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BEHAVIOUR OF CRACKS IN MICROALLOYED STEEL WELDED JOINT
PONAŠANJE PRSLINA U ZAVARENOM SPOJU MIKROLEGIRANOG ČELIKA

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Keywords
- welded joint
- hardness
- impact energy
- fracture mechanics

Abstract

Numerous are examples of failure and damages of welded joints, despite strict codes regarding the quality. The primary causes are defects in welded structures that arise during production or in service. For safe service of structures produced of high strength steel by welding, properties of welded joints have to be determined. For welded joint constituents (parent metal PM, weld metal WM, heat-affected-zone HAZ) these properties are determined: hardness, impact energy and its parts for crack initiation and propagation, and fracture mechanics parameters, fracture toughness, K_{Ic}, and critical J integral, J_{Ic}. These parameters can help in evaluation of welded joint safety, and thus of the entire welded structure.

Ključne reči
- zavareni spoj
- tvrdoća
- energija udara
- mehanika loma

Izvod

Brojni su primeri otkaza i oštećenja zavarenih spojeva, i pored strogih propisa u pogledu kvaliteta. Uzroci su, pre svega, greške u zavarenim konstrukcijama koje nastaju tokom izrade ili u eksploataciji. Za bezbednu eksploataciju konstrukcija izrađenih od čelika visoke čvrstoće zavarivanjem, treba odrediti osobine zavarenog spoja. Za konstituente zavarenog spoja (osnovni metal PM, metal šava WM, zona uticaja toplote HAZ) određeni su tvrdoća, udarna energija i njeni delovi za inicijaciju i širenje prsline, i parametri mehanike loma, žilavost loma, K_{Ic}, i kritični J integral, J_{Ic}. Ovi parametri mogu pomoći u oceni sigurnosti zavarenog spoja, a time i zavarene konstrukcije u celini.

INTRODUCTION

It is often necessary to predict the behaviour and life of old damaged structures in service. When the data about material and welded joints are missing, the assumptions and simplifications have to be involved, /1/, and modelling applied, /2/. For steels of older generation, the safety factor applied in design and reasonable toughness have allowed proper evaluation of fracture resistance, /1/. Requirements for new developed steels are more strict, as for the here analysed low carbon low-alloyed quenched and tempered steel Niomol 490K, Acroni, Jesenice, /3/. The aim of this paper is to consider some aspects, not containing in specification, in addition to already referred data, /4-7/. Special attention is devoted to welded joints, due to their heterogeneity of structure and properties.

MATERIAL AND WELDING TECHNOLOGY

Niomol 490K steel samples are 16 mm thick. The chemical composition is given in Table 1, and mechanical properties are listed in Table 2.

Table 1. Chemical composition (%) of Niomol 490K steel.
Tabela 1. Hemijski sastav (%) čelika Niomol 490K

C	Si	Mn	P	S	Al	Cr
0.10	0.41	0.57	0.008	0.002	0.042	0.53

Table 2. Mechanical properties of Niomol 490K steel.
Tabela 2. Mehaničke osobine čelika Niomol 490K

Direction	Yield stress $R_{p0.2}$, MPa	Tensile strength R_m, MPa	Elongation A, %	Impact energy ISO-V, J
L–T	576	694	28.1	242; 248; 263
T–L	571	699	22.8	245; 248; 255

L – longitudinal direction; T – transversal direction

Following the recommendations for steel and welding consumables two welding procedures are selected: metal manual arc (MMA) welding with electrode EVB NiMo, and CO_2 gas shielded (MAG) welding with wire VAC 60 Ni. For experimental analysis the samples with symmetrical X preparation are butt welded, using both procedures.

The chemical composition of consumables is given in Table 3, and mechanical properties are given in Table 4. Welding parameters for MMA and MAG procedures are shown in Table 5.

Table 3. Chemical composition (%) of welding consumables.
Tabela 3. Hemijski sastav (%) elektrodnog materijala

Consumable	Welding	C	Si	Mn	Ni	Mo	S	P
VAC 60 Ni	MAG	0.08	0.80	1.5	1.10		<0.025	<0.025
EVB NiMo	MMA	0.06	0.45	1.15	2.5	0.40		

Table 4. Mechanical properties of electrode material.
Tabela 4. Mehaničke osobine elektrodnog materijala

Consumable	Yield stress $R_{p0.2}$, MPa	Tensile strength R_m, MPa	Elongation A, %	Impact energy ISO-V, J	
				–20°C	–40°C
EVB NiMo	>510	580-710	>22	>47	>47
VAC 60 Ni	440–510	560 –630	22-30		>47

Table 5. Parameters of welding procedures.
Tabela 5. Parametri postupaka zavarivanja

Consumable	Welding procedure	Average voltage V	Average current A	Welding rate cm/min	Heat input KJ/cm
EVB NiMo	MMA	28	300	32	15–17
VAC 60 Ni	MAG	24	180	20	12–15

TESTING OF WELDED JOINTS

Testing of welded joints is defined by JUS EN 288-3. Mechanical and technological tests are conducted to determine the following properties of PM and welded joints: strength, hardness, impact energy and crack resistance.

Hardness measurement

Hardness measurement is performed according to standards EN 1043-1 and EN 1043-2, using Vickers HV10 method. Measuring is done on Wolpert - Testor V-2, with load 100 N. Measurement positions and hardness distribution for MMA welded joint are shown in Fig. 1, and for MAG in Fig. 2. Measured hardness values are given in Table 6. The results of hardness measurements revealed differences in PM, WM and HAZ properties. Since the welded joints are over-matched, WM has the highest hardness value, corresponding to the selected electrode materials, PM hardness is slightly lower than that of WM, the lowest measured value of hardness is found in HAZ.

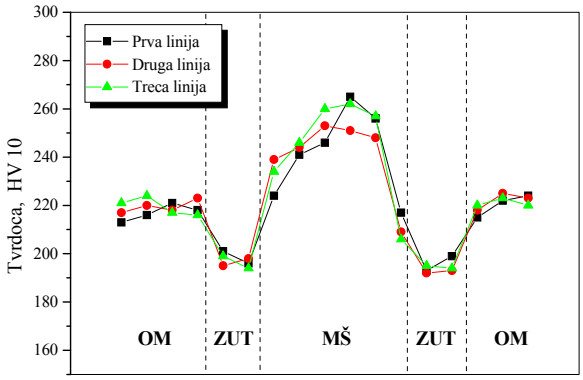

Figure 1. Hardness distribution – MMA welded joint.
Slika 1. Raspodela tvrdoće – MMA zavareni spoj

Tensile tests

Tensile testing of welded joints, defined by standard EN 895, is performed on electro-mechanical machine Wolpert Trebel RM-100, with rate 5 mm/min. Elongation is measured by Hottinger DD1.

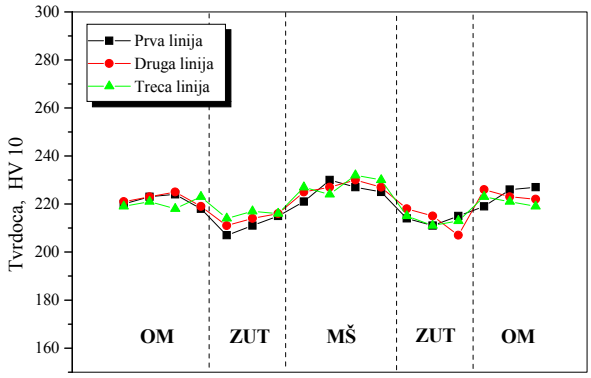

Figure 2. Hardness distribution – MAG welded joint.
Slika 2. Raspodela tvrdoće – MAG zavareni spoj

Table 6. Measured hardness values across welded joint.
Tabela 6. Izmerene vrednosti tvrdoće po preseku zavarenog spoja

Consumable	Welding procedure	Heat input KJ/cm	Hardness HV 10		
			Niomol 490K	HAZ	WM
EVB NiMo	MMA	11-15	200-225	190-200	240-265
VAC 60 Ni	MAG	15-17	200-224	200-215	195-230

The effect of welding technology on strength properties of welded joint constituents is indicated by tests with load transversal to welded joint. The obtained results (Table 7) have shown that all specimens have fractured in PM. This clearly demonstrates that welded joints are over-matched, with weld metal strength higher than that of PM.

Table 7. Results of tensile tests of welded joint specimen.
Tabela 7. Rezultati zateznog ispitivanja epruveta zavarenog spoja

Consumable	Welding procedure	Tensile strength of welded joint R_m, MPa	Fracture position
EVB NiMo	MMA	664	Parent metal
VAC 60 Ni	MAG	671	Parent metal

The results for WM specimen have shown that electrode EVB NiMo (MMA procedure) produced 5 to 15% higher strength properties compared to wire VAC 60Ni (MAG procedure), Table 8, with corresponding higher elongation of VAC 60Ni (24%), compared to EVB NiMo (21%).

Table 8. Results of tensile tests of all weld metal.
Tabela 8. Rezultati zateznog ispitivanja čistog metala šava

Consumable	Welding procedure	Yield stress $R_{p0.2}$, MPa	Tensile strength R_m, MPa	Elongation A, %
EVB NiMo	MMA	548	650	21
VAC 60 Ni	MAG	484	627	24

Table 9. The angle of guided bend testing – MMA welded joint.
Tabela 9. Ugao savijanja oko trna – MMA zavareni spoj

Sample	Weld face	Sample	Weld root	Radiogram rating
S_L - 1	120°-no crack	S_K - 1	82°-crack	2
S_L - 2	120°-no crack	S_K - 2	78°-crack	2
S_L - 3	120°-no crack	S_K - 3	87°-crack	2

Table 10. The angle of guided bend testing – MAG welded joint.
Tabela 10. Ugao savijanja oko trna – MAG zavareni spoj

Sample	Weld face	Sample	Weld root	Radiogram rating
S_L - 1	120°-no crack	S_K - 1	105°-crack	2
S_L - 2	120°-no crack	S_K - 2	97°-crack	2
S_L - 3	120°-no crack	S_K - 3	101°-crack	2

Technological tests - guided bend test

Welded butt joint guided bend test procedure is performed, according to standard EN 910, on mechanical testing machine Amsler. Defects of over 3 mm length are not allowed in any direction. Results of guided bend test are given in Tables 9 and 10. No cracks are found on weld face side for bend angle of 120°. Cracks occurred in weld root side testing, for both, MMA and MAG welded joints.

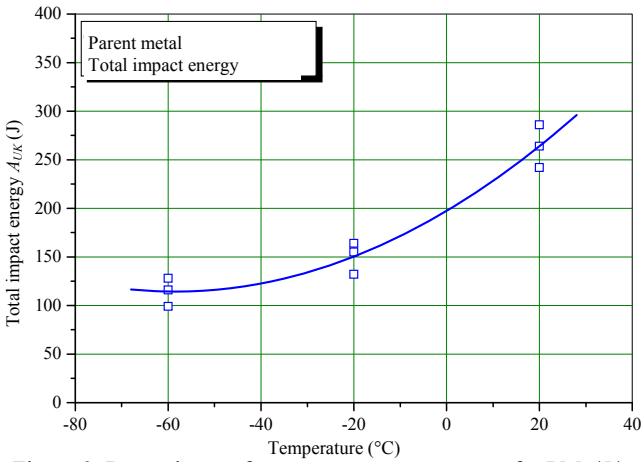

Figure 3. Dependence of A_{uk} on testing temperature for PM, /5/.
Slika 3. Zavisnost A_{uk} od temperature ispitivanja za PM, /5/

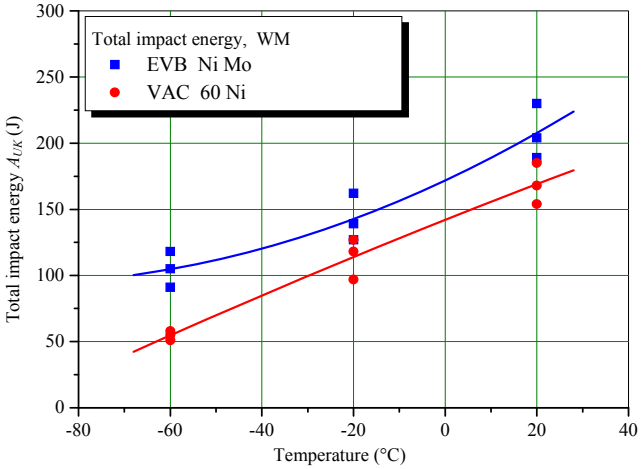

Figure 4. Dependence of A_{uk} on testing temperature for WM, /6/.
Slika 4. Zavisnost A_{uk} od temperature ispitivanja za WM, /6/

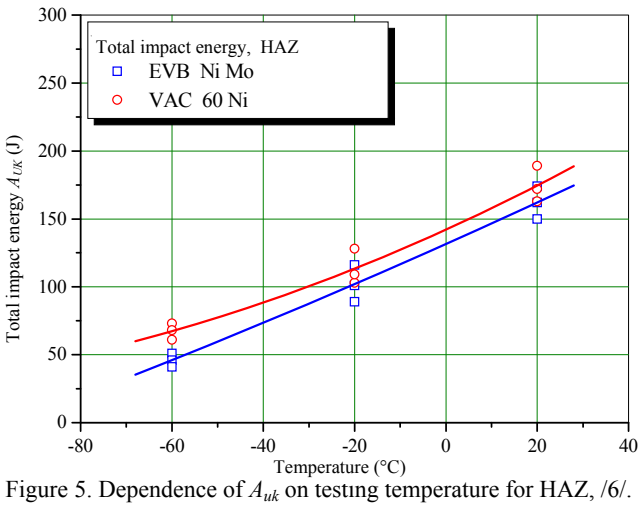

Figure 5. Dependence of A_{uk} on testing temperature for HAZ, /6/.
Slika 5. Zavisnost A_{uk} od temperature ispitivanja za HAZ, /6/

Impact testing

Impact tests are performed according to JUS EN 288-3 standard on instrumented Charpy device Wolpert 300, with V-2 notch in PM (Fig. 3), WM (Fig. 4) and HAZ (Fig. 5) of both welded joint types (MMA, MAG), measuring total impact energy, A_{UK}, at +20°C, –20°C and –60°C, /5/.

PLANE STRAIN FRACTURE TOUGHNESS K_{Ic}

Plane strain fracture toughness, K_{Ic}, is determined via critical J integral, J_{Ic}, by elastic-plastic fracture mechanics standards BS 7448, for welded joint constituents of Nionikral 490K steel with three points bending (SEB) specimens, fatigue pre-cracked in PM (I), WM (II) and HAZ (III), since the condition for thickness B according to ASTM E399 was not fulfilled, with the conversion formula:

$$K_{Ic} = \sqrt{\frac{J_{Ic} E}{1-\nu^2}} \tag{1}$$

where E is elasticity modulus and ν is Poisson's ratio.

The method of elastic compliance with successive unloading is applied. Measuring load F and crack opening displacement (COD), δ, (Figs. 6 and 7) enabled to determine critical value of J-integral, J_{Ic}, and resistance R-curve, dependence of J-integral vs. crack extension Δa (Figs. 6 and 8).

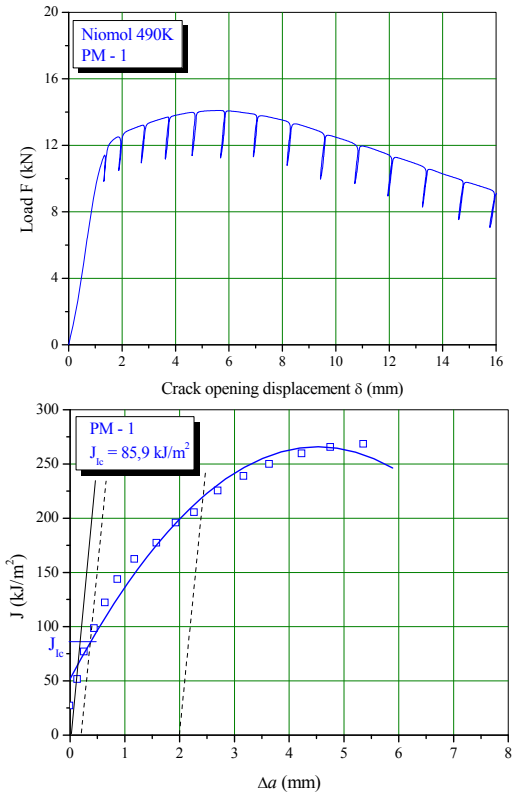

Figure 6. F–δ (top) and J–Δa (bottom) for parent metal PM-1, /6/.
Slika 6. F–δ (gore) i J–Δa (dole) za osnovni metal PM-1, /6/

Average K_{Ic} for PM is 136.6 MPa·m$^{0.5}$, typical for microalloyed steel (Table 11). For WM of EVB NiMo electrode it is 126.9 MPa·m$^{0.5}$, higher than that for VAC 60Ni wire – 114.5 MPa·m$^{0.5}$ (Table 12). The minimal values are obtained for HAZ, indicating that this constituent is critical regarding crack resistance (Table 13).

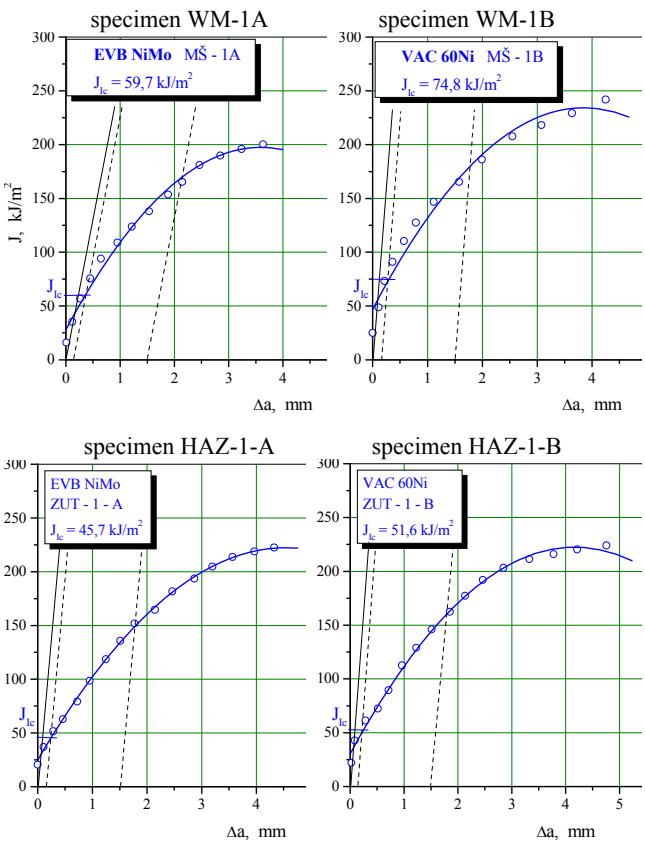

Figure 8. *J*–Δ*a* for specified specimens from welded joint.
Slika 8. *J*–Δ*a* za označene epruvete iz zavarenog spoja

Table 11. Fracture mechanics parameters for PM, /6/.
Tabela 11. Parametri mehanike loma za PM /6/

Specimen	Critical J-integral J_{Ic}, kJ/m^2	Plane strain fracture toughness K_{Ic}, MPa·m$^{0.5}$
BM-1	85,9	142.2
BM-2	79.3	135.3
BM-3	80.0	135.9

Table 12. Fracture mechanics parameters for WM, /6/.
Tabela 12. Parametri mehanike loma za WM, /6/

Specimen	Electrode	Critical J-integral, J_{Ic}, kJ/m^2	Plane strain fracture toughness, K_{Ic}, MPa·m$^{0.5}$
WM - 1A	EVB NiMo	59.7	116.2
WM - 2A		57.0	112.8
WM - 3A		61.4	117.0
WM - 1B	VAC 60Ni	74.8	128.4
WM - 2B		71.7	127.1
WM - 3B		69.5	125.1

Table 13. Fracture mechanics parameters for HAZ, /6/.
Tabela 13. Parametri mehanike loma za HAZ, /6/

Specimen	Electrode	Critical J-integral, J_{Ic}, kJ/m^2	Plane strain fracture toughness, K_{Ic}, MPa·m$^{0.5}$
HAZ-1-A	EVB NiMo	45.7	100.1
HAZ-2-A		47.3	102.5
HAZ-3-A		45.8	100.8
HAZ-1-B	VAC 60Ni	51.6	107.6
HAZ-2-B		53.9	110.7
HAZ-3-B		57.1	114.2

CONCLUSIONS

Heterogeneity of welded joint structure and mechanical properties have an important role in service safety of welded structures. For that properties of welded joint constituents (PM, WM and HAZ) have to be available in design and in-service, in order to define critical location in a component.

Useful insight can be obtained by hardness distribution: MAG welded joint has a more uniform distribution than the MMA joint, with less clear overmatching. Better toughness properties of MAG joint are demonstrated by higher resistance to cracking in guided bend test and by higher fracture toughness. Different behaviour in impact test of WM, with better values for MMA welding, can be explained by eventual deviation from welding regime parameters. It is also necessary to have in mind that location of notch or crack in toughness may have a decisive role on the results.

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