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ASSESSMENT OF THE PRONE TO BRITTLE FRACTURE OF A WELDED JOINT

OCJENA SKLONOSTI KA KRTOM LOMU ZAVARENOG SPOJA

Original scientific paper / Originalni naučni rad

Paper received / Rad primljen:

October 2022.

Paper accepted / Rad prihvaćen:

January 2023.

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Keywords: tensile strength, crack energy initiation, crack energy propagation

Ključne reči: zatezna čvrstoća, energija stvaranja prsline, energija širenja prsline

Abstract

Welded structures place increasing demands on the level of increased resistance to fracture. A large number of fractures of welded structures, which occur during exploitation at a stress level below of the allowable, indicates the danger of brittle fracture. The assessment of brittle fracture susceptibility was analyzed by testing Sharpy specimens, and the total impact energy, components of total impact energy (crack energy initiation and crack energy propagation) were used as parameters in the analysis.

Rezime

Zavarene konstrukcije postavljaju sve veće zahtjeve u pogledu nivoa povećane otpornosti prema lomu. Veliki broj lomova zavarenih konstrukcija, do kojih dolazi u toku eksploatacije pri nivou napona nižem od dozvoljenog, ukazuje na opasnost od pojave krtog loma. Ocjena sklonosti ka krtom lomu je analizirana ispitivanjem Sharpy epruveta, a kao parametri u analizi su korišteni ukupna energija udara, komponente ukupne energije udara (energija stvaranja i energija širenja prsline).

1. Introduction

Steel NIOMOL 490K is intended for the production of welded structures exposed to dynamic load and low temperature, which is why, in addition to sufficient strength, it must also have good toughness. The successful application of this steel depends on the degree of deterioration of the base metal properties during welding [1]. The heat affected zone (HAZ) and the weld metal (WM) can be places of reduced toughness with a transient brittleness temperature shifted to higher temperatures.

The paper was published in its original form in the Proceedings of the 32[nd] Conference with international participation "Welding 2022" held in Tara, Serbia from October 12 to 15, 2022.

The problem is how to assess the toughness in critical areas of the welded joint, i.e. in HAZ. The standard procedure for determining the impact toughness of welded joints is to test Charpy V specimens with a notch tip placed in the WM and in different areas of the HAZ. Impact energy, as an integral value in the Charpy bending test, allows comparison of different materials in terms of their response to impact load. Instrumented testing allows the separation of energy required to initiate a crack and to propagate a crack [2]. Thanks to this data, it is possible to estimate how the location of the notch affects the impact characteristics and the plasticity of the material. Also, it is possible to determine the energy required to create and the energy required to propagate the crack which allows a better understanding of the crack resistance of the test material.

2. Experiment

Steel NIOMOL 490K belongs to the group of microalloyed steels with molybdenum, yield strength min. 490 MPa and guaranteed transient brittleness temperature at -60^{0}C produced in "Železarna ACRONI" Jesenice [3]. The chemical composition of the tested steel is given in Table 1, and the basic mechanical properties in Table 2.

Table 1. *Chemical composition of the tested batch of NIOMOL 490K steel*

Tabela 1. *Hemijski sastav ispitivane šarže čelika NIOMOL 490K*

Chemical composition, mass. [%]						
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 tested steel NIOMOL 490 K*

Tabela 2. *Mehaničke osobine ispitivanog čelika NIOMOL 490 K*

Direction of examination	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

Two welding technologies were used for welding the test specimens: MMA procedure with EVB Ni Mo electrode, manufactured by ACRONI Jesenice, and MAG procedure with VAC 60 Ni wire, manufactured by ACRONI Jesenice. Electrode diameter for MAG procedure was ø1.2 mm, and for MMA procedure was ø3.25-ø4 mm. The chemical composition of the additional material is given in Table 3, and the mechanical properties in Table 4.

Table 3. *Chemical composition of filler materials in mass. [%]*

Tabela 3. *Hemijski sastav dodatnih materijala u masenim [%]*

Welding process	Filler material	C	Si	Mn	Ni	Mo	S	P
MAG	VAC 60Ni	0.08	0.80	1.5	1.10		<0.025	<0.025
MMA	EVBNiMo	0.06	0.45	1.150	2.5	0.40		

Table 4. *Mechanical properties of filler materials*

Tabela 4. *Mehanička svojstva dodatnih materijala*

Welding process	Filler material	Yield stress $R_{p0,2}$ [MPa]	Tensile strength, Rm [MPa]	Elongation A, [%]	*Impact energy, [J]*		
					20°C	-20°C	-40°C
MAG	VAC 60 Ni	440 –510	560 –630	22 - 30			> 47
MMA	EVB NiMo	>510	580-710	>22		>47	>47

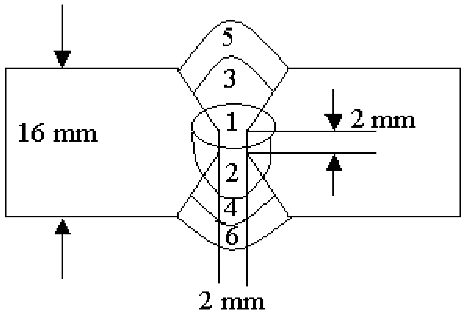


Figure 1. *Welding passes of NIOMOL 490K steel*
Slika 1. *Prolazi pri zavarivanju čelika NIOMOL 490K*

As the coefficient of thermal conductivity is important for the calculation of the thermal cycle, for the tested material it is λ = 0.38 [W / cm^{0}C], and the coefficient of thermal utilization of the heat source η = 0.6–0.7 [5]. By simulating the HAZ, the cooling time is Δt8 / 5 = 10s. Based on these data, the optimal heat input was calculated. The optimal welding parameters for the MMA and MAG process are shown in Table 5.

Table 5. *Parameters of welding processes*

Tabela 5. *Parametri postupaka zavarivanja*

Base material	Welding process	Electrode	Average voltage, [V]	Average current, [A]	Welding rate, [cm/min]	Heat input [kJ/cm]
NIOMOL 490 K	MMA	EVB Ni Mo	28	300	32	15-17
	MAG	VAC 60Ni	24	180	20	12-15

Tensile testing of butt welded joints is defined by standard EN 895: 2008 - Butt welded joints on metallic materials - transverse tensile test [6]. In addition to testing butt-welded joints by transverse and longitudinal tension, this standard also envisages testing of weld metal specimens, i.e. determination of tensile properties of weld metal.

The results of the tensile properties of the butt - welded joints of the butt - welded joint are given in Table 6, and for the tubes extracted from the weld metal are given in Table 7.

Table 6. *Results of tensile tests of welded joint specimens*

Tabela 6. *Rezultati ispitivanja zateznih osobina uzoraka zavarenih spojeva*

Welding process	Filler material	Heat input [kJ/cm]	Tensile properties	
			Welded joint, R_m, [MPa]	Place of fracture
MMA	EVB Ni Mo	15 - 17	664	Base material
MAG	VAC 60 Ni	12-15	671	Base material

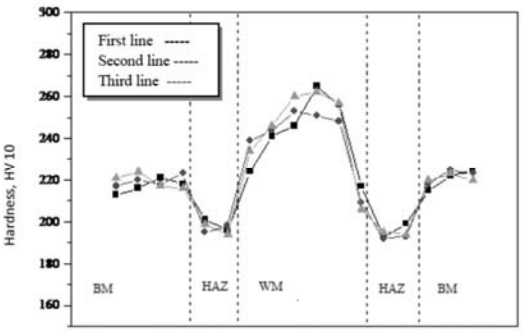
Table 7. *Results of tensile properties of weld metal specimens*

Tabela 7. *Rezultati zateznih osobina uzoraka metala šava*

Welding process	Filler material	Yield stress $R_{p0,2}$, [MPa]	Tensile strength R_m, [MPa]	Elongation A, [%]
MMA	EVB Ni Mo	548	650	21
MAG	VAC 60 Ni	484	627	24

Hardness testing was done according to standards EN 1043-1 and EN 1043-2 [7]. The Vickers method HV 10 was used. The measurement was performed on WOLPERT - V-TESTOR 2. The load was 100 N, and the magnification was 100x.

The scheme of measuring points with graphically displayed hardness values for MMA and MAG procedure is given in Figure 3, the measured hardness values are also given in Table 8.



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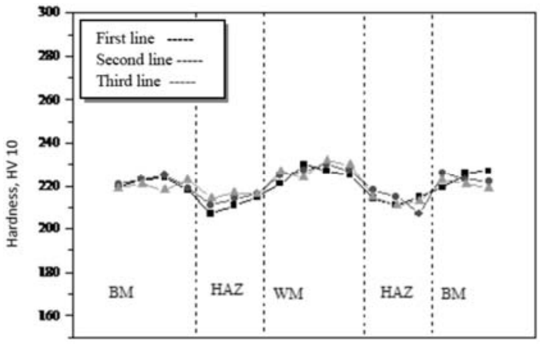

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Figure 3. *Changes of hardness values in weld cross section for: a) MMA welding process, b) MAG welding process*

Slika 3. *Promene vrednosti tvrdoće u poprečnom preseku zavarenih spojeva za: a) postupak zavarivanja - MMA, b) postupak zavarivanje - MAG*

Table 8. *Results of measured hardness*

Tabela 8. *Rezultati izmerene tvrdoće*

Base metal	Welding process	Filler material	Heat input [KJ/cm]	Hardness [HV 10]		
				BM	HAZ	WM
Niomol 490K	MMA	EVB Ni Mo	15–17	200-225	190-200	240-265
	MAG	VAC 60 Ni	11– 15	200-224	200-215	195-230

Impact tests of specimens extracted from welded plates were performed in order to determine the total impact energy (i.e., impact toughness). The test procedure itself is defined by EN 875 [8] standards, including the shape and size of the tube as well as the position of the notch V2, Figure 4. The tests were performed at room temperature, at -20^{0}C and -60^{0}C on an instrumented WOLPERT 300 J Charpy pendulum.

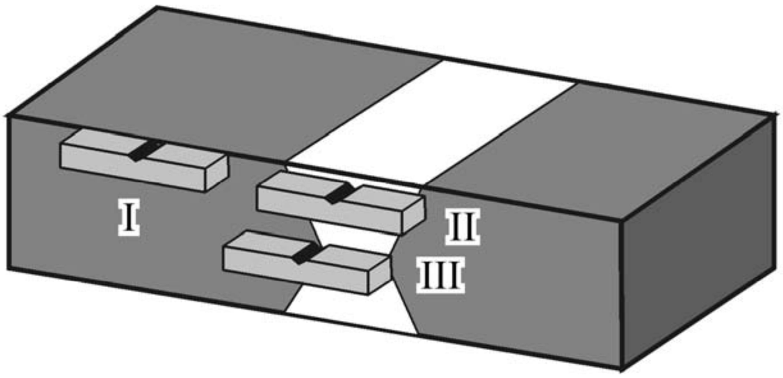

Figure 4. *Scheme of extraction of Charpy specimens from the welded joint*

Slika 4. *Šema isecanja Šarpi uzoraka iz zavarenog spoja*

The results of impact tests for notched specimens in BM are given in Table 9, for notched specimens in WM for MMA welding procedure in Table 10, for V-notched specimens in WM for MAG welding procedure in Table 11, for test specimens with V- notch in the HAZ for the MMA welding procedure in Table 12. and the V-notched specimens in the HAZ for the MAG welding procedure in Table 13.

Table 9. *Results of impact tests of V-notched specimens in BM*

Tabela 9. *Rezultati ispitivanja energije udara uzoraka sa V-zarezom u OM*

Mark specimens	Test temperature, [°C]	Total impact energy, A_{uk}, [J]	Crack initiation energy A_I, [J]	Crack propagation energy A_P, [J]
BM-1	20	264	68	196
BM-2	-20	155	60	95
BM-3	-60	116	55	59

Table 10. *Results of impact tests of V-notched specimens in WM for MMA procedure*

Tabela 10. *Rezultati ispitivanja energije udara uzoraka sa V-zarezom u MŠ za MMA proces*

Mark specimens	Test temperature, [°C]	Total impact energy, A_{uk}, [J]	Crack initiation energy A_I, [J]	Crack propagation energy A_P, [J]
WM-1	20	204	59	196
WM-2	-20	139	53	86
WM-3	-60	105	48	57

Table 11. *Results of impact tests of V-notched specimens in WM for MAG procedure*

Tabela 11. *Rezultati ispitivanja energije udara uzoraka sa V-zarezom u MŠ za MAG postupak*

Mark specimens	Test temperature, [°C]	Total impact energy, A_{uk}, [J]	Crack initiation energy A_I, [J]	Crack propagation energy A_P, [J]
WM-1	20	168	49	119
WM-2	-20	118	43	75
WM-3	-60	55	38	17

Table 12. *Results of impact tests of V-notched specimens in HAZ for MMA procedure*

Tabela 12. *Rezultati ispitivanja energije udara uzoraka sa V-zarezom u ZUTu za MMA proces*

Mark specimens	Test temperature, [°C]	Total impact energy, A_{uk}, [J]	Crack initiation energy A_I, [J]	Crack propagation energy A_P, [J]
HAZ-1	20	162	55	107
HAZ-2	-20	101	48	43
HAZ-3	-60	46	35	11

Table 13. *Results of impact tests of V-notched specimens in HAZ for MAG procedure*

Tabela 13. *Rezultati ispitivanja energije udara uzoraka sa V-zarezom u ZUT za MAG proces*

Mark specimens	Test temperature, [°C]	Total impact energy, A_{uk}, [J]	Crack initiation energy A_I, [J]	Crack propagation energy A_P, [J]
HAZ-1	20	172	58	114
HAZ-2	-20	109	51	58
HAZ-3	-60	68	44	24

The dependence of the total impact energy, Euk, on the test temperature and the notch incision site is given in the diagram in Figure 7, for the notched specimens in BM, WM and HAZ.

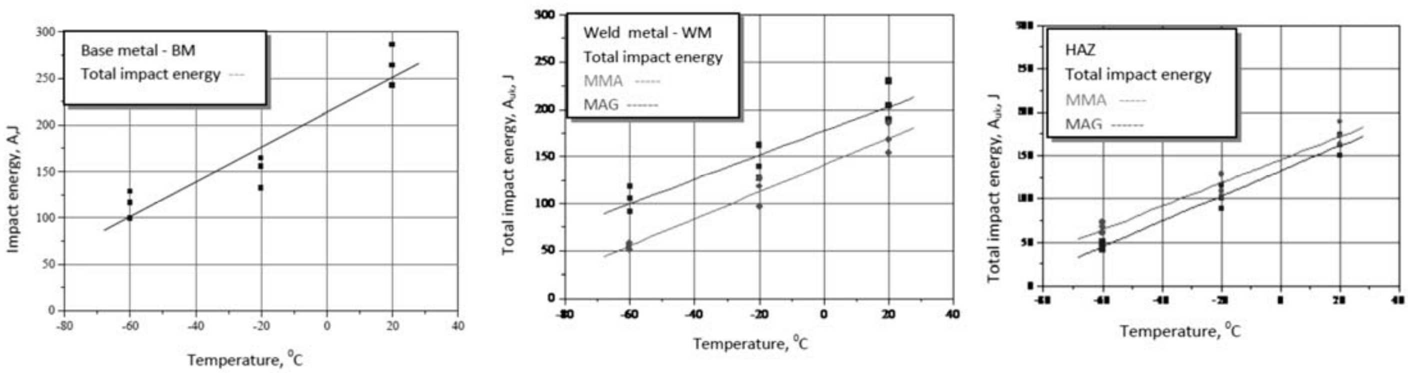

Figure 7. *Dependence of Euk on test temperature for V-notched tubes in BM, WM and HAZ*

Slika 7. *Zavisnost Euk od ispitne temperature za cevi sa V-zarezom u OM, MŠ i ZUT*

Based on the measurement of the total impact energy (impact toughness), in most cases, it is not possible to find out how the work spent on elastic and plastic deformation of the sample until the crack is formed decreases with temperature. This fundamental lack of impact toughness can to some extent be overcome by dividing the impact toughness by the crack generation energy E_I, and the crack propagation energy or fracture energy E_P.

The influence of the test temperature and the location of the V-notch on the values of the crack initiation energy E_I, and the crack propagation energy E_P are shown in the diagram, Figure 8.

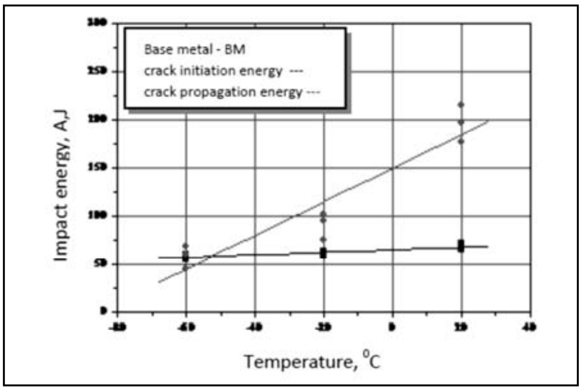

Figure 8. *Relationship of crack initiation energy, A_I, and crack propagation energy, A_P in total impact energy, Auk in the base metal*

Slika 8. *Odnos energije inicijacije prsline, A_I i energije širenja prsline, A_P u ukupnoj energiji udara, Auk u osnovnom metalu*

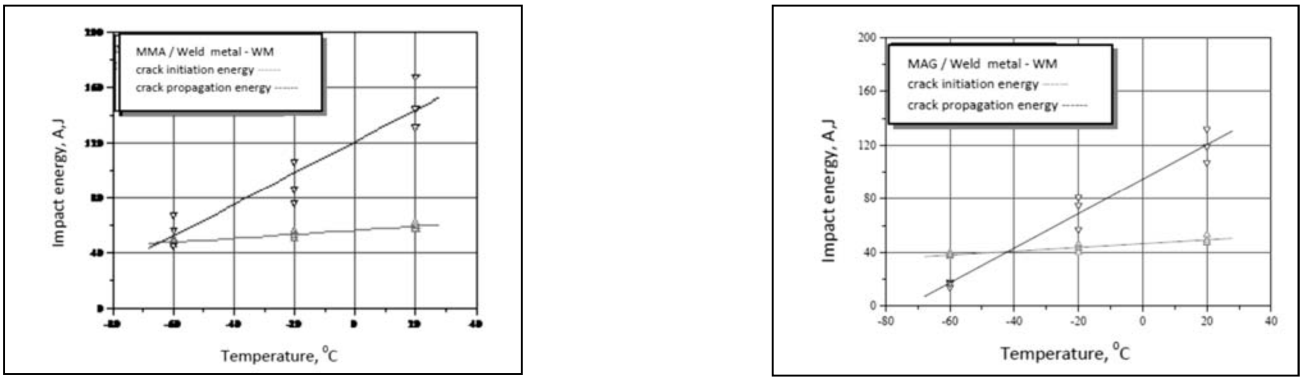

Figure 9. *Relationship of crack initiation energy, A_I, and crack propagation energy, A_P in total impact energy, Auk for weld metals for MMA and MAG welding process*

Slika 9. *Odnos energije inicijacije prsline, A_I i energije širenja prsline, A_P u ukupnoj energiji udara, A_{uk} za metale šavova za MMA i MAG procese zavarivanja*

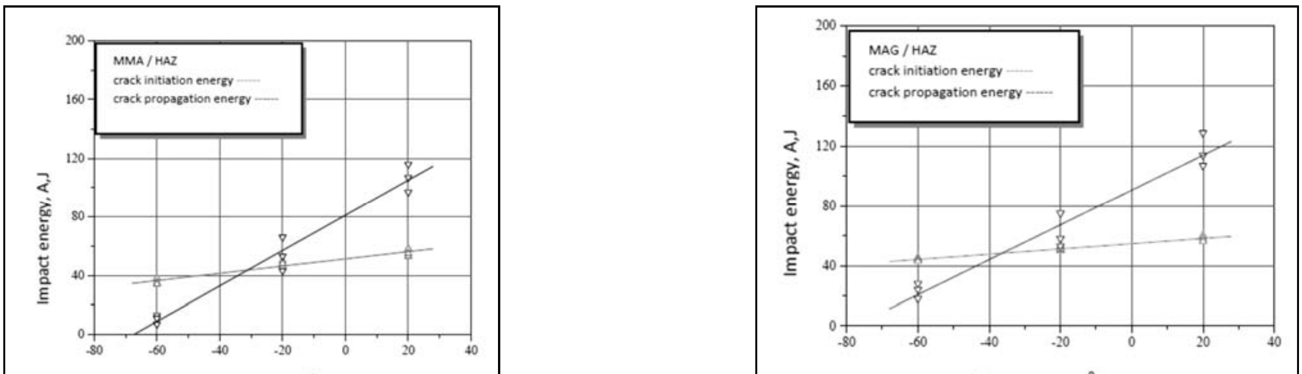

Figure 10. *Relationship of crack initiation energy, A_I, and crack propagation energy, A_P in total impact energy, Auk in HAZ for MMA and MAG welding process*

Slika 10. *Odnos energije inicijacije prsline, A_I i energije širenja prsline, A_P u ukupnoj energiji udara, Auk u ZUTu za MMA i MAG procese zavarivanja*

3. Conclusion

Based on the obtained results we can conclude:

The tensile test results of the welded joint, Table 6, indicate that all tested tubes cracked in the base material, the strength of the weld metal is higher than the strength of the base material. The obtained tensile strength values range from 664MPa for samples where the MMA welding process was used and 671MPa for samples where the MAG welding process was used.

By testing the specimens taken out of the WM, it can be seen that the test results of the test specimens in the MMA welding process are 5 to 15% better than in the test specimens of the MAG welding process. Elongation shows a slightly different dependence. Namely, it increases with the MAG procedure and amounts to 24%, compared to the MMA procedure where the obtained values are on average 21%.

The results of cross-sectional hardness measurements, Table 8, indicate different properties of BM, WM and HAZ. Weld metal, WM, has the highest value of hardness since the strength of the weld metal is higher than the strength of the base material. Slightly lower measured hardness is in BM, and HAZ has the lowest measured hardness value.

Comparing the results obtained by MMA and MAG welding process, it can be seen that the joint obtained by MAG welding process has better toughness, which shows higher resistance to cracking and higher fracture toughness.

Based on the results of impact tests, Tables 9 - 13, it can be conclude that the heterogeneity of the structure accompanied by different mechanical properties of individual areas of the welded joint affects the values of the total impact energy. This especially refers to the obtained values of the total impact energy in the HAZ, which are about 8 to 12% lower than the obtained values for BM and WM. These differences are also related to the chosen welding technology. Namely, slightly higher value of the total impact energy has V-notched tubes in WM and HAZ in MMA procedure compared to MAG welding process.

The greatest influence on the values of the total impact energy, as well as on the components, energy of crack formation and crack propagation energy, then, on the fracture mechanism and the appearance of fracture surfaces has the test temperature, because it is closely related to plastic properties of the tested material. The decrease in temperature favours the formation of a brittle state and is particularly pronounced in this type of steel and welded joint as a typical heterogeneous structure. The total impact energy, Euk decreases with decreasing test temperature successively from room temperature to -60 ^{0}C in all groups of specimens (WM, HAZ, BM). The influence of the test temperature is greatest in V-notched specimens in WM, because the heterogeneity of the structure is greatest here.

3. Zaključak

Na osnovu dobijenih rezultata možemo zaključiti:

Rezultati ispitivanja zatezanja zavarenog spoja, tabela 6, pokazuju da su sve ispitivane cevi napukle u osnovnom materijalu, čvrstoća metala šava je veća od čvrstoće osnovnog materijala. Dobijene vrednosti zatezne čvrstoće se kreću od 664MPa za uzorke gde je korišćen MMA proces zavarivanja, i 671MPa za uzorke gde je korišćen MAG proces zavarivanja.

Ispitivanjem uzoraka izvađenih iz MŠ-a može se videti da su rezultati ispitivanja uzoraka u procesu MMA zavarivanja za 5 do 15% bolji u odnosu na ispitne primerke MAG procesa zavarivanja. Izduženje pokazuje nešto drugačiju zavisnost. Naime, raste kod MAG procesom i iznosi 24%, u poređenju sa MMA procesom gde su dobijene vrednosti u proseku 21%.

Rezultati merenja tvrdoće poprečnog preseka, tabela 8, ukazuju na različita svojstva OM, MŠ i ZUTa. Metal šava, MŠ, ima najveću vrednost tvrdoće jer je čvrstoća metala šava veća od čvrstoće osnovnog materijala. Nešto niža izmerena tvrdoća je u OM, a ZUT ima najmanju izmerenu vrednost tvrdoće.

Upoređujući rezultate dobijene MMA i MAG postupkom zavarivanja, vidi se da spoj dobijen MAG postupkom ima bolju žilavost, što pokazuje veću otpornost na pucanje i veću žilavost loma.

Na osnovu rezultata ispitivanja energije udara, tabele 9 - 13, može se zaključiti da heterogenost konstrukcije praćena različitim mehaničkim svojstvima pojedinih područja zavarenog spoja, utiče na vrednosti ukupne energije udara. Ovo se posebno odnosi na dobijene vrednosti ukupne energije udara u ZUTu, koje su za oko 8 do 12% niže od dobijenih vrednosti za OM i MŠ. Ove razlike se odnose i na izabranu tehnologiju zavarivanja. Naime, nešto veću vrednost ukupne energije udara imaju cevi sa V-zarezom u MŠ i ZUTu kod MMA procesa u odnosu na MAG proces zavarivanja.

Najveći uticaj na vrednosti ukupne energije udara, kao i na komponente, energiju nastanka prsline i energiju širenja prsline, zatim na mehanizam loma i izgled površina loma ima temperatura ispitivanja, jer je usko povezana sa plastičnim svojstvima ispitivanog materijala.

Smanjenje temperature pogoduje formiranju krtog stanja i posebno je izraženo kod ovog tipa čelika i zavarenog spoja kao tipične heterogene strukture. Ukupna energija udara, Euk, opada sa opadanjem ispitne temperature sukcesivno od sobne temperature do -60^0C u svim grupama uzoraka (OM, ZUT, MŠ). Uticaj ispitne temperature je najveći kod uzoraka sa V-zarezom u MŠ, jer je heterogenost strukture najveća ovde.

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