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INFLUENCE OF MECHANICAL PROPERTIES AND MICROSTRUCTURAL HETEROGENEITY OF WELDED JOINT CONSTITUENTS ON TENSILE PROPERTIES AND FRACTURE TOUGHNESS AT PLANE STRAIN, K_{IC}

UTICAJ MEHANIČKIH OSOBINA I HETEROGENOSTI MIKROSTRUKTURE KONSTITUENATA ZAVARENOG SPOJA NA OSOBINE ZATEZANJA I ŽILAVOSTI LOMA U USLOVIMA RAVNE DEFORMACIJE, K_{IC}

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Keywords
- welded joint
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Abstract

Presented in this paper is the analysis of resistance rate to brittle fracture of welded joint constituents of the HSLA Nionikral-70 steel by applying classic and new testing methods. Tensile curves, required for stress analysis and material strength properties, are constructed and fracture mechanics properties, regarding crack development resistance, are measured. Based on the testing results, analysis of the resistance to brittle fracture represents the comparison of the obtained values for the base metal, the weld metal and the heat affected zone.

Ključne reči
- zavareni spoj
- prslina
- zatezna osobine
- napon tečenja
- žilavost loma pri ravnoj deformaciji

Izvod

U ovom radu je prikazana analiza mere otpornosti na krti lom konstituenata zavarenog spoja niskolegiranog čelika povišene čvrstoće Nionikrala 70 primenom klasičnih i novijih metoda ispitivanja. Određene su krive zatezanja neophodne za naponsku analizu i karakteristike čvrstoće materijala i izmerena su svojstva mehanike loma, odnosno otpornosti na razvoj prslina. Na osnovu rezultata ispitivanja, analiza otpornosti na krti lom predstavlja poređenje dobijenih vrednosti za osnovni metal, metal šava i zonu uticaja toplote.

INTRODUCTION

The traditional tensile testing of specimens taken from welded joint gives reliable data only for maximum fracture force and tensile strength, but the elongation data are unreliable because different areas deform differently depending on the attained stress level in them. Therefore, determining the yield stress value is difficult since it can refer to weld metal or base metal depending on their strength ratio. The heat affected zone behaves differently compared to base metal and weld metal during the tensile tests, and its complex composition should also be taken into consideration. Considering different mechanical properties of welded joint areas, it is complicated to predict and interpret behaviour of the whole welded joint. Complete characterization of welded joints from the viewpoint of exploitation properties, implies overview of their behaviour in the presence of defects as well, or in other words, evaluation of their resistance towards crack initiation and propagation as the most dangerous type of defect, /1/. Fracture mechanics defines parameters and introduces new testing methods, with a cause to determine, as accurately as possible, the affinity towards crack development, critical conditions for rapid fracture development, strength of material to rapid crack propagation, or simply to evaluate material behaviour and structural safety in the presence of cracks and other related defects. A welded joint represents a nonhomogeneity by its microstructure and mechanical properties, often by form of geometry, and by stress field as well, which are all affected by different factors and by residual stress after welding. These difficulties, however, do not forbid experimental determination of fracture toughness at plane strain, K_{Ic}, in certain critical areas of the welded joint, or the whole welded joint. Instead, difficulties appear in interpreting the meaning of measured values, as is shown in this paper.

EXPERIMENT

High strength low-alloyed steel, Nionikral-70, is chosen for the base metal and welded joint behaviour tests. It is produced in an electric furnace, cast into blooms, and flat rolled to 18 mm thick slabs. Strengthening is done in combination of a standard improvement (quenching and tempering), followed by grain refinement due to adequately selected chemical composition, microalloying and appropriate deposition. The mechanical properties and chemical composition of the delivered sheet metal are given in Table

1, /1/. "ACRONI-Slovenske Železarne" Jesenice is the material supplier.

Tenacito-75, basic coated, low hydrogen electrode, with diameters of 3.25 and 4 mm, is selected for welding plates. The choice is made according to base material properties, thickness, and the chosen welding procedure /1/, according to ACRONI Jesenice catalogue recommendations. Mechanical properties and chemical composition of the chosen electrodes are given in Table 2, /1/. The welded joint is a butt 2/3 X-weld. Groove preparation is done according to standard SRPS C.T3.030.

Table 1. Mechanical properties and chemical composition (% mass) of Nionikral-70 steel.
Tabela 1. Mehaničke osobine i hemijski sastav (mas. %) čelika Nionikral-70

Batch	Testing direction	Yield strength $R_{p0,2}$ (MPa), min.	Tensile strength, R_m (MPa), min.	Dilatation, ε (%)
180079	L - T	710	770	14

C	Si	Mn	P	S	Cr	Ni	Mo	V	Al
0.10	0.20	0.23	0.009	0.018	1.24	3.10	0.29	0.05	0.08

Table 2. Mechanical properties and chemical composition (% mass) of Tenacito-75 electrode.
Tabela 2. Mehaničke osobine i hemijski sastav (mas. %) elektrode Tenacito-75

Electrode	Yield strength $R_{p0,2}$ (MPa), min	Tensile strength R_m (MPa), min.	Dilatation ε (%)	Impact energy (J)		
				–20°C	–40°C	–60°C
Tenacito-75	725	780	12	110-140	65-95	50-80

C	Mn	Si	Cr	Ni	Mo
0.06	1.45	0.25	0.55	2.0	0.35

TENSILE PROPERTIES

Material strength properties, necessary for a specific structural stress analysis are obtained by tensile tests. Due to the nature of the welded joint (WJ), it is necessary to determine tensile properties of WJ as a whole, as well as for the BM and WM properties, individually.

Tensile testing of the butt welded joint at ambient temperature, including specimen shape and dimensions as well as testing procedure is defined according to standard EN 895, /2/. The standard merely defines extension under the influence of forces perpendicular to joint direction. Only tensile strength of the tested specimen is determined in case of extension perpendicular to butt welded joint direction, and it should not be lower than base metal tensile strength. Shape and dimensions of the specimen for determining the butt welded joint tensile properties are shown in Fig. 1.

The EN 895 standard implies that BM and WM tensile properties should be determined at ambient temperature. Tensile properties are determined according to SRPS EN 10002-1, /3/, and ASTM E8 /4/. Shape and dimensions of specimens for BM and WM tensile properties determination are shown in Fig. 2.

Tensile testing of BM and WM butt welded joint specimens is performed at ambient temperature, 20°C. The tests are performed on an electro-mechanical testing machine SCHENCK TREBELL RM 400, with a range from 0 to 400 kN and elongation control, /1/.

The load rate is 5 mm/min. Elongation is registered by ultrasonic extensometer (for WJ testing specimens) and double extensometer HOTTINGER DD1 (for BM and WM specimens). Measuring accuracy of both extensometers is ±0.001 mm. The obtained results of welded joint tensile properties at ambient temperature are given in Table 3, and for BM and WM in Table 4, /1/. Tensile stress-strain curve for welded joint specimen denoted by ZS-1 is shown in Fig. 3. Tensile stress-strain curves for a specimen cut out from BM, denoted by BM-1, and a specimen denoted by WM-1, are shown in Figs. 4 and 5, respectively.

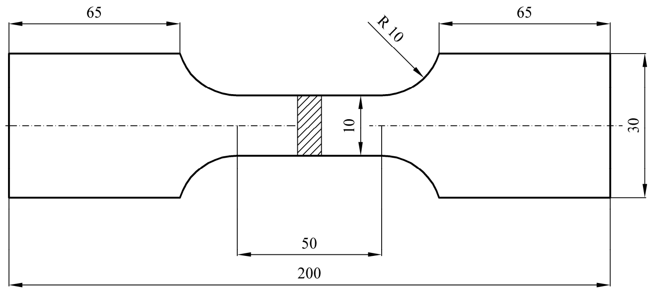

Figure 1. Specimen for determining WJ tensile properties.
Slika 1. Epruveta za određivanje zateznih osobina ZS

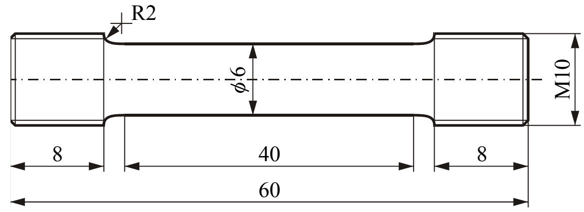

Figure 2. Spec. for determining BM and WM tensile properties.
Slika 2. Epruveta za određivanje zateznih osobina OM i MŠ

Table 3. Welded joint specimen tensile testing results.
Tabela 3. Rezultati ispitivanja zatezanjem ZS

Specimen	Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation A (%)	Ratio $R_{p0.2}/R_m$
WJ-1	727	811	19.6	0.90
WJ-2	719	798	20.4	0.90
WJ-3	723	806	18.6	0.90

Table 4. Tensile test results of BM and WM specimens.
Tabela 4. Rezultati ispitivanja zatezanjem OM i MŠ

Specimen	Yield strength $R_{p0.2}$ (MPa)	Tensile strength R_m (MPa)	Elongation ε (%)	Ratio $R_{p0.2}/R_m$
BM-1	730	824	20.8	0.89
BM-2	723	821	21.5	0.88
BM-3	727	832	20.2	0.87
WM-1	749	858	15.7	0.87
WM-2	757	864	14.7	0.88
WM-3	738	846	16.5	0.87

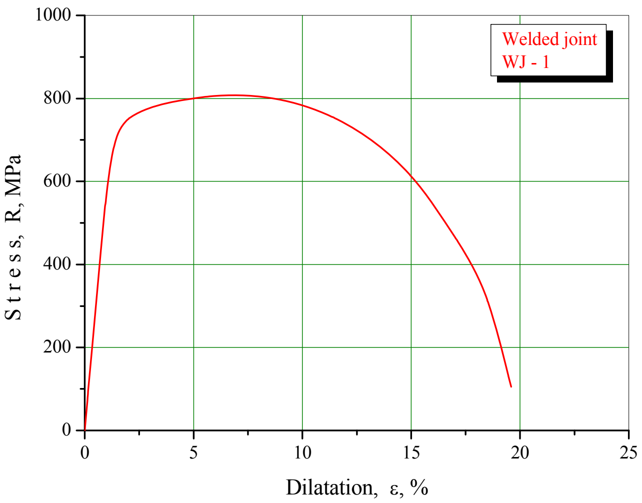

Figure 3. Stress-strain diagram for WJ specimen ZS-1.
Slika 3. Dijagram napon-deformacija za epruvetu ZS-1.

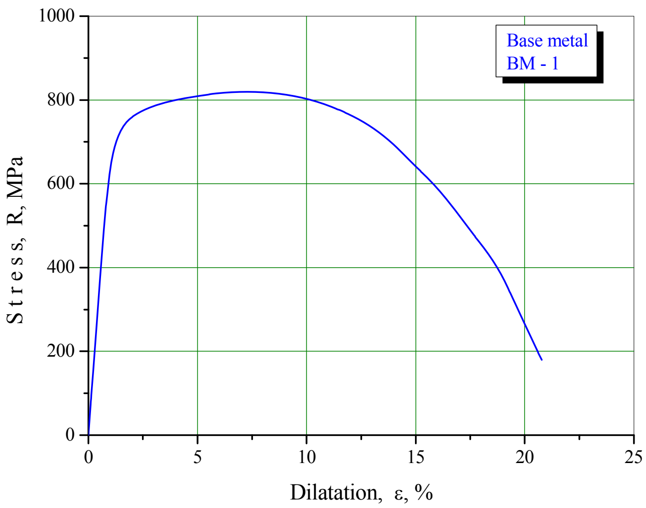

Figure 4. Stress-strain diagram for WJ specimen BM-1.
Slika 4. Dijagram napon-deformacija za epruvetu BM-1

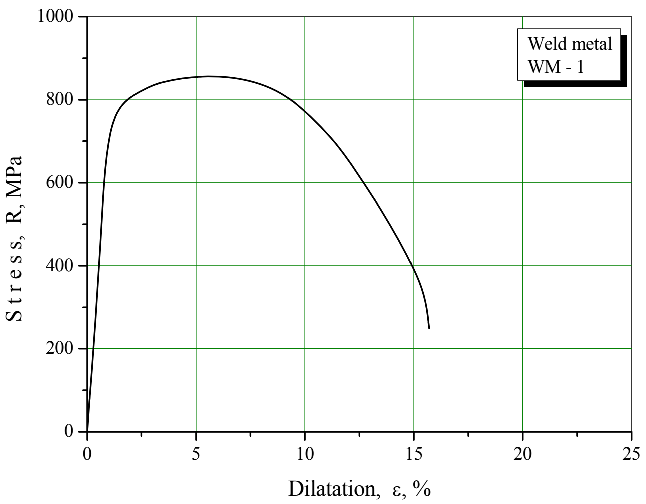

Figure 5. Stress-strain diagram for WJ specimen WM-1.
Slika 5. Dijagram napon-deformacija za epruvetu WM-1

FRACTURE TOUGHNESS K_{Ic}

Fracture mechanics testing of specimens taken from welded plates of Nionikral-70 is performed in order to determine the critical value of stress intensity factor, K_{Ic}. Three point bending specimens (SEB) are used for testing. Their geometry is defined by ASTM E399 standard and it is shown in Fig. 6, /5, 6/. The three point bending specimen has proved to be appropriate in practice, and has been used the most.

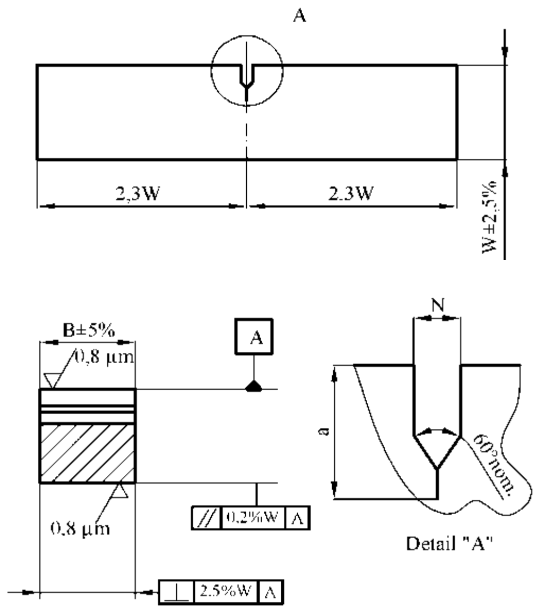

Figure 6. Fracture mechanics testing specimen.
Slika 6. Epruveta za ispitivanje mehanike loma

The testing is performed at room temperature, on the electro-mechanical testing machine SCHENCK TREBEL RM 100. The crack tip opening is registered by special extensometer KLIP-GAGE DD1, with measuring accuracy of ±0.001 mm.

Three groups of specimens are fabricated, based on the notch placement:
– specimens with a notch in the base metal;
– specimens with a notch in the weld metal;
– specimens with a notch in the heat affected zone.

Fracture toughness, K_{Ic}, is determined based on the critical value of J integral, a fracture toughness measure, J_{Ic}, by tests according to ASTM E813-89, /7/. A testing method of single specimen successive partial unload are used for J integral determination. Points on the base dependency curve are obtained from the data pair: the acting force, F, and crack tip opening, δ. Construction of the resistance curve (J-Δa) is requested by the procedure for determining the fracture toughness critical value measure, J_{Ic}, in which crack increment is determined based on the compliance alteration. F-δ and J-Δa diagrams for specimens with a notch in the base metal (BM), weld metal (WM) and heat affected zone (HAZ) are shown in Figs. 7 to 9. The influence of structural heterogeneity on the toughness properties of the welded joint components can be seen from the diagrams, /1/.

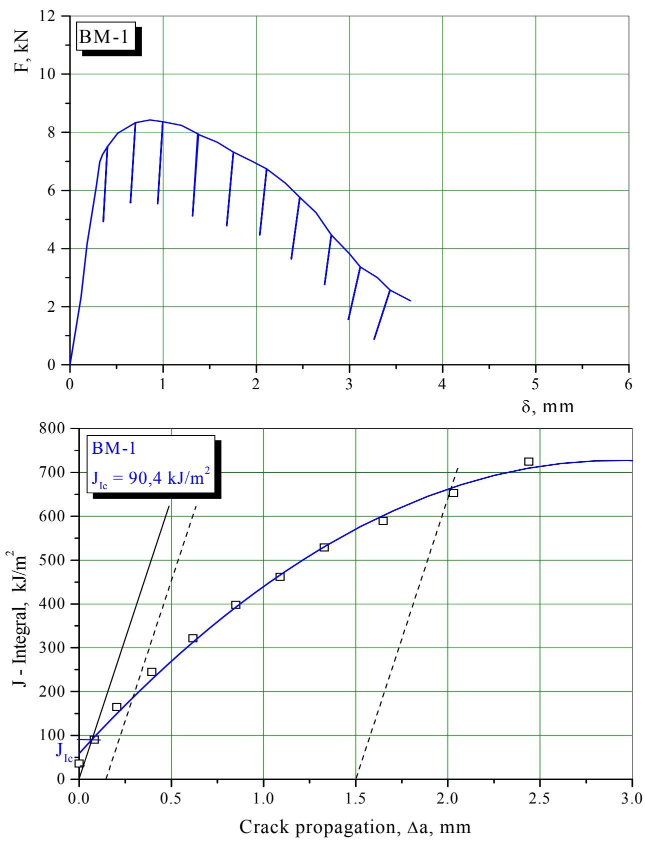

Figure 7. F-δ and J-Δa diagrams of specimen with a notch in BM
Slika 7. F-δ i J-Δa dijagrami za epruvetu sa zarezom u OM

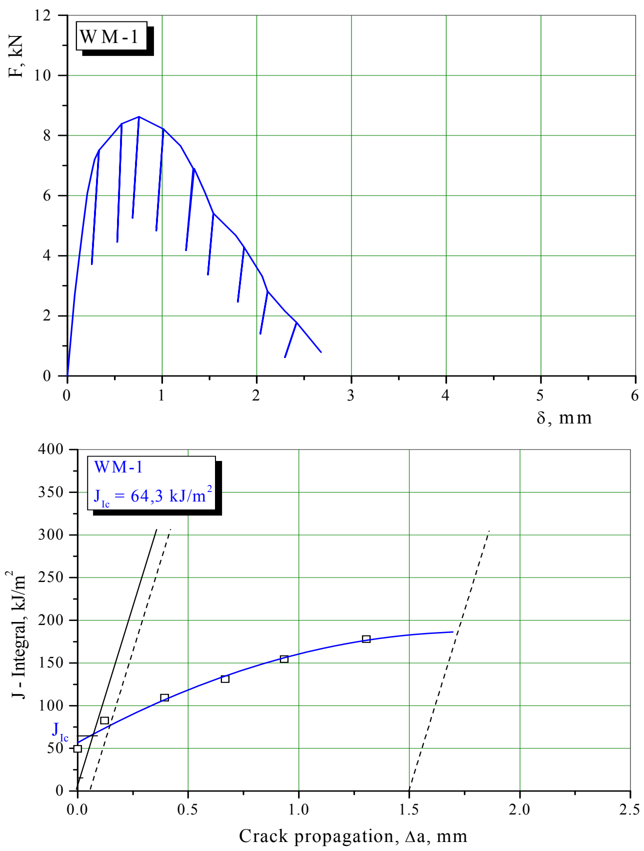

Figure 8. F-δ and J-Δa diagrams of specimen with a notch in WM
Slika 8. F-δ i J-Δa dijagrami za epruvetu sa zarezom u MŠ

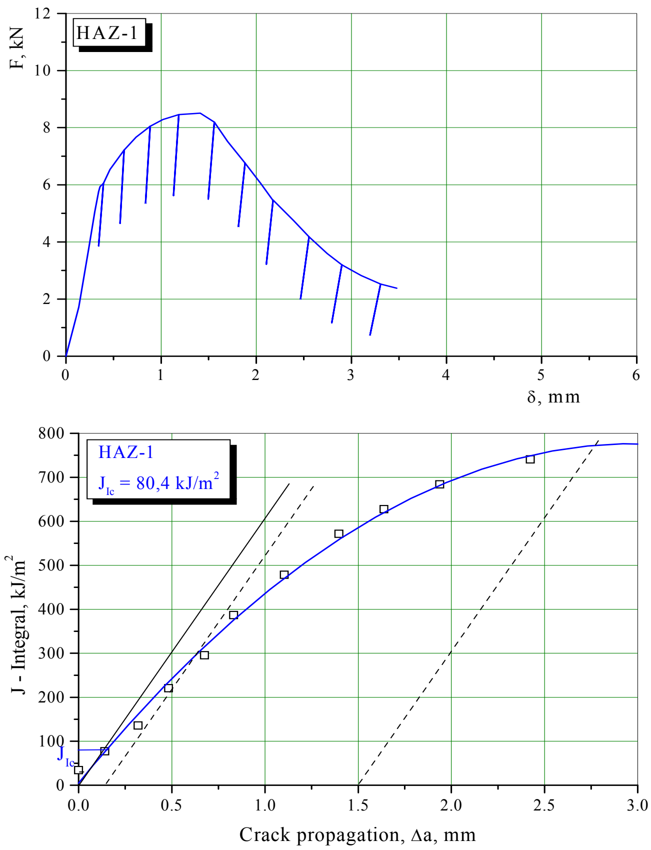

Figure 9. F-δ and J-Δa diagrams of specimen with notch in HAZ
Slika 9. F-δ i J-Δa dijagrami za epruvetu sa zarezom u ZUT

Knowing the values of critical J_{Ic} integral, the value of critical stress intensity factor or fracture toughness at plane strain, K_{Ic}, can be calculated as:

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

Calculated values of fracture toughness under plane strain conditions, K_{Ic}, are given in Table 5, /1/.

Table 5. Values of the fracture mechanics parameters J_{Ic} and K_{Ic}.
Tabela 5. Vrednosti parametara mehanike loma J_{Ic} i K_{Ic}

Specimen	Critical J integral J_{Ic} (kJ/m^2)	Critical stress intensity factor K_{Ic} (MPa·m$^{1/2}$)
BM-1	90.4	142.7
BM-2	94.3	145.8
WM-1	64.3	119.2
WM-2	61.5	116.6
HAZ-1	80.4	131.9
HAZ-2	74.9	127.3

DISCUSSION AND CONCLUSION

Based on the tensile testing results of specimens taken from the welded plate, and from specimen fracture surface analysis, it can be stated that a relatively high level of accordance is achieved between the properties of welded joint and the base metal. The ratio between the obtained values of yield- and tensile strength is from 0.87 to 0.9, which can be considered as a good result, taking into account that the strain values, at the level of values for

Nionikral-70, are achieved simultaneously, /1/. All specimens fractured in the base metal, which clearly indicates the nature of the welded joint. It is the case of *overmatching*, where the strength of welded metal is higher than the strength of the base metal, /1/.

The heterogeneity of the mechanical properties of the welded joint and its components can clearly be seen through the obtained values of fracture toughness under plane strain, K_{Ic}, which is determined indirectly by the J_{Ic} integral. Specimens with a notch in the base metal, have the highest measured value of K_{Ic}. Specimens with a notch in HAZ have slightly lower values of K_{Ic}, however in this particular case the differences are relatively small ranging between 10 to 15 MPa√m, compared to the minimal and the maximal value, /1, 8/. These differences do not have a more significant influence to structures that submitted to static loading in service. However, when it comes to conditions in which structures are submitted to constant variable loading, changes of K_{Ic} value are very significant, because critical crack length, a_c, directly depends on K_{Ic}. Nature of the curves only changes in dependence of notch position or crack initiation point. Almost identical dependence of individual curve nature in each group can be seen by analysing the obtained curves. It should be noted that the difference between specimens is only in maximum force value, which is in direct dependence with the fatigue crack length. It is noticeable that structural and mechanical heterogeneity of the welded joint has significant influence on its resistance to crack development, both in the elastic and in the plastic region, /1, 8/.

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