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EVALUATION OF CRACK SIGNIFICANCE IN WELDED JOINT BY FRACTURE MECHANICS APPROACH

OCENA POMENA RAZPOK V ZVARIH Z METODO MEHANIKE LOMA

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Razpoke nastale v zvarih kroglastih posod iz mikrolegiranega jekla so bile raziskane po metodah mehanike loma. Preiskusi so bili izvr{eni na dveh jeklih, na kaljenem in popu{~enem jeklu legiranem z molibdenom z nominalno mejo plasti~nosti 490 MPa (A) in na normaliziranem jeklu z mejo plasti~nosti 500 MPa, ki je bilo mikrolegirano z vanadijem (B). K zvarjeni spoji so bili pripravljeni z ro~nim elektrooblo~nim varjenjem. Iz zvarov so bili pripravljeni Charpy V preizku{anci z utrujenostno razpoko. Preizku{anci so bili izrezani iz toplotno vplivane cone (HAZ) na razli~ni oddaljenosti od talilne linije. Mikrostruktura v HAZ jekla B je bila raziskana tudi s termi~no simulacijo Charpy V preizku{ancev.

Dolo~eni so bili 3 lomno mehanski parametri: COD, J integral, faktor intenzitete napetosti in, kjer je bilo mogo~e, je bila tudi izmerjena kon~na raztezna cona. Pri jeklu A je bila pri temperaturi ambienta dose‘ena zadostna odpornost proti razpoki, medtem ko je bilo opa‘eno krhko pona{anje nekaterih con pri -60 °C. Deponirani metal je imel pri jeklu A najmanj{o odpornost proti razpoki. Pri jeklu B je bil odgovor na rast razpoke razli~en pri zvarjenih in simuliranih preizku{ancih. Vsi simulirani preizku{anci so se prelomili krhko in pri temperaturah simulacije je bilo mogo~e dolo~iti ‘ilavost loma. Krhkost je bila preverjena tudi pri nateznih preizkusih in razlo‘ena z mikrostrukturo po simulaciji. Odpornost proti razpoki je bila pri tem jeklu ve~ja pri deponiranem materialu, kot pri simuliranih preizku{ancih. V deponiranem materialu niso opa‘ena podro~ja zelo krhkega obna{anja. To se razlaga s postopno spremembo mikrostrukture v HAZ pri depoziciji naslednjih varkov, med tem ko je bila mikrostruktura v simuliranih preizku{ancih enako po vsem preseku.

Klju~ne besede: mikrolegirano jeklo, zvarjeni spoj, toplotno vplivana zona, mehanika loma, razpoka

Cracks in welded joints occurred during service in spherical storage tanks from microalloyed high strength steels, have been studied by fracture mechanics experimental analysis. Two high strength steels were investigated: the quenched and tempered Mo alloyed steel with 490 MPa nominal yield strength (A) and a normalized V microalloyed steel of 500 MPa yield strength (B). Welded K joints were prepared by manual metal arc welding and specimens of Charpy size prepared with fatigue precrack positioned in heat-affected-zone (HAZ) at different distances from fusion line. In addition, HAZ of steel B has been analyzed by thermal simulation with Charpy specimens.

Three fracture mechanics parameters were applied in the analysis: crack opening displacement, J integral, and critical stress intensity factor, and when appropriate the final stretch zone was also measured. By steel A all tested regions of HAZ exhibited a satisfactory crack resistance at room temperature, while in some regions at -60°C brittle behaviour was established. Weld metal of steel A was of the lowest crack resistance properties. Steel B response to crack growth was different for welded joint samples and simulated samples. Crack behaviour of all simulated samples was brittle, and at simulation temperatures of 1350°C and 1100°C plane strain fracture toughness could be determined. It was also confirmed in tensile and instrumented impact testing, and explained in terms of microstructure, obtained by simulation. Crack resistance in the welded joint specimens was higher in comparison to simulated samples and regions of extremely brittle behaviour were not found. This behaviour can be explained by gradual change in HAZ microstructure of welded joint by the deposition of the next passes, whereas in simulated samples only one microstructure was obtained.

Key words: microallyed steel, welded joint, heat-affected-zone, fracture mechanics, crack

INTRODUCTION

In-service fracture of spherical storage tanks /1/, manufactured from microalloyed steels caused by crack occurrence in the heat-affected-zone (HAZ) required the analysis of crack significance /2/ and the evaluation of fitness-for-purpose of cracked tanks until replacement or repair /3/. Better understanding of HAZ regions behaviour can help to a better evaluation of the crack significance.

The response of a welded joint to the loading and environment effect in a welded structure is determined by the response of its weakest region. Mechanical properties and crack resistance of welded joints are dependent on the heterogeneous microstructure of its constituents: parent metal (BM), weld metal and HAZ. HAZ is the most complex microstructure in a welded joint, since it results from the effect of heat and temperature distribution on the phase transformation of parent metal close to the molten welding pool. The variation in mechanical properties, toughness and crack resistance of HAZ, are clearly recognized /4/. For safety prediction, the analysis of welded joint and HAZ in a welded structure includes strength and impact toughness (and fracture toughness as well) properties. The evaluation of these properties in a welded joint is complex and, due to heterogeneous microstructure of HAZ, it is difficult to define a critical microstructure and to determine properly the local behaviour of the metal, such as toughness, as well as to locate the notch root or the crack tip. It is required for these tests to define the critical microstructure and its position within HAZ /5,6/

In order to get a closer insight in the properties of individual microstructures of HAZ, the simulation procedure has to be applied. It is possible to define the critical

Table 1: Chemical composition of tested steels

Steel	C	Si	Mn	P	S	Al	Cu	Nb	Cr	Ni	Mo	V
A	0.06	0.32	1.01	0.014	0.004		0.3	0,06	0.17	0.15	0.23	
B	0.20	0.51	1.42	0.020	0.010	0.018	0.035		0.018	0.574	0.017	0.180

microstructure by simulation and to predict its position in the HAZ by an assumed temperature distribution during the welding. HAZ in a welded joint has no clear boundary between individual microstructures that could be identified by testing of simulated samples. This has to be taken into account when the results of welding process simulation are compared to the behaviour of welded joints. Significant disagreements between the test results of simulated samples and the corresponding welded joint could appear and it is expected that the difference will be more expressed for local parameter, such as fracture toughness, rather than for yield or ultimate tensile strength /7/.

MATERIALS

Two microalloyed steels, intended for spherical storage tank application, were selected for experimental analysis. The first is the quenched and tempered Mo microalloyed steel NIOMOL 490 30 mm thick plates (produced by Steelworks "Jesenice", denoted by A), and the second is a normalized V microalloyed steel of 500 MPa nominal yield strength in thirtheen millimeter plates (denoted by B). The chemical composition of tested steels is given in **Table 1** and mechanical properties are given in **Table 2**.

Table 2: Mechanical properties of tested steels at room temperature

Steel	Yield strength, MPa	Tensile strength, MPa	Impact toughness, J	Hardness, HV_5
A	490	611	203.5	203
B	547	738	130.2	262

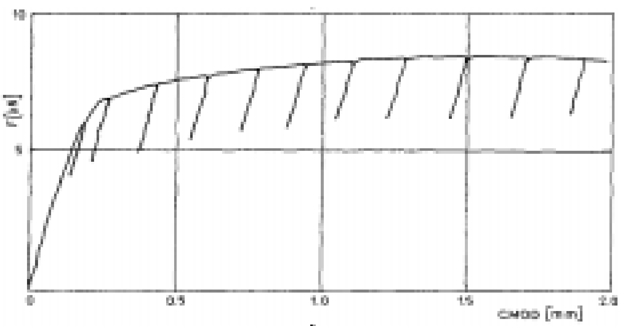

Figure 1: Load *F* vs. crack mouth opening displacement CMOD relationship, obtained for stable crack growth by single specimen unloading compliance technique for J integral testing

Slika 1: Odvisnost obremenitev F_s proti CMOD za stabilno rast razpoke po metodi razbremenitve preizku{anca za dolo~anje J integrala.

APPLIED TESTING METHOD

Fracture mechanics testing was performed applying a single specimen compliance technique for the J - integral evaluation, according to ASTM E1737. Charpy specimens (10x10x55 mm) with a 2 mm long V notch were used. After machining the notch, the fatigue crack was produced on a Crackthronik pulsator, using variable loading with the ratio R = 0.1 and a bending moment of about 40 Nm, in order to achieve the required 1 mm long fatigue crack for 80000 cycles. In this way the specimens with crack ratio a/W = 0.3 and the total crack length of 3 mm were obtained.

The testing at -60°C was performed in a recipient of convenient design, in which specimens were partially merged in the petrolether and liquid nitrogen solution, with V notch and crack opening on the upper side. In this way COD gauge could be applied safely. The testing at -30°C was performed in the temperature cabinet.

Three typical diagrams load *F*, versus crack mouth opening displacement, CMOD, (or load line displacement v_{LL}) were obtained. The first is smooth and uniform (**Fig.1**), and shows a ductile behaviour and stable crack growth with the maximal load achieved for a significant CMOD value preceding the final fracture. The second (**Fig. 2**) corresponds to a brittle behaviour, with a linear F - CMOD relationship. Specimen fractured at first attained maximum load at small CMOD value. The third (**Fig. 3**) exhibites pop-in behaviour. After maximal load, brittle fracture occurred, than brittle crack growth was arrested at lower load level and the testing could be continued.

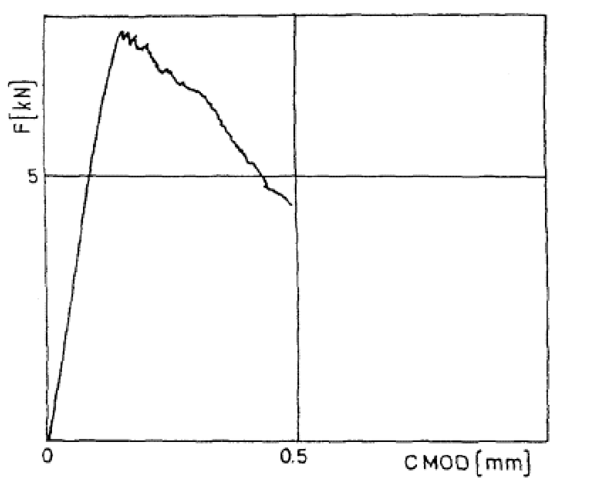

Figure 2: Load *F* vs crack mouth opening displacement CMOD for brittle fracture of the specimen tested at -30°C

Slika 2: Odvisnost obremenitev F proti CMOD za krhek prelom preizku{anca pri -30 °C.

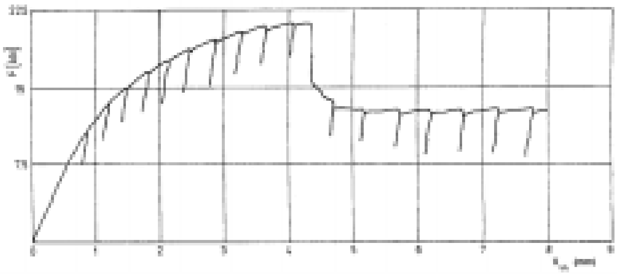

Figure 3: Load F vs. load line displacement v_{LL} relationship with pop-in behaviour
Slika 3: Odvisnost obremenitev F proti V_{LL} z pop-in obna{anjem.

From the relationships load vs. crack mouth opening displacement in **Fig. 1** to **Fig. 3** it is possible to calculate different crack parameters. The stress intensity factor K_Q for three points bending specimens according ASTM E399 could be calculated only from Fig. 2:

$$K_Q = \left(\frac{F_Q S}{BW^{3/2}}\right) f\left(\frac{a}{W}\right) \tag{1}$$

$$f\left(\frac{a}{W}\right) = \frac{3\left(\frac{a}{W}\right)^{1/2}\left[1.99-\left(\frac{a}{W}\right)\left(1-\frac{a}{W}\right)\left(2.15-3.93\frac{a}{W}+\frac{a^2}{W^2}\right)\right]}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}$$

with F_Q as corresponding load, S as specimen span (40 mm in this case), B as specimen thickness (10 mm), W as specimen width (10 mm) and a as crack length measured after the test. The K_Q value represents the plane strain fracture toughness K_{Ic} if the following condition is fulfilled:

$$B = 2{,}5\,\frac{K_I^2}{R_{p0,2}^2} \tag{2}$$

where $R_{p0,2}$ stands for the conventional yield strength.

For all the three relationships the crack tip opening displacement (CTOD) δ according to BS 5762 can be calculated using the general formula:

$$\delta = \frac{K^2(1-\nu^2)}{2R_{p0.2}E} + \frac{0.4(W-a)\nu_p}{0.4W+0.6a+z} \tag{3}$$

with v as Poisson's ratio, E as elasticity modulus, z as knife edge height and v_p as measured crack opening; and the stress intensity factor K for $S = 4W$:

$$K = K_Q = \frac{F_Q S}{BW^{3/2}} f\left(\frac{a}{W}\right) = \frac{4F_Q W}{BW^{3/2}} f\left(\frac{a}{W}\right) = \frac{4F_Q}{BW^{1/2}} f\left(\frac{a}{W}\right) \tag{4}$$

In this experiment the J integral value corresponding to the maximum load was calculated according to ASTM E1737, considering the elastic J_{el} and the plastic component J_{pl}:

$$J = J_{el} + J_{pl} \tag{5}$$

The value of J_{el} can be calculated according to ASTM E1737 for the initial crack length of a and the corresponding point in **Fig. 1**:

$$J_{el} = \frac{K^2(1-\nu^2)}{E} \tag{6}$$

The plastic component J_{pl} corresponds to the energy, represented by the area under load - load line displacement curve (**Fig. 3**). For each point of the relationship it is calculated as:

$$J_{pl} = \frac{2A_{PL}}{Bb} \tag{7}$$

with A_{PL} as area under the load vs. load line displacement record, B as specimen thickness, and $b = B - a$ stands for the actual ligament.

Starting with the initial compliance value corresponding to the initial crack size a, the changes in unloading line slopes in F-CMOD record enable to evaluate the crack growth for each step, required for J R curve determination.

For the steel A the final stretch zone /8/ was also measured by scanning electron microscopy.

The more extended experimental analysis of steel B heat-affected-zone included a microstructural analysis, hardness, tensile and instrumented impact testing of simulated samples and welded joint specimens.

CRACK RESISTANCE TESTING OF STEEL A HEAT-AFFECTED-ZONE

For this experimental analysis K multipass manual arc welding joints of steel A were prepared to obtain a convenient form of HAZ normal to the plate surface (**Fig. 4**). Notch and fatigue precrack were positioned in the weld metal, at the fusion line and on selected positions of HAZ, according to **Fig. 4**.

The application of Charpy type specimens enabled only to compare the crack behaviour of different regions in HAZ, and it is not certain whether the value of fracture toughness parameter for the critical HAZ region was found.

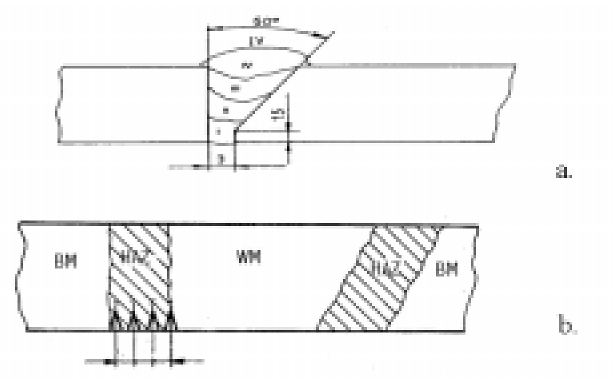

Figure 4: Steel A joint obtained by four passes manual welding arc (a) and crack tip position in the heat-affected-zone (b)
Slika 4: Zvar jekla A pripravljen s 4 ro~nimi varki (a) in polo'aj vrha razpoke v toplotno vplivani zoni (b).

Table 3. Results of fracture mechanics tests on precracked Charpy specimens of steel A welded joint

Specimen	Test temperature °C	Fatigue precrack length mm	Maximum load kN	Load at arrested pop-in kN	Crack tip opening displacement mm	J integral kJ/m^2	Final stretch zone width mm
1	20	3.07	5.65	-	0.18	403	0.140
2	20	4.03	8.35	-	0.27	680	0,290
3	20	4.16	9.50	-	0.20	650	0.190
4	20	3.10	10.70	-	0.60	930	0.560
5	20	3.77	8.10	-	0.34	787	0.310
6	- 60	3.00	10.90	5.4	0.19	100	0.160
7	- 60	4.10	9.20	2.5	0.37	704	0.475
8	- 60	3.60	9.80	3.8	0.45	605	0.437
9	- 60	3.29	10.70	2.1	0.23	318	0.231
10	- 60	3.52	9.60	4.3	0.15	239	0.121

The crack tip is in WM, on specimens 1 and 6 (**Table 3**) on 2 and 7 at the fusion line and on specimens 3 and 8 at 0.2 mm, on 4 and 9 at 0.5 mm, and specimens 5 and 10 at 0.8 mm from the fusion line between the weld metal (WM) and the heat-affected-zone (HAZ). The specimens 1-5 were tested at room temperature, and the specimens 6-10 were tested at - 60°C.

The obtained values for J integral and CTOD corresponding to maximum load in welded joint of steel A and the final stretch zone are listed in **Table 3**.

The diagrams obtained at room temperature are of type presented in **Fig. 1**, and those obtained at -60°C exhibited pop-in behaviour, as in **Fig. 3**.

CRACK RESISTANCE TESTING OF STEEL B HEAT-AFFECTED-ZONE

The analysis of HAZ properties of steel B was performed on simulated and welded joint samples /7/ in order to understand better the crack behaviour and to evaluate properly the response of cracked welded structure to loading, which is required for fitness-for-purpose assessment. The microstructures samples of different regions in HAZ were prepared by simulation on Smitweld LS1402 device. The samples of 11x11x60 mm were heated to different temperature (B1 - 1350°C, coarse grains formation, B2 - -1100°C, fine grains formation, B3 - 950°C, - fine grains region above the A_{c3} temperature, B4 - 850°C, partial transformation between the A_{c1} and A_{c3} temperatures). The cooling time $\Delta t_{8/5}$ of 15 s was constant. These temperatures are accepted as typical for microstructural transformations in HAZ of tested steel B. In addition, samples B5 and B6 were obtained by two successive simulations: first at 1350°C, and than at 750°C (B5) or 650°C (B6). The temperatures for the second simulation were selected above and bellow Ac_1 temperature. The 20 mm long central part of the sample (**Fig. 5**) affected by heat in simulation served as measuring region for hardness (HV_5), tensile test (ϕ 4.5 mm specimen) and Charpy V instrumented impact test (**Table 4**). Microstructures of HAZ regions were examined by light microscopy, and the correspondence to tensile and impact toughness tests diagrams was established (**Fig. 6**).

Precracked specimens for fracture mechanics tests were prepared as described above. The obtained results for simulated samples of steel B are presented in Table 5. It is to be noticed that the brittle behaviour was very clear for the simulation temperature of 1350°C (specimen B1, **Fig. 2**) and 1100°C (B2),), and could only be used for the evaluation of the stress intensity factor K_I and its critical value, the plane-strain fracture toughness, K_{Ic} (denoted by * in Table 5), according to ASTM E399. Stable crack growth, as in **Fig. 1**, was observed for the simulation temperature of 950°C (B3) and 850°C (B4) (the calculated values for stress intensity factor K_I are given in brackets). Double simulation produced a better crack resistance compared to single simulation at 1350°C, however crack behaviour still could be better described as brittle, rather then ductile (compare specimen B6 in Table 5).

Table 4. Test results of simulated samples testing of steel B at room temperature

Sample	Simulation temperature °C	Yield strength MPa	Tensile strength MPa	Elongation, %	Impact toughness J	Hardness, HV5
B1	1350	1101	1101	-	7.7	480
B2	1100	943	1189	12.6	10.6	418
B3	950	818	1036	18.0	46.2	353
B4	850	660	936	11.8	31.6	338
B5	1350/750	815	889	7.3	57.5	364
B6	1350/650	948	1035	12.6	25.2	395

The disposition of the crack tip locations for specimens in different HAZ regions of individual welding runs (I to IV) is shown on **Fig. 7**. The results for welded joints of steel B in CTOD terms are presented in **Table 6**. The microstructure in cross section A-A in **Fig. 7** in coarse grains (GZ) and fine grains (FZ) regions are given in **Fig. 8**.

ANALYSIS OF TEST RESULTS

The smooth shape of the plot (**Fig. 1**) is obtained at room temperature in fracture mechanics testing of steel.

Table 5: Crack tip opening displacement and fracture toughness for simulated samples of steel B

Parameter	Temperature	Sample	B1	B2	B3	B4	B5	B6
Crack opening displacement, δ_c	20°C	mm	0.005	0.008	0.164	0.130	0.095	0.017
Plane strain fracture toughness, K_{Ic}	20°C	N/mm$^{3/2}$	1510*	1498*	(2932)			(2621)
Crack opening displacement, δ_c	-30°C	mm	0.007	0.007	0.022	0.019	0.009	0.013
Plane strain fracture toughness, K_{Ic}	-30°C	N/mm$^{3/2}$	1540*	1518*	(1954)	(2617)	(2066)	(2274)

Table 6: Crack tip opening displacement values for steel B welded joint specimens precracked in HAZ at different distances from fusion line

	Sample	2	4	6	8	11	12	3	1	5	7	9
Distance from fusion line	mm	4	2.3	0.8	0	WM	WM	4	3.5	2	1.2	1
Testing temperature	°C	20	20	20	20	20	20	-30	-30	-30	-30	-30
Crack opening displacement, δ_c	mm	0.32	0.38	0.20	0.32	0.17	0.46	0.29	0.24	0.35	0.30	0.33

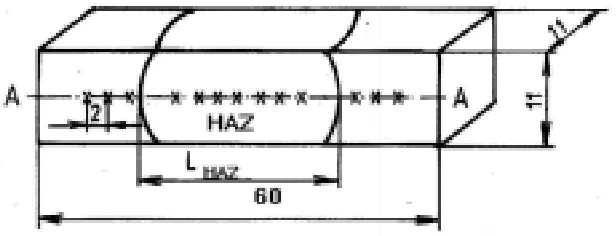

Figure 5: Simulated sample and positions (x) for hardness measurement

Slika 5: Simulirani preizku{anec in mesta (x) merjenja trdote.

A welded joint corresponds to stable crack blunting and growth during the experiment and ductile behavior. However, the specimens were broken in a brittle manner when tested at -60°C, ended by arrested pop-in. A final stretch zone of different size for different crack tip position preceded the final fracture. Two typical loads could be defined for the test performed at -60°C. The first corresponded to the maximal load and the second to the load of arrested pop-in, as given in **Table 3**.

The crack parameters of steel A welded joint HAZ can be evaluated as satisfactory at both, room temperature and -60°C. The agreement between different fracture mechanics parameters (CTOD, J integral, and final stretch zone) is acceptable, having in mind the scatter of measurements. The occurrence of pop-in by testing at -60°C, can be attributed to the higher nil-ductility transition temperature of the microstructure, in which the fatigue precrack tip was positioned. According to obtained results, weld metal could be considered as the critical region of the welded joint, and low values of fracture mechanics parameters at -60°C can be connected with its nil-ductility transition temperature.

Crack growth resistance properties depend on yield strength and brittle fracture would be expected for steels with a high yield strength close to the ultimate strength, whereas the behaviour of steels of lower yield strength is ductile. However, it is not possible to evaluate exactly the yield strength of a welded joint due to its heterogeneous microstructure and by standard tensile testing only ultimate tensile strength is required. Welded joint crack resistance, as a local material parameter, will depend on HAZ microstructure and tensile properties of its critical region. That means that differences in crack behaviour in real welded joints and simulated samples are expectable.

Additional data on strength properties for the complete evaluation of crack behaviour of different regions of steel A HAZ would be required. Parent metal yield strength and ultimate tensile strength can be accepted as referent values for an overmatched welded joint. However, for an accurate analysis this is not sufficient. The next deficiency of performed experiments is connected to microstructure of the regions through which fracture developed, which was not defined. Anyhow, in a real welded joint the temperature gradient effect governs the continuous and gradual transformation of structure and affects the crack behaviour. The effect of the temperature gradient in steel A HAZ can be recognized in results, obtained by testing at -60°C.

In-service crack occurrence in HAZ of V microalloyed steel B required the detailed analysis of mechanical properties, crack resistance and microstructure possibly by simulation of HAZ. The results of mechanical testing of simulated samples are listed in **Table 4**. Testing results indicated regions of very high strength and brittle behaviour in specimens thermally treated at 1350°C and 1100°C. Increased strength and reduced ductility, compared to parent metal, was found also for other simulation temperature. High hardness in simulated samples of steel B corresponds to a 0.2%C content. Increasing hardness and tensile strength of simulated samples can be atributed to a martensitic microstructures /4, 7/ in samples heated to 1350°C and 1100°C (**Fig. 6**). Low impact toughness indicate brittle behaviour at 1350°C and at 1100°C, although by lower temperature a small plasticity is expressed by the difference between the yield stress and ultimate tensile strength. The beneficial effect of subsequent welding passes could be recognized for specimens B5 and B6, and better results are obtained by higher temperature of the second pass (B5 - 750°C).

The crack resistance properties of simulated samples and different regions in HAZ of steel B welded joint samples were represented by the crack opening displacement (COD) at maximum load, the stress intensity factor K_I, and its critical value K_{Ic}, when the condition in Eq. 2 was fulfilled (**Table 5, Table 6**). The brittle behaviour of

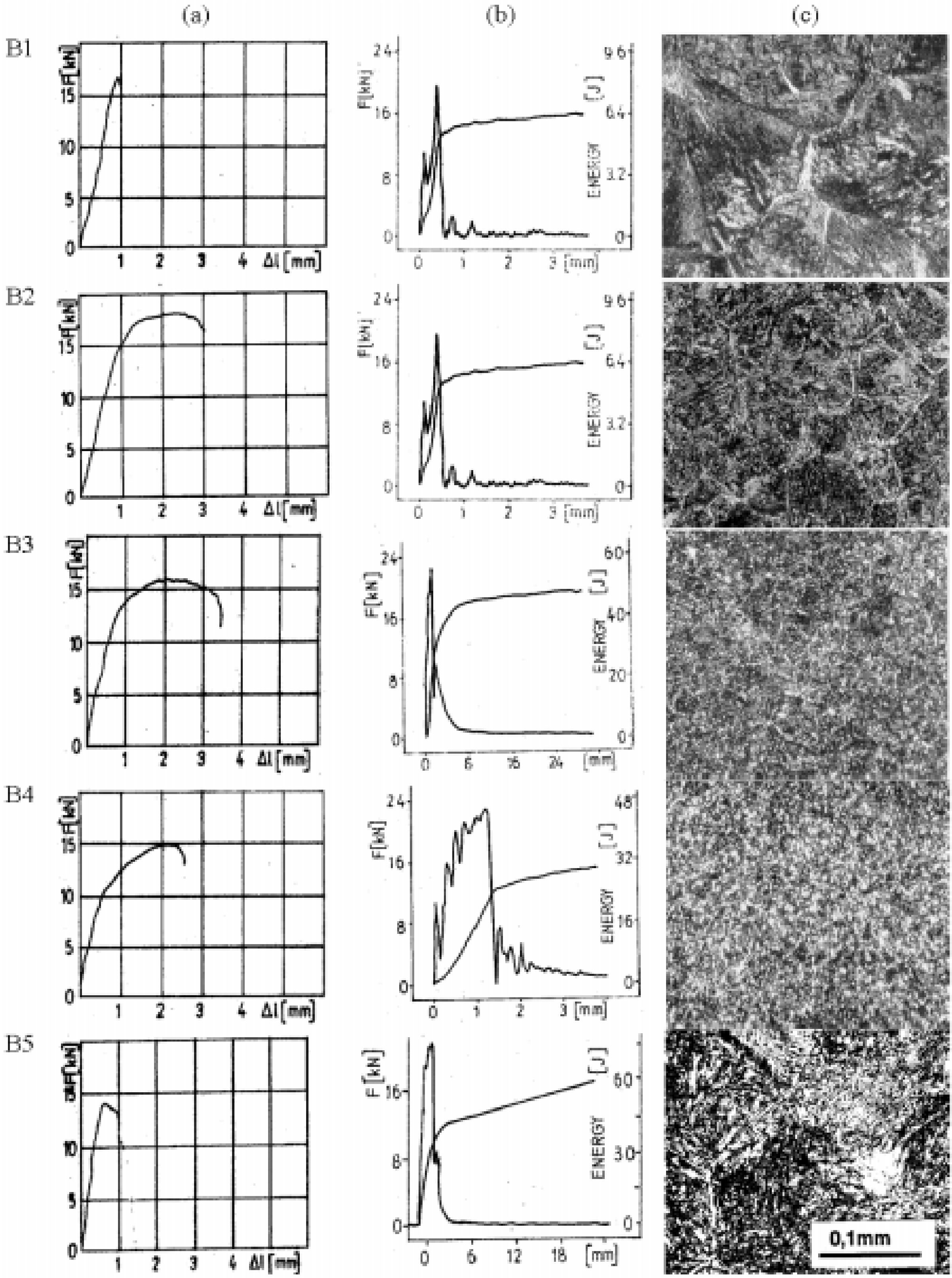

Figure 6: Dependences obtained by tensile tests and instrumented impact tests with corresponding microstructures of samples of steel B, simulated at different temperatures (B1 - 1350°C, B2 - 1100°C, B3 - 950°C, B4 - 850°C, B5 - 1350°C /750°C)
a - tensile test; b - instrumented impact test; c - microstructure

Slika 6: Odvisnosti dobljene pri razteznostnem preizkusu in instrumentiranem udarnem preizkusu in ustrezne mikrostrukture preizku{ancev jekla B dobljene s simulacijo pri razli~ni temperaturi (B1 - 1350 °C, B2 - 1100 °C, B3 - 950 °C, B4 - 850 °C, B5 - 1350°C /750°C)
a - natezni preizkus; b - instrumentirani udarni preizkus; c - mikrostruktura.

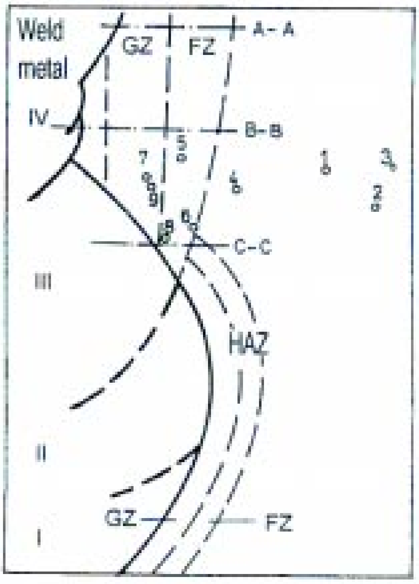

Figure 7: Crack tip locations for specimens 1 to 9 in different HAZ regions of individual welding runs (I to IV) in the welded joint of steel B (compare Table 6)

Slika 7: Polo'aj vrha razpoke za preizku{ance 1 do 9 na razli~nih mestih HAZ za posami~ne varke (I do IV) v zvaru jekla B (primerjaj Tabelo 6).

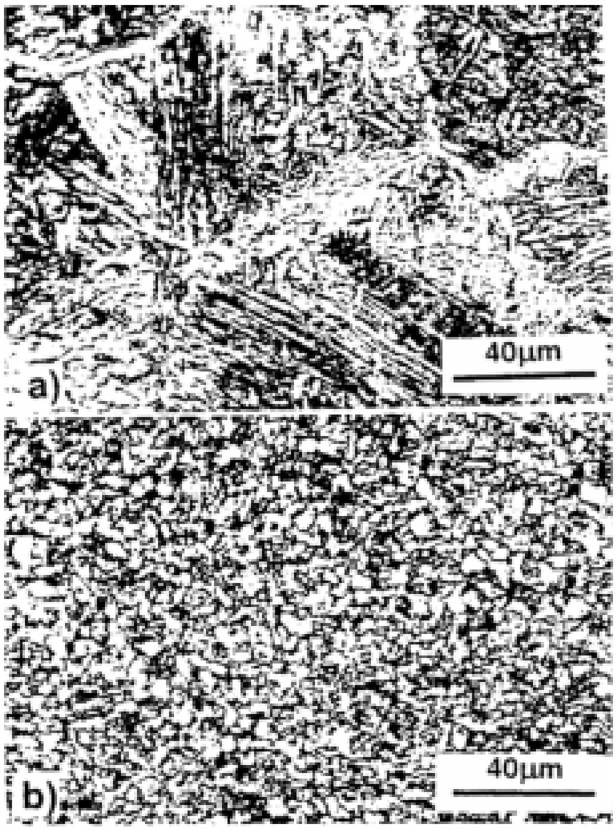

Figure 8: Microstructure of coarse grains - GZ (a) and fine grains - FZ (b) regions in cross section A-A (Fig. 7) of HAZ of steel B welded joint

Slika 8: Mikrostruktura v podro~jih iz velikih zrn - GZ in majhnih zrn - FZ na preseku A-A (sl. 7) toplotno vplivane zone zvara jekla B.

samples B1 and B2 was also confirmed in this testing by low values of crack parameters. Samples B3 and B4 exhibited better crack resistance and the beneficial effect of the second pass is recognized (samples B5, B6). However, the crack resistance of HAZ in welded joint is much better compared to that of the simulated structures at both, room temperatures and -30°C. This is explained by the beneficial effect of subsequent passes and the location of the crack tip in a more convennient microstructure (**Fig. 7**). Brittle microstructure was found also in HAZ of tested welded joint (**Fig. 8**). It was probably limited in size and its effect was small. Due to the effect of temperature gradient and of subsequent passes the overall behaviour of HAZ in welded joint can be evaluated as much better that it could be expected from the results of simulated samples testing. For a detailed analysis of HAZ behaviour, the welding simulation is not sufficient, and the analysis of HAZ in welded joint must be also performed. On the other hand, the local properties of individual regions in HAZ can be analyzed by testing of simulated samples.

The results obtained by double simulation can be evaluated as satisfactory. That means that properly defined welding technology and strictly controlled welding procedure can help to obtain welded joints of acceptable quality. In this way the effect of inconvenient microstructure in HAZ could be significantly reduced.

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