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SADRŽAJ / CONTENTS

Edin Džiho[1,a], Sead Pašić [1,b]

INFLUENCE OF WELDING PARAMETERS ON MECHANICAL PROPERTIES OF WELDED JOINT AT CAPACITY DISCHARGE WELDING PROCESS

UTICAJ PARAMETARA ZAVRIVANJA NA MEHANIČKE OSOBINE ZAVARENIH SPOJEVA KOD PERKUSIONOG KONDENZATORSKOG ZAVARIVANJA

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Keywords: Percussion welding, welding parameters, mechanical properties of welded joint

Ključne reči: Perkusiono kondenzatorsko zavarivanje, parametri zavarivanja, mehaničke osobine zavarenih spojeva

Abstract

Capacity discharge percussion welding is nonconventional welding process where heat source is an electric arc obtained by discharging of capacitor bank. The arching time is very short, around 10 ms, and depends on a few parameters such as: capacity of capacitor bank, voltage, movement speed of welded pieces during welding. During arching a certain amount of material is melted and after that squeezed out by applied force used in welding process. Quantity of squeezed material depends upon heat input, intensity of the force pressing the wires during welding and many other parameters. Mechanical properties of welded joints depend on welding parameters. In this paper is described the influence of capacity discharge percussion welding parameters on mechanical properties of welded joints.

Rezime

Perkusiono kondenzatorsko zavarivanje je nekonvencionalni postupak zavarivanja koji kao izvor toplote koristi električni luk dobijen pražnjenjem kondenzatorske baterije. Vrijeme gorenja električnog luka je dosta kratko, reda oko 10 ms i zavisi od više parametara, u prvom redu kapaciteta kondenzatorske banke, napona do kojeg su napunjeni kondenzatori, brzine primicanja komada koji se međusobno zavaruju. Za vrijeme procesa gorenja električnog luka se topi određena količina metala koja nakon toga biva istisnuta pod dejstvom sile kojom se pritiskuju žice u toku zavarivanja. Količina istisnutog metala zavisi od unosa toplote, intenziteta pritiskivanja žica u toku zavarivanja, kao i drugih parametara. Mehaničke osobine također zavise od parametara zavarivanja. U ovom radu je opisan uticaj parametara zavarivanja na mehaničke osobine zavarenih spojeva kod kondenzatorskog perkusionog zavarivanja.

The paper was published in its original form in the Proceedings of the 31st Conference with international participation "Welding 2020" held in Kladovo, Serbia from 13 to 16 October 2021

1. Introduction

All welding processes that use capacitor capacity as an energy source are considered capacitor discharge welding processes. There are a number of these processes, however, the most common are capacitor discharge percussion welding - CDPW, CD stud welding and capacitor discharge welding. [1]

Capacitor discharge percussion welding is a butt welding method of the metal pieces under the influence of a mechanical load applied during or immediately after an electric arc burning. The arc is obtained by discharging the energy previously stored to the capacitors in order to melt the connecting surfaces. [2]

A main characteristic of a capacitor discharge percussion welding compared to other capacitor discharge welding processes is a creation of the joints in solid phase during mutual moving of the pieces to be joined. This moving causes collisions of work pieces at the end of the process and provides a relatively constant electric arc. [1, 2]

There are several parameters on which welding process depends, but as main influencing parameters are determined:

- charging voltage of capacitors bank,
- capacity of capacitors bank,
- intensity of a pressing force of the wires during welding,
- velocity of the wires during welding.

Thus, by discharging the capacitor bank, a short term electric arc is generated and melts a certain amount of metal. After that, the pieces are mutually joined with certain force. This is the main reason why this process is commonly used for joining wires and similar shape products of small dimensions. In this paper were used the wires made of austenitic steel and the influence on welding parameters related to a mechanical properties of a welded joint was analysed.

2. Experimental procedure

In the experimental part of this paper the main goal was to show the influence of welding parameters on mechanical properties of the welded joint. The idea was to choose the optimal parameters in order to get the welded joints with the best mechanical properties as well as the best geometry. All the above mentioned was planned to be achieved by varying a heat input, a force pressuring a pieces during welding and electric arc burning time. A heat input was varied in two ways. First way was to change voltage of capacitor bank and the other was to change capacity of capacitor bank. Varying of the time of burning of the electric arc was being done by changing the velocity of the approaching of the wires during welding, among other parameters. The velocity was being changed by changing duration of the step on stepper motor which was used for approaching of the wires during welding. The experiment was executed with two different diameters of wires, 1,0 mm and 1,6 mm.

The samples used for welding were made of austenitic steel CrNi19-9, which chemical composition is given in the table 1.

Table 1. *Chemical composition of parent material*

Tabela 1. *Hemijski sastav osnovnog materijala*

Material grade acc. DIN	C_{max} [%]	Si [%]	Mn [%]	Cr [%]	Ni [%]	Fe [%]
ER 308LSi	0,03	0,88	1,0-2,5	19,0-22,0	9,0-11,0	rest

In order to get a repeatability of the results, all the samples were prepared in same way. A front surface of one wire was flat, and the same surface of another wire was conically processed under the angle of approximately 60 degrees, figure 1.

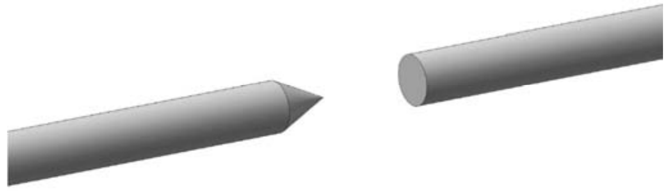


Figure 1. *Welded joint preparation [4]*

Slika 1. *Priprema zavarenog spoja [4]*

This way of preparing samples geometry is chosen because of very small diameters, which means that the standard preparations, given by ISO, would be very difficult to execute. Before the main experiment, a preliminary one was executed with a goal to determine the boundaries of the parameters.

Knowing the nature of the welding process it was decided to vary the parameters on three levels inside the established boundaries. It was decided to base the experiment on Taguchi's robust method in order to minimize the number of the samples. Based on the number of parameters or factors and the number of levels on which parameters were planned to vary, using this method there were available L9 and L27 matrices. An L9 matrix was chosen for this experiment with four factors on three levels.

Through preliminary experiment for 1,0 mm diameter wire it was determined that the values of the parameters should be inside the boundaries given in table 2. All other parameters were taken as unchangeable, the polarity was taken in a way that the flat wire was connected to a positive pole, total displacement of the jaws was limited to 10 iterations of stepper motor, the welding was executed in argon protection atmosphere. With these parameters filled in an orthogonal matrix, the design of the experiment is generated as shown in table 2.

Table 2. *Design of experiment for 1,0 mm wire [4]*

Tabela 2. *Parametri procesa za eksperimente za žicu od 1,0 mm [4]*

Exp. No.	Voltage [V]	Capacity [mF]	Force [N]	Speed [mm/s]
M1	45	8,8	4,7	16,3
M2	45	13,2	5,7	13,1
M3	45	17,6	6,7	9,8
M4	60	8,8	5,7	9,8
M5	60	13,2	6,7	16,3
M6	60	17,6	4,7	13,1
M7	90	8,8	6,7	13,1
M8	90	13,2	4,7	9,8
M9	90	17,6	5,7	16,3

Using the same principle, the procedure was implemented for 1,6 mm diameter wire. Because of higher diameter wire, higher heat input was needed. Based on this, the design of the experiment was executed as given in table 3.

Table 3. *Design of experiment for 1,6 mm wire [4]*

Tabela 3. *Parametri procesa za eksperimente za žicu od 1,6 mm [4]*

Exp. No.	Voltage [V]	Capacity [mF]	Force [N]	Speed [mm/s]
V1	70	17,6	6,2	16,3
V2	70	22,0	6,7	13,1
V3	70	26,4	7,3	9,8
V4	80	17,6	6,7	9,8
V5	80	22,0	7,3	16,3
V6	80	26,4	6,2	7,3
V7	90	17,6	6,2	13,1
V8	90	22,0	6,7	9,8
V9	90	26,4	7,3	16,3

The experimental samples were being welded following the design of experiment with three repetitions. The heat input was being changed by changing the capacity, hence alternate switching of different number of capacitors as well as by changing the voltage of capacitor bank. The shape of a current impulse as well as the voltage during welding was recorded on computer so it was possible to follow the value of current and the welding process duration.

After the welding, the samples were photographed with a suitable magnification to evaluate the joint geometry. After that, the examination of tensile strength was executed. Considering specimens dimensions, and fact that expected failure is at HAZ, only reasonable parameter of mechanical properties for analysis was tensile strength. Tensile testing was done on hydraulic tensile testing machine HMT.50.EM, which has maximum force of 50 kN. Beside of tensile strength of material at one sample from each parameter set was measured hardness.

In tensile strength rating, as main parameter average tensile strength was primary parameter, and as STDEV was rated as second criteria. Reason for this doubled rating is because of consideration that samples with huge amount of squeezed melted material will have higher tensile strength. Results of tensile testing are given at table 3. for 1,0 mm wires diameter and table 4. for 1,6 mm wire diameter.

***Table 4** Experiment results of 1,0 mm wire [4]*

***Tabela 4.** Rezultati eksperimenta sa žicom od 1,0 mm [4]*

Parameter set	Tensile strength [MPa]				
	Specimen			Average	STDEV
	1	2	3		
M1	793,2	743,5	721,9	752,9	50,8
M2	910,3	842,8	817,4	856,9	66,8
M3	786,8	611,1	663,3	687,1	125,4
M4	623,8	693,9	713,0	676,9	65,2
M5	761,4	827,6	567,8	718,9	187,7
M6	942,2	552,3	928,0	807,5	307,5
M7	873,1	819,9	783,0	825,4	63,0
M8	766,8	804,6	962,4	844,6	144,2
M9	891,2	929,2	896,3	905,6	28,6

***Table 5.** Experiment results of 1,6 mm wire [4]*

***Tabela 5.** Rezultati eksperimenta sa žicom od 1,6 mm [4]*

Parameter set	Tensile strength [MPa]				
	Specimen			Average	STDEV
	1	2	3		
V1	655,5	678,9	306,9	547,1	416,6
V2	596,8	596,8	711,2	634,9	132,0
V3	661,4	603,7	714,2	659,8	110,4
V4	675,4	648,0	504,8	609,4	183,2
V5	0,00	0,0	0,0	0	0
V6	531,5	707,2	690,3	643,0	193,8
V7	686,3	709,7	742,5	712,8	56,4
V8	628,1	603,7	674,9	635,6	72,2
V9	763,9	721,1	596,8	693,9	173,6

Form those data can be seen that samples with M9 set of welding parameters have the best average tensile strength and smallest STDEV at the same time for 1,0 mm wire diameter. For 1,6 mm wire diameter the best average tensile strength and smallest STDEV value is at V7 set of welding parameters. As the input parameter for Taguchi's analysis is taken a mean value for each set of experimental samples. Taguchi's analysis showed that the voltage is the most influential factor in both the mean values, the signal-to-noise ratio, as well as in standard deviations, table 6.

***Table 6.** Response table for 1,0 mm wire [4]*

***Tabela 6.** Tabela odgovora za žicu od 1,0 mm [4]*

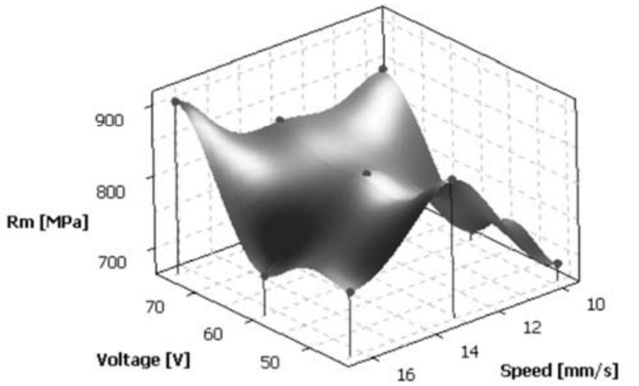
Response Table for Signal to Noise Ratios Larger is better				
Level	Voltage	Capacity	Force	Speed
1	52,45	51,21	51,78	52,17
2	53,53	52,77	52,19	53,10
3	50,49	52,48	52,49	51,19
Delta	3,04	1,57	0,72	1,91
Rank	1	3	4	2
Response Table for Means				
Level	Voltage	Capacity	Force	Speed
1	429,4	365,3	412,2	430,7
2	507,3	469,5	417,2	474,7
3	337,5	439,4	444,7	368,8
Delta	169,8	104,1	32,5	105,8
Rank	1	3	4	2
Response Table for Standard Deviations				
Level	Voltage	Capacity	Force	Speed
1	49,64	23,20	70,77	72,45
2	110,88	98,56	43,89	76,25
3	25,43	64,18	71,28	37,25
Delta	85,46	75,36	27,38	39,00
Rank	1	2	4	3

The second most influential factor in the mean values and the signal-to-noise ratio is the speed of the wire approaching during welding, i.e. the duration of arc burning. By standard deviation, this parameter is only in third place. After that, the capacity of the capacitor bank is the third most influential factor, while at standard deviations the capacity of the capacitor bank is the second most influential factor. And finally, all analyzes showed that force is on the last place.

3. Results and disscusion

The influence of several welding parameters on the average value of tensile strength was analyzed, and since it is a very complex process, the dependence on combinations of certain parameters is shown. In Taguchi's analysis, voltage proved to be the most influential factor. Since, in the expression for the energy on the capacitor, the voltage has a square potency, unlike other parameters, the voltage, with a small error, can be considered as the heat input.

As shown in Figure 5, the average value of the tensile strength of the welded joint increases with increasing voltage, i.e. heat input. At the same time, the influence of the wire approach speed, as well as the force intensity, cannot be clearly related.



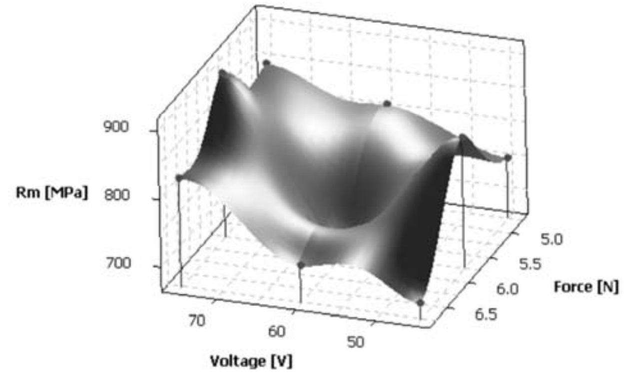
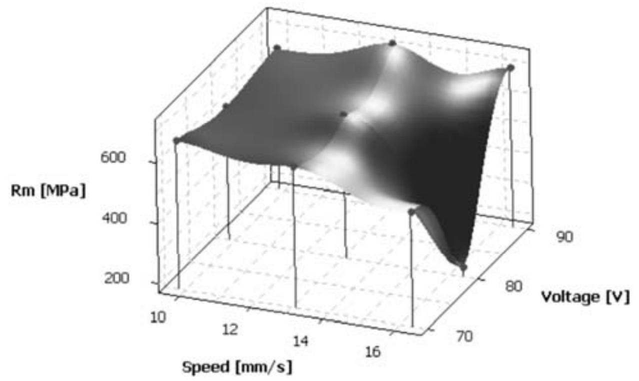


Figure 5. *Dependence of tensile strength on welding parameters for 1,0 mm wire [4]*

Slika 5. *Zavisnost zatezne čvrstoće od parametara zavarivanja žice od 1,0 mm [4]*

In general, the best result is for the medium wire approach speed, except for the maximum voltage. Impact of force pressing wires in combination with voltage is quite complex analyzed. The best results were achieved in combination of extreme values of those parameters.



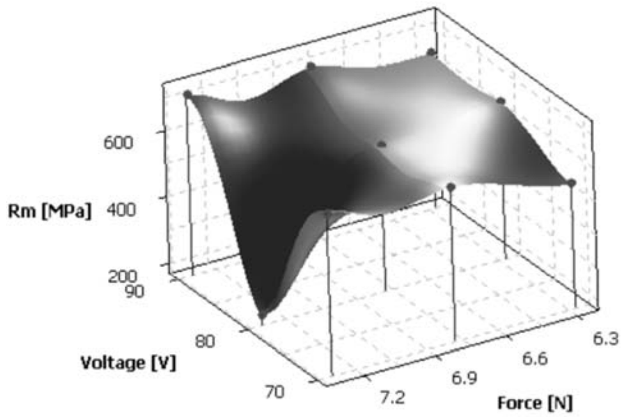


Figure 6. *Dependence of tensile strength on welding parameters for 1,6 mm wire [4]*

Slika 6. *Zavisnost zatezne čvrstoće od parametara zavarivanja žice od 1,6 mm [4]*

At 1,6 mm diameter wires can be concluded that increasing heat results with higher tensile strength. At the same time, in combination with other parameters, increasing approaching speed of wires results with better tensile strength values, as well as increasing force pressing wires during welding. In both cases maximum values of these parameters in combination with mean value of voltage have the worst result.

Analysing the dependence of tensile strength from the combination of force and velocity, at both wire diameters, it can be observed that the best results are in the combination of the mean values of these parameters. By analysing the extremes, it can be concluded that combinations of higher force and lower speed and vice versa give a better result.

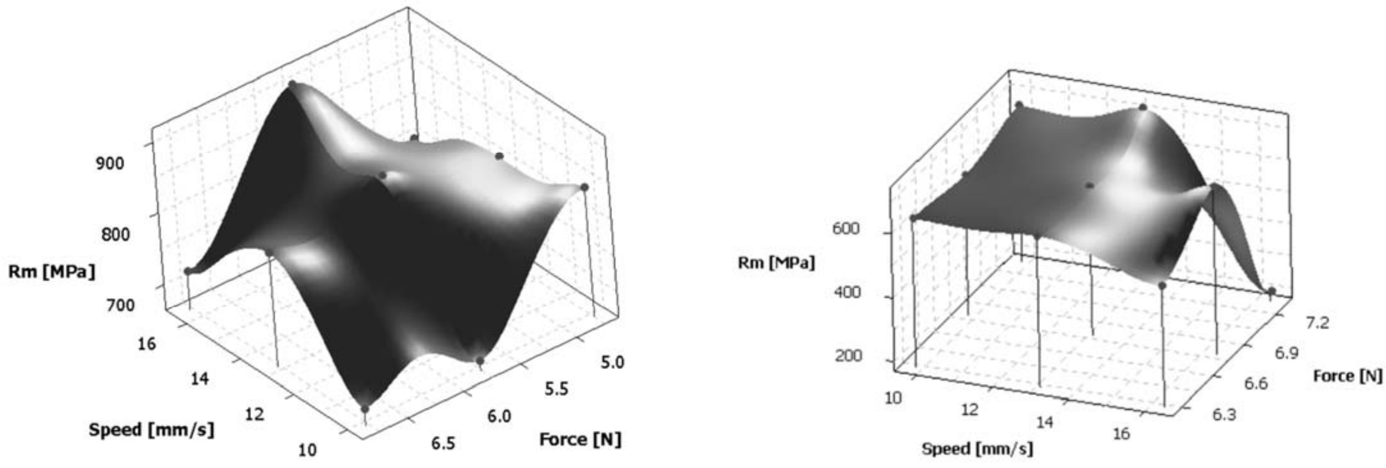


Figure 7. *Dependence of tensile strength on welding parameters for 1,0 mm and 1,6 mm wires [4]*

Slika 7. *Zavisnost zatezne čvrstoće od parametara zavarivanja za žice od 1,0 mm i 1,6 mm [4]*

Based on Taguchi analyses for both wire diameters optimal parameters were determined, and samples were welded using those parameters. Those samples justified expectations. Beside of the tensile strength, on three parameter sets samples hardness HV1 was measured. Measured values are shown on figure 8.

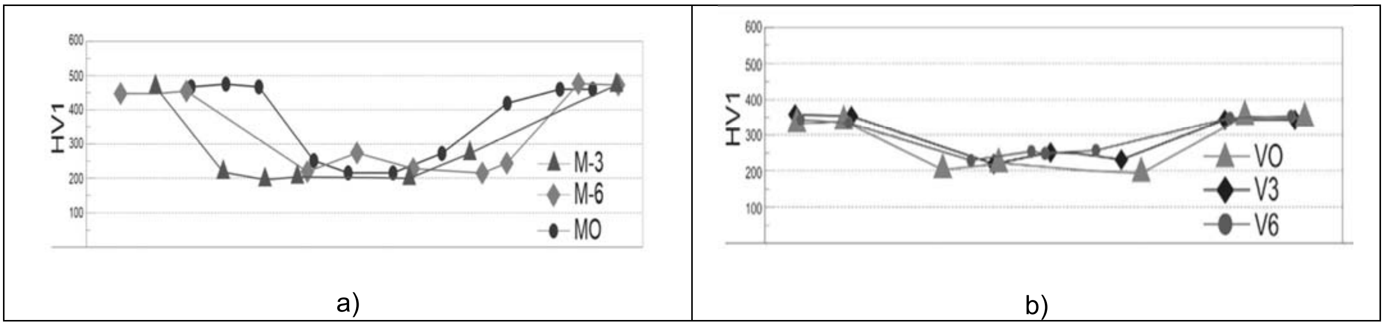


Figure 8. *Dependence of hardness on welding parameters for 1,0 mm and 1,6 mm wires [4]*

Slika 8. *Zavisnost tvrdoće od parametara zavarivanja za žice od 1,0 mm i 1,6 mm [4]*

4. Conclusion

Based on the conducted experimental research and statistical processing of the results, the following can be concluded:

The voltage of charging the capacitor bank is the most effective parameter of the welding process on tensile strength of welded joints. Reason for that is in fact that voltage exponentially affects the heat input. From the charging voltage of the capacitor bank depends the intensity of the current during welding, which reflects on the amount of melted material. With the increase of the voltage, the amount of melted metal increases, which in combination with other parameters has a direct impact on the geometry of the welded joint, the mechanical characteristics and hardness of the joint, as well as the metallography.

4. Zaključak

Na osnovu sprovedenog eksperimentalnog istraživanja i statističke obrade rezultata može se zaključiti sledeće:

Napon punjenja kondenzatorske baterije je najefikasniji parametar procesa zavarivanja za zateznu čvrstoću zavarenih spojeva. Razlog za to je činjenica što napon eksponencijalno utiče na unos toplote. Od napona punjenja kondenzatorske baterije zavisi intenzitet struje tokom zavarivanja, što se odražava na količinu rastopljenog materijala. Sa povećanjem napona povećava se količina istopljenog metala, što u kombinaciji sa drugim parametrima ima direktan uticaj na geometriju zavarenog spoja, mehaničke karakteristike i tvrdoću spoja, kao i na metalografiju.

The second most influential parameter is the speed of approaching of the wires during welding, from which depends the total duration of the welding process (arcing time). It was noted that the speed of approaching of the wires during welding affects the intensity of the current at the first pulse in such a way that with the increase in the speed of approach of the wires the intensity of the current rises slightly to a certain value, and then again decreases. The influence of the welding speed on the amount of squeezed metal weld is not unambiguous and there are significant differences in the effect at different wire diameters.

The pressure force intensity of the wires during welding in some cases is in the second, and in some in the third place, as a factor that impacts the welding process. In general, the influence of the pressure force intensity of the wires during welding on the characteristics of the welded joint is not unambiguous. Therefore, it is observed in combination with other parameters of the welding process.

The analysis showed that the smallest influence on the welding process has the capacity of the capacitor bank, and it is not possible to notice a certain dependence of the characteristics of the joint from the capacity of the capacitor bank.

Analysing hardness shows reduction of hardness at welding zone. It was expected because parent material is in cold drawn state. This reduction of hardness is more significant at 1,0 mm diameter wires that is because those wires have higher hardness in general. All samples show smaller hardness at HAZ then in welded metal. Samples welded with higher heat input have more pronounced hardness decrement, and those wires were connected on anode during welding. It can be concluded that hardness has expected dependence on heat input as well as polarity of wires.

Drugi najuticajniji parametar je brzina približavanja žica tokom zavarivanja, od čega zavisi ukupno trajanje procesa zavarivanja (vreme pražnjenja luka). Primećeno je da brzina približavanja žica tokom zavarivanja utiče na intenzitet struje pri prvom impulsu na način da sa povećanjem brzine približavanja žica intenzitet struje blago raste do određene vrednosti, a zatim ponovo opada. Uticaj brzine zavarivanja na količinu stisnutog metalnog šava nije jednoznačan i postoje značajne razlike u efektu kod različitih prečnika žice

Intenzitet sile pritiska žica pri zavarivanju u nekim slučajevima je na drugom, a u nekim na trećem mestu, kao faktor koji utiče na proces zavarivanja. Generalno, uticaj intenziteta sile pritiska žica tokom zavarivanja na karakteristike zavarenog spoja nije jednoznačan. Stoga se posmatra u kombinaciji sa drugim parametrima procesa zavarivanja.

Analiza je pokazala da najmanji uticaj na proces zavarivanja ima kapacitet baterije kondenzatora, te se ne može uočiti određena zavisnost karakteristika spoja od kapaciteta kondenzatorske baterije.

Analiza tvrdoće pokazuje smanjenje tvrdoće u zoni zavarivanja. Očekivano je jer je osnovni materijal u hladno vučenom stanju. Ovo smanjenje tvrdoće je značajnije kod žica prečnika 1,0 mm, jer te žice uopšte imaju veću tvrdoću. Svi uzorci pokazuju manju tvrdoću na HAZ nego u zavarenom metalu. Uzorci zavareni sa većim unosom toplote imaju izraženiji opadanje tvrdoće, a te žice su pri zavarivanju bile povezane na anodu. Može se zaključiti da tvrdoća ima očekivanu zavisnost od unešene toplote kao i polariteta žica.

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UTJECAJ BALANSA POLARITETA AC MIG POSTUPKA NA GEOMETRIJSKE KARAKTERISTIKE NAVARA PRI PREVLAČENJU DUPLEKS ČELIKOM

INFLUENCE OF POLARITY BALANCE DURING AC MIG CLADDING ON GEOMETRIC CHARACTERISTICS OF DUPLEX STEEL LAYER

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Rezime

Modificirani prijenosi metala pri MAG zavarivanju donose niz prednosti u tehnološkom i operativnom smislu. Isto tako, iste je moguće primijeniti i za navarivanje pri čemu je nužno razumjeti utjecaj specifičnih parametara. U ovom radu, s ciljem ispitivanja utjecaja balansa polariteta AC MIG postupka na geometrijske značajke i makrostrukturu sloja pri navarivanju konstrukcijskog čelika kvalitete S355JR žicom dupleks čelika kvalitete 2205 izrađena su tri uzorka s različitim balansima struje. Provedena su ispitivanja geometrije navarenog sloja kao i stupnja miješanja te su prikazani rezultati koji ukazuju na značajne promjene geometrije ovisno o promjeni balansa polariteta.

Abstract

Modified metal transfers in MAG welding bring a number of advantages in terms of technology and operation. Likewise, it is possible to apply the same for cladding, where it is necessary to understand the influence of certain parameters. In this paper, the influence of the polarity balance of the AC MIG process on the geometrical characteristics and macrostructure during cladding of S355JR grade steel with 2205 duplex steel wire was investigated by producing three specimens with different current balances. Tests on the geometry of the welded layer as well as on the dilution rate were performed, and results indicating significant changes in geometry as a function of the change in polarity balance.

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1. Uvod

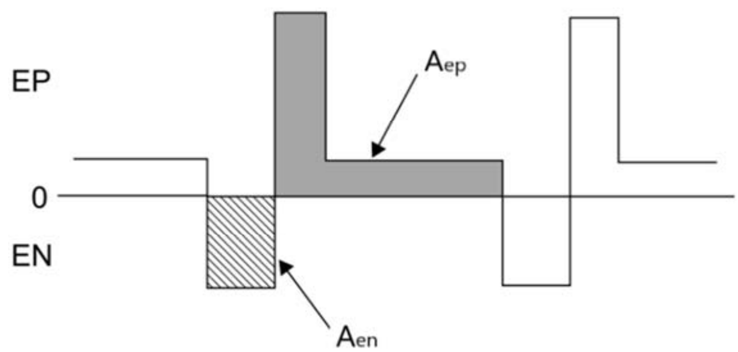
Upotreba i primjena dupleks čelika se svakodnevno intenzivira međutim još uvijek postoji dosta otvorenih pitanja u smislu primjene i ponašanja ove vrste čelika, posebno kada je u pitanju tehnologija zavarivanja i navarivanja. Osim što je cijena dupleks čelika niža od cijene austenitnih čelika slične otpornosti na koroziju, zbog nižeg sadržaja nikla i molibdena, proizvođači stalno unaprjeđuju i izrađuju nove dupleks legure čelika, kao što su lean dupleks čelici [1]. Dupleks čelici imaju izvrsna mehanička svojstva i otpornost na koroziju koju ne mogu postići ni austenitni ni feritni nehrđajući čelici. Iz tih razloga koriste se u najzahtjevnijim okruženjima, kao što su „offshore“ postrojenja, kemijska industrija i druge procesne industrije [2]. AC MIG (Alternating Current Metal Inert Gas) postupak zavarivanja je razvijen u Japanu za zavarivanje tankih limova (automobilska industrija, brodogradnja), ali u Europi nije bio dostupan sve do kasnih 1990-ih [3]. AC MIG je modificirana inačica MIG postupka čija su svojstva dobivena kombinacijom primjenom izmjenične struje za razliku od klasičnog MIG postupka gdje je žica na pozitivnom polu. Glavne prednosti AC MIG postupka zavarivanja nad konvencionalnim MIG zavarivanjem su veći depozit materijala uz manju penetraciju, sposobnost premošćivanja razmaka među pločama te smanjen unos topline [4]. Sve ove značajke mogu bitno utjecati na tehnologiju navarivanja dupleks žice na konstrukcijski čelik pri čemu su opcije upravljanja miješanjem i depozitom na puno višoj razini u odnosu na konvencionalni MAG postupak.

2. Osvrt na značajke AC MIG postupka i dupleks čelika

2.1 AC MIG

Karakteristika AC MIG postupaka zavarivanja su varijabilne promjene polariteta (eng. VP GMAW) zbog čega se mijenjaju količine nataljenog dodatnog materijala te posljedično postiže drugačija distribucija topline na žicu i radni komad. Prednosti koje AC MIG postiže mijenjanjem pozitivnog i negativnog polariteta rezultiraju boljom kontrolom nad geometrijom oblika profila zavara i penetracijom te manjim deformacijama. Jasno je da to čini ovaj proces prihvatljivijim za zavarivanjem materijala koji su osjetljivi na unos topline, kao što su to visokočvrsti čelici, aluminij ili nehrđajući čelici. Glavne značajke izmjenične struje su frekvencija i balans polariteta koji se mogu podešavati te je zato nužno kvantificirati njihov utjecaj na svojstva zavarenog spoja. Balans negativnog i pozitivnog polariteta je definiran faktorom EN (elektronegativni period) koji predstavlja omjer perioda u kojem je elektroda na minus polu (-) u odnosu na cijelu periodu AC ciklusa [5] prema izrazu (1) gdje je A_{en} površina negativnog polariteta AC ciklusa a A_{ep} površina pozitivnog polariteta cjelovitog AC ciklusa prema slici 1.

$$\text{EN omjer} = \frac{A_{en}}{A_{ep} + A_{en}} \cdot 100\% \tag{1}$$

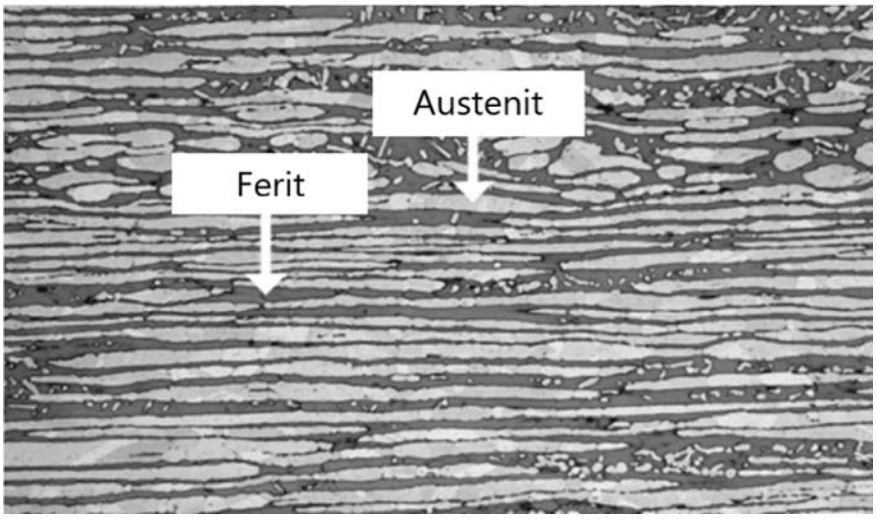


Slika 1. *Prikaz faktora balansa polariteta EN [5]*

Figure 1. *Representation of EN polarity balance factor [5]*

2.2. Dupleks čelici

Dupleks čelici ili austenitno-feritni čelici su vrsta nehrđajućih čelika čija je struktura dvofazna, te sadrži oko 40 - 60% ferita, dok je ostatak austenit, slika 2. Karakteriziraju ih izrazito dobra mehanička i antikorozivna svojstva. Iznimno su otporni na koroziju, posebice na lokalne vrste korozije kao što su rupičasta, interkristalna i napetosna korozija. Osim odličnih antikorozivnih svojstava, dupleks čelici imaju iznimna mehanička svojstva, gdje je primjerice vlačna čvrstoća dupleks čelika gotovo dvostruko veća nego kod austenitnih i feritnih nehrđajućih čelika. To je iz razloga što je struktura sitnozrnata, što je puno teže postići u materijalu sa samo jednom fazom [6].



Slika 2. *Dvofazna mikrostruktura dupleks nehrđajućeg čelika [7]*

Figure 2. *Two-phase microstructure of duplex stainless steel [7]*

Dupleks čelike se može podijeliti u nekoliko skupina prema kemijskom sastavu, a oznaka PREN (engl. Pitting Resistance Equivalent Number) označava djelotvornu sumu koja se koristi za procjenu otpornosti na rupičastu koroziju, a računa se prema izrazu (2) :

$$PREN = \%\,Cr + 3{,}3 \times (\%\,Mo) + 30 \times (\%\,N) \qquad (2)$$

Podjela dupleks čelika se može provesti kako slijedi:

1. Dupleks čelici prve generacije – ne sadrže dušik - azot,
2. Dupleks čelici druge generacije – sadrže između 0,1 % i 0,25 % dušika - azota,
3. Dupleks čelici treće generacije – PREN ≤ 40,
4. Superdupleks čelici - 40 ≤ PREN ≤ 45,
5. Hiper-dupleks čelici - PREN ≥ 45.

Dupleks čelici se smatraju dobro zavarljivim nehrđajućim čelicima. Međutim, za razliku od osnovnih konstrukcijskih čelika zahtijevaju detaljnije poznavanje pojava koje se javljaju tokom zavarivanja, te mehaničkih i korozijskih svojstava nakon zavarivanja. Zavarljivost dupleks čelika uveliko ovisi od unosa topline kao i od parametrima zavarivanja koje je potrebno pažljivo odrediti kako ne bi došlo do feritizacije strukture. Feritizacija strukture je povećani udio feritne strukture (više od 80 %) te je nepoželjna pojava jer dovodi do stvaranja krhkih struktura i smanjenja korozijske postojanosti. Zbog toga se koriste dodatni materijali predviđeni za zavarivanje dupleks čelika s dodatkom dušika u zaštitnom plinu, čime je moguće postići pozitivan utjecaj na stvaranje austenitne strukture [6].

3. Eksperimentalni rad

U eksperimentalnom dijelu provedeno je AC MIG navarivanje na konstrukcijskom čeliku S355JR (grupa 1.2 prema normi HRI CEN ISO/TR 15608:2018) debljine 10 mm i dimenzije 120x70 mm, s dodatnim materijalom odnosno žicom dupleks čelika debljine ϕ 1,2mm kvalitete 2205 (grupa 9.1 prema normi HRI CEN ISO/TR 15608:2018). Korištena je plinska mješavina argon s dodatkom 2,5% CO_2 Inoxline C2 (grupa M12 po normi EN ISO 14175:2008). Kemijski sastav i mehanička svojstva žice su prikazana u tablicama 1. i 2. Kako bi se kvantificirao utjecaj faktora polariteta EN provedeno je navarivanje s više različitih razina prema dozvoljenom rasponu sinergijskih krivulja izvora struje za zavarivanje. Ostali parametri su držani konstantnim tako što je korišten automatski uređaj za zavarivanje koji je održavao nagib pištolja, brzinu zavarivanja i udaljenost sapnice od radnog komada za sve uzorke, a na izvoru struje su podešeni stalni parametri jakosti struje, napona električnog luka, dinamičke karakteristike kao i protok plina, tablica 3. Izrađena su tri uzorka s različitim EN omjerima s ciljem utvrđivana EN omjera na geometriju navara kao i stupnja miješanja, tablica 4.

Tabela 1. *Kemijski sastav žice dupleks 2205 [8]*

Table 1. *Chemical composition of duplex 2205 wire [8]*

Kemijski sastav, element	maseni udio, %
C	≤ 0,020
P	≤ 0,020
Si	0,50
Mn	1,60
S	≤ 0,015
Cr	23,00
Ni	9,00
Mo	3,20
N	0,16

Tablica 2. *Mehanička i fizikalna svojstva žice dupleks 2205 [8]*

Table 2. *Mechanical and physical properties of duplex 2205 wire [8]*

Mehanička svojstva pri 20°	
Granica razvlačenja $R_{p0,2}$,MPa	600 (20°C); 420 (300°C)
Vlačna čvrstoća R_m , MPa	750 (20°C); 600 (300°C)
Istezanje A, %	25 (20°C); 20 (300°C)
Udarni rad loma, J	130 (20°C); 50 (-196°C)
Tvrdoća, HV10	240 HV10

Table 3. *Adjusted welding parameters*

Tabela 3. *Podešeni parametri navarivanja*

Parametar	Oznaka	Vrijednost
Struja	I	160 A
Protok plina	Q	18 l/min
Napon	U	25 V
Brzina zavarivanja	v_z	25 cm/min
Nagib pištolja	/	90°, neutralna tehnika
Slobodni kraj žice	L	15 mm
Brzina dodavanja žice	$v_ž$	8,3 m/min
Dodatni materijal	/	DUPLEKS 2205
Osnovni materijal	/	S355JR
Zaštitni plin	/	Ar + 2,5% CO_2

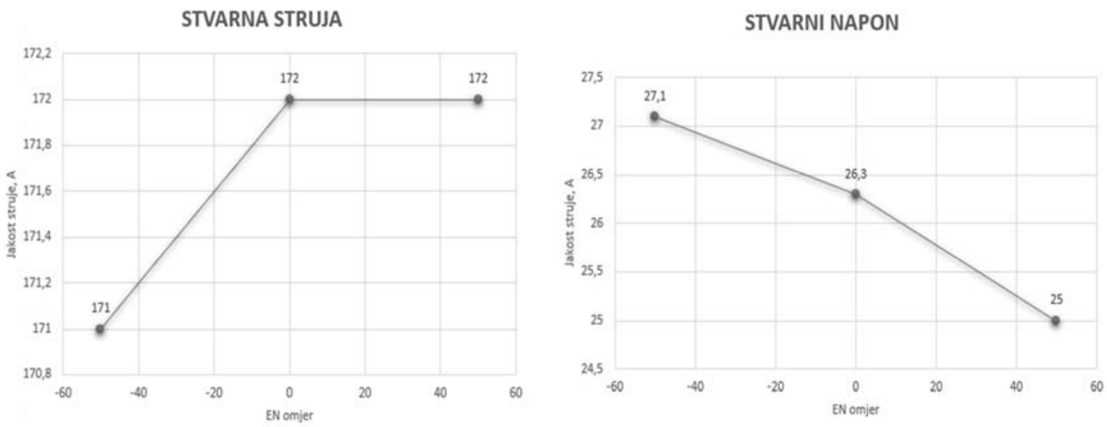
Tablica 4. *Vrijednosti balansa polariteta EN prema sinergijskoj krivulji izvora struje*

Table 4. *EN polarity balance values according to the synergy curve of the current source*

Oznaka uzorka	EN omjer
2	-50
1	0
3	50

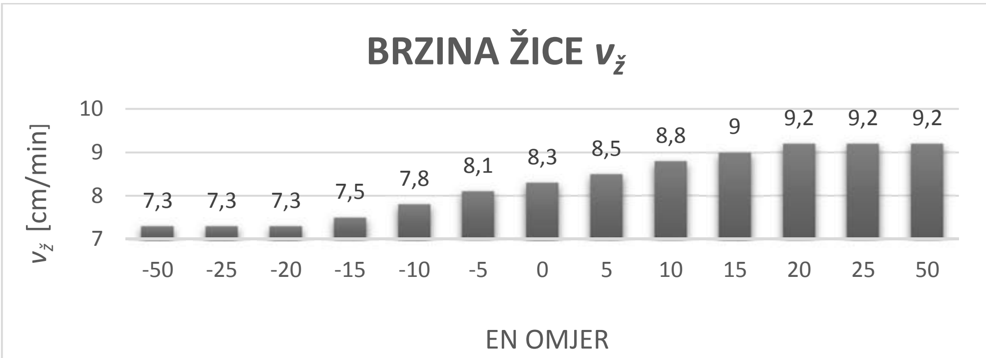
Tijekom navarivanja određeni parametri su se mijenjali ovisno o postavki EN omjera. Stvarni parametri jakosti struje i napona u ovisnosti o EN omjeru prikazani su na slici 3. Iz slike se može uočiti kako se s povećanjem EN omjera povećava iznos struje dok se stvarni napon smanjuje što se može pripisati stalnoj promjeni polariteta te nestabilnosti u ionizaciji i stabilnosti električnog luka

Ovisnost promjene brzine dodavanja žice izmjerena je u ovisnosti o promjeni EN omjera. Zapisane su vrijednosti brzine dodavanja žice za EN omjere u inkrementima od 5 jedinica kako bi se dobio precizan uvid u taj odnos. Ovisnost brzine dodavanja žice o EN omjeru prikazano je na slici 4. Brzina žice raste s porastom EN omjera jer je stopa taljenja žice veća zbog duljeg trajanja negativnog dijela polariteta koji koncentrira veći iznos topline na elektrodu, ali i zbog nešto veće prosječne struje pri većim EN omjerima, te se može zaključiti kako se i povećanjem EN omjera povećava i količina rastaljenog materijala.



Slika 3. *Ovisnost jakosti struje i napona o EN omjeru*

Figure 3. *Dependence of current and voltage of the EN ratio*

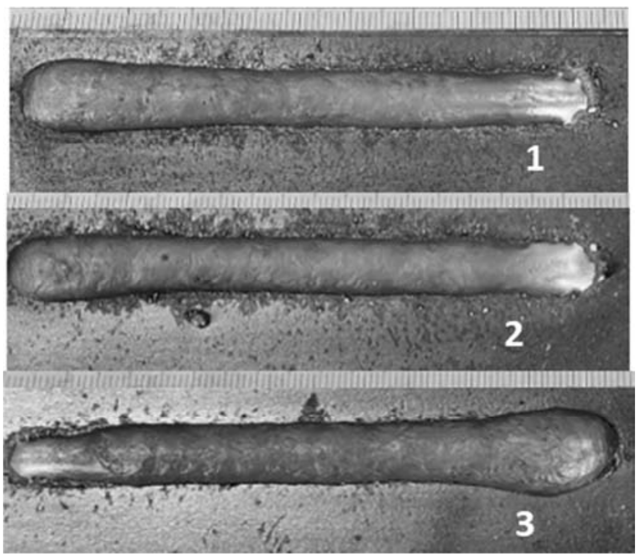


Slika 4. *Ovisnost brzine dodavanja žice o EN omjeru*

Figure 4. *Dependence of wire feeding speed of EN ratio*

4. Rezultati i diskusija

Vizualnom kontrolom navara prema zahtjevima HRN EN ISO 17637 nisu uočene površinske pogreške, no može se uočiti kako dolazi do povećanja intenziteta rasprskavanje kapljica s povećanjem EN omjera, slika 5.

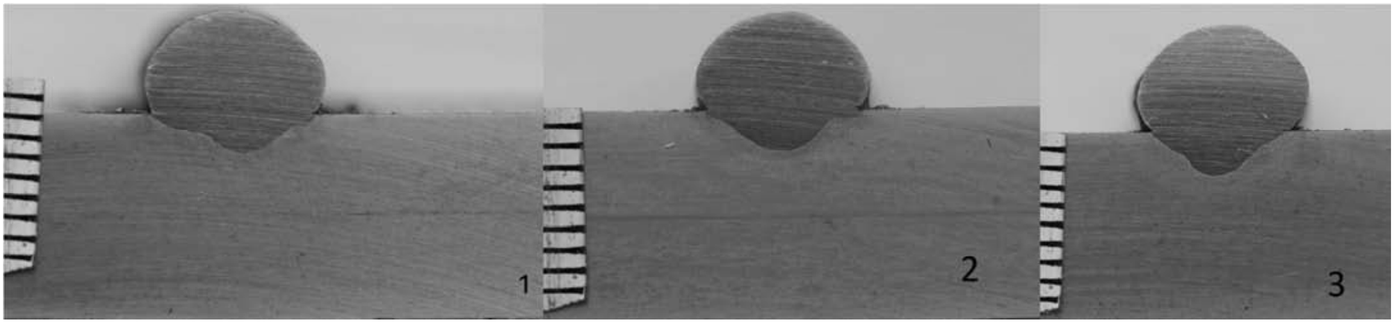


Slika 5. *Rezultati navarivanja uzoraka (uzorak 1 EN 0, uzorak 2 EN -50 i uzorak 3 EN +50)*

Figure 5. *Results of welding samples (sample 1 EN 0, sample 2 EN -50 and sample 3 EN +50)*

4.1 Makroanaliza uzoraka

Za brušenje uzoraka su korišteni brusni papiri granulacija navedenim redoslijedom: P100, P150, P240 i P320. Poliranje je izvedeno na stroju Minitech 233 s brzinom rotacije od 300 o/min uz korištenje vode koja služi za hlađenje i uklanjanje odvojenih čestica. Za poliranje su korišteni brusni papiri granulacija P320, P600, P1000, P2400 i P4000. Slika 6 prikazuje uzorke nakon nagrizanja.

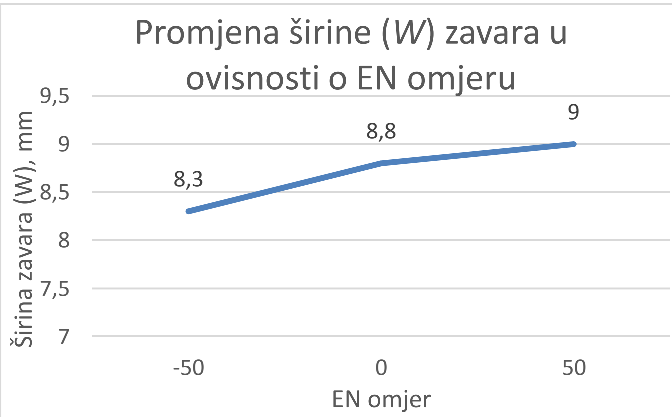


Slika 6. *Makroizbrusci nakon poliranja i nagrizanja (uzorak 1 EN 0, uzorak 2 EN -50 i uzorak 3 EN +50)*

Figure 6. *Macrosamples after polishing and etching (sample 1 EN 0, sample 2 EN -50 and sample 3 EN +50)*

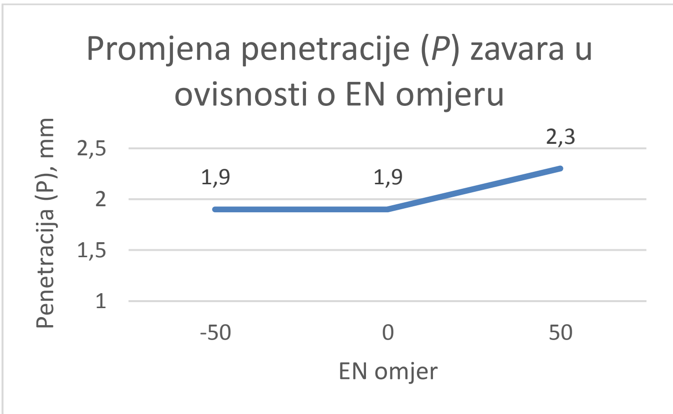
Izlazni parametri makrostrukture, čiji su omjeri analizirani su širina zavara (*W*), nadvišenje zavara (*R*) i penetracija (*P*). Navedeni izlazni parametri računati su mjerenjem duljina linija u programu ImageJ. Poželjna geometrija navara treba biti sa što manjom penetracijom, najvećom širinom zavara te pravilnog nadvišenja zavara. Na dobivenim uzorcima se odmah uočava veliko nadvišenje zavara tj. njegov nepoželjan oblik, a posebno za potrebe navarivanja. To posebno može predstavljati problem kod slaganja i formiranja navarenog sloja jer je moguće dobiti neprotaljene zone i djelomično naljepljivanje.

Ipak, kada bi se gledao utjecaj EN omjera na poželjnu geometriju zavara, neki parametri daju bolje rezultate od drugih. Najpoželjniji rezultat bi bio da omjer *W/R* i *W/P* budu što veći, odnosno da zavar ima najveću širinu (*W*), uz najmanju penetraciju (*P*) i nadvišenje (*R*). Na slikama 7., 8. i 9. mogu se uočiti generalni trendovi rasta penetracije (*W*), nadvišenja (*P*) i širine (*R*) zavara u ovisnosti o EN omjeru.



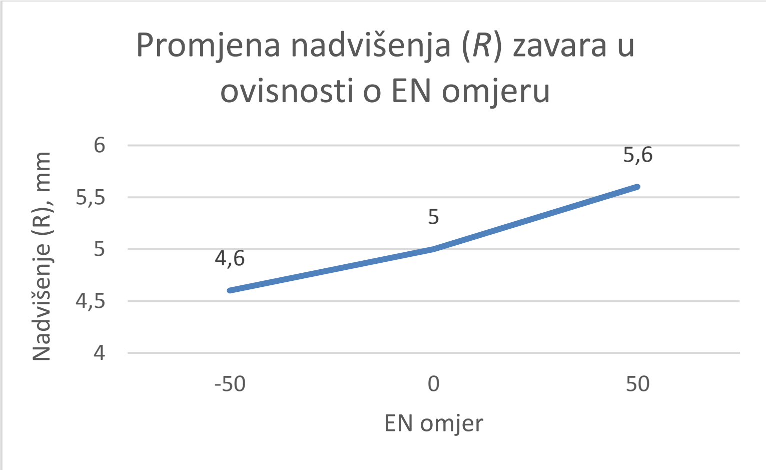
Slika 7. *Utjecaj EN omjera na širinu zavara (W)*

Figure 7. *Impact of EN ratio on weld width (W)*



Slika 8. *Utjecaj EN omjera na penetraciju zavara (P)*

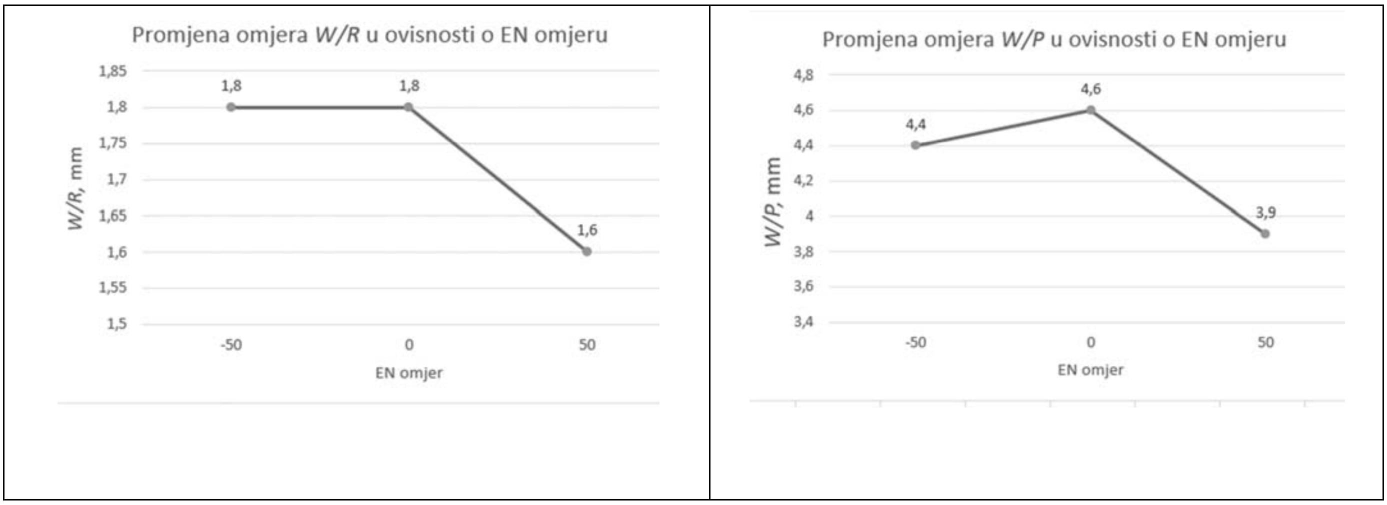
Figure 8. *Impact of EN ratio on weld penetration (P)*



Slika 9. *Utjecaj EN omjera na nadvišenje zavara (R)*

Figure 9. *Impact of EN ratio on weld overhang (R)*

Dijagram koji pokazuje ovisnost faktora *W/R* i *W/P* o EN omjeru prikazan je na slici 10. Tako najpoželjnije rezultate za faktore *W/R* daju uzorci s EN -50 i EN 0, dok najbolji rezultat za *W/P* daje uzorak navaren EN omjerom od 0 u kojem elektroda provede jednako vrijeme i na pozitivnom i negativnom polu.



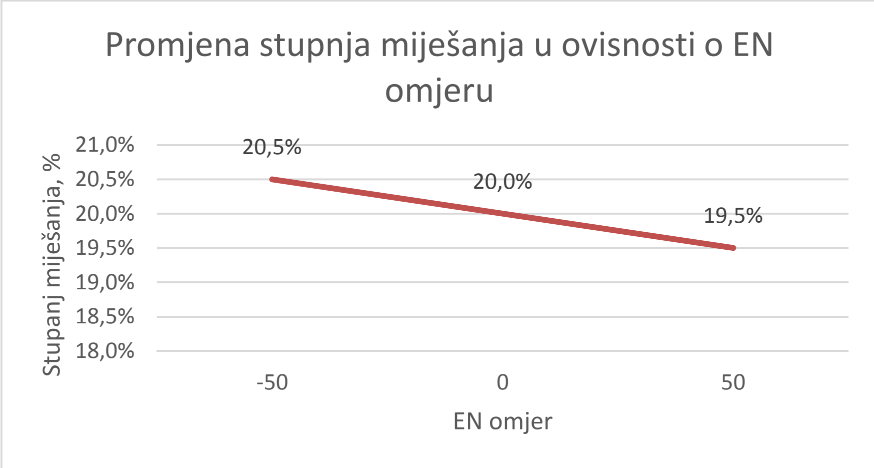
Slika 10. *Utjecaj EN omjera na faktore W/R i W/P*

Figure 10. *Impact of EN ratio on W/R and W/P factors*

4.2 Analiza stupnja miješanja

Kako ne bi došlo do prevelike kontaminacije metala navara iz područja osnovnog materijala što rezultira većim rizikom od nastanka krhkih mikrostruktura i pukotina, prijelazna zona treba biti što manja odnosno stupanj miješanja treba biti što manji. Ovo je osobito bitno kod zavarivanja materijala s visokim antikorozivnim svojstvima i ugljičnih feritno-perlitnih čelika [9].

Na slici 11 su grafički prikazani rezultati stupnjeva miješanja u ovisnosti o EN omjeru. Uspoređujući rezultate s dijagrama sa slike 11., pokazano je kako stupanj miješanja blago pada povećanjem balansa polariteta, a najbolji rezultat s najmanjim stupnjem miješanja je dobiven kod uzorka s EN od +50.



Slika 11. *Ovisnost promjene stupnja miješanja i EN omjera*

Figure 11. *Dependence of the change in mixing degree and EN ratio*

5. Zaključak

Ispitan je utjecaj balansa polariteta AC MIG postupka zavarivanja s ciljem određivanja najpovoljnije geometrije navara. Navarivan je dupleks 2205 nehrđajući čelik na konstrukcijski čelik S355JR. Dobiveni rezultati se mogu rezimirati kako slijedi:

- Brzina žice raste s porastom EN omjera jer je brzina taljenja žice veća te se može zaključiti kako se i povećanjem EN omjera povećava i količina rastaljenog materijala.
- Prilikom analize geometrije navara najpoželjniji rezultat je da omjer *W/R* i *W/P* budu što veći, odnosno da zavar ima najveću širinu (*W*), uz najmanju penetraciju (*P*) i nadvišenje (*R*), što je dobiveno kod uzorka gdje je EN omjer iznosio 0.
- Prilikom analize stupnja miješanja zaključeno je kako stupanj miješanja ima tendenciju pada pri povećanju EN omjera, te je dobiveno kako uzorak s EN omjerom 50 ima najmanji stupanj miješanja, odnosno rezultat koji je najpovoljniji.

Za optimalnu primjenu AC MIG postupka pri navarivanju važno je ustanoviti utjecaj balansa EN polariteta kao bi se postigli što bolji rezultati u industrijskoj primjeni i povećalo razumijevanje ponašanja ovakve modificirane metode prijenosa metala. U daljnjem radu potrebno je uzeti u obzir i druge plinske mješavine te provesti kemijsku analizu metala navara.

5. Conclusion

The influence of the polarity balance of the AC MIG welding procedure was examined with the aim of determining the most favourable welding - cladding geometry. Duplex 2205 stainless steel is cladded to S355JR structural steel. The results obtained can be summarized as follows:

- The speed of the wire increases with the increase in the EN ratio because the melting speed of the wire is higher, and it can be concluded that the amount of melted material also increases with an increase in the EN ratio.
- When analyzing the weld geometry, the most desirable result is that the W/R and W/P ratios are as large as possible, i.e. that the weld has the largest width (W), with the smallest penetration (P) and exceed (R), which was obtained with the sample where the EN ratio was 0.
- During the analysis of the degree of mixing, it was concluded that the degree of mixing tends to decrease when the EN ratio increases, and it was obtained that the sample with an EN ratio of 50 has the lowest degree of mixing, that is, the most favourable result.

For the optimal application of the AC MIG procedure during welding, it is important to establish the influence of the EN polarity balance in order to achieve the best possible results in industrial application and to increase the understanding of the behaviour of this modified method of metal transfer. In further work, it is necessary to take into account other gas mixtures and carry out a chemical analysis of the cladded metal.

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ZIMSKI SASTANCI MEĐUNARODNOG INSTITUTA ZA ZAVARIVANJE

Ovogodišnji Zimski sastanci Međunarodnog instituta za zavarivanje (IIW Winter Meetings 2023) su održani u sedištu Međunarodnog instituta za zavarivanje (IIW) u Đenovi (Italija), tačnije u prostorijama Italijanskog instituta za zavarivanje u periodu od 16. do 20. januara.

Za razliku od prakse koja je bila primenjivana do početka 2020. godine, tačnije do Covid pandemije, kada su ovi tradicionalni sastanci bili masovni i praktično su obuhvatali rad svih Komisija IIW, radnih grupa ili radnih tela, kao i svih rukovodećih tela, ovoga puta takva masovnost nije ni bila ponuđena članovima IIW-a, a ni zainteresovanim učesnicima.

Analiza zbog čega je masovnost, a samim tim i efikasnost i efektivnost IIW zimskih sastanaka bila, bar po mišljenju većine učesnika, ograničenog dometa biće svakako urađena u sledećem periodu.

No, da se zadržimo na činjenicama: Ovogodišnji susreti koji su održami u sedištu IIW (od 2020. godine) u Đenovi (Italija) su započeti 16. januara sastankom radne grupe za regionalnu saradnju, gde je diskutovano o najznačajnjim događajima u oblasti zavarivanja u svetu koji se održavaju pod okriljem IIW-a.

Pored ovoga održan je i sastanak radne grupe pod nazivom Tehnički komitet i to su bile jedine dve grupe koje su održale sastanak u okviru zimskih susreta. Ovoga puta nije bio planiran nijedan sastanak neke tehničke komisije.

Koncept Zimskih sastanaka je bitno promenjen jer je težište bilo na sastancima radnih tela iz domena rukovođenja kao što su: Odbor direktora IIW (IIW Board of Directors), radna grupa za rukovođenje pri Odboru direktora IIW (WG-WG-GOV), radna grupa za finansije i rizik pri odboru direktora IIW (WF-FAR), Odboru za tehnička pitanja (TMB) i Savetodavnog veća IIW–a (IIW Advisry Council).

Održani su pojedinačni sastanci svih ovih tela, ali je osnovni cilj bio da se Bord direktora IIW detaljnije upozna sa radom ovih tela u cilju poboljšanja rada svih struktura u IIW. U tom cilju su održane i radionice članova Odbora (Borda) direktora IIW sa nabrojanim telima posebno. Pored toga Odbor direktora je održao i svoj završni sastanak gde je analiziran efekat zimskih susreta.

ČLANOVI BORDA DIREKTORA SA IZVRŠNIM DIREKTOROM IIW

Zimski sastanci IAB grupe (Grupe za ovlašćivanje) koja se sastoji od tri sastanaka i to sastanaka Grupe A koja se bavi pravilima, sadržajevima kurseva, razradi svake metodske jedinice za svaki kurs koji se oržava po pravilima IIW kao i tematikom izmena, dopuna, razrade ili dorade šta je ono što polaznici IIW kurseva treba da ''ponesu'' sa kursa kao i međunarodnom bazom pitanja za testove. Sastanak Grupe B koja se bavi realizacijom pravila i sistemom ocenjivanja ANB-ova, odnosno Nacionalnih nominovanih tela za ovlašćivanje i obimom akreditacije postojećih ANB-ova i treći sastanak predstavnika ANB-ova nisu održani u okviru Zimskih susreta.

Umesto toga održana je radionica članova Odbora direktora IIW sa Odborom IAB grupe. Ne ulazeći u detalje kakav je bio dnevni red svih ovih sastanaka, radionice ili radnih grupa, dokumeti sa ovih sastanaka kao što su: dnevni red, zapisnici i slično mogu biti dostupni na upit. Najvažnija tema je bila Strategija IIW za period 2023-2028.

Svečana večera

U pitanju je strategija razvoja IIW za sledeći petogodišnji period i to: plan razvoja strategije, analiza postojeće strategije, nova vizija, misija, nove vrednosti i projekti, poređenje postojeće i nove strategije, ciljevi strategije i operacioni plan zai period 2023-2028.

Diskusija je u toku na svim nivoima. Na zimskim sastancima su razmatrani i usvojeni su Predlog globalnih ciljeva strategije i Operacionalizacija aktivnosti radi ostvarivanja postavljenih ciljeva.

Usvajanje ovog značajnog dokumenta je planirano za sledeću Godišnju Skupštinu IIW-a koja će biti održana 16. Jula 2023 godine u Singapuru.

Dr Vencislav Grabulov član Odbora direktira IIW i gospodin Luca Costa – izvršni direktor IIW

SASTANCI IAB GRUPE

Sastanci IAB grupe su održani na daljinu po sistemu ON-LINE tokom decembra 2022 i januara 2023. godine.

Na sastanku grupe A koja se bavi analiziranjem, izmenama, dopunama i poboljšanjem sadržaja kurseva i bazom ispitnih pitanja kao i načinom izvođenja ispita, najvažniji su bili posebni sastanci tzv. "šampiona" iz pojedinih oblasti na kojima su detaljno razmatrana pitanja iz međunarodne baze. Ovi sastanci su bili održavani po nekoliko dana u navedenom periodu, pri čemu su analizirana pitanja, odgovri na postavljena pitanja, sprovedena statistika za svako pitanje, kako globalno za sve ANB-ove tako i za svaki ANB posebno.

Ovaj naporan rad će svakako poboljšati i ujednačiti princip ocenjivanja na nivou članica.

U radnim grupama su aktivno učestvovali i naši predstavnici i to za IIW Kurseve za inženjere, tehnologe I specijaliste i to:

Za modul 1. Prof. dr Olivera Popović

Za modul 2. Dr Vencislav Grabulov

Za modul 3. Prof.dr Nenad Fric

Za modul 4. Prof.dr. Miloš Đukić

Svi naši predstavnici su značajno doprineli radu radnih grupa, za šta su pohvaljeni od strane moderatora za svaki modul.

Dr *Vencislav Grabulov*

Internacionalni inženjeri zavarivanja (IWE) / Evropski inženjeri zavarivanja (EWE);
Internacionalni tehnolozi zavarivanja (IWT) / Evropski tehnolozi zavarivanja (EWT);
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INFLUENCE OF CHANGES IN THE MICROSTRUCTURE OF THE WELDED JOINT DUE TO FRICTION STIR WELDING OF ALUMINIUM ALLOYS 2024 AND 5083 ON THE ELECTRICAL CONDUCTIVITY AND ELECTROCHEMICAL PARAMETERS IN CORROSIVE ENVIRONMENTS

UTICAJ PROMENE MIKROSTRUKTURE ZAVARENOG SPOJA USLED ZAVARIVANJA TRENJEM ALATOM LEGURA ALUMINIJUMA 2024 I 5083 NA ELEKTRIČNU PROVODLJIVOST I ELEKTROHEMIJSKE PARAMETRE U KOROZIONIM SREDINAMA

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Keywords: friction stir welding, weld characterization, alloy 2024-T351, alloy 5083-H111

Ključne reči: zavarivanje trenjem alatom, karakterizacija zavarenog spoja, legura 2024-T351,legura 5083-H111

Abstract

In this paper physical and metallographic properties of a dissimilar aluminium alloy friction-stir-welded joint (FSW) of non-heat treated aluminium alloy 5083-H111 as well as heat treated aluminium alloy 2024-T351 are examined. The chosen tool for welding had a standard screw thread radius, and for the welding parameters the ratio R/v = 750/73 was chosen. In order to determine the change in electrical conductivity and electrochemical parameters of the base materials and the welded joint in corrosive environments depending on the change in microstructure due to welding, metallographic analysis of the welded joint on an optical microscope was performed, and electrical conductivity and electrochemical parameters of the base material and the welded joint were also examined.

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

Rezime

U ovom radu ispitane su fizičke i metalografske osobine raznorodnog zavarenog spoja legure aluminijuma 5083-H111, koja se termički ne obrađuje, i legure aluminijuma 2024-T351, koja se termički obrađuje, dobijenog postupkom zavarivanja trenjem alatom (Friction Stir Welding-FSW). Zavarivanje je izvršeno pomoću alata standardnog radijusa navoja, sa parametrima Vrot/Vzav = 750/73.

U cilju utvrđivanja promene električne provodljivosti i elektrohemijskih parametara osnovnog materijala i zavarenog spoja u korozionim sredinama u zavisnosti od promene mikrostrukture usled zavarivanja, izvršena su metalografska ispitivanja zavarenog spoja na optičkom mikroskopu, merenje električne provodljivosti i elektrohemijskih parametara osnovnog materijala i zavarenog spoja.

1. Introduction

The friction stir welding (FSW) process was developed and patented by the British Welding Institute- TWI, in December 1991 [1, 2].

The FSW procedure is process of joining materials in a solid state using the appropriate tool, without melting, protective armor and without the use of additional material. The resulting joint is a consequence of the effect of mechanical work and generated heat [3, 4]. During FSW welding due to simultaneous deformation and recrystallization processes (static and/or dynamic), and depending on the combination of applied parameters of the welding process, there is intense crushing of grains in the joint structure. Characteristic parts of the joint created by FSW are: TMAZ- thermo-mechanical affected zone, HAZ- heat affected zone and “nugget zone”- fine grain recrystallized area. The main welding parameters are tool travel speed (welding speed), $\mathbf{V_{tr}}$, and tool rotation rate, $\mathbf{V_{rot}}$ [3, 5].

Thermo-mechanical affected zone (TMAZ) is the part of the base metal that is simultaneously exposed to the effect of elevated temperature and the effect of mechanical load. In the structure, deformed, elongated grains which follow the flow of material mixing during the welding process can be clearly observed. Also, due to the influence of the heat effect, the grains may become coarse.

Heat affected zone (HAZ) is an area that is exposed to the effect of elevated temperature, but is not exposed to the effect of mechanical load. The heat effect can induce small scale phase transformation, such as grain coarsening and precipitation [6, 7, 8].

Nugget zone is a completely recrystallized area, which has a fine - grained structure, gained due to elevated temperature resulting from intense plastic deformation during welding [3, 5, 6]. Electrical conductivity is sensitive to structural changes. It depends on the amount of elements in the solid solution and the amount and nature of the sediment particles. Electrical conductivity also depends on grain size. Each grain boundary represents an obstacle for the movement of electrons, which means that by reducing the grain size, the electrical conductivity also decreases [8]. It is well known that 2024 aluminum alloy possesses moderate yield strength and good damage tolerance while 5083 aluminum alloy has good balance between light weight and corrosion resistance [9].

The aim of this work is to examine the influence of the change in the microstructure of the butt welded joint of two plates, made of different aluminum alloys (2024 - T351 and 5083 - H111), by the FSW process, on electrical conductivity and electrochemical parameters in corrosive environments.

2. Experimental part

Two plates, 65 mm wide, 500 mm long and 6 mm thick, made of dissimilar aluminum alloys are butt welded using a FSW method. The following parameters were used for welding: tool rotation rate, V_{rot}, was 750 rpm and tool travel speed (welding speed), V_{tr} , was 73 mm/min. The chemical composition of aluminum alloys 2024-T351 and 5083- H111 is shown in Table 1.

Table 1. *Chemical composition of AA2024 and AA5083 plates.*

Tabela 1. *Hemijski sastav ploča AA2024 i AA5083.*

Alloy	Element , (mass. %)								
	Mg	Mn	Si	Fe	Cu	Cr	Zn	Ti	Al
AA2024	1,45	0,60	0,06	0,16	4,28	0,003	0,08	0,03	rest
AA5083	4,60	0,55	0,24	0,24	0,07	0,10	0,07	0,02	rest

2.1 Macrostructure and microstructure analyses

Macrostructural and microstructural examinations of the welded joint were performed on samples taken from a cross-section in relation to the direction of the welded joint. The specimen for macrostructure was then mechanically ground using sand papers with grit sizes P240 to P2500. The macrostructure was revealed by etching in Tucker’s reagent (45ml HCl, 15ml HNO_3, 15ml HF, 25ml H_2O) for 5 seconds.

The microstructure was observed on an optical microscope. The specimen for microstructure was mechanically ground using sand papers with grit sizes P240 to P4000, mechanically polished with the use of a diamond polishing suspensions with particle sizes of 7/5 μm, 5/3 μm и 3/2 μm. Subsequently, the specimens were electrochemically polished and etched. Electrochemical polishing of specimen was carried out using a perchloric acid-based solution (200 ml ethanol, 35 ml H_2O, 10 ml 60% solution of $HClO_4O$)

at 25 V for 8 seconds. The electrochemically etched using Barker's reagent (5 g HBF_4 (48%), 200 ml H_2O) at 12 V for 120 seconds.

2.2 Measurement of electrical conductivity

Electrical conductivity was measured on the "Förster SIGMATEST D 2.068" device in % IACS (International Anneald Copper Standard) units. All measurement was performed at room temperature at a test frequency of 120 Hz.

2.3 Corrosion test

The corrosion tests were conducted on the base materials, AA2024-T351 and AA5083-H111, as well as on the face and root of the welded joint. The areas exposed to the electrolyte were 1cm^2 for all measured zone. All the experiments were conducted in 3.5 % NaCl solution at room temperature (25 ± 2 ºC).

All experiments were carried out using a three-electrode system. A saturated calomel electrode (SCE), a large platinum sheet, and a measured zone with the area of 1 cm^2 were served as a reference electrode (RE), counter electrode (CE), and working electrode (WE), respectively.

3. Results

3.1 Macrostructure and microstructure

The characteristic macrostructure of the cross-section of the joint and the position of its areas (nugget, TMAZ, HAZ and base metals, BM) are shown in Figure 1. The thermo-mechanical affected zone (TMAZ) with pronounced deformed grains, a nugget with recognizable ring structure, and sleeve. The area of HAZ is poorly defined and cannot be clearly observed. Microstructures of base metals are shown in Figure 2.

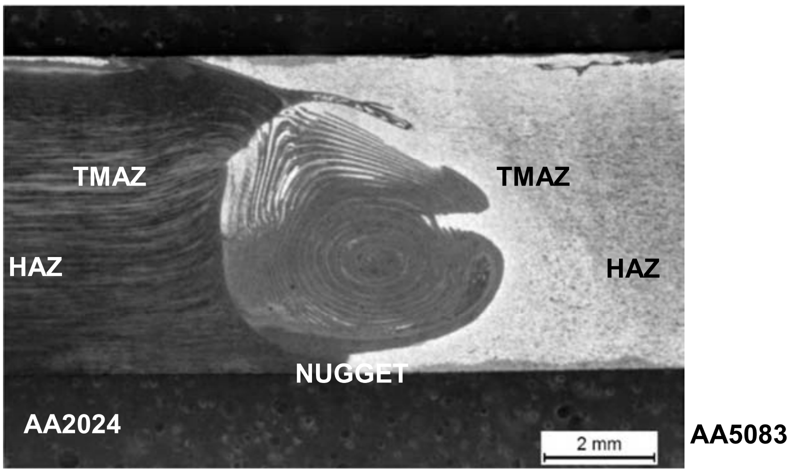
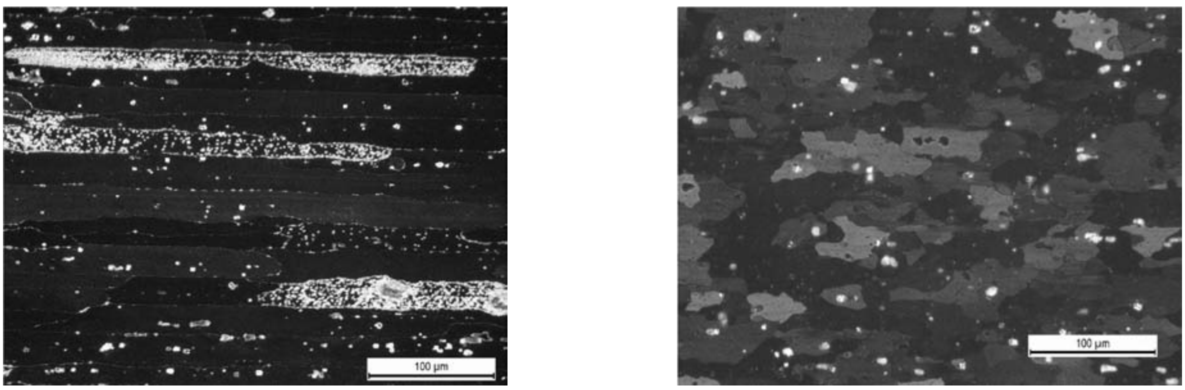


Figure 1. *The macrostructure of cross- section of welded joint.*

Slika 1. *Makrostruktura poprečnog preseka zavarenog spoja.*



a) b)

Figure 2. *Microstructures of base metals: a) AA2024- T351 and b) AA5083- H111.*

Slika 2. *Mikrostrukture osnovnih metala: a) AA2024- T351 i b) AA5083- H111.*

The microstructure of aluminum alloy 2024-T351 is characterized by elongated grains, which is a consequence of the rolling process, while in alloy 5083- H111 the mechanical direction of the grains is less pronounced. The microstructures of the welded joint zones are shown in Figures 3-5.

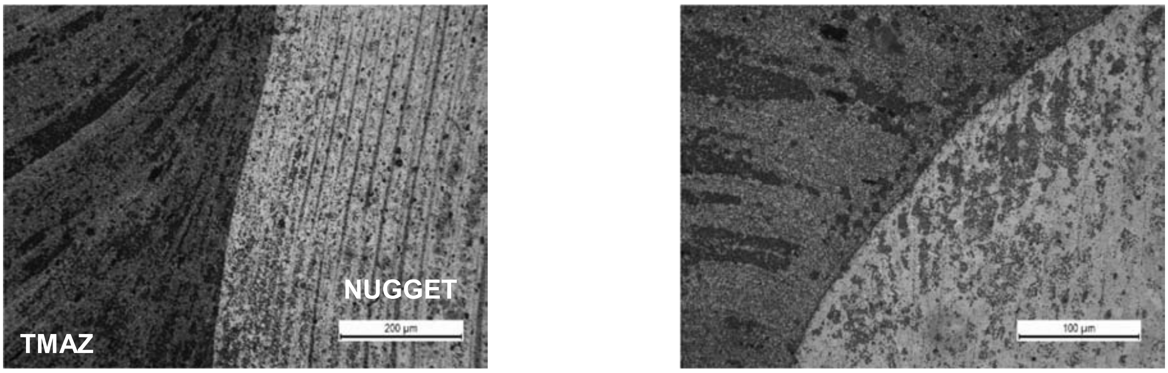
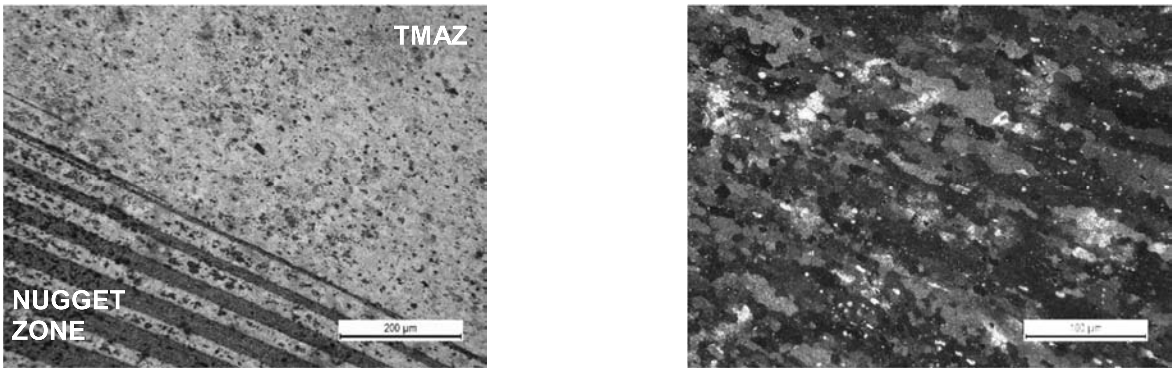


Figure 3. *The microstructure of the welded joint on the side of alloy 2024 at the border of TMAZ- nugget.*

Slika 3. *Mikrostruktura zavarenog spoja na strani legure 2024 na granici TMAZ-sočivast šav.*

The microstructure of the welded joint is inhomogeneous. Grains of different sizes and orientations can be observed in different parts of the welded joint. Figure 3 shows the microstructure of the welded joint on the side of alloy 2024. In TMAZ grains are strongly deformed and elongated in the direction of material flow during the welding process, while small and recrystallized grains are characteristic of the nugget zone.

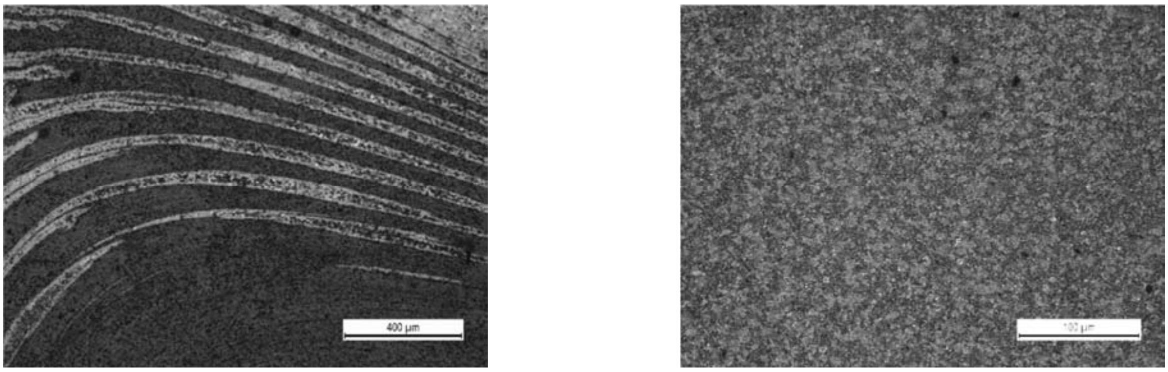


a) b)

Figure 4. *The microstructure of the welded joint on the side of alloy 5083: a) the border of TMAZ- nugget and b) TMAZ.*

Slika 4. *Mikrostruktura zavarenog spoja na strani legure 5083: a) granica TMAZ- sočivast šav i b) TMAZ.*

Figure 4 shows the microstructure of the weld joint on the side of alloy 5083. Deformed and elongated grains are clearly visible in the thermo-mechanical affected zone, Figure 4b.



a) b)

Figure 5. *The microstructure of the welded joint- nugget zone at different magnifications.*

Slika 5. *Mikrostruktura zavarenog spoja –sočivastog šava pri različitim uvećanjima*

The appearance of a ring structure, which is shown in Figure 5 a) is characteristic of the nugget zone. In the nugget zone, the expected complete recrystallization of grains occurred.

3.2 Electrical conductivity

Electrical conductivity was measured on the FSW specimens in different zones of the surface of the joints, as shown in Figure 6. Zones 4-5 represent the weld metal, while zone 5 represent nugget zone. Figure 7 shows the change in electrical conductivity through the welded joint. On the x- axis, Figure 7, are marked the zones where electrical conductivity was measured, which are shown in Figure 6.

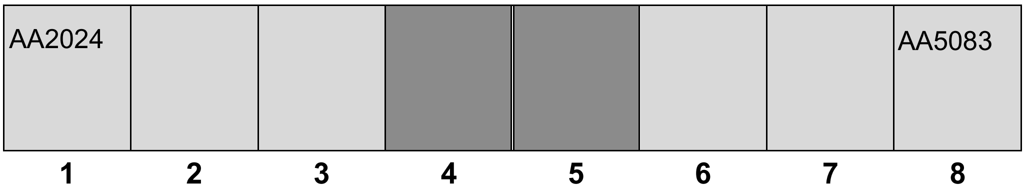


Figure 6. *Zones of the welded specimen for measuring electrical conductivity.*

Slika 6. *Zone zavarenog uzorka za merenje električne provodljivosti.*

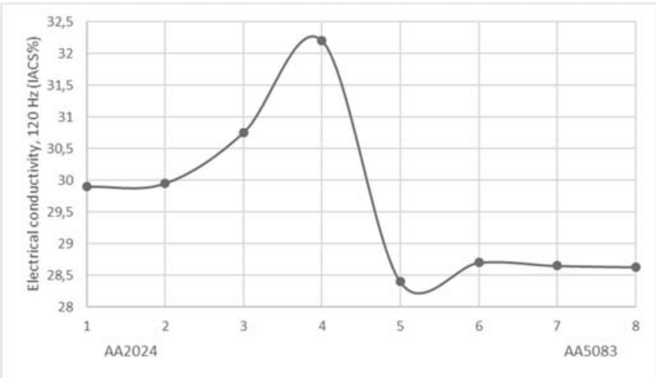


Figure 7. *The change in electrical conductivity of the welded joint.*

Slika 7. *Promena električne provodljivosti zavarenog spoja.*

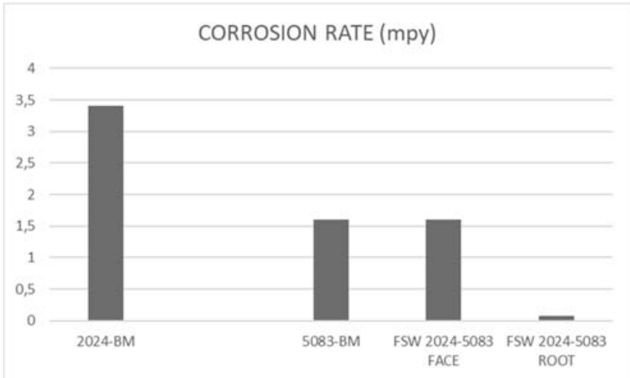


Figure 8. *Corrosion rate (CR) values of the measured zones.*

Slika 8. *Vrednosti brzine korozije (CR) merenih zona.*

The precipitation strengthened alloy 2024 - T351 has a higher electric conductivity than alloy 5083 - H111. The highest electrical conductivity was observed in TMAZ from the side of alloy 2024, while the lowest electrical conductivity was observed in nugget zone, where the grain is the smallest. Also, a slight increase in electrical conductivity is observed in TMAZ on the side of alloy 5083.

3.3 Corrosion resistance

Corrosion rate values (CR) obtained from the potentiodynamic polarization curves for the measured zones are presented in Figure 8. Alloy 2024 has a higher corrosion rate than alloy 5083. The face of the weld metal has an approximate corrosion rate value as alloy 5083, while the root of the weld metal has the lowest corrosion rate value.

4. Conclusions

The values of thermal and electrical conductivity at room temperature mainly depend on the type of alloying elements and their concentration in solid solution and outside it, on the grain size and the concentration of other defect in the crystal lattice. With the decrease in grain size, a decrease in electrical conductivity is recorded, as a consequence of the increase in the number of boundaries that are obstacles to the movement of

4. Zaključci

Vrednosti toplotne i električne provodljivosti na sobnoj temperaturi uglavnom zavise od vrste legirajućih elemenata i njihove koncentracije u čvrstom rastvoru i van njega, od veličine zrna i koncentracije drugog defekta u kristalnoj rešetki. Sa smanjenjem veličine zrna beleži se smanjenje električne provodljivosti, kao posledica povećanja broja granica koje su prepreka kretanju elektrona. Povećanje električne provodljivosti može biti electrons. The increase in electrical conductivity may be due to the increase in grain size in HAZ and TMAZ, while the decrease in electrical conductivity is related to the fine - grained structure of the nugget.

The corrosion behavior of the friction-stir-welded joints of AA 2024-T351 and AA 5083-H111 was investigated and discussed by potentiodynamic measurements. The obtained results showed that AA 2024 has much lower corrosion resistance than AA 5083.

The highest corrosion resistance is in the root of the weld metal, which is a completely recrystallized area, with a fine- grained structure, gained due to elevated temperature resulting from intense plastic deformation during welding.

This phenomenon of the effect of temperature increase due to intense plastic deformation during welding on the corrosion resistance of welded joints should be the subject of further research.

posledica povećanja veličine zrna u HAZ i TMAZ, dok je smanjenje električne provodljivosti povezano sa sitnozrnom strukturom sočivastog šava.

Korozivno ponašanje spojeva zavarenih trenjem alatom AA 2024-T351 i AA 5083-N111 je ispitano i diskutovano potenciodinamičkim merenjima. Dobijeni rezultati su pokazali da AA 2024 ima mnogo manju otpornost na koroziju od AA 5083.

Najveća otpornost na koroziju je u korenu metala šava, koji je potpuno rekristalizovana površina, sa finozrnom strukturom, koja se dobija usled povišene temperature usled intenzivne plastične deformacije tokom zavarivanja.

Ovaj fenomen uticaja povećanja temperature usled intenzivne plastične deformacije pri zavarivanju na korozionu otpornost zavarenih spojeva treba da bude predmet daljih istraživanja.

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WELDABILITY BETWEEN STEEL TYPE 304H AND STEEL TYPE P91 FOR HIGH TEMPERATURE APPLICATIONS

ZAVARIVOST IZMEĐU ČELIKA TIPA 304H I ČELIKA TIPA P91 ZA PRIMENE NA VISOKIM TEMPERATURIMA

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Ključne reči: P91, 304H, zavarljivost, različit zavareni spoj

Abstract

This paper presents research about weldability between two dissimilar steels, martensitic steel P91 and 304H austenitic steel. Both materials are being preferred as a structural material for higher temperature applications due to their good mechanical properties at high temperatures. The mechanical properties at high temperature, such as tensile strength and creep resistance, are very important factors that ensure the application of materials. The P91 is modified martensitic Cr steel with higher amount of chromium which improves the higher temperature strength and molybdenum that increases creep resistance. On the other hand, the 304H represents advance austenitic stainless steel with controlled carbon content, which makes it ideal for applications requiring good mechanical properties at elevated temperatures. With increasing the demand of high efficiency in the power generation industry the high temperature applications usually require joints between advanced austenitic stainless steels and new class martensitic stainless steels in order to achieve the goal with the increased steam parameters. Therefore, this paper focuses on the weldability assessment between these two different steels and the characteristics of the weld metal.

Rezime

Ovaj rad predstavlja istraživanje zavarljivosti između dva različita čelika, martenzitnog čelika P91 i 304H austenitnog čelika. Oba materijala se preferiraju kao strukturalni materijali za primenu na višim temperaturama zbog svojih dobrih mehaničkih svojstva na visokim temperaturama. Mehanička svojstva na visokim temperaturama, kao što su zatezna čvrstoća i otpornost na puzanje, su veoma važni faktori koji obezbeđuju primenu materijala. P91 je modifikovani martenzitni Cr čelik sa većom količinom hroma koji poboljšava višu temperaturnu čvrstoću i molibdena koji povećava otpornost na puzanje. S druge strane, 304H predstavlja napredni austenitni nerđajući čelik sa kontrolisanim sadržajem ugljenika, što ga čini idealnim za aplikacije koje zahtevaju dobra mehanička svojstva na povišenim temperaturama. Sa povećanjem zahteva za visokom efikasnošću u industriji proizvodnje električne energije, aplikacije na visokim temperaturama obično zahtevaju spojeve između naprednih austenitnih nerđajućih čelika i nove klase martenzitnih nerđajućih čelika kako bi se postigao cilj sa povećanim parametrima pare. Stoga se ovaj rad fokusira na procenu zavarljivosti između ova dva različita čelika i karakteristike metala šava.

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1. Introduction

One of the reasons for using materials in high temperature applications are the ultra-super critical coal-fired power plants working with higher steam conditions. During electricity crises and the new methods for clean energy the use of coal needs to satisfy the environmental requirements and take care about the air pollutants [1]. Thus, the reduction of CO_2 emissions is by increasing the operating temperatures and pressure. The goal is to increase the efficiency and reduce the carbon footprint of new and existing fossil fired power plants.

The demand is being met with development of advanced materials that have enhanced high temperature mechanical properties, high temperature creep resistance and high temperature corrosion resistance. The utilization of the advanced materials in advanced power plant systems depends on their ability to be welded. Therefore, the weldability plays a significant role in the selection of materials.

The steel P91 is part of the group of heat-resistant steels and with its great mechanical properties: creep strength, thermal conductivity, high resistance to thermal fatigue, low coefficient of thermal expansion is suitable material for high temperature applications. The materials are used in new and revitalized power plants, for steam generators, fast breeder reactors and other heavy-duty applications [2, 3].

The austenitic 304H stainless steel is characterized by high heat resistance in elevated temperatures. For boiler super heater tubes experiencing 630°C, austenitic stainless steels 304H, 316 or 347H are used and for steam headers is used P91 steel. The heater tubes needs to be welded with the steam headers that are why these dissimilar welds become necessary.

2. Martensitic modified steel P91

ASME Boiler and Pressure Vessel Code, Section IX, [4] defines the creep strength-enhanced ferritic steels as a family of ferritic steels whose creep strength is enhanced by the creation of a precise condition of microstructure, specifically martensite or bainite, which is stabilized during tempering by controlled precipitation of temper-resistant carbides, carbo-nitrides or other stable and/or meta-stable phases.

Martensite-ferritic steels modified with Cr, Mo, V and Nb are the new creep resisting steels used in applications for high temperature and pressure systems. In the 9-12% Cr steels family first was developed 12%Cr steel that have high carbon content resulting with formation of martensite with high carbon content causing problems during welding. The next modified steel was with reduction of chromium and carbon content and modification by adding niobium. The martensitic steel was modified by adding vanadium and niobium and was created the steel P91 (A335) with improved creep resistance. The amount of Nb and V added enables the formation of submicron MX type carbonitride (M=Nb, V; X=C, N) with particle size lower than 0.1μm and the presence of these particles improves the creep resistance of the steel [5]. According to EN 10216-2 the P91 steel is defined as X10CrMoVNb9-1.

The chemical composition of steel P91 according to specification ASTM A355 is given in table 1 and it produces a fully martensitic structure figure 1 [6]. The martensite start temperature (M_s) is around 400°C and it finish at martensite temperature (M_f) around 200°C. The as-tempered microstructure consists of a fine prior austenite grains containing a lath-like tempered martensite structure with a high dislocation density that is stabilized by $M_{23}C_6$ carbides and MX (Nb, V) carbo-nitrides.

Table 1. *Chemical composition of steel P91 (in wt.%) according to ASTM A355*

Tabela 1. *Hemijski sastav čelika P91 (u tež.%) prema ASTM A355*

C	Mn	Si	P	S	Cr	Ni	Mo	V	Al	Nb	N	Fe
0,08 ÷0.12	0.30 ÷0.60	0.20 ÷0.50	max. 0.015	max. 0.010	8.00 ÷9.50	max. 0.40	0.85 ÷1.05	0.18 ÷0.25	max. 0.04	0.06 ÷0.10	0.03 ÷0.07	Bal.

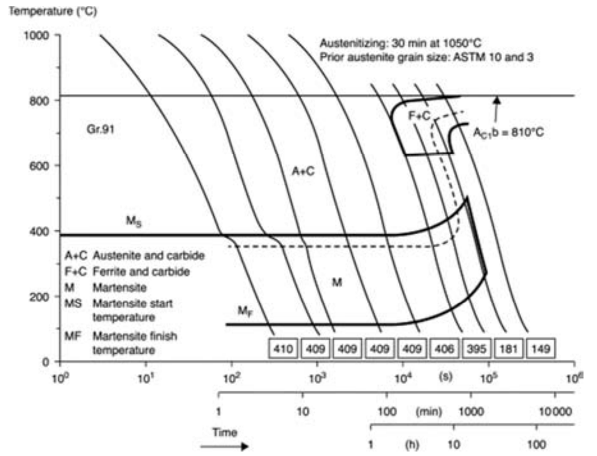

Figure 1. *Continuous cooling transformation curves for P91 steel [6]*

Slika 1. *Dijagram kontinuiranog hlađenja za čelik P91*

In figure 2 [6] is presented illustration of grade P91 structure, after normalizing and tempering [6]. Tempered martensitic structure is presented where $M_{23}C_6$ carbides (M is rich in Cr) are shown as lath, block, packet and prior austenite grain boundaries. The carbonitrides (MX) are distributed in the matrix within lath and at the boundaries. The coexistence of subgrains of lath and block and fine precipitates are responsible for the high creep strength of steel P91.

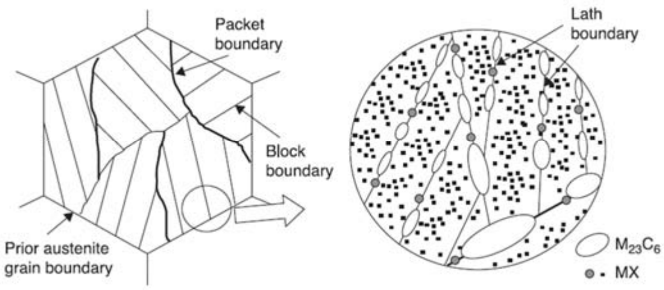

Figure 2. *Illustrated tempered martensitic structure of steel grade P91 [6]*

Slika 2. *Ilustracija kaljene martenzitne strukture čelika kvaliteta P91 [6]*

In order to exhibit a martensitic microstructure (figure 3), the chemical composition is balanced according to a formulation modified on the Chromium-Nickel Balance (CNB) where the elemental contents are in weight percent [7].

CNB = Cr+6Si+4Mo+1.5W+11V+5Nb+9Ti+12Al-40C-30N-4Ni-2Mn-1Cu

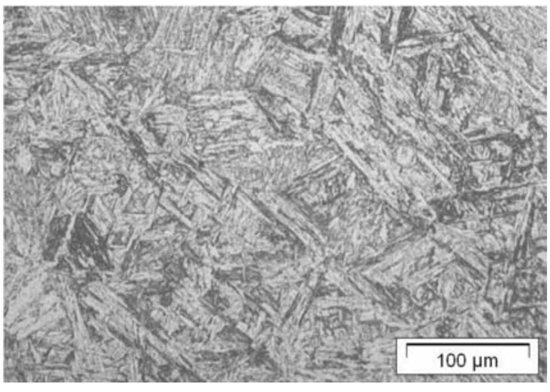

Figure 3. *Martensitic microstructure of P91 steel [8]*

Slika 3. *Martenzitna mikrostruktura čelika P91 [8]*

Depending on the value of CNB there are different quantities of delta ferrite, CNB less than 10, delta ferrite is not present, between 10 and 12 is not easily present and for CNB above 12 significant quantities of delta ferrite are present.

The mechanical properties of P91 steel at 20°C according to ASTM A355 are given in table 2. The mechanical properties are corresponding to the correctly carried out heat treatment: normalization at temperatures of 1040-1060°C for 1 hour, cooling in still air and tempering at temperatures of 760-780°C.

Table 2. *Mechanical properties of P91 steel at 20°C according to ASTM A355*

Tabela 2. *Mehanička svojstva čelika P91 na 20°C prema ASTM A355*

Ultimate tensile strength, MPa	**Yield stress, MPa**	**Charpy V notch impact strength, J**	**Brinell hardness**	**A_5, %**
585 min.	415 min.	40 min.	250 max.	17 min.

Due to its high creep resistance, comparable to 18-8 austenitic steel, P91 steel is qualified as low-alloy steel intended for service at elevated temperatures [2].

Brozda and Zeman [9] investigated the tendency of P91 steel to cracking as a result of heat treatment. Their investigation showed that the P91 steel is resistant to reheat cracking. It does not show any tendency to hot cracking and is resistant to reheat cracking in the coarse grain area of the HAZ. Their investigation was carried out on specimens subjected to the action of a simulated thermal cycle of maximum temperature T_{max} = 1250°C, each simulated thermal cycle was applied within the temperature range 450-650°C. The area reduction Z had a minimum value for each thermal cycle employed with test pieces treated in a thermal-strain simulator, lower than the permitted value of Z=20%.

3. Austenitic stainless steel 304H

Alloy 304H (1.4948) stainless steel is modification of alloy 304 where the carbon content is controlled to a range of max. 0.08% due to improved high temperature strength to elements exposed to temperature above 700°C (table 3). Austenitic stainless steel, Super 304H, according to EN designation X6CrNi18-10, is intended for applications with super heater and reheater tubes due to its special properties: excellent heat resistance in raised temperatures. The chemical composition, mechanical properties, weldability and corrosion/oxidation resistance make the steel ideal for high temperature applications.

Table 3. *Classification of creep resistant steels*

Tabela 3. *Klasifikacija čelika otpornih na puzanje*

Heat-resistant steels and special materials				
Bcc structure (body-cantered cubic)				Fcc structure (face-cantered cubic)
Up to 400°C	Up to 500°C	500 to 600°C	600 to 650°C	Above 700°C
Unalloyed	Alloyed		High-alloyed	
Ferritic-pearlitic steels, fine-grain structural steels	Mo-alloyed steel	Bainitic (martensitic) ferritic steels	Martensitic 9 to 12% chromium steels	Austenitic steels, Ni and Co-materials
P235GH	16Mo3	13CrMo4-5	X10CrMoVNb9-1	X8CrNiNb16-13
P355NH	18MnMo4-5	10CrMo9-10	X22CrMoV12-1	X8NiCr32-20
No extra proven methods; higher purity; fine grain	Tr-increase through molybdenum alloying	Carbide/nitride formation + tempering	Precipitation hardening + spec. heat treatment	Fcc structure with high crystal recovery temperature

In table 4 is given the chemical composition of super 304H steel. Due to its controlled carbon content to max. 0.08% provides improved high temperature strength and great creep strength when working in high temperature applications. It is used for applications up to 800°C for boilers, heat exchangers, pipelines, steam exhausts.

Table 4. *Chemical composition of super 304H steel (in wt. %)*

Tabela 4. *Hemijski sastav super čelika 304H (u tež. %)*

C	Mn	Si	P	S	Cr	Ni	N	Fe
0,04 ÷ 0.08	max. 2.00	max. 1.00	max. 0.035	max. 0.015	17.00 ÷ 19.00	8.00 ÷ 11.00	max. 0.11	Bal.

Minimum mechanical properties required by ASTM A213 & ASME SA-213 are given in table 5:

Table 5. *Mechanical Properties of 304H steel at 20°C according to ASTM A213 & ASME SA-213*

Tabela 5. *Mehanička svojstva čelika 304H na 20°C prema ASTM A213 i ASME SA-213*

Ultimate tensile strength, MPa	Yield stress, MPa	Modulus of elasticity kN/mm^2	Brinell hardness	A_5, %
515 min.	205 min	200	201 max.	40 min.

4. Type IV cracking in steel P91

The type IV cracking represent creep cracking and occurs during service in the heat affected zone of ferritic steel weldments. The new creep strength enhanced materials require special attention during welding so that they can retain their high temperature properties.

In Figure 4 are presented the different regions of heat affected zone with creep failure locations [10].

The welds of P91 steel are subjected to Type IV cracking even though it possesses good strength because of carbide precipitation. It occurs during service and it is located in the FG-HAZ (fine-grain) or IC-HAZ (intercritical grain). A Type-IV cracking in intercritical or fine grain HAZ was seen predominant in high temperature creep testing of this material resulting in pre-mature failure of the weld joints [10].

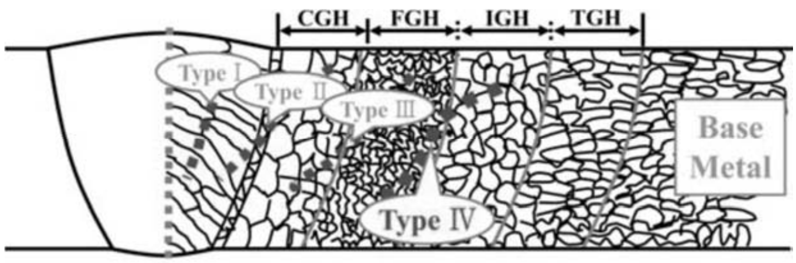

Figure 4. *Different damage type of heat affected zone with creep failure locations [10]*

Slika 4. *Različiti tip oštećenja zone uticaja toplote sa lokacijama lomova usled puzanja [10]*

To mitigate the type IV cracking research is carried out by Swaminathan et al. [11] by modification of alloy composition by addition of boron. Boron with controlled nitrogen added in P91 steel in the temperature range of 600-650°C has provided a better resistance to Type IV cracking in the material.

5. Welding between P91 and 304H

With the composition, microstructure, properties and process parameters are often determined the weldability of material. The American welding society handbook defines weldability as “the capacity of a material to be welded under the imposed fabrication conditions into a specific, suitable designed structure and to perform satisfactorily in the intended service [12]".

In figure 5 is presented schematic diagram of subzones in HAZ of P91 corresponding to the calculated equilibrium phase diagram [13].

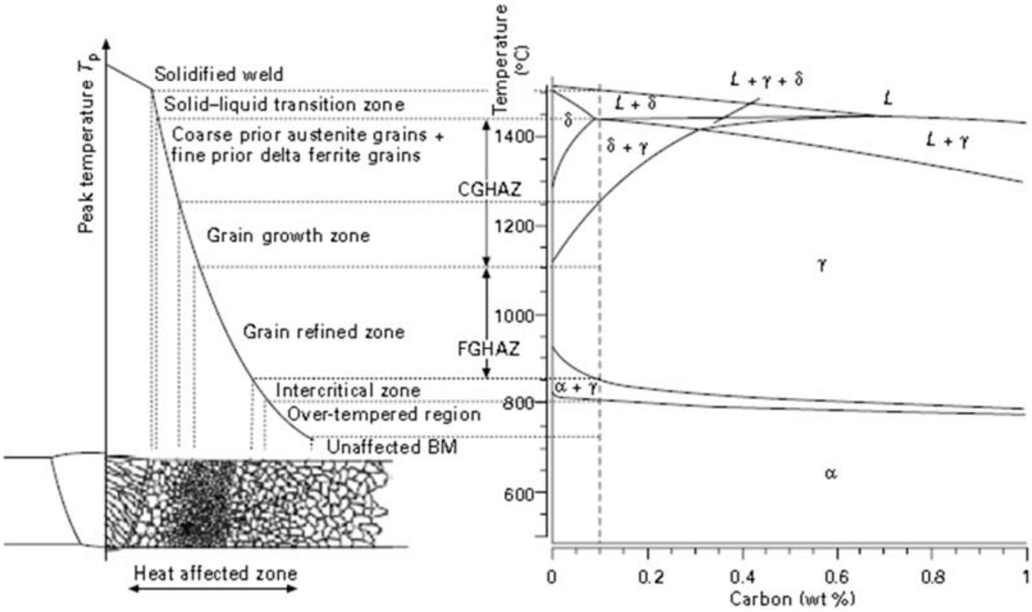

Figure 5. *Equilibrium phase diagram of steel P91 [13]*

Slika 5. *Ravnotežni fazni dijagram za čelik P91 [13]*

To maintain and assure quality welds special attention should be dedicated to temperature time cycle of steel P91 as shown in figure 6 [14]. All heat treatment operations are a key factor when welding P91 steel for obtaining the required toughness and creep resistance.

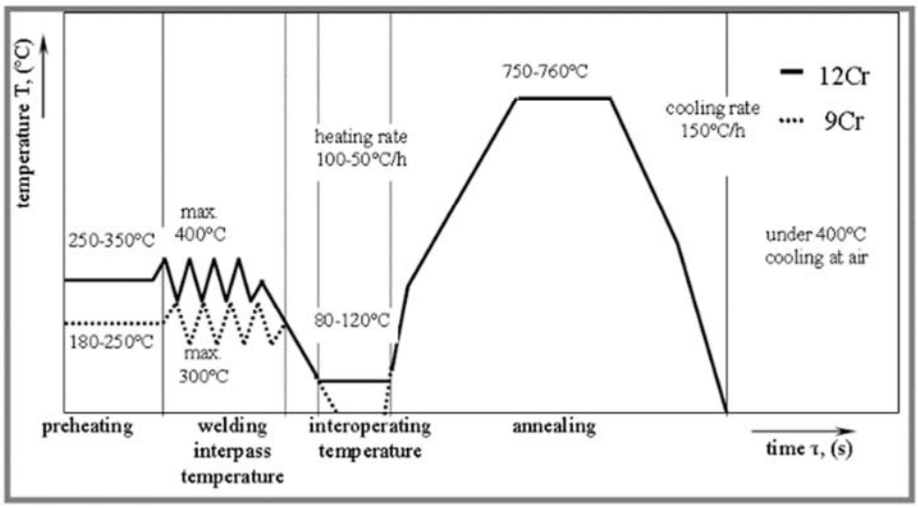

Figure 6. *Temperature time cycle during welding of martensitic 9 or 12% chromium steels [14]*

Slika 6. *Temperaturni ciklus u zavisnosti od vremena tokom zavarivanja martenzitnih čelika sa 9 ili 12% hroma [14]*

Joining of austenitic and martensitic steel structural heterogeneities may occur on the line of fusion of the welded joint at the points of their joining or during the operation at elevated temperatures [15]. Due to the mismatch between the coefficients of thermal expansion (CTE) and carbon migration, failures have been reported in these welds for many high temperature tubular applications [16].

When martensitic steel is welded with austenitic steel it is commonly used filler materials based on nickel. Filler materials based on nickel provide transition in coefficients of thermal expansion (CTE) and efficient for stopping the carbon diffusion from the low Cr material into high Cr material compared with conventional austenitic base material [16, 17]. When welding martensitic P91 steel with austenitic stainless 304H steel, the best way is to create a buffer layer on the low alloyed side of the joint. First the P91 steel needs to be buffered with nickel based alloy and followed by a heat treatment. Buffered and after heat treatment the P91 steel can be welded with the austenitic stainless 304H steel using filler materials with nickel based alloy without any further pre-heating and heat treatment after welding. Also, on the 304H steel is not performed any buffering to avoid transformation of austenite structure with cracks.

There are other several ways to perform the joining of dissimilar metals. One of them is rotary friction welding which does not involve melting and widens the choice of interlayer materials and also the ability to employ multiple interlayers to ensure a smoother change in CTE (coefficient of thermal expansion) between the two base materials [18]. And laser gas metal arc (hybrid) welding which together with FSW are presenting low heat input processes, with reduction in residual stresses and distortion and potential elimination of type IV cracking.

6. Creep strength of dissimilar metal welds

The creep phenomenon which occurs at elevated temperatures plays a major role in failure of welded joints. In ASME Section II, at elevated-temperature creep regions, the allowable stress is determined by several factors, such as 100% of the average stress to produce a creep rate of 0.01%1000h, 67% of the average stress and 80% of the minimum stress to cause rupture at the end of 100 000h [19].

In dissimilar weld between P91 steel and austenitic stainless steel, the creep was seen occurring on the P91 steel side. The joints are usually tested at temperature range of 550-700°C and it was observed that creep life of such joints is of P91 [20].

According to Zielinski at all [15], after 105 000h service of dissimilar welded joint at maximum working temperature of approximately 540°C there where revealed insignificant degree of degradation of the microstructure of base material and HAZ on the austenitic material side. The most degraded area was HAZ on the martensite steel side. The changes in the microstructure due to production of material, welding and heat treatment of the welded joint, contribute to accelerate damage during service and results in type IV cracking.

7. Conclusion

A very little research work is being carried out on base metal and weld metal between P91 steel and 304H austenitic stainless steel. In ultra-super critical power plants this type of joints are with an increasing demand because of their better performance. Therefore, for the accurate prediction of weld joints, its accuracy in service life is essential.

Zielinski at all [15] considered on the possibility of applying the PWHT of P91 steel in the lower acceptable range of annealing temperature due to the occurrence of degraded microstructure of the dissimilar welded joint within HAZ on the P91 steel side.

For achieve good microstructural welded joint between martensitic P91 steel and austenitic 304H steel, it is necessary to respect all the recommendations and parameters for welding, post weld heat treatment and the use of a suitable nickel-based filler material.

7. Zaključak

Veoma malo istraživačkog rada se sprovodi na osnovnom metalu i metalu šava zavarenih spojeva između P91 čelika i 304H austenitnog nerđajućeg čelika. U ultra-super kritičnim elektranama ova vrsta spojeva ima sve veću primenu zbog svojih boljih osobina. Zbog toga je neophodno pouzdano projektovanje zavarenih spojeva, uzimajući u obzir tačno predviđanje životnog veka takvog spoja.

Zielinski [15] je razmatrao mogućnost primene termičke obrade nakon zavarivanja kod čelika P91 u nižem prihvatljivom opsegu temperature žarenja, zbog pojave degradirane mikrostrukture raznorodnog zavarenog spoja unutar ZUTa na strani čelika P91.

Da bi se postigla dobra mikrostruktura zavarenog spoja između martenzitnog P91 čelika i austenitnog 304H čelika, neophodno je poštovati sve preporuke i parametre za zavarivanje, termičku obradu nakon zavarivanja i upotrebu odgovarajućeg dodatnog materijala na bazi nikla.

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DRUGI POZIV

12. MEĐUNARODNO ZNANSTVENO-STRUČNO SAVJETOVANJE SBZ 2023

„STROJARSKE TEHNOLOGIJE U IZRADI ZAVARENIH KONSTRUKCIJA I PROIZVODA, SBZ 2023."

SLAVONSKI BROD (26. i 27. 04. 2023.) i POŽEGA (28. 04. 2023.)

TEME

Nove tehnologije i materijali
Postupci zavarivanja
Robotizacija i automatizacija
Posude pod tlakom
Zavarivanju srodne tehnike (toplinska rezanja, lemljenje, naštrcavanje materijala …)
Ostale strojarske tehnologije (OMD, lijevanje, površinska zaštita …)
Izrada zavarenih konstrukcija
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Pouzdanost i sigurnost zavarenih proizvoda i konstrukcija
Zavarljivost materijala
Dodatni materijali za zavarivanje
Oprema za zavarivanje i srodne postupke
Kadrovi i obrazovanje u zavarivanju
Metalurgija
Ekologija i zaštita na radu
Ekonomski aspekti kod izrade strojarskih konstrukcija (tehnologičnost, održavanje …)

VAŽNI DATUMI

22. veljače 2023.	Prijava sažetaka
08. ožujka 2023.	Obavijest o prihvaćanju sažetaka
10. travnja 2023.	Krajnji rok za slanje radova
17. travnja 2023.	Krajnji rok za prijavu sudionika

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DATUM I MJESTO ODRŽAVANJA

26. i 27. 04. 2023. Slavonski Brod, Sveučilište u Slavonskom Brodu (Đuro Đaković - Ulica 108. brigade ZNG)
28. 04. 2023. Požega, tvrtka Magma

KOTIZACIJA

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Društvo za tehniku zavarivanja Slavonski Brod	Univerza v Mariboru Fakulteta za strojništvo	Sveučilište u Slavonskom Brodu	The Faculty of Materials Science and Technology in Trnava	Đuro Đaković Grupa Slavonski Brod

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U skladu s Programom stručnog usavršavanja Hrvatske komore inženjera strojarstva, sudjelovanje u radu skupa boduje se s određenim brojem bodova.

NAPOMENA: Svi prikupljeni osobni podaci su zaštićeni od zloupotreba i isti se obrađuju u skladu sa GDPR-om.

Miloš Pavlović[1,a], Vladan Jeremić[1,b], Nenad Rajić[1,c]

PONAŠANJE MATERIJALA X10CrMoVNb9-1 PRILIKOM PONOVLJENOG TERMIČKOG TRETMANA TOKOM MONTAŽE

BEHAVIOR OF X10CrMoVNb9-1 MATERIAL DURING REPETED THERMAL TREATMENT DURING INSTALLATION

Stručni rad / Professional paper

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Keywords: X10CrMoVNb9-1, heat treatment, mechanical properties, microstructure.

Rezime

U radu su prikazani uporedni rezultati ispitivanja uzoraka kolektora od čelika X10CrMoVNb9-1. Ispitivan je uticaj ponovljene termičke obrade na osobine materijala, pri čemu su uzorci prošli različit broj termičkih ciklusa. Ovaj materijal se najčešće koristi za cevi i cevne priključke otporne na visoke pritiske i temperature. Čelik se odlikuje visokim svojstvima termičke čvrstoće, zbog čega se koristi u termoelektranama za cevi pregrejača, kolektora kao i za cevi parovoda visokog pritiska. Ima primenu i pri visokim temperaturama čak do 600°C. Cilj ovog rada je ponašanje materijala prilikom ponovljene termičke obrade koja se tokom montaže cevovoda često dešava, a uzrokovana je popravkom grešaka u zavarenom spoju, pogrešnom montažom cevovoda i sličnim postupcima.

Abstract

The paper presents comparative test results of X10CrMoVNb9-1 steel collector samples. The influence of repeated heat treatment on the properties of the material was investigated, and the samples underwent a different number of thermal cycles. This material is most often used for pipes and pipe connections resistant to high pressures and temperatures. Steel is characterized by high thermal strength properties, which is why it is used in thermal power plants for superheater pipes, collectors as well as for high pressure steam pipes. It can be used even at high temperatures up to 600°C. The aim of this paper is the behaviour of the material during repeated heat treatment, which often occurs during the installation of the pipeline, and is caused by the repair of defects in the welded joint, incorrect installation of the pipeline and similar procedures.

Rad je u izvornom obliku objavljen u Zborniku radova sa 32. Savetovanja sa međunarodnim učešćem „Zavarivanje 2022“ održanog na Tari, Srbija od 12. do 15. oktobra 2022. godine.

1. Uvod

Materijal X10CrMoVNb9-1 spada u grupu visokolegiranih čelika sa utvrđenim osobinama na povišenim temperaturama. Čelik je razvijen 1974 godine u OAK RIDGE NL u SAD sa oznakom P91/T91, a njegova primena u termoelektranama je počela početkom 90-tih godina prošlog veka. Ovaj materijal se najčešće koristi za cevi i cevne priključke otporne na visoke pritiske i temperature. Čelik se odlikuje visokim svojstvima termičke čvrstoće, zbog čega se koristi u termoelektranama za cevi pregrejača, kolektora kao i za cevi parovoda visokog pritiska. Ima primenu i pri visokim temperaturama čak do 600°C. Hemijski sastav i mehaničke osobine [1] prikazani su u tabelama 1 i 2.

Tabela 1. *Hemijski sastav X10CrMoVNb9-1 prema SRPS EN ISO 10216-2 [1]*

Table 1. *Chemical composition of the X10CrMoVNb9-1 according to SRPS EN ISO 10216-2 [1]*

	SADRŽAJ ELEMENATA (%)								
	C	**Mn**	**Si**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Al**
Zahtev SRPS EN ISO 10216-2	0.08 do 0.12	0.30 do 0.60	0.20 do 0.50	max 0.020	max 0.010	8.0 do 9.5	0.85 do 1.05	≤0.40	≤0.04 0
	Cu	**Nb**	**V**	**N**	Fe				
	≤0.30	0.06 do 0.10	0.18 do 0.25	0.030 do 0.070	ostatak				

Tabela 2. *Mehaničke osobine X10CrMoVNb9-1 prema SRPS EN ISO 10216-2 [1]*

Table 2. *Mechanical properties of the X10CrMoVNb9-1 according to SRPS EN ISO 10216-2 [1]*

	Temperatura	Napon tečenja Re_H /$Rp_{0.2}$	Zatezna čvrstoća Rm	Izduženje A	Energija loma KV
Zahtev SRPS EN ISO 10216-2	(°C)	(N/mm^2)	(N/mm^2)	(%)	(J)
	20	min 450	630-830	min 19	27
	600	min 215	/	/	/

Uticaj legirajućih elemenata na osobine materijala je višestruk. Hrom kao glavni legirajući element povećava prokaljivost, korozionu otpornost i otpornost na oksidaciju usled dejstva pregrejane pare. Kako je Cr karbidotvorni element, prisutan je u sastavu karbida tipa $M_{23}C_6$, koji se izdvajaju iz metalne matrice tokom termičke obrade. Molibden povećava prokaljivost i ulazi u sastav čvrstog rastora i na taj način podiže čvrstoću materijala. V i Nb su veoma važni zbog toga što imaju visok afinitet prema C i N, i tokom termičke obrade se izdvajaju u obliku fino dispergovanih čestica tipa MX koje povećavaju otpornost na puzanje usled toga što predstavljaju prepreke za kretanje dislokacija. Azot preko čvrstog rastvora podiže čvrstoću materijala i bitna je komponenta za formiranje karbonitrida sa V i Nb koji povećavaju otpornost na puzanje. Kao austenitizator, N usporava nastanak δ-ferita tokom procesa termičke obrade. Kako Ni snižava Ac_1 temperaturu, a iznad sadržaja 0,6 % snižava i otpornost na puzanje, potrebno je njegov sadržaj smanjiti na max 0,3 % [2].

Što se tiče termičke obrade, manje debljine materijala se isporučuju kao +NT (normalizacija i otpuštanje), dok se veće debljine materijala (debljine iznad 10 mm) isporučuju u stanju +QT (kaljenje i otpuštanje) [1]. Optimalna temperatura sa koje se radi normalizacija ili kaljenje je u opsegu od 1060°C do 1080°C. Na nižim temperaturama ne dolazi do potpunog rastvaranja karbida i karbonitrida i prelaska svih elemenata u γ-čvrsti rastvor, dok su više temperature nepoželjne zbog velikog rasta zrna i nastanka δ-ferita. Tokom hlađenja na vazduhu ili u ulju, sa pomenute temperature, dolazi do austenitno – martenzitne transformacije i formiranja presićenog čvrstog rastvora. Žarenjem u temperaturnom opsegu od 730°C do 780°C [3, 4] i kasnijim kontrolisanim hlađenjem, dolazi do otpuštanja mikrostrukture i izdvajanja precipitata unutar i po granicama zrna.

Mehanizam izdvajanja precipitata je šematski prikazan [2]:

$M_3C \rightarrow (M_{23}C_6 + M_2X) \rightarrow (M_{23}C_6 + MX)$

Kako su u pitanju difuzioni procesi na koje utiču temperatura i vreme, prečnik izdvojenih čestica se računa prema sledećoj formuli:

$d = \alpha(t \cdot D_0 \exp(-Q/RT))^{0,5}$

α – koeficijent koji je u funkciji hemijskog sastava matrice

t – vreme (s)

D_0 – konstanta (m^2/s)

Q – energija aktivacije difuzije (J/mol)

R – univerzalna gasna konstanta (8,31 J/mol K)

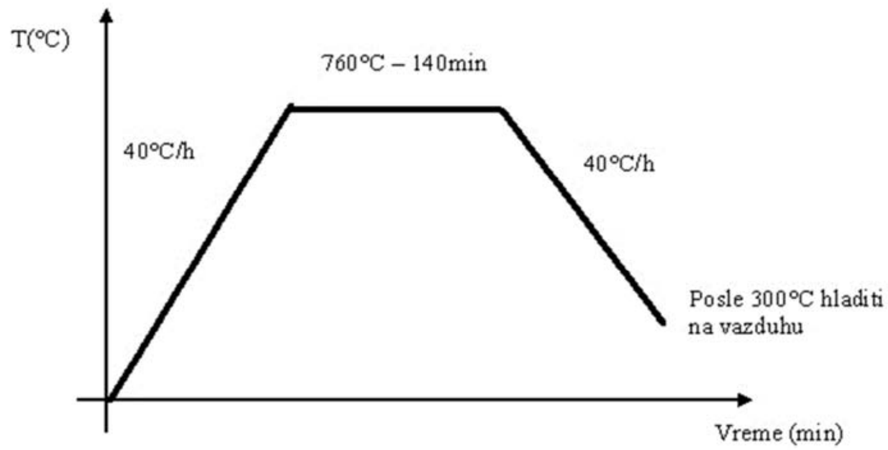
T – temperatura (K)

Čestice tipa $M_{23}C_6$ se izdvajaju po granicama primarnih austenitnih zrna, dok se čestice tipa MX fino disperguju unutar metalne matrice. Preporučeno vreme držanja na temperaturi žarenja je 2,5 min/mm [3, 4, 5]. Žarenje u temperaturnom intervalu između Ac1 i Ac3 može dovesti do pojave neotpuštenog martenzita u mikrostrukturi, a produženo vreme držanja dovodi do koalescencije karbida i karbonitrida i smanjenja otpornosti na puzanje.

Mikrostruktura nakon pravilno izvedene termičke obrade je otpušteni martenzit sa fino izdvojenim česticama tipa $M_{23}C_6$ po granicama zrna i subzrna i česticama tipa MX koje su fino dispergovane u metalnoj matrici. Ova mikrostruktura obezbeđuje najbolji odnos između čvrstoće i žilavosti, kao i najveću otpornost na puzanje [2, 6, 7].

2. Eksperiment

Cilj ovog rada je ispitivanje ponašanja materijala prilikom ponovljene termičke obrade, koja se tokom montaže cevovoda često dešava, a uzrokovana je popravkom grešaka u zavarenom spoju, pogrešnom montažom cevovoda i sličnim postupcima. U tu svrhu, deo kolektora, Ø 508 x 55 mm, je isečen na tri jednaka dela koji su podvrgnuti termičkom tretmanu, jedan, dva i tri puta sukcesivno. Režim termičke obrada uzoraka je prikazana na dijagramu (slika 1) i istovetan je sa termičkom obradom koja se sprovodi na terenu prilikom montaže cevovoda prema standardu [3, 4].



Slika 1. *Dijagram termičkog tretmana X10CrMoVNb9-1 korišćen u eksperimentu*

Figure 1. *Heat treatment diagram of X10CrMoVNb9-1 used in the experiment*

Slika 2. Peć ST-01 korišćena u eksperimentu

Figure 2. Furnace ST-01 used in the experiment

Termička obrada je izvedena u peći, proizvođača ST Elektrik, marka ST-01 sa 6-kanalnim pisačem, koja je prikazana na slici 2.

Nakon završetka termičke obrade, iz uzoraka su isečene epruvete i pripremci za mehaničko-metalografska ispitivanja. Epruvete su isečene transferzalno u odnosu na osu kolektora.

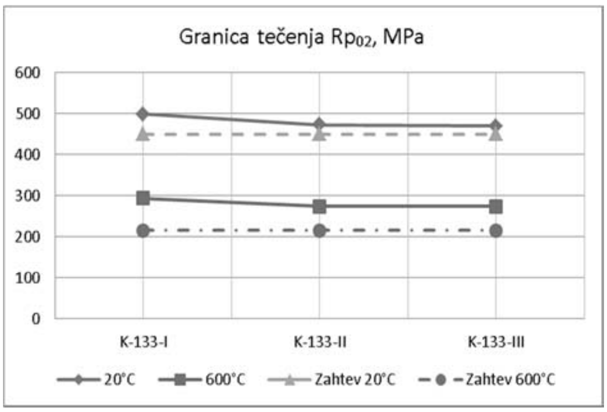
3. Rezultati i diskusija

Kako bi se procenio uticaj ponovljene termičke obrade na materijal X10CrMoVNb9-1, epruvete koje su isečene iz uzoraka kolektora su ispitane na zatezanje na sobnoj temperaturi i na 600°C [8, 9]. Ispitivanje na zatezanje je izvršeno na univerzalnoj mašini za ispitivanje, model FR-B 295/25M, opsega opterećenja 250 KN, klase 0,5. Za ispitivanje na sobnoj temperaturi, korišćen je ekstenziometar dugačkog hoda, tip MFX 500 – B, dok je za ispitivanje zatezanjem na 600°C korišćen ekstenziometar za ispitivanje na povišenim temperaturama, tip MFHT 5, i peć za ispitivanje na povišenim temperaturama, tip KD 200, opsega od 200°C do 900°C. Rezultati ispitivanja zatezanjem su prikazani u tabeli 3 i slikama 3, 4 i 5.

Tabela 3. *Rezultati ispitivanja zatezanjem uzoraka kolektora koji su prošli različit broj termičkih tretmana*

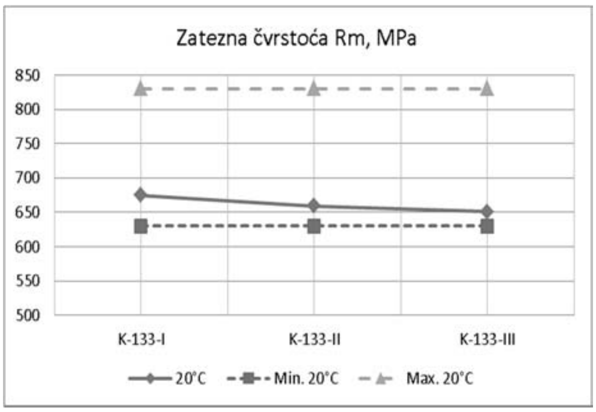
Table 3. *Tensile test results of collector samples that underwent different number of thermal treatments*

Ispitivanje zatezanjem					
Metoda: SRPS EN ISO 6892-1; 2020 [7]; SRPS EN ISO 6892-2: 2018, metoda B [8]					
Uređaj: univerzalna kidalica: Fore Test, FR-B 295/25M					
Uzorak br.	Mere epruvete	Temperatura	Napon tečenja $Re_H/Rp_{0.2}$	Zatezna čvrstoća Rm	Izduženje A
	(mm)	(°C)	(N/mm^2)	(N/mm^2)	(%)
K-133-I	Ø 9,99	20	496	675	24,44
	Ø 10,00	20	502	674	22,92
	Ø 7,99	600	284	/	/
	Ø 8,00	600	302	/	/
K-133-II	Ø 9,99	20	475	660	24,71
	Ø 10,00	20	468	658	25,88
	Ø 8,01	600	271	/	/
	Ø 7,99	600	277	/	/
K-133-III	Ø 10,01	20	471	653	24,68
	Ø 10,00	20	466	649	24,46
	Ø 8,01	600	274	/	/
	Ø 8,02	600	273	/	/
Zahtev SRPS EN ISO 10216-2		20	min 450	630-830	min 19
		600	min 215	/	/



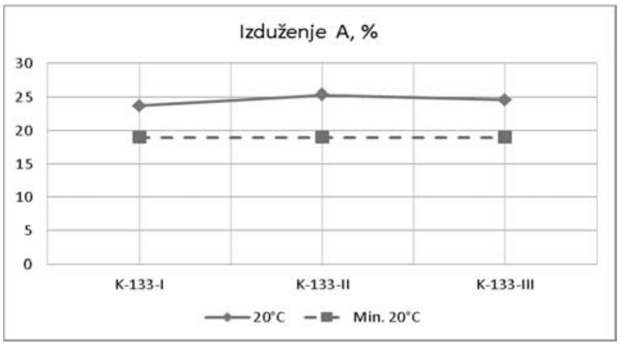
Slika 3. Rezultati ispitivanja zatezanjem, Rp_{02}, MPa

Figure 3. Tensile test results, Rp_{02}, MPa



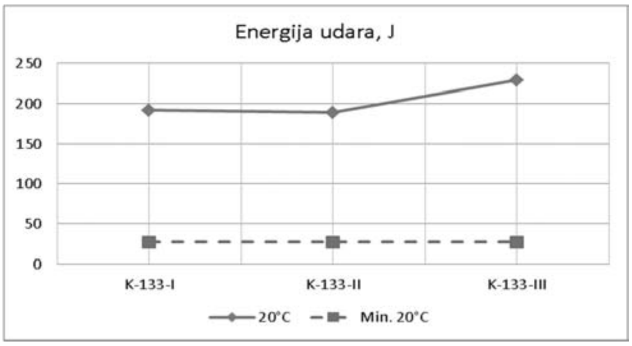
Slika 4. Rezultati ispitivanja zatezanjem, Rm, MPa

Figure 4. Tensile test results, Rm, MPa



__Slika 5.__ Rezultati ispitivanja zatezanjem, izduženje A, %

__Figure 5.__ Tensile test results, elongation A, %



__Slika 6.__ Rezultati ispitivanja energije udara

__Figure 6.__ Impact energy test results

Rezultati ispitivanja zatezanjem na sobnoj temperaturi su zadovoljili zahteve standarda SRPS EN ISO 10216-2 za sve ispitane epruvete. Primetno je da sa povećanjem broja termičkih tretmana blago opadaju vrednosti mehaničkih osobina ($Rp_{0,2}$, Rm), dok se vrednosti prekidnog izduženja (A) povećavaju, što je karakteristika duktilnosti materijala. Trend pada granice tečenja na 600°C sa povećanjem broja termičkih tretmana je takođe uočljiv, iako su sve izmerene vrednosti iznad kriterijuma propisanih standardom.

Ispitivanje energije udara je sprovedeno na Šarpi klatnu VEB PS 30 na standardnim epruvetama sa zarezom „2V” na sobnoj temperaturi u skladu sa standardom SRPS EN ISO 148-1: 2017 [10]. Rezultati ispitivanja energije udara su prikazani u tabeli 4 i na slici 5.

__Tabela 4.__ Rezultati ispitivanja energije udara uzoraka kolektora koji su prošli različit broj termičkih tretmana

__Table 4.__ Impact energy test results of collector samples that have undergone different thermal treatments

Ispitivanje udarom				
Metoda: SRPS EN ISO 148 – 1: 2017 [10]			Uređaj: Šarpijevo klatno VEB PS 30	
Uzorak br.	Mere epruvete	Temperatura	Energija udara KV “2V”	Srednja vrednost
	(mm)	(°C)	(J)	(J)
K-133-I	9,97 x 9,96 x 54,60	24	208	192
	10,09 x 10,01 x 54,97	24	187	
	10,05 x 10,04 x 54,87	24	181	
K-133-II	9,9 x 9,98 x 54,65	24	176	189
	9,98 x 9,99 x 55,08	24	180	
	9,98 x 9,98 x 55,2	24	212	
K-133-III	10,03 x 10,00 x 55,09	24	273	229
	10,09 x 10,00 x 55,25	24	209	
	10,03 x 10,02 x 55,17	24	207	
Zahtev SRPS EN ISO 10216-2		20	27	

Srednja vrednost energije udara tri epruvete je približno jednaka za uzorke koji su jedanput i dva puta prošli termički tretman, dok je za uzorak koji je tri puta termički tretiran vrednost energije udara nešto viša.

Karakteristika svih ispitanih epruveta je duktilan izgled loma, slike 7, 8 i 9. Sve izmerene vrednosti energije udara su značajno iznad minimalno propisane vrednosti za čelik X10CrMoVNb9-1 prema SRPS EN ISO 10216-2.

Slika 7. *Izgled preloma epruveta iz uzorka kolektora koji je jedanput termički tertiran prema dijagramu termičke obrade, K-133-I.*

Slika 7. *Izgled preloma epruveta iz uzorka kolektora koji je jedanput termički tertiran prema dijagramu termičke obrade, K-133-I. (fali prevod)*

Slika 8. *Izgled preloma epruveta iz uzorka kolektora koji je jedanput termički tertiran prema dijagramu termičke obrade, K-133-II.*

Slika 8. *Izgled preloma epruveta iz uzorka kolektora koji je jedanput termički tertiran prema dijagramu termičke obrade, K-133-II. (fali prevod)*

Slika 9. *Izgled preloma epruveta iz uzorka kolektora koji je jedanput termički tertiran prema dijagramu termičke obrade, K-133-III.*

Slika 9: Izgled preloma epruveta iz uzorka kolektora koji je jedanput termički tertiran prema dijagramu termičke obrade, K-133-III. (fali prevod)

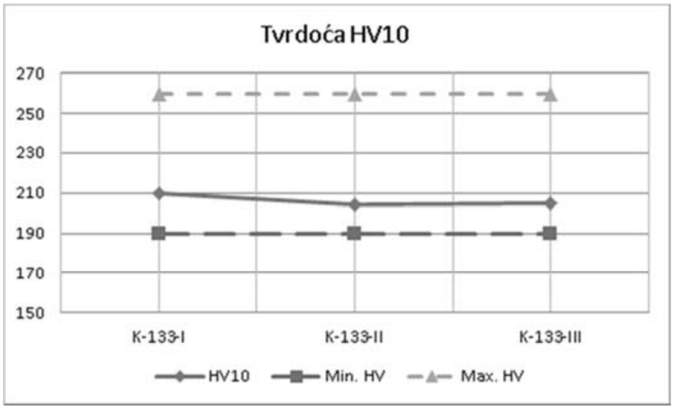
Tvrdoća je izmerena po poprečnom preseku uzoraka, na uređaju za merenje makro tvrdoće WILSON VH1150. Korišćena je metoda merenja tvrdoće po Vikersu [11, 12], sa opterećenjem 98,1 N (HV10). Rezultati ispitivanja tvrdoće su prikazani u tabeli 5 i na slici 10.

Tabela 5. *Rezultati ispitivanja tvrdoće uzoraka kolektora koji su prošli različit broj termičkih tretmana*

Table 5. *Test results of the hardness of collector samples that underwent different number of thermal treatments*

Ispitivanje tvrdoće											
Metoda: SRPS EN ISO 6507 – 1: 2018 [11]						Uređaj: WILSON VH1150					
Uzorak br.	Broj merenja										Srednja vrednost
	1	2	3	4	5	6	7	8	9	10	
K-133-I	206	211	209	212	215	212	215	215	206	205	210 HV
	1	2	3	4	5	6	7	8	9	10	
K-133-II	206	205	212	209	211	209	206	198	195	197	204 HV
	1	2	3	4	5	6	7	8	9	10	
K-133-III	197	201	201	209	209	214	211	209	204	197	205 HV
Zahtev VGB – R 508L [12]		190 HV ÷ 260HV									

Izmerene vrednosti tvrdoća su najviše na uzorku koji je prošao jedan termički tretman, dok su na preostalim uzorcima, koji su termički tretirani, dva i tri puta, te vrednosti malo niže. Kako standardom SRPS EN ISO 10216-2 [1] nisu propisane vrednosti tvrdoća za materijal X10CrMoVNb9-1, kao kriterijum prihvatljivosti su uzete vrednosti 190 HV ÷ 260HV prema VGB – R 508L [13]. Može se uočiti da su srednje vrednosti tvrdoća, za sva tri uzorka zadovoljila zadati kriterijum. Minimalno propisana vrednost tvrdoće od 190 HV, obezbeđuje da u strukturi nema nepoželjnog ferita.

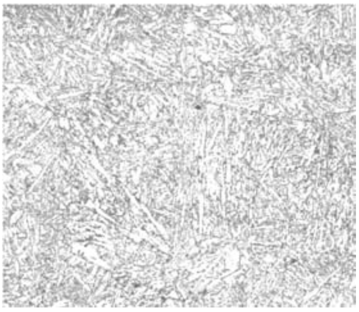


Slika 10. *Dijagram tvrdoće HV10 ispitivanih uzoraka.*

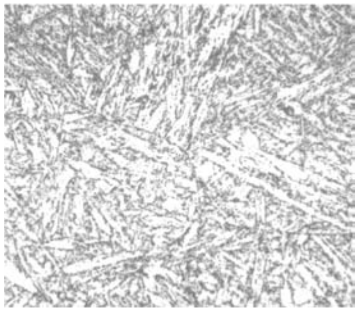
Figure 10. *HV10 hardness diagram of the tested samples.*

Metalografska mikrostrukturna ispitivanja su izvršena na pripremcima koji su isečeni iz uzoraka kolektora koji su podvrgnuti različitom broju termičkih tretmana. Pre ispitivanja je urađena priprema na poluautomatskom uređaju za pripremu metalografskih uzoraka, tip ECOMET 30 Grinder&Polisher, single semi-automatic i pripremci su nagriženi u reagensu za razvijanje mikrostrukture poboljšanih čelika, kojima pripada i čelik X10CrMoVNb9-1.

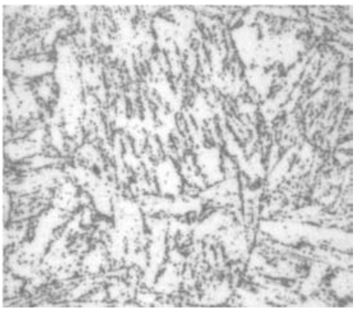
Kao reagens je korišćena pikrinsko-sona kiselina [14]. Ocena mikrostrukture je izvedena uz pomoć optičkog mikroskopa AXIO SCOPE A1 sa digitalnom kamerom, AXIO CAM Icc1 i softverom Axiovision lite. Za posmatranje mikrostrukture, korišćena su uvećanja 200x, 500x i 1000x. Karakteristične mikrostrukture prikazane su na slikama 11, 12 i 13.



a) OM, 200:1



b) OM, 500:1



c) OM, 1000:1

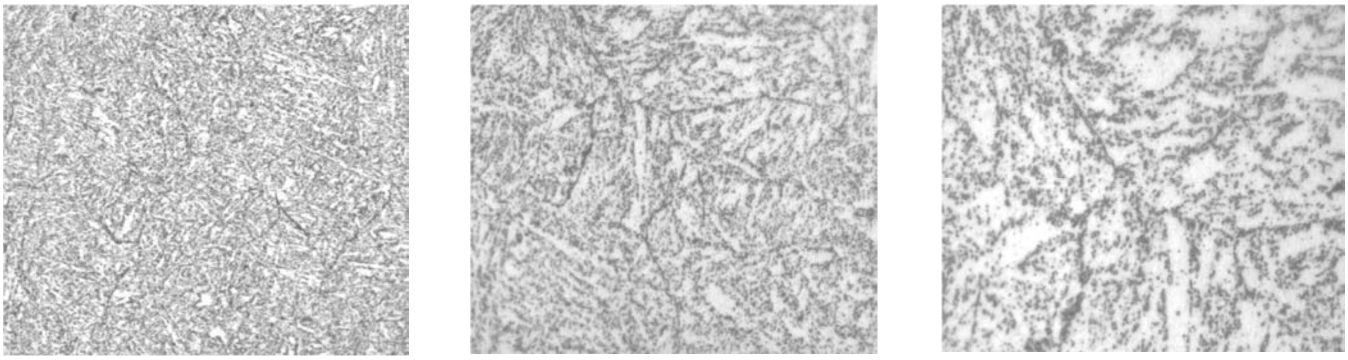
Slika 11. *Mikrostruktura uzorka K-133-I koji je jedanput termički tretiran*

Figure 11. *Microstructure of the K-133-I sample that was thermally treated once*

a) OM, 200:1 b) OM, 500:1 c) OM, 1000:1

***Slika 12.** Mikrostruktura uzorka K-133-II koji je dva puta termički tretiran*

***Figure 12.** Microstructure of sample K-133-II that was thermally treated twice*



a) OM, 200:1 b) OM, 500:1 c) OM, 1000:1

***Slika 13.** Mikrostruktura uzorka K-133-III koji je tri puta termički tretiran*

***Figure 13.** Microstructure of the K-133-III sample that was thermally treated three times*

Mikrostrukturu ispitanih uzoraka kolektora čini otpušteni martenzit sa precipitatima koji su izdvojeni unutar i po granicama primarnih austenitnih zrna i mala količina zaostalog austenita, što predstavlja poželjnu mikrostrukturu [6]. Bitno je napomenuti da se korišćenom optičkom mikroskopijom ne može utvrditi tačan sastav izdvojenih čestica, već je pretpostavka da se po granicama zrna nalaze karbidne čestice tipa $M_{23}C_6$, gde M predstavlja Cr, dok su unutar zrna fino dispergovane čestice tipa MX, gde M predstavljaju elementi V i Nb, dok je X zamenjen sa C i N, što znači da su u pitanju precipitati karbonitrida. Za potpuniju analizu potrebno je uključiti i neku od tehnika elektronske mikroskopije (SEM, TEM). Poređenjem mikrostruktura uzoraka koji su prošli različit broj termičkih tretmana, zapaža se da je sa povećanjem broja termičkih tretmana došlo do manje koalescencije izdvojenih čestica, naročito onih koje su izdvojene po granicama zrna, tako da najdisperzniju mikrostrukturu ima uzorak koji je prošao jedan termički ciklus.

4. Zaključak

U radu su prikazani uporedni rezultati ispitivanja uzoraka kolektora od čelika X10CrMoVNb9-1. Ispitivan je uticaj ponovljene termičke obrade na osobine materijala, pri čemu su uzorci prošli različit broj termičkih ciklusa. Uočen je trend, da sa povećanjem broja termičkih ciklusa mehaničke osobine (granica tečenja, zatezna čvrstoća i tvrdoća) opadaju, dok vrednosti koje su pokazatelj duktilnosti materijala (energija udara i izduženje) rastu. Taj pad mehaničkih osobina nije veliki i može se objasniti činjenicom da sa povećanjem broja

4. Conclusion

The paper presents the comparative results of testing collector samples made of steel X10CrMoVNb9-1. The influence of repeated heat treatment on the properties of the material was investigated, with the samples undergoing different number of thermal cycles. A trend was observed, that with an increase in the number of thermal cycles, the mechanical properties (yield strength, tensile strength and hardness) decrease, while the values that are an indicator of the material's ductility (impact energy and elongation) increase. The drop termičkih tretmana dolazi do male promene u veličini i disperziji karbidnih i karbonitridnih precipitata [12], što je metalografski delimično i potvrđeno, korišćenjem tehnike optičke mikroskopije. Uprkos tome što je konstatovan mali pad mehaničkih osobina, sve izmerene vrednosti su u granicama propisanim standardom SRPS EN ISO 10216-2 za čelik X10CrMoVNb9-1, što upućuje na zaključak da je na pomenutom materijalu moguće izvoditi termičku obradu veći broj puta, striktno se pridržavajući zadatih parametara.

U ovom radu je ispitan uticaj ponovljene termičke obrade na osobine osnovnog materijala. Kako se tokom montaže cevovoda javlja potreba za korišćenjem zavarivanja, interesantno bi bilo istražiti uticaj ponovljenog termičkog ciklusa i na delove zavarenog spoja koji nisu bili obuhvaćeni ovim radom (zona uticaja toplote i metal šava).

in mechanical properties is not great and can be explained by the fact that with an increase in the number of thermal treatments, there is a small change in the size and dispersion of carbide and carbonitride precipitates [12], which was partially confirmed metallographically, using the optical microscopy technique. Despite the fact that a small drop in mechanical properties was noted, all measured values are within the limits prescribed by the SRPS EN ISO 10216-2 standard for steel X10CrMoVNb9-1, which leads to the conclusion that it is possible to perform heat treatment on the mentioned material a large number of times, strictly adhering to given parameters.

In this work, the influence of repeated heat treatment on the properties of the base material was examined. As the need to use welding during pipeline installation, it would be interesting to investigate the effect of repeated thermal cycles on parts of the welded joint that were not included in this work (heat-affected zone and weld metal).

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