensity factor K_{Ic} correspond to the obtained impact energy values. The highest values are obtained with austenitic filler metal, i.e., the maximum crack length was allowed in those plates.
- Resulting values of toughness in HAZ are in all cases higher than those for the weld metal toughness, which indicates that HAZ is not the weakest place in the welded joint.
- Welding using the lowest heat input is recommended, since, in this way, lower mixture degree between filler metal and basic metals is achieved.
- In plate No. 3 (austenitic filler metal, the lowest heat input energy), the highest values of total impact energy and its components have been achieved. In addition, in this case, the highest value of the critical stress intensity factor has been obtained, implying that the maximum critical crack length in exploitation is allowed, which extends the service life of the construction. Based on this, this welding technology can be recommended for the welding of heterogeneous steels – ferritic and austenitic.

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