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WELDABILITY OF AUSTENITIC HEAT RESISTANT STEELS
ZAVARLJIVOST VATROOTPORNIH AUSTENITNIH ČELIKA

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Ključne reči: austenitni vatrootporni čelik, krupno zrnasta struktura, GTAW, metal šava

Abstract

Austenitic heat-resisting steels are used in a wide range of industries. Their use is motivated not only by their excellent mechanical properties but also due to their excellent resistance to corrosion and the ability to withstand high temperatures. These steels are prone to defects and challenges during welding because of their high content of Cr, Ni, Al, and other alloying elements. The main problem is the high heat energy input, which causes differences in structure between the welded joint and the surrounding area. The relatively high heat input and cooling in the heat-affected zone (HAZ) causes carbide formation and, as a result, coarse grain formation, which is undesirable for obtaining favourable mechanical properties. This study investigates the weldability of two heat-resistant austenitic steels (EN X12CrNi23-13 and EN X8CrNi25-21) using the gas tungsten arc welding (GTAW) technique. Both materials are separately analyzed, and the results are discussed in terms of potential welding techniques and technological plan improvements to achieve high-quality welds without pre-heating or any other additional post-welding heat treatment, which is important for the industry because it can reduce production time and cost.

Rezime

Austenitni vatrootporni čelici koriste se u raznim oblastima industrije. Njihova upotreba je motivisana ne samo odličnim mehaničkim svojstvima već i odličnom otpornošću na koroziju i sposobnošću da izdrže visoke temperature. Ovi čelici su skloni defektima i izazovima tokom zavarivanja zbog visokog sadržaja Cr, Ni, Al i drugih legirajućih elemenata. Glavni problem je veliki unos energije zavarivanja, što uzrokuje razlike u strukturi između zavarenog spoja i okolnog materijala. Relativno veliki unos toplote i hlađenje u zoni uticaja toplote (ZUT) uzrokuje stvaranje karbida i kao rezultat toga formiranje krupnog zrna, što je nepoželjno za dobijanje povoljnih mehaničkih osobina. Ova studija istražuje zavarljivost dva austenitna vatrootporna čelika (EN X12CrNi23-13 i EN X8CrNi25-21) primenom tehnike zavarivanja netopljivom volframovom elektrodom u zaštitnoj atmosferi inertnog gasa. Oba materijala se posebno analiziraju, a rezultati se razmatraju u smislu potencijalnih tehnika zavarivanja i poboljšanja tehnološkog plana za postizanje visokokvalitetnih zavara bez predgrevanja ili bilo koje druge dodatne termičke obrade posle zavarivanja, što je značajno za industriju jer može smanjiti vreme i troškove proizvodnje.

The paper was published in its original form in the Proceedings of the 2nd Conference with international participation "Welding and welded structures" held in Sarajevo, BiH, from October 25 to 27, 2023.

1. Introduction

Greenhouse gas emissions are a major global concern in nowadays living. Thermal power plants contribute to this significantly because fossil fuel combustion is one of the main sources of greenhouse gases [1]. According to research, steam temperature and pressure have a significant impact on a power plant's efficiency [1 - 3]. Most of the electricity-generating equipment in power plants operates at very high temperatures from 600°C to 1400 °C and high steam pressures in the range of 20MPa and more [2]. These operating pressures and temperatures are even higher for high-efficiency power plants than they are for conventional older-generation power plants, and as a result, they need less coal to produce the same amount of energy [2, 4]. As operating temperatures rise, structural components must meet higher standards for use in power plants with high temperatures. As a result, a variety of heat-resistant steels have been created [1] that can withstand harsher operating conditions to meet these demands. While the operating conditions don't call for any special mechanical characteristics, they do call for strong anti-corrosion and high resistance to heat destruction. Low-alloy steels cannot be used in hostile environments or at temperatures higher than 550°C because they lose strength at high temperatures and form a thick layer of oxide. To avoid additional costs, steel microstructure must remain stable over an extended period while operating defect-free. When conventional steel is exposed to high temperatures, strengthening precipitates dissolve or coagulate, which significantly reduces strength and mechanical properties and speeds up corrosion [4]. These unfavourable conditions could result in failures.

Heat-resistant steels themselves belong to the group of high alloy steels and the basic alloying element added to steel is Cr. With a greater presence of chromium (Cr), the heat resistance increases, and with the presence of other alloying elements such as Ni, Al, Mo, Ti, etc. the steel improves the mechanical properties. Based on the microstructural characteristics these steels can be ferritic steels with main alloying elements (Cr, Si, and Al), ferritic-austenitic steels, ferritic-martensitic steels, martensitic and austenitic steels with main alloying elements (Cr, Ni, Si, and less frequently Al and Ti).

Two types of heat-resistant steels are used in power plants: ferritic-martensitic and austenitic steels [2]. The ferritic-martensitic grades include trace amounts of Mg, Mo, S, C, and Ni, which are primarily present to aid in precipitation strengthening and high-temperature behaviour [2]. The martensitic steels are designed for operation at steam temperatures below 650 °C [2, 5]. The main steam pipes in fossil power plants with steam temperatures up to 600 °C have frequently been made of martensitic heat-resistant P91 and P92 steels [1]. In comparison to martensitic heat-resistant steel, austenitic heat-resistant steel has a higher resistance capability to oxidation [1]. Also, austenitic steels are significantly stronger, more ductile, and have higher creep-rupture strength than ferritic/martensitic steels [2]. These steels are widely used in many industries like chemical, pharmaceutical, cement, and food industries, as well as in aviation, navy, and architecture. This is due to their superior cold hardening and polishing capabilities, high oxidation and corrosion resistance, mature manufacturing process, good deformation, and mechanical properties at elevated temperatures [5, 6]. However, due to the formation of carbides and nitrides in the microstructure, which coarsens during use, commercial heat-resistant austenitic steels have low creep rupture strengths at high temperatures [7, 8]. The carbides at the boundaries are the ideal location for cavity nucleation under creep-fatigue loading conditions, which calls into question the creep-fatigue life of the structure.

Austenitic stainless steels are also used when joining dissimilar metals [9]. The tensile strength of joints between structural C-steel and austenite stainless steel was studied by Cam et al. in a recent publication [9]. They discovered that joints fracture at low-strength base metal sides and that there are certain inhomogeneities in the weld metal microstructure, which contained three phases: ferritic-austenitic, baintic, and martensitic phases. Welding can be difficult because residual stresses in the joint may result from the different thermal conductivities of austenitic stainless steel and carbon steel [9]. As opposed to welding martensitic and ferritic steels, welding austenitic heat-resistant steels only presents two difficulties: poor heat dissipation and increased electrical resistance. Intergranular corrosion can happen in the base material as well as the heat-affected zone (HAZ). It's also possible that internal stresses contribute to the formation of hot cracks during the weld cooling process. Austenitic heat-resistant steels contain different amounts of alloying elements which can allow steel to pass through the precipitates during service and thus provide high-temperature stress strength, grain refinement, and precipitation hardening [10]. But when the welding process is used these characteristics might change, because of the effect of the localized high temperature [10], so it is important to study the creep rupture strength and mechanical properties of welded joints of these steels.

In the present research, the weldability of two types of austenitic heat-resistant steels (X12CrNi23-13 and X8CrNi25-21) is investigated. The experiment consists of welding two samples from both materials with gas tungsten arc welding (GTAW) with assigned parameters according to the assigned welding technology. After welding the samples, several tests were done bending, hardness, tension, non-destructive tests with penetrants, and radiography. The findings demonstrate that it is possible to reduce the cost of welding during the construction of structures by adjusting some of the parameters, such as current strength and welding speed. By doing so, it is possible to avoid preheating and additional heat treatment during the welding of these pieces. Additionally, data on critical properties and information on the microstructural characteristics are provided. The study's main objective is to offer an initial understanding of the mechanical and weldability characteristics of austenitic heat-resistant steels. It identifies potential next steps for additional research, and the findings can act as a fundamental manual for welding these steels with GTAW.

2. Materials, experiments and methods

The two welded plates used in the investigation are made of two different austenitic heat-resistant steel plates with the designations EN X12CrNi23-13 and EN X8CrNi25-21. The mechanical characteristics and chemical composition of these steels are listed in Tables 1 and 2.

Table 1. *Mechanical properties of the investigated austenitic heat-resistant steels*

Tabela 1. *Mehanička svojstva ispitivanih austenitnih vatrootpornih čelika*

Designation		Mechanical properties					
EN	AISI	R_m	$R_{p0,2}$	A_5	Z	KU	HB
		N/mm^2		%	%	J	
X12CrNi23-13	S309	500-700	210	35	43	21	192
X8CrNi25-21	S310	500-700	210	35	42	23	192

Table 2. *Chemical composition of the investigated austenitic heat-resistant steels*

Tabela 2. *Hemijski sastav ispitivanih austenitnih vatrootpornih čelika*

Designation		Chemical composition, [mass %]								
EN	AISI	C	Si	Mn	P	S	Cr	Ni	N	Fe
X12CrNi23-13	S309	0.15	1.0	2.0	0.045	0.015	22.0-24.0	12.0-14.0	0.11	rest
X8CrNi25-21	S310	0.10	1.5	2.0	0.045	0.015	24.0-26.0	19.0-22.0	0.11	rest

Data from both tables indicate that there are only minor variations in the Cr and Ni contents between these materials. The dimensions of the plates are 150 x 150 x 2.5mm and 150 x 150 x 6mm. The welding technique used is GTAW with different welding parameters for each set of plates. The welding on the thinner plate (sample 1) is a two-sided facing joint with one passage. The thicker plate (sample 2) is prepared with X shaped grove for a butt-weld joint done with several passes, performed using the same device (Cea Matrix 250 HF) that was used for welding the thinner plate. The temperature of the work pieces before welding and between each pass is measured with an infrared thermometer Steinel HL Scan. The protective gas during the welding of both materials is Argon with a content of 99.99% due to the provision of deeper penetration and quality protection of HAZ from inclusions from the atmosphere. The flow is 14 l/min. The filler material for both steels is an W 23 12 L Si bar with a diameter of 2.0mm. At a 23°C ambient temperature, sample 1 is welded without any preheating. A 64A current is used for the frontal pass, which is followed by a 29°C cooling period before the next pass is made on the opposite side. The sample is rotated, cleaned at the root, and then welded using the same 64 A current. Following the application of the first layer, the piece is rotated once more to the opposite side for the application of the second pass, which uses a current of 62 A. Since the time between these operations is short, the intermediate temperature remains at the value of 50°C. After the second side of the joint has been welded, the object is removed from the worktable, visually inspected, and then cooled in air. Figure 1 illustrates the pre-welding preparation, the welding process, and the deformation that results from too much heat being applied to the material. The short cooling period the piece had between rotation and the other side's welding is what caused the deformation.

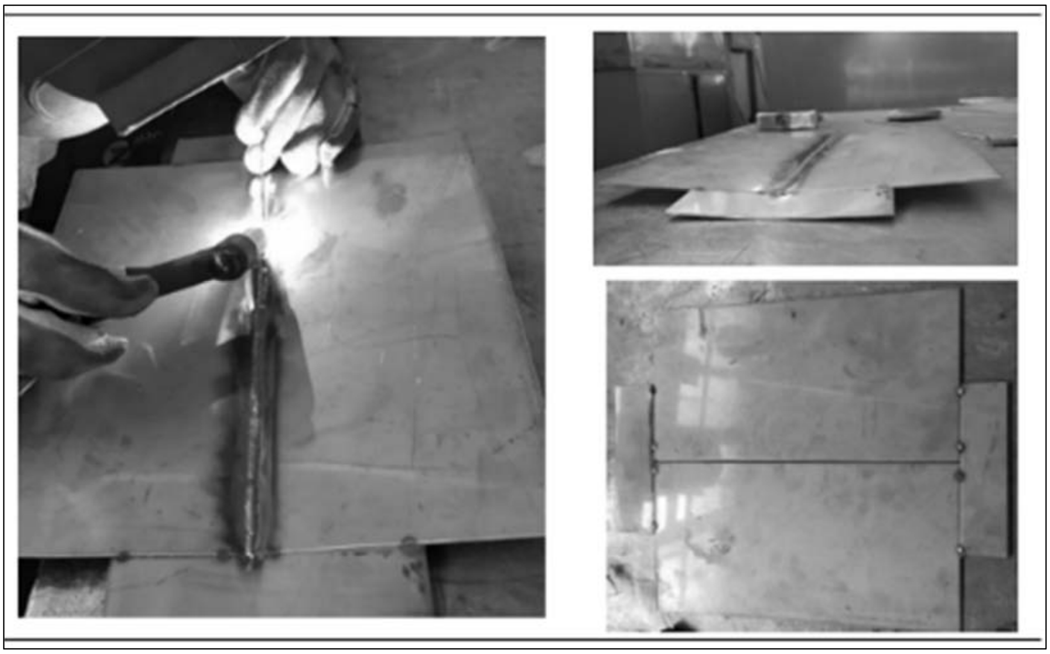


Figure 1. *Pre-welding preparation, welding, and deformation after welding of sample 1*

Slika 1. *Priprema pred zavarivanje, zavarivanje i deformacija nakon zavarivanja uzorka 1*

The second sample is also welded without preheating at an ambient temperature of 23°C and the preparation of the sample is shown in Figure 2. The second sample is welded on two sides, with three passes on each side with the same device as the first sample with argon as a protective gas. The filler material used has a diameter of 2mm, and the tungsten electrode used has a diameter of 2.4mm. The values for the current and the various temperatures between the layers are shown in Table 3.

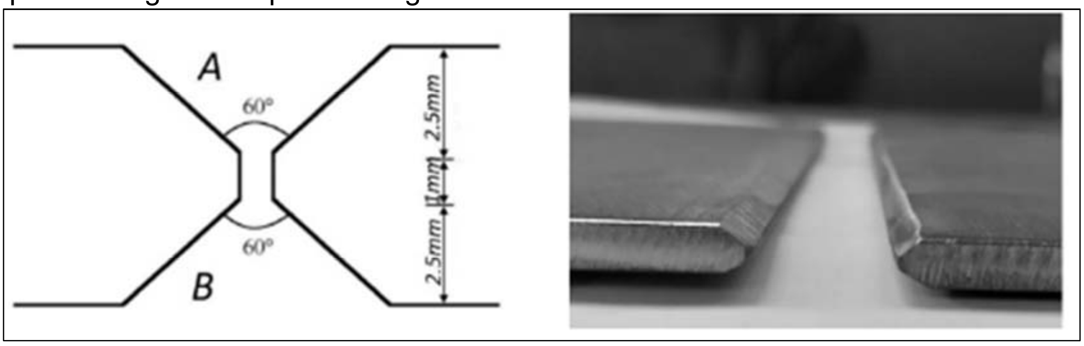


Figure 2. *Sample 2, preparation with X-shaped grove for butt welded joint*

Slika 2. *Uzorak 2, priprema sa X žljebom za sučeono zavareni spoj*

Table 3. *Arc current used and measured inter pass temperatures*

Tabela 3. *Primenjena struja zavarivanja i izmerene međuprolazne temperature*

Pass number	Current used [A]	Temperature measured in between layers [^oC]
1	93	20
2	93	152
3	109	47
4	109	100
5	120	52
6	120	159

The filler material for both steels is an W 23 12 L Si bar with a diameter of 2.0mm and mechanical properties and chemical composition are shown in Table 4 and Table 5.

Table 4. *Mechanical properties of filler material*

Tabela 4. *Mehanička osobine dodatnog materijala*

Designation	Mechanical properties			
W 23 12 L Si	R_m [N/mm^2]	$R_{p0.2}$ [N/mm^2]	A_5	Z
	510	320	-	-

Table 5. *Chemical composition of filler material*

Tabela 5. *Hemijski sastav dodatnog materijala*

Designation	Chemical composition, [mass. %]						
W 23 12 L Si	C	Si	Mn	P	Cr	Ni	Fe
	0.03	0.76	1.32-	0.0022-	23.65	12.76	rest

To prove the quality of the welded joints, several tests are done that can be categorized as non-destructive (penetrants and radiography) and destructive testing (macrostructure and microstructure examination, hardness testing, bending and tensile testing). The radiographic method includes an examination for detecting errors in the welded joint: cracks, slag inclusions, porosity, and lack of root fusion. The samples were tested according to the standard EN 17636-1. The source is 2x2 in size and emits X-rays. The irradiation time is 30s for sample 1 and 42s for sample 6mm. According to the EN 3452 standard, penetrant testing entails the following steps: cleaning and degreasing the surface of the material being tested, application of the penetrant, removal of the penetrant with water or a cloth, and application of a developer that draws the penetrant out of the cracks. These procedures were carried out on both samples. Two testing samples are created from both welded plates for the macrostructure examination, as shown in Figure 3.

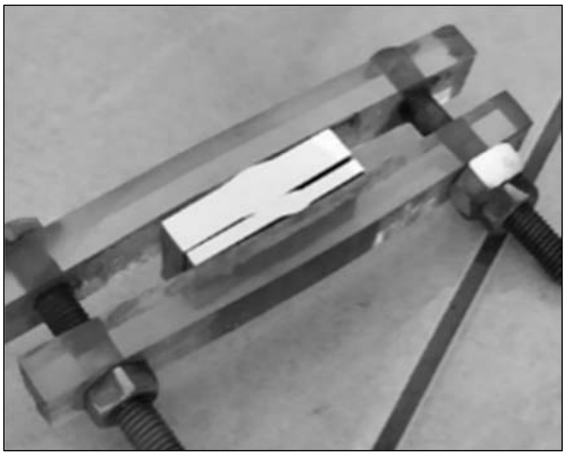
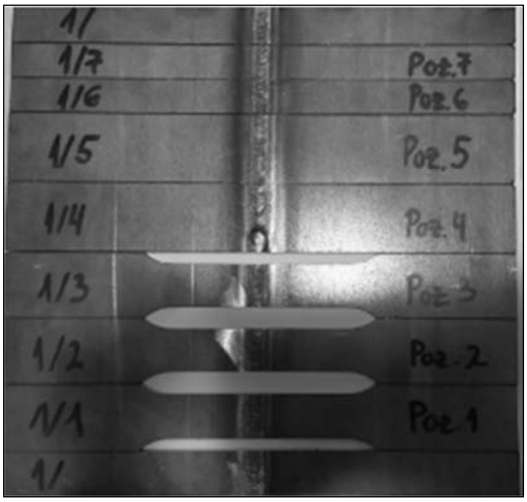


Figure 3. *Samples for macrostructure testing for both welded plates*

Slika 3. *Uzorci za ispitivanje makrostrukture za obe zavarene ploče*

Additionally, tests for hardness, bending, and tensile strength have been conducted. Figure 4 displays the samples from these tests for both materials. The label's first number denotes the sample's number, and its second number, the location of the testing sample.



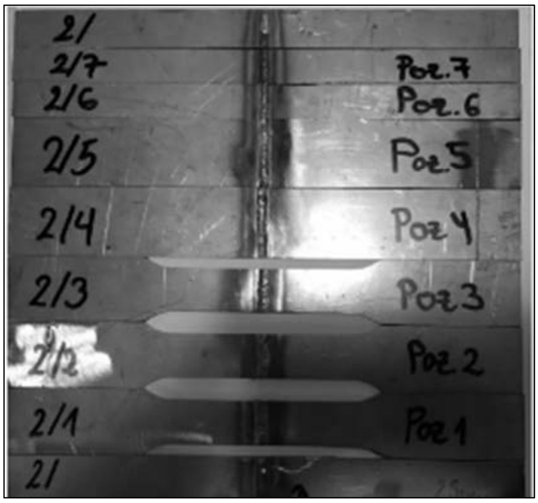


Figure 4*. Testing samples for tensile, bending and hardness testing*

Slika 4. *Uzorci za ispitivanje zatezanjem, savijanjem i za ispitivanje tvrdoće*

The hardness testing is carried out according to standard EN 6507-1 with a diamond indenter tool with hardness 10HV. Although the indented samples can be ground and polished for microstructure analysis, other samples were created for this study's microstructure analysis. These were ground and polished in preparation for microstructure analysis. The polishing step was done with a polisher cloth and the addition of Al_2O_3 with gradation up to 5μm. The samples were quickly dried after being etched for a brief period with a V 2A etchant. Later, the structure is examined under an optical microscope, and pictures are created for later analysis. Using bend testing of the butt-welded joints in accordance with standard EN 910, the capacity of the austenitic heat-resistant steels to bend around the welded joint was investigated. A pin with a 4a diameter is used to bend the samples around the welded joint face and welded joint root at an angle of up to 120 degrees. The pin is 15mm wide and passes between the cylinders. Figure 5 shows the procedure for both samples. For the bend test result to be considered acceptable, neither the weld nor the metal should have failed.

The standard tensile testing machine SHIMADZU, which has a maximum capacity of 250 kN, is used for the tensile testing. Three specimens from each welded plate with dimensions in accordance with ISO6892 and EN895-Part 1 are tested on a total of six samples. The test is conducted at a 5 mm/min speed.

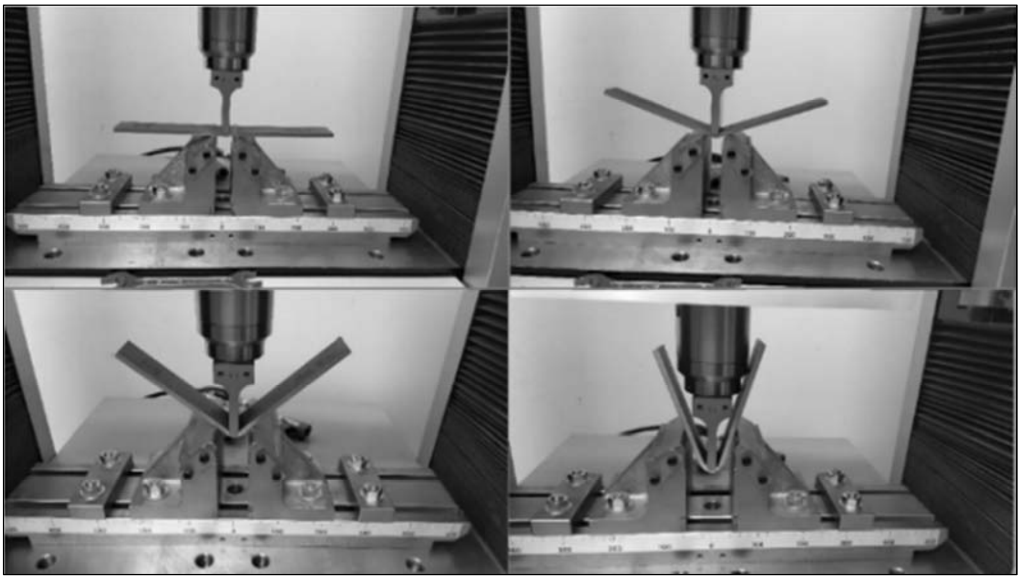
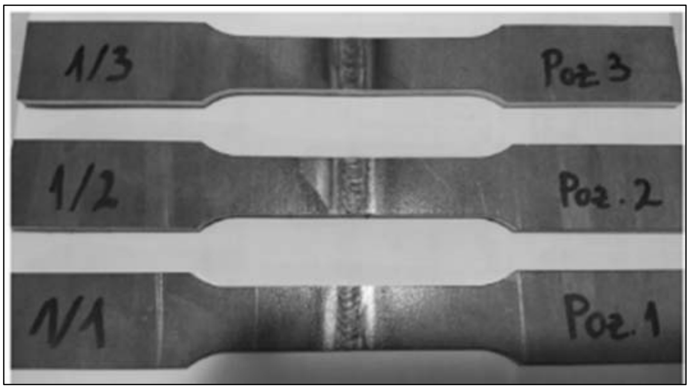


Figure 5. *Triple point bending testing*

Slika 5. *Ispitivanje savijanjem u tri tačke*

The tensile tests were performed with an accuracy of 0.001 mm at room temperature. The samples prepared for this testing are shown in Figure 6.



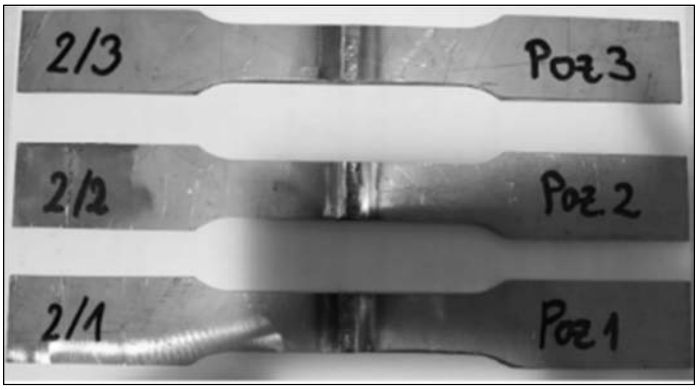
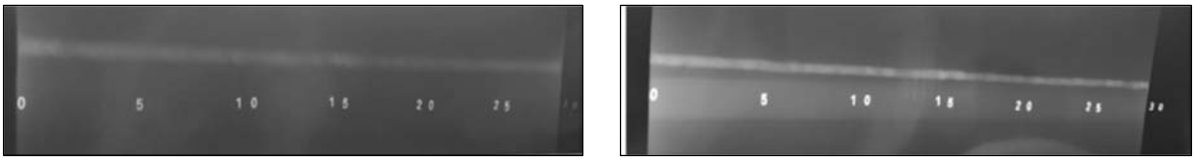


Figure 6. *Tensile testing specimens*

Slika 6. *Uzorci za ispitivanje zatezanjem*

3. Results and discussions

The results of the radiography testing has shown in sample 1, lack of root fusion and many pores with dimensions that do not meet the requirements for a high-quality welded joint were observed. Only a few minor pores were found in the second sample, which are not thought to be important for the joint's capacity to support weight. Due to the careful selection of the X-grove plate preparation, the multiple passes of welding, and the maintained temperature between them, the second sample has a higher quality. Figure 7 displays both radiograms. The results from penetrant testing demonstrated that the weld and its surrounding area are free of any defects.

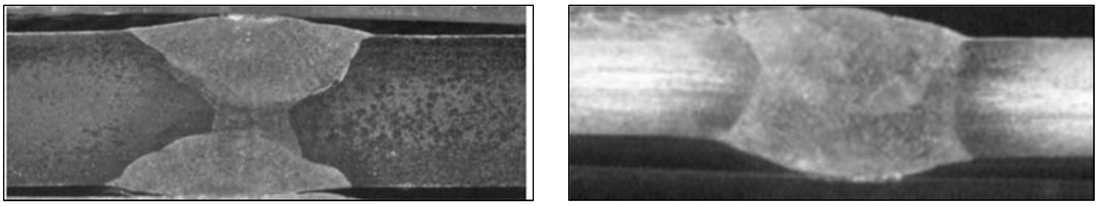


a) b)

Figure 7. *Results of the radiography testing a) sample 1, b) sample 2*

Slika 7. *Rezultati radiografskog ispitivanja a) uzorak 1, b) uzorak 2*

The metallographic examination, macroscopic and microscopic examinations, is carried out to ascertain the fundamental structure of the austenitic steel and to determine the quality of the produced welded joint in terms of defined eligibility criteria according to standard EN288-3. The macrostructure of the welded samples is shown in Figure 8.



a) b)

Figure 8. *Macrostructure of welded joints of both samples a) sample 1, b) sample 2*

Slika 8. *Makrostruktura zavarenih spojeva oba uzorka a) uzorak 1, b) uzorak 2*

The base metal, the metal of the heat-affected zone, and the weld metal, which expresses the groove fill area, are shown as the components of the welded joint in Figure 8. The macrostructures of the welded joint samples under examination demonstrate that the welding process and selected welding technology have been met in full. In Figure 9 the micrographs the microstructures of 3 specific zones: base metal, HAZ and weld metal for sample 1 on the left side and sample 2 on the right side are presented.

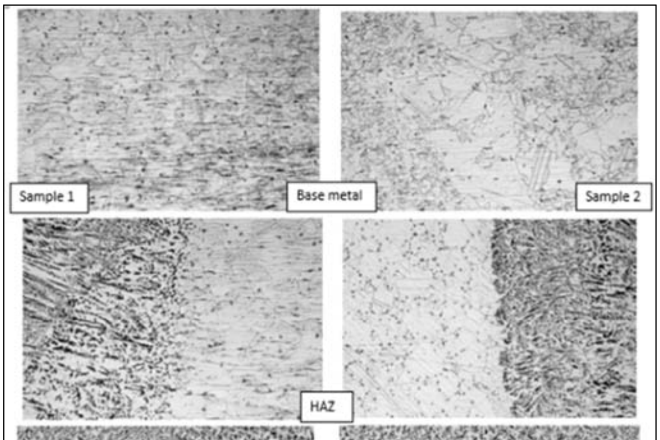


Figure 9. *Microstructure in base metal, weld metal and HAZ for Sample 1(left side) and Sample 2 (right side)*

Slika 9. *Mikrostruktura osnovnog metala, metala šava i ZUT za uzorak 1 (leva strana) i uzorak 2 (desna strana)*

The base metal for both samples shows a typical austenitic grain matrix containing annealing twins and some non-metallic inclusion. The micrographs that represent the heat-affected zone on both samples clearly indicate the changes from the composition of the base metal to weld metal. The transition zone is dendritic with a coarser grain structure and a new phase that is emerging within the grains, a dense and dark micro constituent that resembles a perlite structure. There is a presence of precipitated carbides inside and along the grain boundaries, as well as a slight rounding of the grains, which are both caused by the heat input. Sample 2 is characterized by cellular dendritic microstructure, and in Sample 1 the overlay is a bit different the cells and dendrites are not always well-defined. It is generally accepted that the ratio of chromium equivalent (Creq) to nickel equivalent (Nieq) determines the solidification microstructure [11]. There are several causes for the formation of these differences in the microstructures. Different microstructures that form in both grades of stainless steel may be explained by differences between the solidification modes of these materials (sample 1- 309S and sample 2 – 310S). The primary phase formed during the 310S solidification is austenite and when cooled to room temperature, this austenite doesn't change. Weld metal has a distinctive dendritic structure with large, elongated grains, and it seems that the grain size and the twins of the specimens experienced significant changes during the thermal cycles caused by the welding. The grains are larger and elongated, the twins are thicker. The images make it obvious that the most crucial component of the welded joint is the transition between the Heat Affected Zones and weld metal. There are noticeable differences in the size and shape of the formed grains, which makes that area more brittle. Therefore, for more in-depth analysis, a 500:1 magnification is required.

There are no extreme differences in hardness between the base metal, HAZ, and weld zone. There is a slight rise in hardness in the second sample in the weld zone which is expected. On the contrary, the first step shows an undermatch case of weld the hardness in the base metal is higher than the one measured in the welded zone. Due to the limitations of optical measurement and the imperfections in the tip geometry, the results are characterized by significant uncertainties. The differences between these zones can be more accurately measured if a smaller indentation tool is used. Results from hardness testing are given in Figure 10.

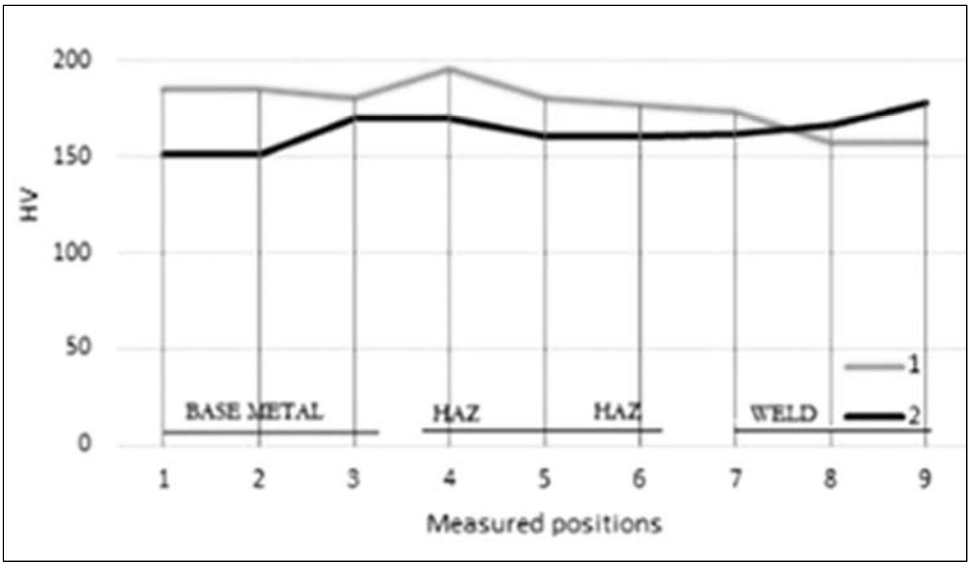


Figure 10. *Hardness testing results for samples 1 and 2*

Slika 10. *Rezultati ispitivanja tvrdoće za uzorke 1 i 2*

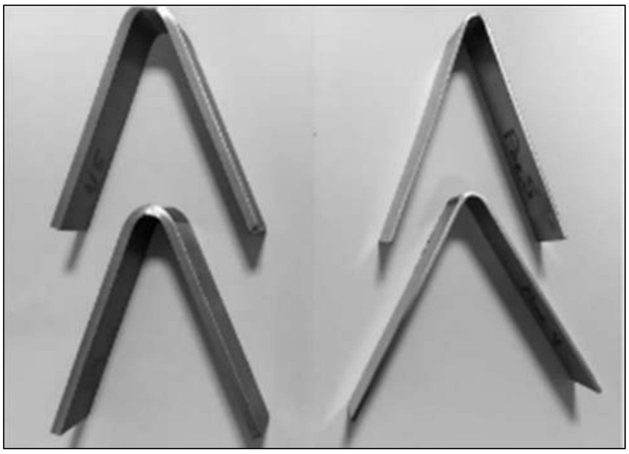


Figure 11. *Bending tested samples*

Slika 11. *Uzorci za ispitivani savijanjem*

The bending test results for specimens from both welded plates indicate that the performed welding process is of high quality since there were no signs of cracks upon reaching the bend angle of 120^0. No discernible difference was found between the specimens based on the measured angles. Due to the material's high strength and the lack of a machine that can handle the demands of this kind of material, the samples failed to break. However, the value is greater than the necessary service value, leading to the conclusion that the weld satisfies the requirements for bending. In the first sample, the fracture occurs in the base material, while in the second sample, the fracture precisely occurs in the zone that separates the base metal from the weld metal, as shown in Figure 11.

All measured angles and the maximum load in samples taken from the sample 1 and sample 2 welded plates are listed in Table 6.

Table 6. *Angles and maximal loading during the bending test*

Tabela 6. *Uglovi i maksimalno opterećenje pri ispitivanju savijanjem*

Sample	1.1	1.2	2.1	2.2
α [^{0}]	136	136	140	122
F [N]	6056.72	6027.22	6981.09	6656.28

Tensile testing results revealed consistency in measurements, and measured sizes were roughly the same in each test specimen that was observed. According to Figures 12. and 13, the fracture for the specimens from the thinner plate occurs in the base metal as opposed to the specimens from the second plate, where the fracture occurs precisely in the heat-affected zone, which is the zone between the base metal and the weld.

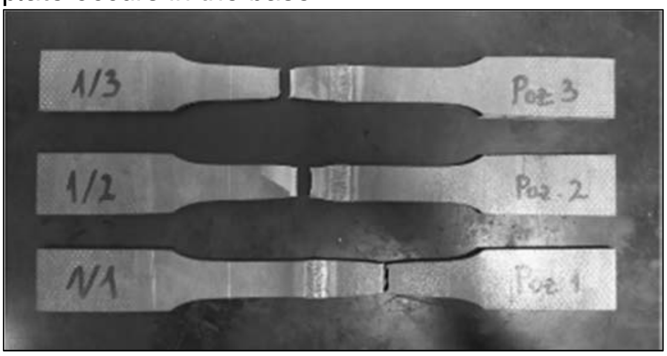


Figure 12. *Tensile tested specimens from sample 1*

Slika 12. *Uzorci ispitani zatezanjem iz uzorka 1*

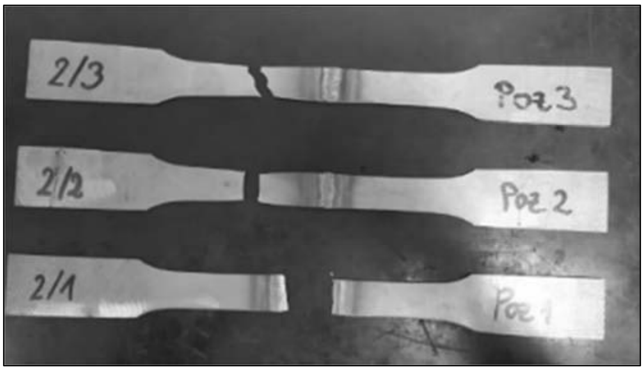


Figure 13. *Tensile tested specimens from sample 2*

Slika 13. *Uzorci ispitani zatezanjem iz uzorka 2*

Figure 14. displays the test results for each of the six specimens. Thicker plate samples exhibit higher yielding and maximum stress than thinner plate samples. Only one sample from the thicker plate fractured in the welded zone; the welds in the thinner plate samples did not fail.

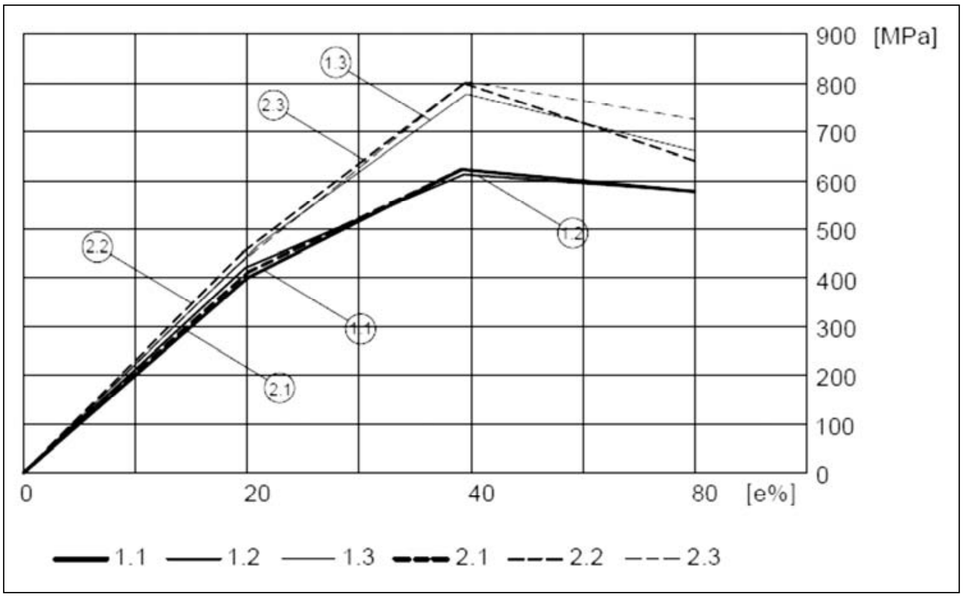


Figure 14. *σ – ε diagram for each tensile test specimen*

Slika 14. *σ – ε dijagram za svaki uzorak ispitivan zatezanjem*

4. Conclusions

The impact of the welding process, or the choice of the welding process technology, on mechanical and operational properties, is carefully examined based on several variables that accurately describe the behaviour of the base metal, welded joint, and its component parts. Chemical micro segregation during solidification facilitates the understanding of microstructure formation in austenitic steel weld overlays. Each weld overlay has a microstructure that is typical of the cast microstructure of a complex alloy, where the chemically homogeneous liquid phase solidifies into a less homogeneous solid. Along with evaluating the quality of the welding technology that has been used, this examination also establishes the boundaries of the various structures that

4. Zaključci

Uticaj procesa zavarivanja, odnosno izbora tehnologije procesa zavarivanja, na mehanička i radna svojstva, pažljivo se ispituje na osnovu nekoliko varijabli koje tačno opisuju ponašanje osnovnog metala, zavarenog spoja i njegovih sastavnih delova. Hemijska mikro segregacija tokom očvršćavanja olakšava razumevanje formiranja mikrostrukture austenitnog čelika. Svaki sloj šava ima mikrostrukturu koja je tipična za livenu mikrostrukturu složene legure, gde se hemijski homogena tečna faza očvršćava u manje homogenoj čvrstoj fazi. Uz procenu kvaliteta korišćene tehnologije zavarivanja, ovim ispitivanjem se utvrđuju i granice različitih struktura koje čine zavareni spoj.

comprise the welded joint. Further research on austenitic heat-resistant steels can be done using the properties that were examined in this study. Since the thicker sample that was welded produced better results, it can be used to conduct additional research on how high temperatures affect mechanical properties while still utilizing the same welding technique.

Dalja istraživanja austenitnih vatrootpornih čelika mogu se obaviti korišćenjem osobina koje su ispitivane u ovoj studiji. Pošto je deblji zavaren uzorak dao bolje rezultate, može se koristiti za sprovođenje dodatnih istraživanja o tome kako visoke temperature utiču na mehanička svojstva dok se i dalje koristi ista tehnika zavarivanja.

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AKTIVNI TOPITELJ BAZIRAN NA NANO I MIKRONSKIM ČESTICAMA TiO_2 ZA A-TIG ZAVARIVANJE

ACTIVATED FLUX BASED ON TiO_2 NANO AND MICRO PARTICLES FOR A-TIG WELDING

Originalni naučni rad / Original scientific paper

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Ključne reči: aktivni topitelj, TIG zavarivanje, nerđajući čelik, dubina uvara,

Keywords: activated flux, TIG welding, stainless steel, penetration depth

Rezime

U ovom radu, prikazana je tehnologija zavarivanja A-TIG, varijanta TIG postupka sa primenjenim aktivacionim topiteljem. Prikazano je eksperimentalno ispitivanje inovativnog topitelja baziranog na mešavini nano i mikronskih oksidnih čestica. Izvršeno je ispitivanje zeta potencijala topitelja, makro ispitivanje, ispitivanje mikrostrukture i mikrotvrdoće. Takođe, na osnovu dobijenih rezultata, prikazan je model kretanja tečnog metala u metalu šava. Na osnovu toga je identifikovan mehanizam povećanja dubine uvara, a to je promena smera kretanja od ivice prema sredini metala šava i u dubinu, čime se povećava dubina uvara. Pokazano je da najveću efikasnost ima mešavina nano i mikronskih čestica, zbog efekta mlevenja aglomerisanih nano čestica.

Abstract

In this paper, the A-TIG welding technology, a variation of the TIG welding process with an activated flux, was presented. An experimental investigation of an innovative flux based on a mixture of nano and micron oxide particles in solvent was shown. The zeta potential of the flux, the macro test, the microstructure and microhardness test were performed. Also, based on the obtained results, a model of the liquid metal flow in the weld metal is shown, where the increase in depth occurs due to a change in the direction of liquid metal flow from the edge to the middle of the weld metal. It has been shown that the mixture of nano and micron particles has the highest efficiency, due to the grinding effect of agglomerated nano particles.

1. Uvod

TIG zavarivanje (Tungsten Inert Gas) je jedan od najčešće korišćenih postupaka zavarivanja električnim lukom, posebno za zavarivanje obojenih metala i nerđajućih čelika, zahvaljujući postizanju izuzetno visokog kvaliteta zavarenih spojeva. Osnovni nedostatak u odnosu na MIG (Metal Inert Gas) postupak, je produktivnost, pre svega zahvaljujući relativno maloj brzini izvođenja postupka s jedne strane i maloj dubini uvara. Mali uvar je posledica kretanja tečnog metala, koji se kreće od sredine tečnog metala prema periferiji, odnosno liniji stapanja. Nakon toga, tečni metal teče duž linije stapanja prema dole, što rezultuje relativno širokom, ali ujedno i plitkom metalu šava. To je korisno u slučaju da se zavaruje tanak lim, ali za zavarivanje većih debljina, potrebna je primera radi V- priprema žleba i zvarivanje u više prolaza [1]. To u velikoj meri povećava cenu postupka, jer se osim troškova složenije pripreme, svaki prolaz iziskuje utrošak električne energije, netopljive elektrode i što je još važnije, relativno skupi inertni zaštitni gas i dodatni materijal kako bi se popunio prostor između limova. To ujedno znači, da se povećavaju mogućnosti nastanka grešaka, te je TIG zavarivanje pre svega rezervisano za zavarivanje tanjih poprečnih preseka osnovnog materijala.

Za rešavanje ovog problema i proširenje efikasne upotrebe TIG zavarivanja na deblje poprečne preseke uz snižavanje troškova, 1960-tih godina prošlog veka, na Paton institutu u Kijevu, u bivšem SSSR, u današnjoj Ukrajini, pojavio se postupak zavarivanja A-TIG, koji podrazumeva upotrebu aktivacionog topitelja [2]. Topitelj ovog tipa se nanosi na osnovni materijal, na mesto zavarivanja neposredno pre izvođenja postupka TIG. Raspadom SSSR-a, princip A-TIG je obelodanjen ostatku sveta i time doživeo renesansu, jer je rad nastavljen uz nova naučna saznanja.

Aktivacioni topitelji se sastoje od metalnih oksida (SiO_2, TiO_2, Al_2O_3, itd.) u etanolu, metanolu ili acetonu kao rastvaraču. Na taj način se dobija topitelj, u vidu tečnosti koji se nanosi četkicom ili u vidu spreja [3-5]. Tokom zavarivanja, električni luk rastapa i redukuje metal iz čestica oksida, dolazi do topljenja osnovnog materijala i izmene toka tečnog metala usled manipulacije površinskim naponom. Umesto uobičajenog toka od sredine prema liniji stapanja (TIG), kod A-TIG se sumnja da se uspostavlja izmenjen tok od ivica prema sredini i dole u dubinu. Rezultat je znatno uži ali višestruko dublji šav, čime se zavareno spoj umesto u nekoliko prolaza, može izvesti u samo jednom, uz višestruko smanjene troškove pripreme, utrošak zaštitnog gasa i bez dodatnog materijala [6-8].

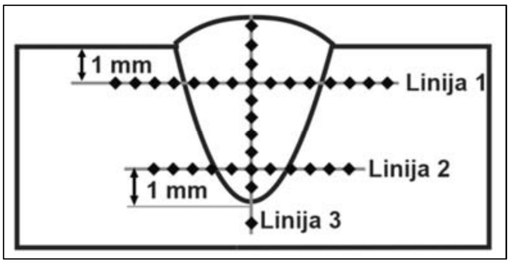
U ovom radu su prikazani rezultati zavarivanja, odnosno pretapanja bez i sa različitim topiteljima baziranim na nano i mikronskim česticama. Izvršena su makro ispitivanja, ispitivanje mikrostrukture i mikrotvrdoće, a na osnovu dobijenih rezultata, definisan je model kretanja tečnog metala u metalu šava i mehanizam povećanja dubine uvara.

2. Eksperiment

Osnovni materijal je bio austenitni nerđajući čelik AISI 304 (X5CrNi18-10), čiji je hemijski sastav: <0.03% C, 0.5% Si, 1.3% Mn, <0.008% Si, 18.03% Cr, 0.003% P, 0.01% Al, 0.41% Cu, 9.51% Ni, 0.012% Sn, 0.07% V, ostatak Fe. Širina osnovnog materijala bila je 50 mm, debljina 10 mm, a dužina 400 mm. Zavarivanje, tačnije pretapanje u cilju ispitivanja efekta aktivacionog topitelja je izvršeno u jednoj liniji, po sredini uzorka, sa prethodno nanesenim topiteljima različitog sastava. Ispitano je sedam pločica pojedinačne dužine 50 mm, jedna bez, a ostale sa topiteljima. Topitelji su dobijeni na bazi nanočestica TiO_2 nominalnog prečnika 20 nm i mikronskih čestica nominalnog prečnika 300 nm. Topitelji su dobijeni u sledećim odnosima: čiste mikronske čestice (uzorak 5M), odnos 4:1 (u korist mikronskih čestica, uzorak 4M1N), odnos 3:2 (uzorak 3M2N), odnos 2:3 (uzorak 2M3N), odnos 1:4 (uzorak 1M4N) i 0:5 (uzorak 5N). Čestice su bile izmerene analitičkom vagom. Rastvarač je bio aceton, a mešanje je izvršeno magnetnim mešačem u trajanju 10 min. Stvarne veličine čestica u acetonu su izmerene metodom zeta potencijala, što je inovativna metoda karakterizacije u slučaju ispitivanja topitelja.

Zavarivanje je izvršeno jednosmernom strujom 200 A, elektrodom of volframa sa 2 % torijum-oksida (crvena elektroda), čiji je vrh naoštren pod uglom 90°. Gorionik je bio prečnika 12,7 mm. Rastojanje do osnovnog materijala je bilo 2 mm, a brzina kretanja podešena na traktoru za zavarivanje je bila 100 mm/min. Zaštitni gas je bio argon, sa protokom 12 l/min.

Nakon zavarivanja, izvršena je karakterizacija pretopljenih uzoraka. Metalografsko ispitivanje je izvršeno standardnom tehnikom pripreme: isecanjem poprečno u odnosu na šav, montiranjem u polimerni nosač, brušenjem SiC brusnim papirima različite granulacije (od P80 do P2000) i poliranjem dijamantskim suspenzijama granulacije 6, 3, 1 i ¼ µm. Nagrizanje je izvršeno carskom vodom. Ispitani su makro preseci, kao i mikrostrukture u različitim zonama. Mikrotvrdoća po Vikersu je izmerena sa opterećenjem 100g, prema šemi datoj na slici 1, uz rastojanje između otisaka od 0,5 mm.

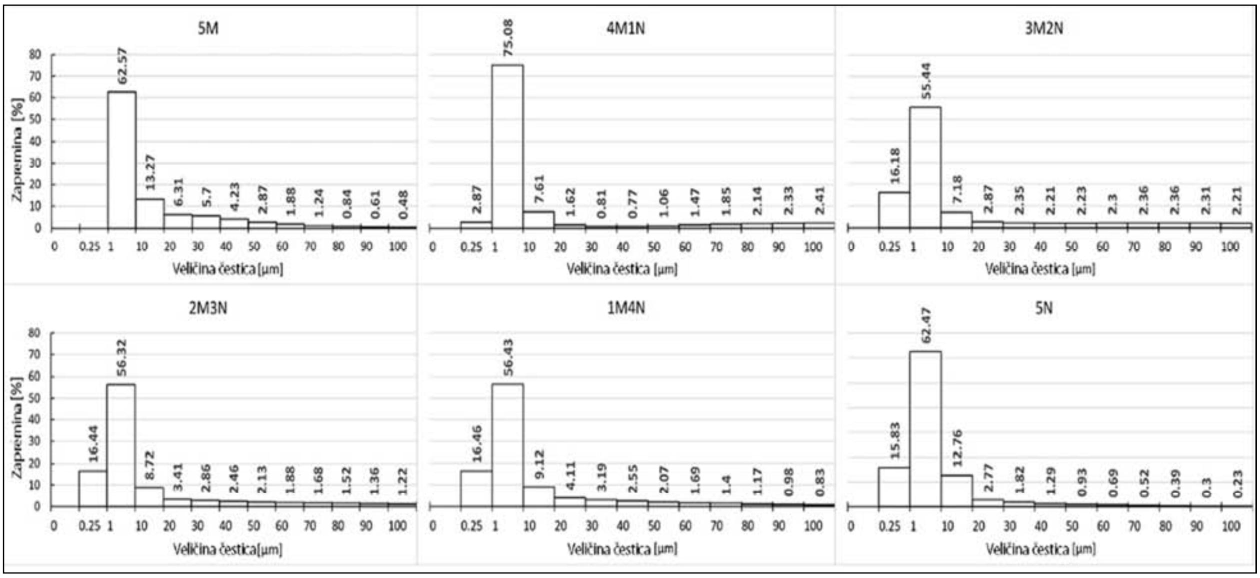


Slika 1. *Šema merenja mikrotvrdoće*

Figure 1. *Microhardness measurement scheme*

3. Rezultati i diskusija

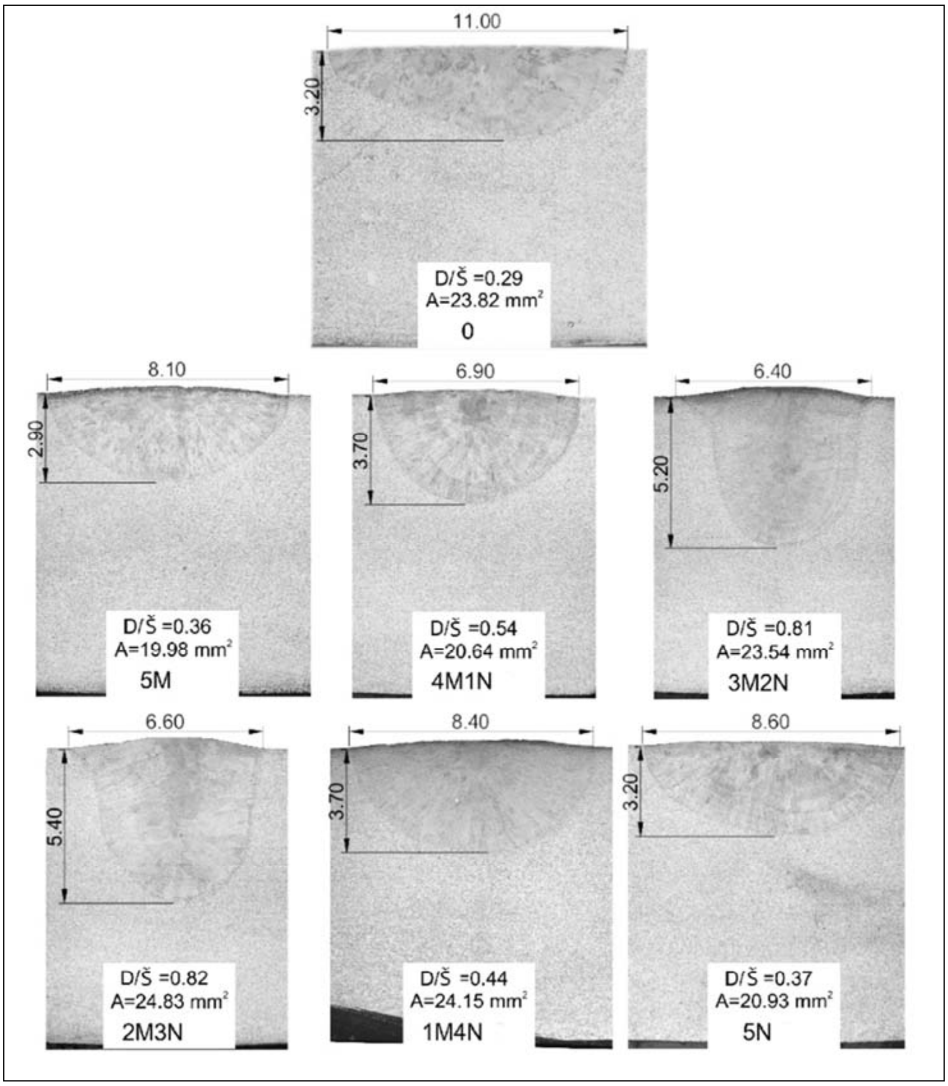
Rezultati ispitivanja zeta potencijala prikazani su na slici 2. Vidi se da je zapreminska distribucija čestica najpovoljnija kod uzoraka 3M2N, 2M3N i 1M4N, s obzirom da je udeo čestica najmanjih dimenzija ispod 1 μm i od 1 do 10 μm najveći. Naime, manje čestice su osetljivije na izlaganje visokoj temperaturi i brže se redukuju, oslobađajući kiseonik koji direktno utiče na promenu površinskog napona u metalu šava s jedne strane, a s druge strane, metal koji participira u metalnim oksidima, aktivnoj supstanci topitelja, utiče na sužavanje električnog luka u procesu zavarivanja [9]. Interesantno je da uzorak 5N koji sadrži isključino nano čestice, nije u prednosti u odnosu na uzorke koji sadrže i nano i mikronske čestice, a pogodno objašnjenje može da se pronađe u činjenici da nano čestice aglomerišu, odnosno spajaju se tokom mešanja. Kako je njihova koncentracija veća u uzorku 5N nego kod uzoraka 3M2N i 2M3N, srednja rastojanja između čestica su manja, te je jasna i povećana tendencija za njihovim spajanjem. Osim toga, drugo objašnjenje se može pronaći u teoriji da se tokom mešanja, aglomerisane nano čestice sudaraju sa mikronskim česticama. Kako su veze između nano čestica u aglomeratima Van der Waalsove, inače relativno slabe veze, daleko slabije u odnosu na veze unutar mikronske čestice (kovalentne), tokom mešanja, odnosno sudara, dolazi do rafinacije aglomerisanih čestica i poboljšanja njihove reaktivnosti [10].



Slika 2. *Rezultati ispitivanja zeta potencijala za uzorke različitih topitelja*

Figure 2. *Zeta potential test results for samples of different fluxes*

Makro prikazi zavara dati su na slici 3. Pored toga, na slici 3 su date dubine uvara, odnosi dubine i širine metala šava (D/Š) i površine pretopljenog materijala, kao indikatori efikasnosti pojedinih topitelja. Na osnovu datih rezultata, može da se konstatuje da najveću dubinu uvara, odnos D/Š i površinu metala šava imaju smeše 3M2N i 2M3N, kod kojih je sadržaj mikronskih i nano oksidnih čestica blizak. Pored toga, oblik metala šava se u potpunosti menja, iz polukružnog, odnosno poluelipsastog oblika u oblik koji možda najbolje može da se opiše kao oblik vaze. Ovi rezultati su u skladu sa rezultatima merenja zeta potencijala, tj. sa rezultatima prikazanim na slici 2.

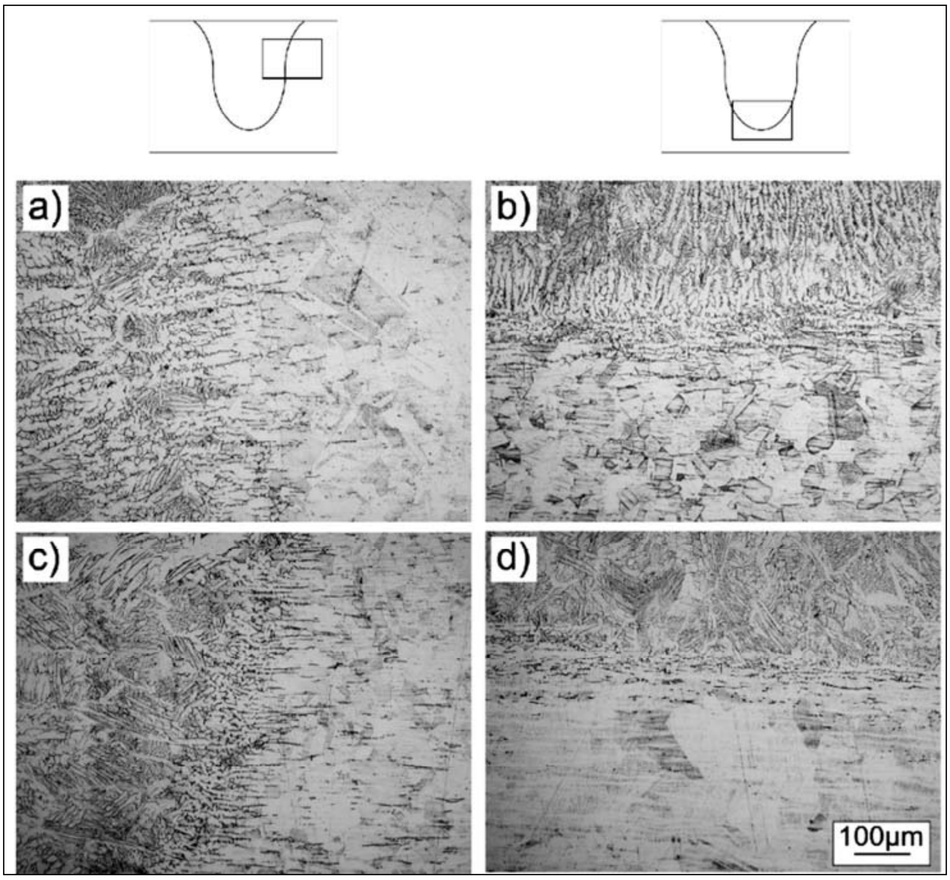


Slika 3. *Makro prikazi metala šava sa indikovanim uzorkom, dubinom uvara, odnosom dubine i širine metala šava (D/Š) i površinom pretopljenog materijala*

Figure 3. *Macro views of weld metal with indicated sample, weld depth, weld metal depth-to-width ratio (L/W) and melted area*

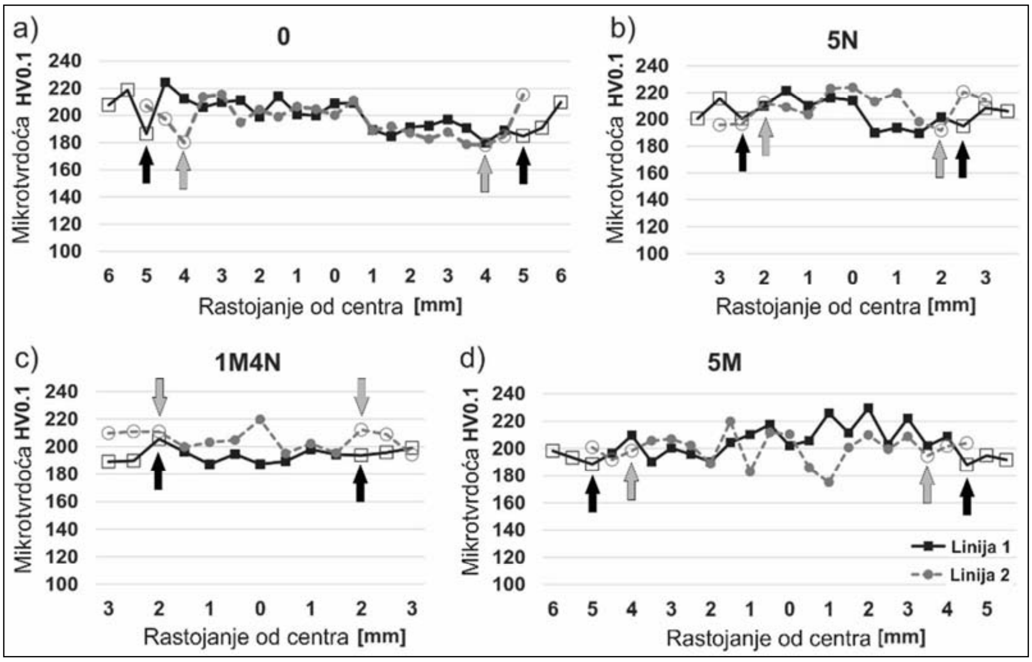
Mikrostrukture u pojedinim zonama, u blizini linije topljenja, prikazane su na slici 4. Na slici 4 se vidi da je kod uzorka 0 dobijenog bez topitelja mikrostruktura u blizini linije topljenja krupnozrna, za razliku od uzorka dobijenog sa topiteljem. Međutim, ispod metala šava, u blizini linije topljenja, krupnozrna mikrostruktura se javlja kod uzorka dobijenog uz primenu topitelja, ali ne i kod uzorka dobijenog bez topitelja. To je potvrđeno i kod uzoraka kod kojih je merena mikrotvrdoća, slike 5 i 6, označeno strelicama. Naime, kod oba uzorka, mikrotvrdoća u zonama krupnog zrna je niža u odnosu na druge zone gde su prisutna zrna nepromenjene veličine.

Na osnovu dobijenih rezultata, može se predstaviti model kretanja tečnog metala, slika 7. Kod uzorka koji je zavaren bez topitelja, konvencionalnim postupkom TIG, krupno zrno, odnosno niža tvrdoća ispod površine i pored linije stapanja rezultat je činjenice da je u toj zoni izvršena rekristalizacija od strane toka tečnog metala na visokoj temperaturi. Kako struja tečnog metala skreće prema dole, prema dubini metala šava, temperatura opada i efekat na osnovni materijal se smanjuje. S druge strane, krupno zrno i smanjena tvrdoća u zoni koja je blizu dna metala šava kod uzorka dobijenog sa topiteljem, rezultat je rekristalizacije toka tečnog metala na visokoj temperaturi, koji teče od linije topljenja na površini prema centru metala šava i prema dubini, čime se značajno povećava dubina uvara. Kada tečni metal dostigne najnižu tačku, kreće se prema gore, ali kako je već predata najveća količina toplote, nema rekristalizacije u zoni koja je bliža površini.



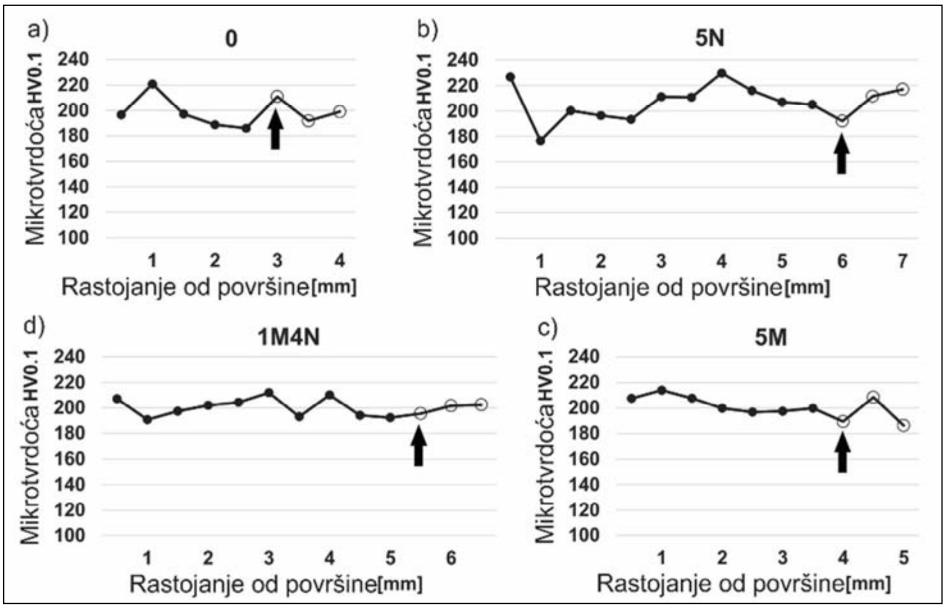
Slika 4. *Mikrostrukture pored linije stapanja: a) ispod površine uzorka 0, b) u dnu metala šava, c) ispod površine uzorka 3M2N, d) u dnu uzorka 3M2N*

Figure 4. *Microstructures near the fusion line: a) under the surface of the sample 0, b) at the bottom of the weld metal, c) under the surface of sample 3M2N, d) at the bottom of sample 3M2N*



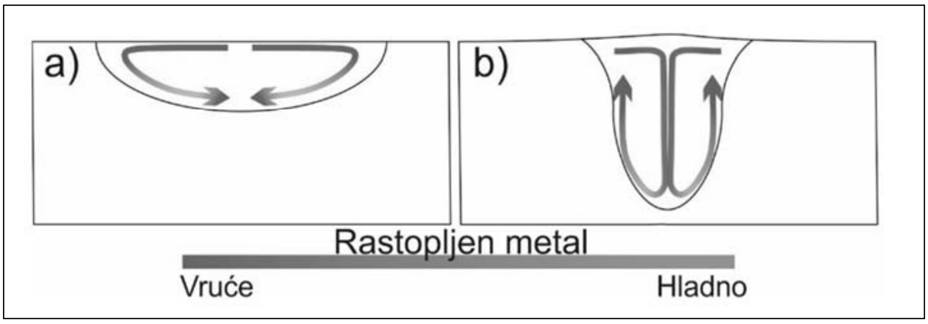
Slika 5. *Mikrotvrdoća po horizontali, linije 1 i 2*

Figure 5. *Horizontal microhardness, lines 1 and 2*



Slika 6. *Mikrotvrdoća po dubini, linija 3*

Figure 6. *Microhardness by depth, line 3*



Slika 7. *Tok tečnog metala: a) TIG, b) A-TIG zavarivanje*

Figure 7. *Liquid metal flow: a) TIG, b) A-TIG welding*

Rekristalizacija u zoni koja je ispod šava kod uzorka zavarenog sa topiteljem, u slučaju zavarivanja sa punim provarom bi prenelo najveći deo toplote na podložnu pločicu, bez efekta ili sa minimalnim efektom na osnovni materijal. S druge strane, kod uzorka dobijenog bez topitelja, konvencionalnim TIG postupkom, krupno zrno je neposredno ispod površine, uz liniju stapanja, što je znatno nepovoljnije, jer potencijalno smanjuje mehaničke osobine zavarenog spoja.

4. Zaključak

Zavarivanje TIG sa aktivacionim topiteljem (A-TIG) predstavlja značajan napredak u odnosu na TIG zavarivanje, pre svega u pogledu zavarivanja većih poprečnih preseka. Kao takav, postupak A-TIG po produktivnosti može da konkuriše MIG postupku, uz kvalitet spoja koji je sličan TIG zavarivanju. Postižu se značajne uštede u odnosu na TIG, pre svega vezane za jeftiniju i bržu pripremu, bez potrebe za V pripremom osnovnog materijala. Takođe, zavarivanje osnovnog materijala veće debljine TIG postupkom je potrebno zavarivanje u više prolaza, uz značajan utrošak zaštitnog gasa i dodatnog materijala, dok je kod A-TIG dovoljan jedan prolaz i nije uopšte potreban

4. Conclusion

TIG welding with an activation flux (A-TIG) represents a significant improvement over TIG welding, primarily in terms of welding larger cross-sections. As such, the A-TIG process can compete with the MIG process in terms of productivity, with joint quality similar to TIG welding. Significant savings are achieved compared to TIG, primarily related to cheaper and faster preparation, without the need for V preparation of the base material. Also, welding the base material with a larger thickness using the TIG process requires welding in several passes, with a significant consumption of shielding gas and additional material, while with A-TIG one pass is sufficient and no additional material is needed at all. All this makes the A-TIG dodatni materijal. Sve ovo A-TIG postupak čini znatno produktivnijim postupkom u odnosu na TIG.

Dalja istraživanja u ovoj oblasti bi trebalo da daju definitivan odgovor na pitanje kakve su mehaničke osobine zavarenih spojeva dobijenih A-TIG postupkom i da li ti rezultati čine zavarene spojeve dobijene ovim postupkom usklađene sa važećim standardima i zahtevima za kvalifikacijom tehnologije zavarivanja.

process a significantly more productive process compared to TIG.

Further research in this area should give a definitive answer to the question of what are the mechanical properties of the welded joints obtained by the A-TIG process and whether these results make the welded joints obtained by this process aligned with the current standards and requirements for the qualification of welding technology.

Zahvalnost

Ovaj rad rezultat rada autora u okviru projekta pod naslovom „Inovativni materijali i tehnologije spajanja“ Laboratorija za ispitivanje materijala i Laboratorije za zavarivanje, Departmana za proizvodno mašinstvo, Fakulteta tehničkih nauka.

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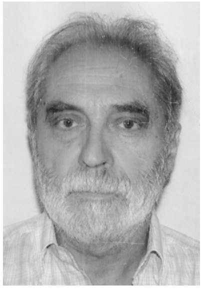
IN MEMORIAM

Dana 29. novembra 2023. godine napustio nas je naš dragi prijatelj i dugogodišnji saradnik



OGNJEN HAS

1946 – 2023.

OGNJEN (Zdenko) HAS je rođen 18.05.1946. godine u Beogradu, gde završava osnovnu školu „Žarko Zrenjanin“, a potom i Petu beogradsku gimnaziju. Upisuje Arhitektonski fakultet. Posle druge godine studija počinje da radi kao sekretar Unije bioloških naučnih društava Jugoslavije, koja izdaje stručnonaučni časopis. Ognjen organizuje izlazak časopisa i radi kao tehnički urednik. Posle osam godina prelazi u YUWELD gde se susreće sa problematikom zavarivanja, koja postaje njegova opsesija, na sreću čitave zavarivačke zajednice, ne samo Srbije, već i regiona.

U vreme najvećih previranja, početkom devedesetih godina prošlog veka, kada su se aktivnosti u području zavarivanja pomerale na sporedni kolosek, mnoge firme koje su se bavile tehnologijama zavarivanja, sečenja, reparaturnog zavarivanja i lemljenja i/ili bili njihova podrška, gasile su svoje aktivnosti ili napuštale naše tržište, Ognjen Has je pokazao izuzetnu hrabrost i odlučnost i osnovao sopstvenu firmu "HONEX" koja je postala simbol profesionalnosti, kompetentnosti i korektnosti.

Te davne 1992. godine, osnovati firmu koja bi se bavila zastupništvom proizvođača opreme za zavarivanje, prodajom dodatnih i potrošnih materijala za zavarivanje činilo se kao hrabar i rizičan potez. Pokazalo se da je Ognjen bio i vizionar. Zajedno sa suprugom Ljiljanom razvio je firmu koja je postala veoma moćna u području zavarivanja sa svih aspekata.

Na sreću zavarivačke zajednice, zahvaljujući pre svega svojoj upornosti, časnom stavu i posvećenosti poslu, Ognjen Has je kroz svoj dugogodišnji rad na plasmanu opreme i materijala za zavarivanja uspeo da pronikne u sve tajne tehnologije zavarivanja, savremenih robota kao i potreba našeg tržišta. Iza toga stoji veličina Ognjena Hasa: izuzetan rad i sposobnost da animira saradnike da ga prate i postignu rezultat.

Ognjen Has je bio i ostao onakav kakvo je i zavarivanje, spajao je ljude. Bio je komunikativan, duhovit, stvarao je poznanastva, gajio korektnost i naravno, pomagao zavarivački esnaf. Od samog početka "HONEX" je postao značajan i uticajan faktor u zavarivačkoj zajednici Srbije. Nesebično je pomagao svima, kako stručno, savetima, tako i tehničko-tehnološkim rešenjima. Hasovo opredeljenje da pomogne zavarivačku zajednicu, pa čak i konkurenciju, realnost je koja ga je pratila. Zbog toga se sa sigurnošću može reći da svako ko ga je poznavao ili imao privilegiju da sarađuje ili druži sa njim ima samo reči hvale i poštovanja.

Ne smemo zaboraviti da su Ognjen i njegov "HONEX" u vreme devedesetih, kada je to bilo najteže, bili veoma bitan oslonac za aktivnosti DUZS i časopisa Zavarivanje i zavarene konstrukcije. Ognjen Has i "HONEX" kontinuirano su učestvovali i pomagali sve aktivnosti Društva za unapređivanje zavarivanja u Srbiji, održavanje Savetovanja, seminara, takmičenja, izdavanje časopisa... Hasova veza sa Društvom je bilo nešto što se podrazumeva.

Odlazak Ognjena Hasa predstavlja nenadoknadiv gubitak za zavarivačku zajednicu, ne samo u Srbiji. Iza Ognjena ostaće praznina, ali i neizbrisiv trag i sećanje na izvanrednog saradnika, prijatelja i čoveka kao sinonim za filozofiju časnog poslovnog kodeksa ponašanja, sećanje koje će živeti u nama i sa nama.

Dr Vencislav Grabulov, IWE,dipl.ing.

Mihajlo Aranđelović [1,a], Radomir Jovičić [1], Branislav Đorđević [1], Nikola Milovanović [1], Simon Sedmak [1]

DEVELOPMENT OF AN ANALOGICAL MODEL FOR STRAIN MONITORING OF WELDED JOINT REGIONS DURING UNIAXIAL TENSILE TESTING

RAZVIJANJE ANALOGNOG MODELA PRAĆENJA POMERANJA ZONA ZAVARENOG SPOJA TOKOM ISPITIVANJA JEDNOOSNIM ZATEZANJEM

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Keywords: welding, uniaxial testing, strain

Ključne reči: zavarivanje, jednoosno zatezanje, pomeranje

Abstract

The idea behind the idea of developing this method was to introduce reference points at important locations, such as the fusion line and heat-affected zones, the displacement of which would be monitored during the uniaxial testing, and then measured at key moments. The uniaxial tensile test process was recorded with a high-resolution camera so that changes could be observed during the test. The reason why this approach was chosen was that the crucial zones could be adequately marked and thus allows the allocation of the appropriate frame in order to monitor the strain of each welded joint zone individually.

Rezime

Ideja iza pokušaja razvijanja ove metode se sastoji u tome da se na bitne lokacije kao što su linija stapanja i zone uticaja toplote unesu reperne tačke čije bi se pomeranje tokom ispitivanja pratilo i merilo u ključnim momentima. Proces ispitivanja jedno-osnim zatezanjem je sniman kamerom u visokoj rezoluciji kako bi mogle da se uoče promene tokom ispitivanja. Ovakav pristup je odabran kako bi mogle krucijalne zone da se adekvatno obeleže i na taj način omogućiti izdvajanja odgovarajućeg frejma kako bi se pomeranje svake zone zavrenog spoja ponaosob.

1. Introduction

It is common practice to consider welded joints as a whole, in the case of new joints, and repaired joints alike [1-4]. In reality, a welded joint has at least six regions with different mechanical properties, which is of particular significance in the cases where defects are present which could initiate a crack in the joint [5-8]. It is best to observe displacements and strains for each individual welded joint region, including two areas in the parent material and four area on either side of the heat affected zone – two between the HAZ and the parent material and two at the fusion line, between WM and HAZ. Individual behavior of all of these regions will be shown in this paper. For the purpose of experiments which will be shown here, the upper and lower sides of the weld will be monitored, in accordance with relevant standards, as shown in figure 1 [9].

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.

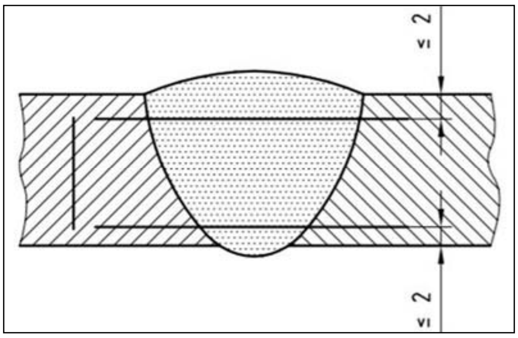

Figure 1: *Top and bottom lines of a welded joint, as defined by standard SRPS EN ISO 9015 [9]*

Slika 1*: Gornja i donja linija zavarenog spoja, kako je definisano standardom SRPS EN ISO 9015 [9]*

2. Experiment

Plates were made of carbon steel S275JR [10], welded using filler material VAC 60 [11], with M21 shield gas (18% CO_2 + 82% Ar). After welding, the joint was tested using non-destructive test methods, and no defects were detected. Specimens were tkan out of the plates, according to the cutting plan provided by standard SRPS EN ISO 15614 [12].

Reference points were placed on specimens 5.1 and 5.2, and these specimens were recorded using an HD camera. Displacement recording was performed synchronously with tensile testing, in order to ensure that the start and end time during testing was the same. All specimens were divided into two zones: Top zone (which represents the weld face) and Bottom zone (which corresponds to the root side). Each zone had 6 measuring points: two in the PM, two in the transition area between PM and heat affected zone, and two at the fusion line. Their displacements can provide insight into the general behaviour of each individual welded joint region.

Images which showed the measured displacement of reference points were directly correlated to stress-strain (figures 2 and 3) and time – stress – strain diagrams. Point 0 represents the initial position of the specimen after 2 seconds of tension, i.e. the moment at which equilibrium state is achieved. Time moment for point 2 (6^{th} second) was selected within the elastic region, immediately before plasticity would start to occur. Specimen geometry at initial moment 0 and final point 11 are shown in figures 4 – 7. All points after this one are located in the plastic region of the diagrams. An example of measuring distances is given in figures 4 and 5, whereas graphs with displacement values are shown in figures 8 – 11.

Table 1. *Moments during which stresses and strains were measured/determined, specimen 5.1*

Tabela 1. *Trenuci tokom kojih su mereni/određeni naponi i deformacije, uzorak 5.1*

Point	Stress [MPa]	Strain [%]	Time [s]
0	/	/	2
1	275	1	12
2	341	2	17
3	401	4	26
4	431	6	35
5	451	8	46
6	461	10	54
7	466	12	62
8	467	13	68
9	466	14	73
10	457	16	82
11	409	20	100

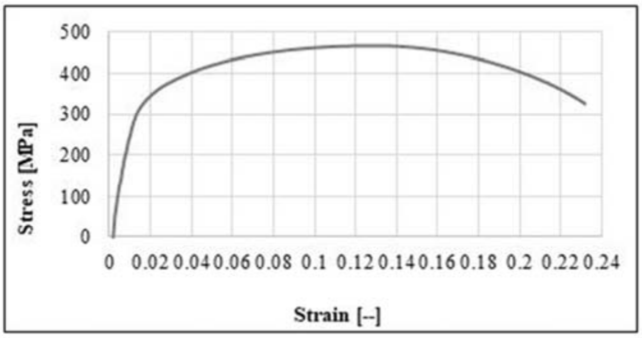

Figure 2. *Stress-strain diagram, specimen 5.1*

Slika 2. *Dijagram napon-deformacija, uzorak 5.1*

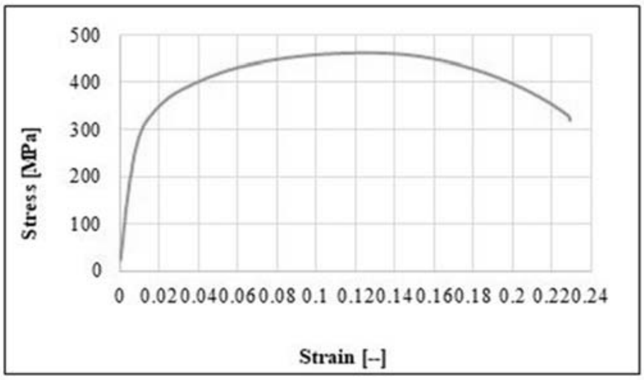

Figure 3. *Stress-strain diagram, specimen 5.2*

Slika 3. *Dijagram napon-deformacija, uzorak 5.2*

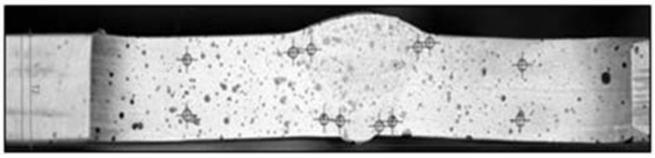

Figure 4. *Specimen 5.1: time point 0 (2s)*

Slika 4. *Uzorak 5.1: vremenska tačka 0 (2s)*

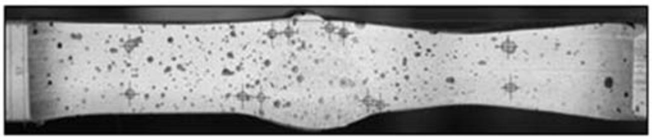

Figure 5. *Specimen 5.1: time point 11 (100s)*

Slika 5. *Uzorak 5.1: vremenska tačka 11 (100s)*

Table 2. *Moments during which stresses and strains were measured/determined, specimen 5.2*

Tabela 2. *Trenuci tokom kojih su mereni/određeni naponi i deformacije, uzorak 5.2*

Points	Stress [MPa]	Strain [%]	Time [s]
0	/	/	2
1	250	0.7	7
2	344	2	12
3	398	4	22
4	429	6	32
5	447	8	41
6	456	10	50
7	461	12	60
8	462	13	63
9	460	14	69
10	451	16	78
11	395	20	99

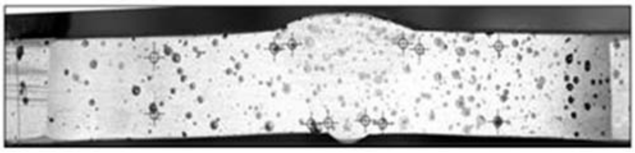

Figure 6. *Specimen 5.2: time point 0 (2s)*

Slika 6. *Uzorak 5.2: vremenska tačka 0 (2s)*

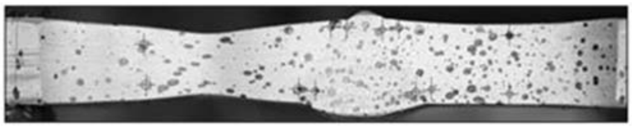

Figure 7. *Specimen 5.2: time point 11 (99s)*

Slika 7. *Uzorak 5.2: vremenska tačka 11 (99s)*

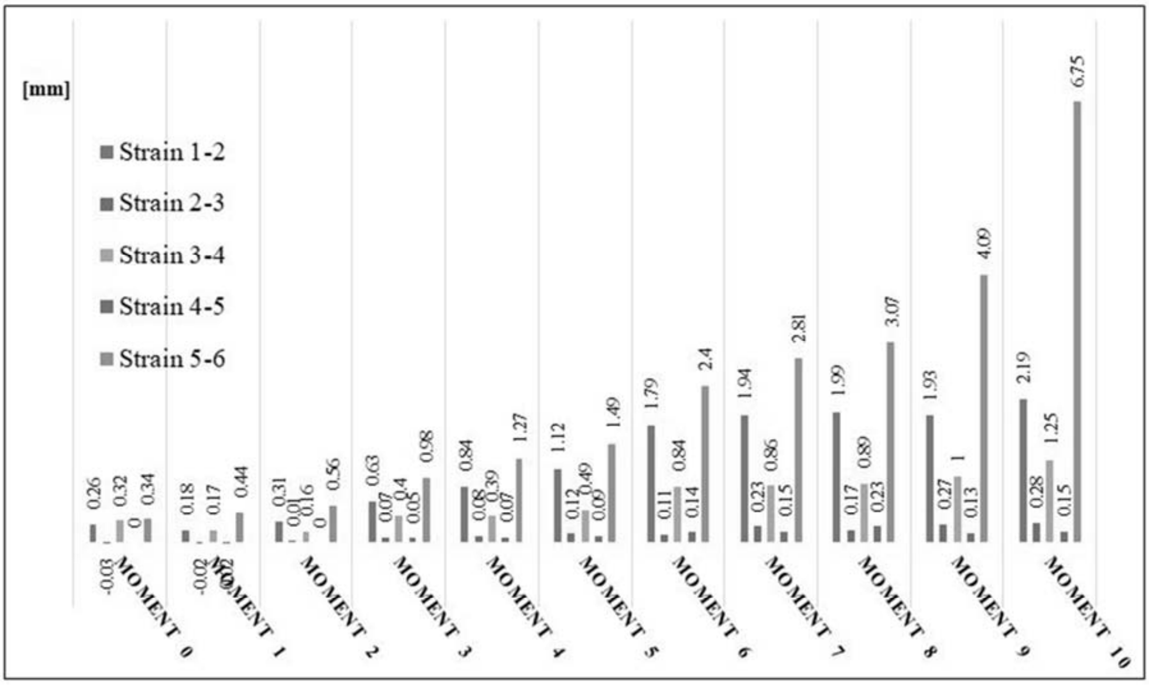

Figure 8. *Weld face point displacements specimen 5.1*

Slika 8. *Pomeranja tačke sa lica zavara za uzorak 5.1*

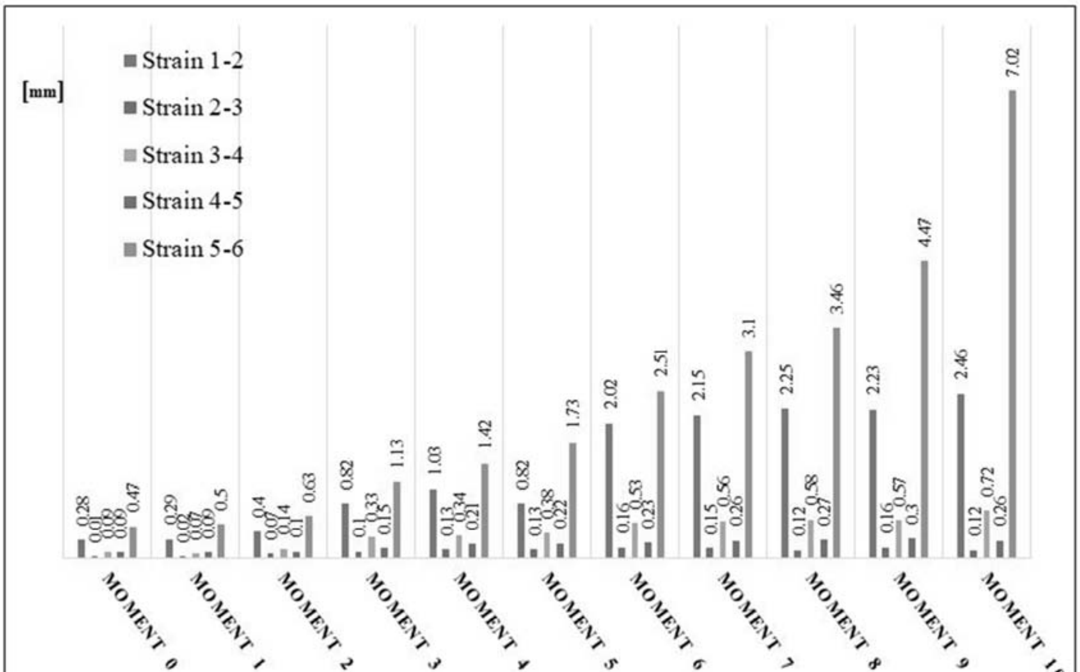

Figure 9. *Weld root point displacements specimen 5-1*

Slika 9. *Pomeranja tačke u korenu zavara za uzorak 5.1*

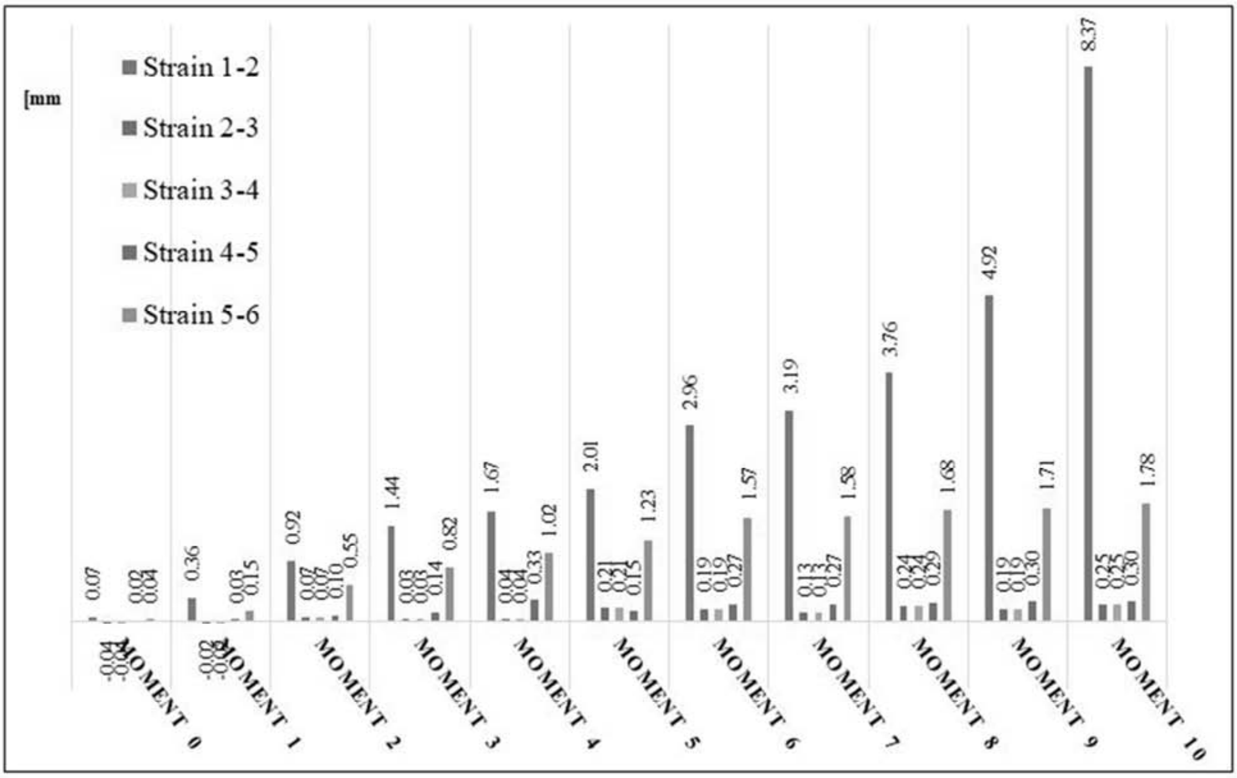

Figure 11. *Root face point displacements, specimen 5-2*

Slika 11. *Pomeranja tačke u korenu zavara za uzorak 5-2*

3. Discussion and conclusions

Strain at failure for both specimens (5.1 and 5.2) was around 23%, at force magnitude of 77 kN (corresponding to a stress of around 300 MPa), and both specimens entered the plastic strain stage at this point, whereas failure occurred in the parent material for both specimens. Largest displacement was measured in point 5-6 in the case of specimen 5.1, in the weld root area. This displacement was 7.02 mm, whereas the highest displacement in the case of specimen 5.2 was measured in the weld face area – 8.37 mm in points 1-2. Smallest displacement values were recorded in the heat affected zone, weld face side, in points 4-5 and it had a magnitude of 0.15 mm. For the second specimen, displacement was lowest in the heat affected zone between points 2-3. Hence, lowest displacement (and strain) occurred in the heat affected zones for both specimens, whereas the highest values were in the parent material, on the side where the tensile force was applied. This was expected due to the considerable difference in mechanical properties between the HAZ and the PM. Due to a noticeably lower yield stress and tensile strength in the parent material, it started to deform much earlier compared to the HAZ. These results have, among other things, confirmed that the welding technology was properly selected, since the failure did not occur in the weld or the

3. Diskusija i zaključci

Deformacija pri lomu za oba uzorka (5.1 i 5.2) iznosila je oko 23%, pri sili od 77 kN (što odgovara naponu od oko 300 MPa), i oba uzorka su u ovom trenutku ušla u fazu plastične deformacije, dok je do loma došlo u osnovnom materijalu kod oba uzorka. ajveći pomak je izmeren u tački 5-6 u slučaju uzorka 5.1, u oblasti korena šava. vaj pomak je iznosio 7,02 mm, dok je najveći pomak u slučaju uzorka 5,2 izmjeren u području lica šava – 8,37 mm u tačkama 1-2. ajmanje vrednosti pomaka zabeležene su u zoni uticaja toplote, na strani lica šava, u tačkama 4-5 i imale su veličinu od 0,15 mm. Za drugi uzorak, pomeranje je bilo najmanje u zoni uticaja toplote između tačaka 2-3. Dakle, najmanji pomeraj (i deformacija) nastao je u zonama uticaja toplotote za oba uzorka, dok su najveće vrednosti bile u osnovnom materijalu, na strani gde je primenjena sila zatezanja. vo je bilo očekivano zbog značajne razlike u mehaničkim svojstvima između zone uticaja toplote i osnovnog materijala. bog primetno nižeg napona tečenja i zatezne čvrstoće osnovnog materijala, on je počeo da se deformiše mnogo ranije u odnosu na zonu uticaja toplote. vi rezultati su, između ostalog, potvrdili da je tehnologija zavarivanja bila pravilno odabrana, jer nije došlo do loma u metalu šava ili zoni uticaja toplote, što je problem koji se često sreće u praksi. Rezultati prikazani u ovom radu heat affected zone, which is a problem that is commonly encountered in practice. Results shown in this paper indicate that each individual welded joint region had shown different tensile behaviour, in terms of strain and displacements. This is, for example, reflected in the 20% difference in displacement values for HAZ between the two specimens, even though they were taken from the same welded plate. Hence, this methodology confirmed the initial assumption that the welded joint should not be viewed as whole, but rather as a combination of individual regions. This approach could be further improved by dividing the heat affected zone into subregions with different microstructures. The main disadvantage of this method is that is has lower accuracy compared to other conventional measuring method, and therefore it is recommended to be used in combination with these methods (such as digital image correlation) in order to obtain better results.

pokazuju da je svaka pojedinačna oblast zavarenog spoja pokazala različito zatezno ponašanje, u smislu deformacije i pomaka. vo se, na primer, ogleda u razlici od 20% u vrednostima pomaka u zoni uticaja toplote između dva uzorka, iako su uzeti iz iste zavarene ploče. akle, ova metodologija je potvrdila početnu pretpostavku da zavareni spoj ne treba posmatrati kao celinu, već kao kombinaciju pojedinačnih regiona. vaj pristup bi se mogao dalje poboljšati podelom zone uticaja toplote na podoblast sa različitim mikrostrukturama. Glavni nedostatak ove metode je što ima manju tačnost u odnosu na druge konvencionalne metode merenja, pa se stoga preporučuje da se koristi u kombinaciji sa ovim metodama (kao što je korelacija digitalne slike) kako bi se dobili bolji rezultati.

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MEHANIČKA SVOJSTVA SUČEONIH ZAVARENIH SPOJEVA RAZLIČITIH LEGURA ALUMINIJUMA 2024-T351 / 6082-T6 DOBIJENIH MIG POSTUPKOM ZAVARIVANJA

MECHANICAL PROPERTIES OF BUTT WELDED JOINTS OF DISSIMILARI ALUMINUM ALLOYS 2024-T351 / 6082-T6 OBTAINED BY MIG WELDING

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Ključne reči: zavareni spojevi različitih legure aluminijuma, legura aluminijuma 2024-T351, legura aluminijuma 6082-T6, MIG postupak zavarivanja, mikrostruktura, mehanička svojstva zavarenih spojeva

Keywords: welded joints of different aluminium alloys, aluminium alloy 2024-T351, aluminium alloy 6082-T6, MIG welding process, microstructure, mechanical properties of welded joints

Rezime

Ovaj rad ima za cilj da predstavi efekte MIG postupka zavarivanja na mehanička svojstva sučeonog zavarenog spoja različitih legura aluminijuma 2024-T351 i AA 6082-T6. Legura AA 6082 T6 je dobro zavariva klasičnim fuzionim postupcima zavarivanja (MIG i TIG), dok je legura 2024-T351 gotovo nezavariva. Za zavarivanje ovih dveju legura Al korišćen je MIG postupak zavarivanja na limu debljine 8 mm koristeći dodatni materrijal 4043A (AlSi5) i mešavinu argona i helijuma kao zaštitnog gasa. Analiziran je uticaj MIG zavarivanja na dobijenu strukturu i mehanička svojstva zavarenog spoja. Procena mehaničkih svojstava zavarenog spoja različitih Al legure je vršena ispitivanje tvrdoće prema Vikersu, ispitivanje na zatezanje i savijanja zavarenih uzoraka.

Abstract

This paper aims to present the effects of the MIG welding on the mechanical properties of a butt-welded joint of dissimilar aluminium alloys 2024-T351 and AA 6082-T6. Aluminium alloy 6082 T6 is well weldable by classical fusion welding processes (MIG and TIG), while aluminium alloy 2024-T351 is almost non-weldable. For the welding of these two Al alloys, the MIG welding was used on an 8 mm thick sheet using filler material 4043A (AlSi5) and a mixture of argon and helium as a shielding gas. The influence of MIG welding on the obtained structure and mechanical properties of the welded joint was analyzed. The assessment of the mechanical properties of the welded joint of dissimilar Al alloys was performed by Vickers hardness testing, tensile and bending tests of the welded samples.

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

Aluminijum je metal koji je veoma rasprostranjen u zemljinoj kori. Posle čelika, aluminijum je najviše korišćen metal. Spada u grupu lakih metala. Približno tri puta je lakši od čelika. Aluminijumske konstrukcije se često koriste u transportnoj tehnici, u automobilskoj industriji, u industriji šinskih vozila, u brodogradnji, u avioindustriji i čak u svemirskim tehnologijama. Za proizvodnju lakih konstrukcija transportnih sredstava koriste se različite legure aluminijuma, koje imaju određena svojstva (čvrstoću, tvrdoću, žilavost, udarnu žilavost, otpornost materijala na savijanje i rast prsline, antikorozivna svojstva) uz malu gustinu materijala.

Aluminijum ima slaba mehanička svojstva. Povećanje niske čvrstoće aluminijuma moguće je: legiranjem, hladnom deformacijom, termičkom obradom i kombinacijom ovih mogućnosti: legiranjem i hladnom deformacijom ili legiranjem i termičkom obradom. Legirajući elementi su: bakar, mangan, silicijum, magnezijum i cink. Legure aluminijuma su uglavnom dvokopmonentne i trokomponentne. Legure aluminijuma su podeljene u osam grupa, koje nose oznake od 1XXX do 8XXX.

Legure aluminijuma serije 3XXX, 4XXX i 5XXX su aluminijumske legure termički neobradive, koje se ojačavaju rastvaranjem legirajućih elemenata u čvrstom rastvoru i plastičnom preradom (deformaciono ojačavanje). Legure aluminijuma serije 2XXX, 6XXX, 7XXX koje sadrže legirajuće elemente bakar, silicijum i magnezijum i cink, respektivno, su termički obradive legure. Termička obrada, u najširem smislu, odnosi se na operacije zagrevanja do određene temperature i hlađenja, koje se izvode u svrhu promene mehaničkih svojstava, povećanja tvrdoće i čvrstoće.

Konstrukcije automobila, vozova, brodova, aviona, svemirskih letilica, koje se izrađuju od različitih legura aluminijuma spajaju se najčešće klasičnim postupcima zavarivanja topljenjem MIG i TIG, eventualno postupcima zavarivanjem trenjem sa mešanjem, postupkom zavarivanja laserom i elektronskim snopom. Postupcima zavarivanja topljenjem lako se spajaju materijali koji imaju dobru zavarljivost. Materijal je dobro zavarljiv ako je određenim postupkom zavarivanja moguće napraviti takav zavareni spoj koji će izazvati najmanju moguću nehomogenost u šavu, koji će se dobro ponašati u svim eksploatacionim uslovima (opterećenje, korozija, visoka ili niska temperatura i sl.) u radnom veku korišćenja zavarenog proizvoda ili konstrukcije. Na zavarljivost legura aluminijuma utiču brojni faktori kao što su: veći afinitet prema kiseoniku pri čemu se stvara teško topljiv oksid, veća toplotna provodljivost i veći koeficijent toplotnog širenja, veliko skupljanje pri očvršćavanju i velika rastvorljivost vodonika u tečnoj fazi, koja se smanjuje drastično pri očvršćavanju. Zavarivanjem legura aluminijuma smanjuju se mehanička svojstva u ZUT-u, snižava se koroziona postojanost, dolazi do nastajanja pora i uključaka, dolazi do nastajanja oksidacionog sloja Al_2O_3 na površini metala zbog velikog afiniteta aluminijuma prema kiseoniku, dolazi do pojave hladnih i toplih prslina. Legure aluminijuma se zavaruju sa dodatnim materijalom povećanog sadržaja Si ili Mg [1].

U poslednje vreme, vodeći proizvođači opreme za zavarivanje omogućavaju razne modifikacije MIG i TIG postupaka zavarivanja, kao što je AC MIG sa pulsiranjem tokom zavarivanja jednim ili duplim pulsom, ili TIP TIG sa automatskim dodavanjem tople žice.

Ako tehnologija postupka zavarivanja nije prikladna, mogu se pojaviti defekti u području metala šava, čime se smanjuje pouzdanost zavarene konstrukcije. Mogu se pojaviti defekti zavarenih spojeva poput poroznosti, prslina, nedostatka penetracije ili nedostatka fuzije [2].

U ovom radu su data istraživanja mehaničkog ponašanja zavarenog spoja ostvarenog MIG postupkom zavarivanja između različitih legure aluminijuma 2024 T351 i 6082 T6 koristeći dodatni materijal S Al 4043A (AlSi5).

2. Eksperimantalna procedura i rezultati

Eksperimentalna istraživanja su bila fokusirana na određivanju uticaja MIG postupka zavarivanja na metalurška i mehanička svojstva zavarenih spojeva legura 2024-T351 i 6082-T6. Legura aluminijuma 2024 spada seriji legure 2XXX gde je glavni legirajući elemenat bakar. Mehaničke osobine ovih legura dostižu vrednosti kao kod ugljeničnih čelika. Ovako visoka čvrstoća legura je zahvaljujući jedinjenju $CuAl_2$ koje se izdvaja u obliku taloga. Taložno ojačavanje ove grupe legura odvija se kroz postupak veštačkog starenja. Kako ove legure nemaju dobru otpornost na koroziju, često se prevlače (plakiraju) čistim aluminijumom radi antikorozione zaštite. Legure serije 2XXX zbog visoke čvrstoće, dobrih svojstva na zamorna opterećenja, zbog posedovanja svojstava visoke tolerancije oštećenja se koriste za izradu delova u avioindustriji. Ove legure se zovu durali (duraluminijum). Sa dodatkom elemenata kao što su Mg i Li, moguće je smanjiti specifičnu gustinu i poboljšati performanse Al legura za primenu za izradu delova u avio industriji [3]. Legure serije 2XXX po pravilu imaju lošu zavarljivost klasičnim postupcima zavarivanja topljenjem (MIG, TIG), zbog velike osetljivosti ka pojavi toplih prslina, kao i zbog rastvaranja čestica taloga. Uglavnom za zavarivanje ovih legura koristi se postupak zavarivanja trenjem sa mešanjem [4,5].

Legura aluminijuma 6082 pripada seriji legura 6XXX legura gde su legirajući elementi silicijumom i magnezijumom. Ove legure su pogodne za termičku obradu (žarenje, kaljenje, starenje). Legure sistema Al-Mg-Si imaju umerenu čvrstocu i dobru otpornost na koroziju, u poređenju sa drugim termički obradivim Al legurama. Tipično za ove legure je da imaju dobru sposobnost oblikovanja i prihvatljivu zavarljivost.

Hemijska i mehanička svojstva legura 2024-T351 i 6082-T6 koje su predmet ovog istraživanja spajane MIG postupkom date su u tabeli 1.

Hemijski sastav korišćenog dodatnog materijala pri zavarivanju prikazan je u tabeli 2.

Tabela 1. *Hemijski sastav i mehanička svojstva legure aluminijuma 2024 T351 i 6082 T6 [6]*

Table 1. *Chemical composition and mechanical properties of aluminum alloy 2024 T351 and 6082 T6 [6]*

	Mn %	Fe %	Mg %	Si %	Cu %	Zn %	Ti %	Cr %	Al %
6082 T6	0,4 - 1,0	0 - 0,5	0,6 - 1,2	0,7 - 1,3	0 - 0,1	0 - 0,2	0 - 0,1	0 - 0,25	Balance
2024 T351	0,65	0,17	1,56	0,046	4,7	0,11	0,032		Balance

	Yield strength, min R_{eh}	Ultimate tensile strength, min R_m	Elongation at break, min A	Hardnes s
	[MPa]	[MPa]	[%]	[HV]
2024 T351	310	425	10	137
6082 T6	260	310	10	95

Tabela 2. *Hemijski sastav dodatnog materijala žice EN ISO 18273 S Al 4043A (AlSi5)*

Table 2. *Chemical composition of the filler material of wire EN ISO 18273 S Al 4043A (AlSi5)*

Mn %	Fe %	Mg %	Si %	Cu %	Zn %	Ti %	Be %	Al %
<0,15	<0,6	<0,2	4,5 - 5,5	<0,3	<0,1	<0,15	<0,0003	Balance

Dimenzije ploča koje su korišćene za zavarivanje bile su dužine 300 mm, širine 125 mm i debljine 8 mm. Parametri zavarivanja dati su u tabeli 3.

Tabela 3. *Parametri zavarivanja za MIG postupak zavarivanja sučeonih zavarenih spojeva za materijal EN AW 2024-T351 / EN AW 6082-T6*

Table 3. *Welding parameters for the MIG butt weld welding process for the material EN AW 2024-T351 / EN AW 6082-T6*

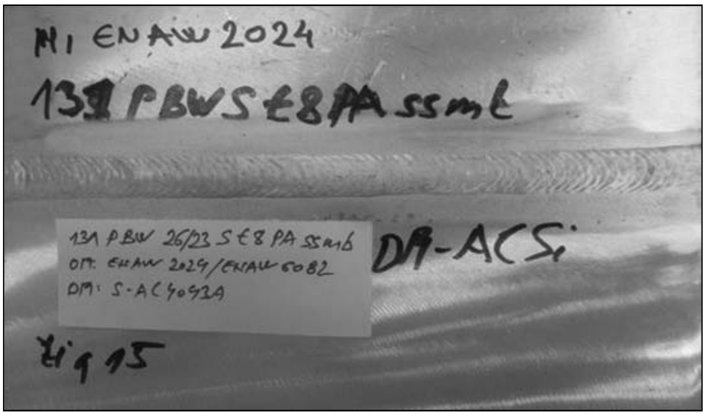
Broj prolaza	Postupak EN ISO 4063	Struja zavarivanja I [A]	Napon zavarivanja U [V]	Dužina zavara / prolaza [cm]	Brzina žice [m/min]	Temperatura predgrevanja i međuprolaza [°C]	Brzina zavarivanja v [mm/s]	Uneta toplota [J/mm] H=I·U·η/v
1	131	150	21	30	6,2	40	7	360
2	131	160	22	30	6,5	90	11,5	245
3	131	160	22	30	6,5	90	7,7	366
Efficiency η=0,8								

Ostali podaci vezani za korišćeni uređaj za zavarivanje, zaštitne gasove, predgrevanje i ostalo prikazani su u tabeli 4.

Tabela 4. *Ostale karakteristike procesa zavarivanja*

Table 4. *Other characteristics of welding process*

Aparat za zavarivanje:	Fronius Trans Puls Synergic 4000
Zaštitni gas:	I3-ArHe-30
Protok gasa:	18 l/min
Prečnik šobe:	Ø 12 mm
Rastojanje šobe:	8 – 12 mm
Ugao gorionika:	90 ˚ , Tehnika “unapred”
Način predgrevanja:	Ne (zagrejano heftanjem)



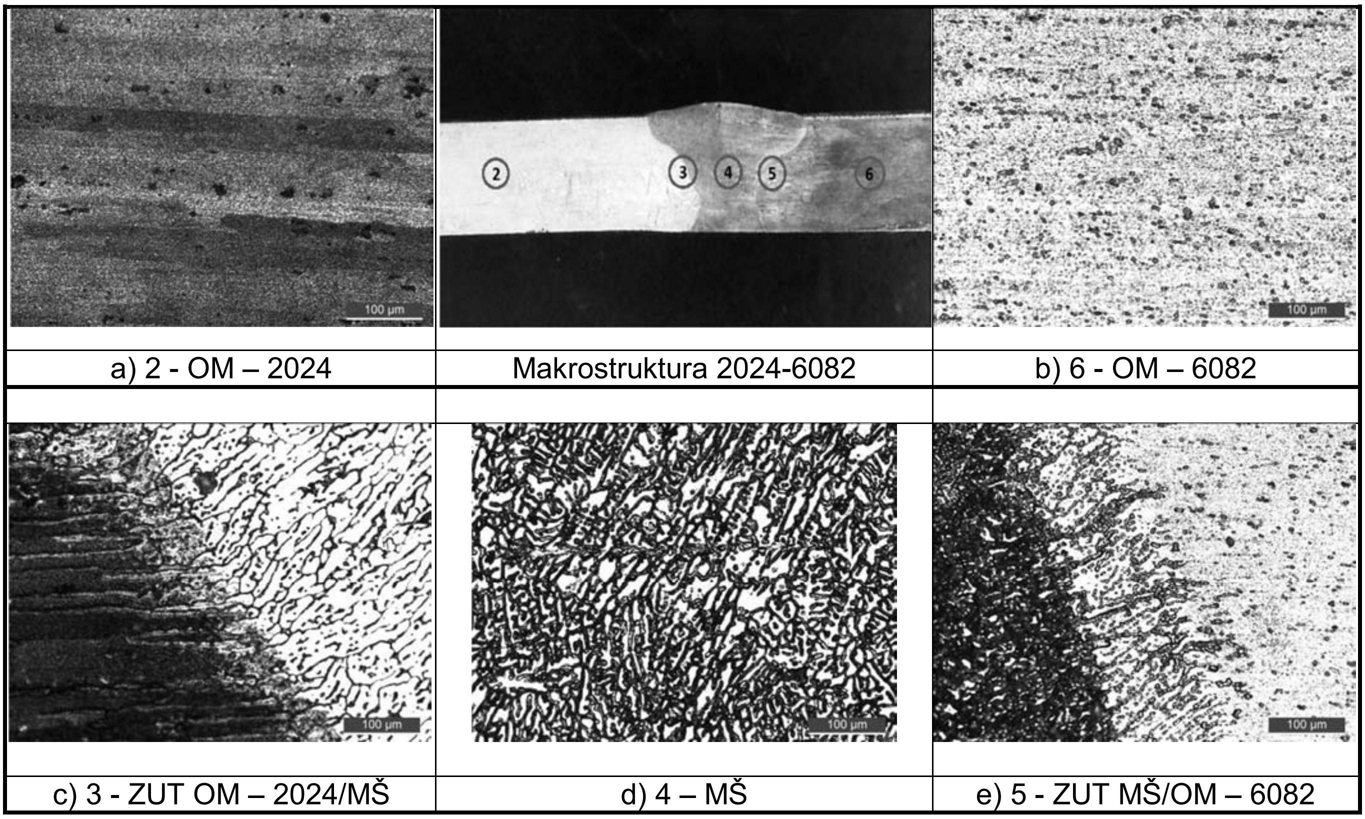
Slika 1. *Izgled zavarenog spoja, lice šava*

Figure 1. *Appearance of the welded joint, the weld metal face*

Slika 2. *Makrostruktura zavarenog spoja rađenog sa korenom letvom, poprečni presek*

Figure 2. *Microstructure of a welded joint made with a root lath, cross section*

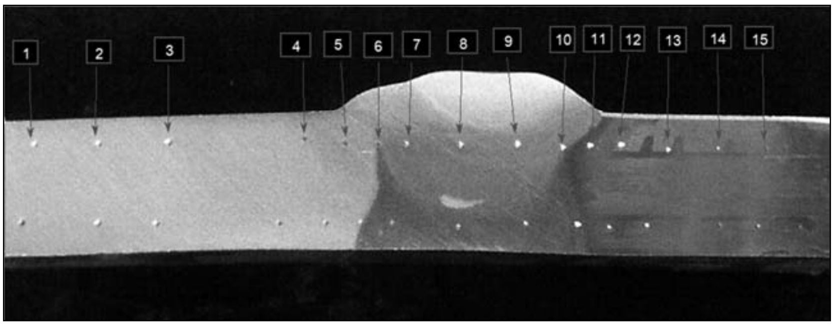
Iz zavarenih uzoraka su isečene epruvete postupkom sečenja vodenim mlazom. Pripremljenu su epruvete za ispitivanje makro- i mikrostrukture zavarenih šavova, za ispitivanje tvrdoće, za ispitivanje udarne žilavosti metodom instrumentiranog Šarpijevog klatna, epruvete za ispitivanje na zatezanje, epruvete za ispitivanje parametara mehanike loma i brzine rasta prsline. Za analizu mikrostrukture zavarenog spoja korišćen je optički mikroskop Leica Q500MC. Mikrostruktura je ispitivana na poprečnom preseku uzoraka nakon uobičajene metalografske pripreme i nagrizanja u Kelerovom reagensu. Na slici 3 date mikrostrukture zavarenog spoja u zonama osnovnih materijala, zonama uticaja toplote i u metalu šava.



Slika 3. *Mikrostruktura zavarenog spoja*

Figure 3. *Microstructure of the welded joint (OM=BM, ZUT=HAZ, MŠ=WM)*

Merenje tvrdoće prema Vikersu je vršeno na uređaju za merenje tvrdoće Willson VH1150. Prema standardnoj procedure po tri merenja tvrdoće su rađena u osnovnom metalu 2024-T351 (OM1), tri u zoni uticaja toplote (ZUT) na strani OM1, tri u metalu šava (MŠ), tri u zoni uticaja toplote (ZUT) na strani osnovnog metala 6082-T6 (OM2) i tri u osnovnom metalu 6082-T6. Na slici 4 prikazana su mesta merenja tvrdoće u zavarenom spoju blizu čela i blizu korena spoja.



Slika 4. *Mesta merenja tvrdoće na zavarenom spoju*

Figure 4*. Hardness measuring points on the welded joint*

Rezultati merenja tvrdoće dati su u tabeli 5, a dijagram profila tvrdoće sa merenjima duž dva horizontalna pravca blizu čela i blizu korena zavarenog spoja data je na slici 5.

***Tabela 4.** Rezultati merenja tvrdoće zavarenog spoja blizu korena šava*

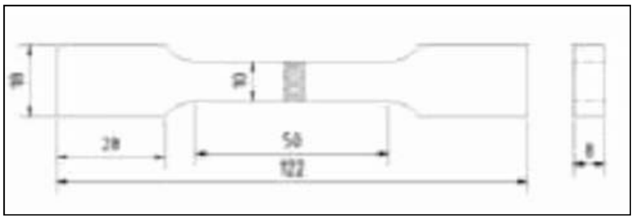
***Table 4.** Hardness results for welded joint near the root of the seam*

Merno mesto	Položaj mesta otiska	Izmerena vrednost (HV)	Merno mesto	Položaj mesta otiska	Izmerena vrednost (HV)
1/16	OM 1	142,7/150,7	9/24	MŠ	80,0/108,1
2/17	OM 1	149,0/152,8	10/25	ZUT 2	73,9/67,0
3/18	OM 1	137,7/142,6	11/26	ZUT 2	68,3/66,7
4/19	ZUT 1	125,0/120,9	12/27	ZUT 2	62,7/65,4
5/20	ZUT 1	141,1/135,6	13/28	OM 2	72,9/74
6/21	ZUT 1	59,7/116,7	14/29	OM 2	87,9/88,3
7/22	MŠ	73,7/88,5	15/30	OM 2	84,1/90,1
8/23	MŠ	74,4/83,3			
OM– osnovni metal = (BM) ZUT – zona uticaja toplote = (HAZ) MŠ – metal šava = (WM)					

***Slika 5.** Raspodela tvrdoće kroz sučeoni MIG zavareni spoj legura 2024-T351/6082-T6*

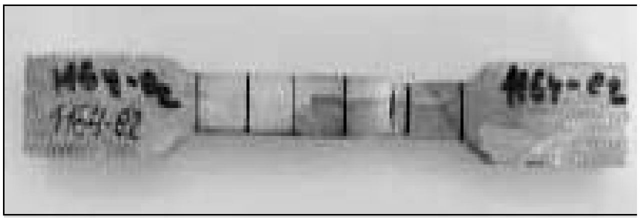
***Figure 5**. Hardness distribution through a butt MIG welded joint of alloys 2024-T351/6082-T6, (OM=BM, ZUT=HAZ, MŠ=WM)*

Zatezna svojstva su određena na sobnoj temperaturi korišćenjem kidalice Shimadzu AG-X 300 kN. Korišćene su epruvete definisane standardom ASTM E8M dobijene iz zavarenih uzoraka upravno na zavareni spoj. Dimenzije epruvete date su na slici 6. Na slici 7 prikazana je epruveta nakon loma.



__Slika 6.__ Dimenzije epruvete za ispitivanje na zatezanje

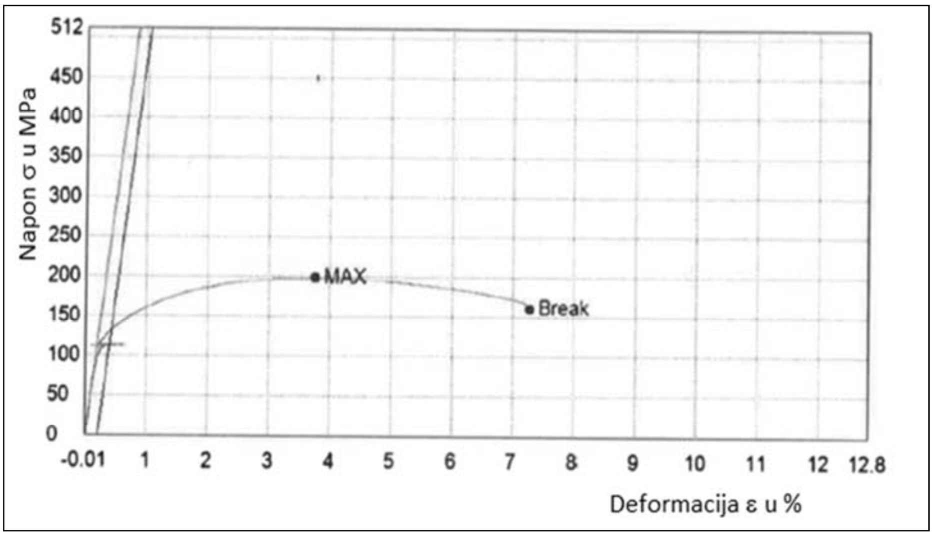
__Figure 6.__ Dimensions of the tensile test sample



__Slika 7.__ Epruveta nakon ispitivanja na zatezanje

__Figure 7.__ Test sample after tensile test

Relacija između napona i deformacije pri ispitivanju na zatezanje data je na slici 8, a rezultat ispitivanja prikazan je u tabeli 5.



__Slika 8.__ Dijagram napon-deformacija

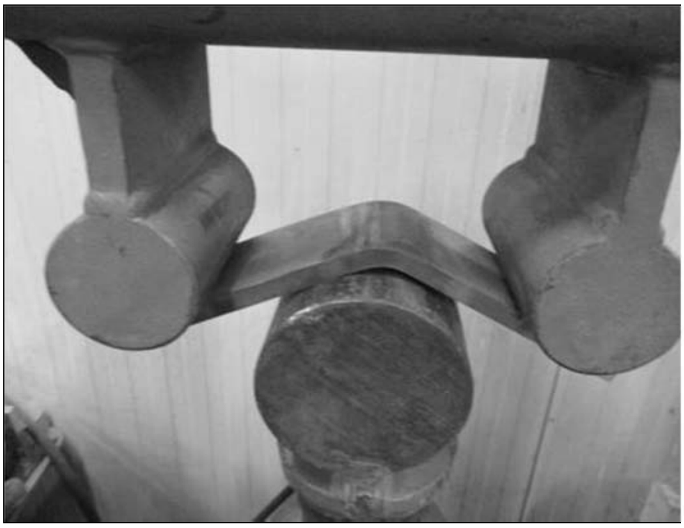
__Figure 8.__ Stress-strain diagram

__Tabela 5.__ Rezultati ispitivanja na zatezanje

__Table 5.__ Tensile test results

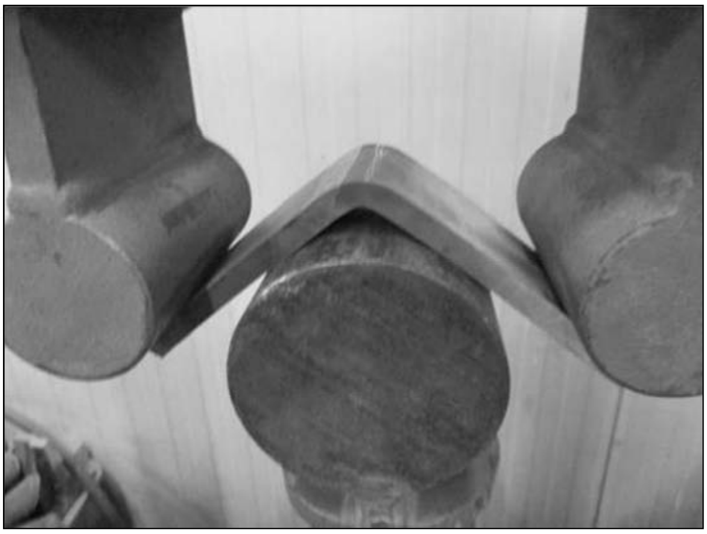
Dimenzije uzorka	Početna merna dužina	Granica tečenja $R_{p0,2}$ [MPa]	Zatezna čvrstoća R_m [MPa]	Izduženje posle prekida A_{50} [%]
8x10	50	113	198	7,3

Testovi savijanja korena i lica zavarenog spoja su data na slici 9 i 10. Test je vršen u uslovima sobne temperature primenom metode savijanja u tri tačke.



Slika 9. *Savijanje korena zavarenog spoja*

Figure 9. *Bending of the root of the welded joint*



Slika 10. *Savijanje lica zavarenog spoja*

Figure 10. Bending of the face of the welded joint

3. Diskusija rezultata

U ovom radu sprovedena su makrostrukturna, mikrostrukturna i mehanička ispitivanje svojstva zavarenog šava kojim su spojeni različiti materijali AA 2024-T351, koji je gotovo nezavariv klasičnim postupcima zavarivanja i AA 6082-T6 dobro zavariva legura. Zavarivanje izvršeno MIG postupkom u zoni zaštitnog gasa mešavine Ar i He sa dodatnim materijalom 4043A.

Mikrostruktura OM1 - legure aluminijuma 2024-T351 prikazana je na slici 3a. Na uzorku su uočena izdužena zrna u pravcu valjanja. Prisutne su čestice sitnog taloga.

Mikrostruktura OM2 – legure aluminijuma 6082-T6, prikazane na slici 3b. Na uzorku se uočava IMF izdvojen u obliku krupnijih čestica u smeru valjanja i sitne čestice taloga nastale u procesu starenja.

Unosom toplote spajaju se osnovni metali i dodatni metal, te se stvara zona metala šava sa strukturom koja je drugačija od strukture osnovnih metala. Veći procenat silicijuma (oko 5%) u hemijskom sastavu dodatnog materijala je koristan za povećanje duktilnosti zavarene strukture. Zona topljenja, ili oblast metala šava, nastaje popunjavanjem prethodno pripremljenog žleba rastopljenim dodatnim materijalom. Po završetku očvršćavanja metal šava ima karakterističnu strukturu livenja. Sloj koji poslednji očvršćava ima izrazito dendritnu strukturu, za koju je karakteristična pojava likvacije, tj. lokalne hemijske nehomogenosti, zbog nedostatka vremena za difuziju atoma legirajućih elemenata. Na slici 3d prikazana je mikrostruktura metala šava. Uočavaju se čestice taloga izdvojene po granicama zrna. Zrna su različitih veličina i imaju usmerenu orijentaciju, saglasno [7].

Na slici 3e data je mikrostruktura ZUT-a između metala šava i osnovnog metala 6082 T6. U MŠ do ZUT-a prisutna je uska zona stubastih kristala. Talog je izdvojen po granicama zrna i unutar zrna u krupnoj formi. Talog u ZUT-u je izdvojen nasumično kao globularne krupne čestice. Na slici 3c data je mikrostruktura ZUT-a između metala šava i osnovnog metala 2024 T351. U ZUT-u talog je izdvojen po granicama zrna. U MŠ do ZUT-a talog je izdvojen po granicama zrna stubaste orijentacije.

Što se tiče mehaničkih svojstava sučeonog zavarenog spoja 2024-T351/6082-T6, legura 2024-T351 ima mehanička svojstva (zatezna čvrstoća i granica tečenja) kao konstrukcioni čelici. Mehanička svojstva ove legure su značajno veća od svojstava 6082-T6 zbog efekta bakra koji povećava čvrstoću.

Mikrostruktura metala šava dobijena MIG postupkom zavarivanja se značajno razlikuje od mikrostrukture osnovnih metala, pa saglasno tome su i mehanička svojstva zavarenog spoja manja od mehaničkih svojstava osnovnih metala. Ispitivanjem na zatezanje je uočena i manja duktilnost.

Presek površine loma epruvete za ispitivanje na zatezanje prikazan je na slici 7. Lokacija loma je u OM2 – 6082-T6. Rezultati ispitivanja na savijanje ukazuju na loša tehnološka svojstva zavarenih spojeva. Mali ugao savijanja do pojave prsline ukazuje da su zavareni spojevi veoma krti saglasno [7, 8, 9 i 10].

Tvrdoća metala šava, mereno blizu čela i blizu korena je oko 80 HV, što je manje u odnosu na mekši osnovni metal 6082-T6 koji ima tvrdoću oko 90 HV, a značajno manje u odnosu na osnovni metal 2024-T351, koji ima tvrdoću oko 150 HV. Tvrdoća ZUT-a prema osnovnom metalu 6082-T6 je oko 60HV, manja nego u zoni metala šava zbog rasta zrna u ovoj zoni. Na drugoj strani, ZUT prema osnovnom metalu 2024-T351 ima tvrdoću oko 120 HV.

4. Zaključak

Na osnovu napred navedenog može se zaključiti:

- Maksimalna zatezna čvrstoća zavarenog spoja je (198 MPa) u poređenju sa (310 MPa) legure 6082-T6 koji je slabiji materijal zavarenog spoja, odnosno smanjenje čvrstoće je oko (36%).
- Utvrđeno je da se lom epruvete ispitivane na zatezanje dogodio na strani legure aluminijuma 6082-T6.
- Tvrdoća metala šava je 55% niža u odnosu na tvrdoću osnovnog metala 2024-T351.
- Za poboljšanje performansi zavarenih spojeva različitih legura aluminijuma 2024-T351 i 6082-T6 moraju se odabrati optimalni parametri zavarivanja.

4. Conclusion

Based on the results of the performed investigation, it can be concluded:

- The maximum tensile strenght od welded joint is (198 MPa) compared to (310 MPa) alloy 6082-T6 which is a weaker welded joint material, so the reduction in strenght is about (36%).
- The fracture of the tensile test sample was found to occur on the 6082-T6 aluminium alloy side.
- Weld metal hardness is 55% lower than base metal hardness 2024-T351.
- To improve the performance of welded joints of different aluminium alloys 2024-T351 and 6082-T6, optimal welding parameters must be selected.

Zahvalnost

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IMPLEMENTATION OF A WELDING 4.0 WELDING QUALITY MANAGEMENT SYSTEM EXPLAINED ON REAL APPLICATIONS IN MANUFACTURING AND EDUCATION

IMPLEMENTACIJA SISTEMA UPRAVLJANJA KVALITETOM ZAVARIVANJA WELDING 4.0 PRIKAZANA NA REALNIM PRIMENAMA U PROIZVODNJI I OBRAZOVANJU

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Key words: digitalization, welding, quality assurance, quality management, WPQR, WPS, welding coordinator, welding supervisor

Abstract

Discovering savings potentials, ensuring cost-effective manufacture and documenting every weld are three requirements, which couldn't be more different. It is precisely in quality assurance and quality management where documentation is increasingly gaining in importance. For welding companies, this entails making a record of the different welding parameters. In conventional work practices, the relevant values are written down by hand. Most of these values are hold values, which are displayed on the machine at the end of the welding process. However, such values do not provide any indications on how the parameters have changed during the welding process. Modern Welding 4.0 systems not only meet almost all requirements for a quality assurance documentation system, but provide much, much more. Welding 4.0 systems record and log all welding parameters on a continuous basis, something, that is becoming mandatory on an increasingly more frequent basis. The data can be used to demonstrate at any time that required parameters have been met and that the weld features the required characteristics as a result. In addition, the recorded data can be used for exact calculations on manufacturing time or material consumption, as well for starting optimization processes and management decisions. The Paper shows and explains the basic principles of Welding 4.0 systems and explains the benefits on real examples from the welding manufacturing and welding education.

Ključne reči: digitalizacija, zavarivanje, obezbeđenje kvaliteta, upravljanje kvalitetom, WPQR, WPS, koordinator zavarivanja, inspektor zavarivanja

Rezime

Otkrivanje potencijala ušteda, obezbeđivanje isplative proizvodnje i dokumentovanje svakog zavara su tri zahteva, koji ne mogu biti drugačiji. Upravo u osiguranju kvaliteta i upravljanju kvalitetom dokumentacija sve više dobija na značaju. Za kompanije koje se bave zavarivanjem, ovo podrazumeva vođenje evidencije o različitim parametrima zavarivanja. U konvencionalnim radnim praksama relevantne vrednosti se zapisuju rukom. Većina ovih vrednosti su vrednosti koje se zadržavaju i koje se prikazuju na mašini na kraju procesa zavarivanja. Međutim, takve vrednosti ne daju nikakve indikacije o tome kako su se parametri promenili tokom procesa zavarivanja. Moderni sistemi za zavarivanje 4.0 ne samo da ispunjavaju skoro sve zahteve za sistem dokumentacije za osiguranje kvaliteta, već pružaju mnogo, mnogo više. Sistemi zavarivanja 4.0 sakupljaju i beleže sve parametre zavarivanja na kontinuiranoj osnovi, nešto što sve češće postaje obavezno. Podaci se mogu koristiti da se u bilo kom trenutku pokaže da su ispunjeni traženi parametri i da zavareni spoj kao rezultat ima tražene karakteristike. Pored toga, snimljeni podaci se mogu koristiti za tačne proračune vremena proizvodnje ili potrošnje materijala, kao i za pokretanje procesa optimizacije i donošenje upravljačkih odluka. U radu su prikazani i objašnjeni osnovni principi Zavarivanje 4.0 sistema i objašnjene su prednosti na stvarnim primerima iz proizvodnje pri zavarivanju i za obrazovanje u zavarivanju.

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.

Introduction

Making Industry 4.0 a reality can be easy – no matter your company's size or focus. The benefits are as clear as day: Strengthened interconnectedness of products and people increases efficiency and quality, while reducing costs and preserving resources. Welding companies are adding measurable value throughout the company's entire value chain. Thanks to intelligent monitoring and transparent planning, production, quality management, welding coordination personnel, final costing and administration processes, one can always keep track of everything.

1. Analysing, controlling and managing welding processes

Discovering savings potentials, ensuring cost-effective manufacture and documenting every weld are three requirements which couldn't be more different. The modular quality management software EWM Xnet helps to unite these three tasks in a single solution, thus benefiting both small welding firms and major global corporations. EWM Xnet is fully compatible with Industry 4.0, a German government computerisation project, and already supports networking for complex manufacturing sequences – from mass production to a one-off single item.

Figure 1. *The quality circle in welding technology*

Slika 1. *Krug kvaliteta u tehnologiji zavarivanja*

2. Documentation – yesterday and today

It is precisely in quality assurance and quality management where documentation is increasingly gaining in importance. For welding companies, this entails making a record of the different welding parameters. In conventional work practices, the relevant values are written down by hand. Most of these values are hold values which are displayed on the machine at the end of the welding process. However, such values do not provide any indications on how the parameters have changed during the welding process. EWM Xnet not only meets all requirements for a quality assurance documentation system, but provides much, much more.

EWM Xnet records and logs all welding parameters on a continuous basis, something which is becoming mandatory on an increasingly more frequent basis. The data can be used to demonstrate at any time that required parameters have been met and that the weld features the required characteristics as a result. Figure 1 shows the connection between the different components related with the quality in welding.

3. Documentation of all machine data

EWM Xnet is a component within EWM's Multimatrix technology. As all components in the overall welding chain come from a single source, they can also be optimally matched to one another. This is why EWM Xnet not only logs the two parameters welding current and welding voltage as is the case with machines customary in the trade. EWM Xnet also accesses the machine data itself and logs all relevant parameters (Figure 2). In addition to the two performance data current and voltage, this also includes the arc energy, wire feed speed and JOB number, including header data on wire characteristics such as wire material and wire diameter. Logging of all relevant machine data with

EWM Xnet is used for quality assurance. Changes to the armature current during wire feeding, for example, may indicate imperfections which can cause the contact tip or the liner to clog. It is not possible to detect such problems if only the current and voltage are logged.

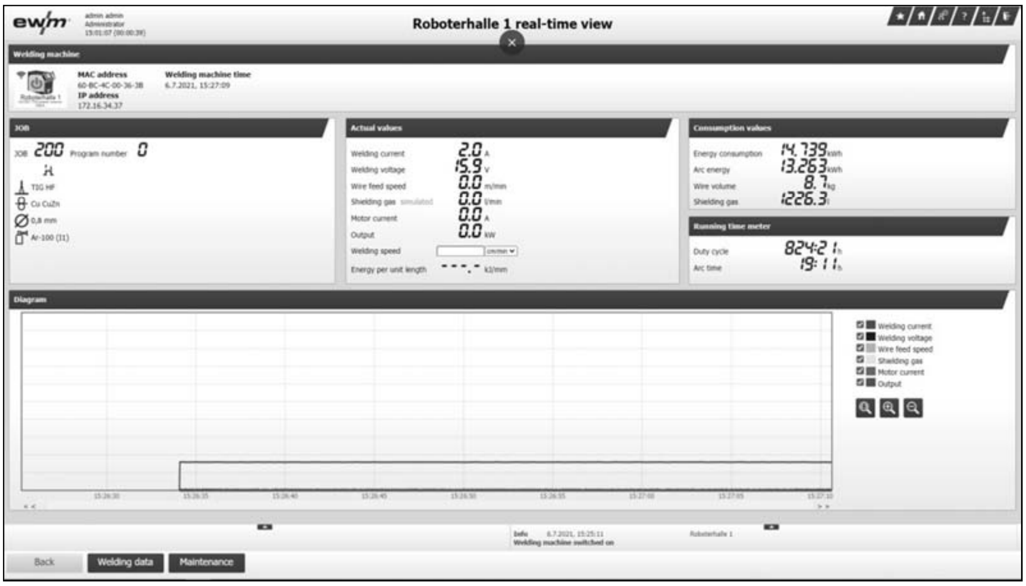

Figure 2. EWM Xnet server

Slika 2. EWM Xnet server

4. Savings potential on replacement parts

Wear is a subtle process. Changing replacement parts too early pushes up costs: first of all, a component which is still functional is replaced and, secondly, replacing the part takes up work time which could be spent on production. On the other hand, if replacement parts are changed too late, it can bring about sudden production downtime and cause wastage. Changing replacement parts in good time, but not too soon means savings potential for any company.

Wear changes welding parameters only slightly at a slow pace. Such changes are not obvious when looking at data. As EWM Xnet logs all machine data, the software can also access this data. Parameter limits indicate the optimum time to fit replacement parts. Replacement parts are thus not fitted after a pre-determined number of cycles, but when it becomes necessary. This saves time and money.

5. Analysing non-productive times

Non-productive times can be analysed thanks to the distinct classification for welds, welding times and components. The duty cycle and effective welding time for each individual machine can be contrasted. If the ratio of the two values is very low, this can indicate that non-productive times are too long. EWM Xnet helps to detect non-productive times, thus revealing savings potentials in the production sequence (Figure 3).

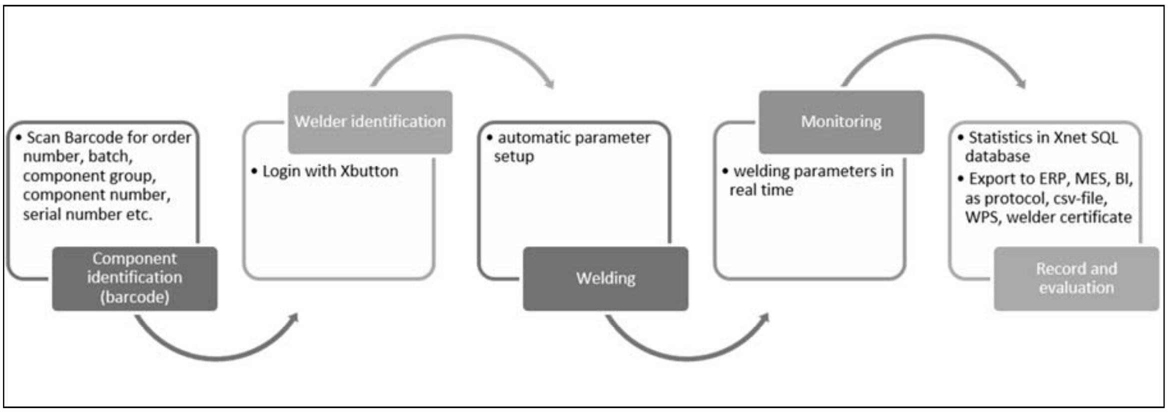

Figure 3. Savings potentials in the production sequence

Slika 3. Potencijali uštede u proizvodnom nizu

6. Maintenance – precisely scheduled and as per standard

Servicing and maintenance must be carried out on both a regular and irregular basis. Coolant is changed on a regular basis after one year, but wire feed rollers have no foreseeable precise replacement date. This is because their need for replacement depends on many different parameters, such as period of use, material diameters and conveying speed. EWM Xnet features setting options for both regular maintenance, as in the case of coolant, and non-regular maintenance for items such as wire feed rollers. What's more, these settings can be made for each welding machine on an individual basis. Regularly reoccurring maintenance cycles can be configured with scheduling instructions and plain text information as can a message indicating that wire feed rollers need to be replaced.

EWM Xnet displays a suitable alert message on the screen at the right time, perfectly clear in plain text. Information is delivered where it is needed, that is to say, to the welder or the welding supervisor who coordinates maintenance or servicing. Adjusted maintenance and servicing cycles ensure production is planned with foresight, which, in turn, increases product quality. This also means that the requirements specified in EN 1090 or EN ISO 3834 is met. Clearly documented maintenance procedures can also make costs transparent and allow them to be incorporated into calculations.

7. Final costing – not a closed book

A quote is easily drawn up with the calculated values based on data drawn from experience. But do they truly reflect reality? Final costing does not present a problem with EWM Xnet, no matter whether you have one or several components, a larger production lot or even a whole production line. What's more, it does not depend on the number of welding machines involved in completing the order.

Before starting an order, the counter readings on the machines used are set to zero for the following consumption items: welding consumables, shielding gas and electricity (Figure 3 and Figure 4). Once work is complete, EWM Xnet automatically displays the cumulative values. The overall consumption rates for consumption items are immediately available. These values can also be broken down for each individual machine or group of machines – when different production plants or lines need to be compared with one another, for example.

Figure 4. *Welder scans the barcode on the component using a barcode scanner*

Slika 4. *Zavarivač skenira bar kod na komponenti koristeći bar kod skener*

8. Software compatible with all user interfaces

EWM Xnet is web-based and compatible with all operating systems. Once the program is installed on the company's own server, it can be accessed by all machines linked to the server in a similar way to a website. Devices include fixed PCs, laptops, tablets and smartphones.

Having EWM Xnet available on PCs or laptops at workstations is certainly recommendable for daily work. welding procedure tests, it can also be beneficial and practical to stand directly next to the welder with a tablet and track data in real time in graph format. Production sequences and welding process plans can be optimised during process or product development. Data is not only available on the tablet, but can also be accessed on all other PCs, both online and at a later point in time.

If evaluation software has already been established for operations, EWM Xnet transfers the recorded data to this system, where they can be further processed as required.

9. Personalised users

Different users can be provided with different access rights in EWM Xnet. This applies to the actual access rights themselves as well as to the number of machines which may be accessed. Supervisors can gain access to machines that they are responsible for. It can be useful for product planners to compare different product lines with one another and they therefore receive access to all machines in production. Administrator rights cover user management, including issuing user rights on an individual basis, plus machine management and integration of new machines.

10. New machines – easily integrated with drag and drop

Machines are displayed in both a list and on a site plan in EWM Xnet. The site plan is entered as a diagram and shows the individual locations where welding machines are installed. The drag and drop function allows you to move new machines into the position where they are to be used, usually a welding booth. If the position of this machine should be permanently changed at any time, the site plan can be easily adjusted accordingly.

A site plan offers a decided advantage over table format as people are generally more familiar with the location of the machine than its exact name. This makes it easier to correlate.

Data from machines is transferred to the network online via LAN or WLAN (Figure 5) or offline using a USB flash memory. If a machine is outside the network, the data is logged offline. Data is transmitted to the network either when the machine logs into the network when it is next online or using a USB flash memory which uploads the data from the machine.

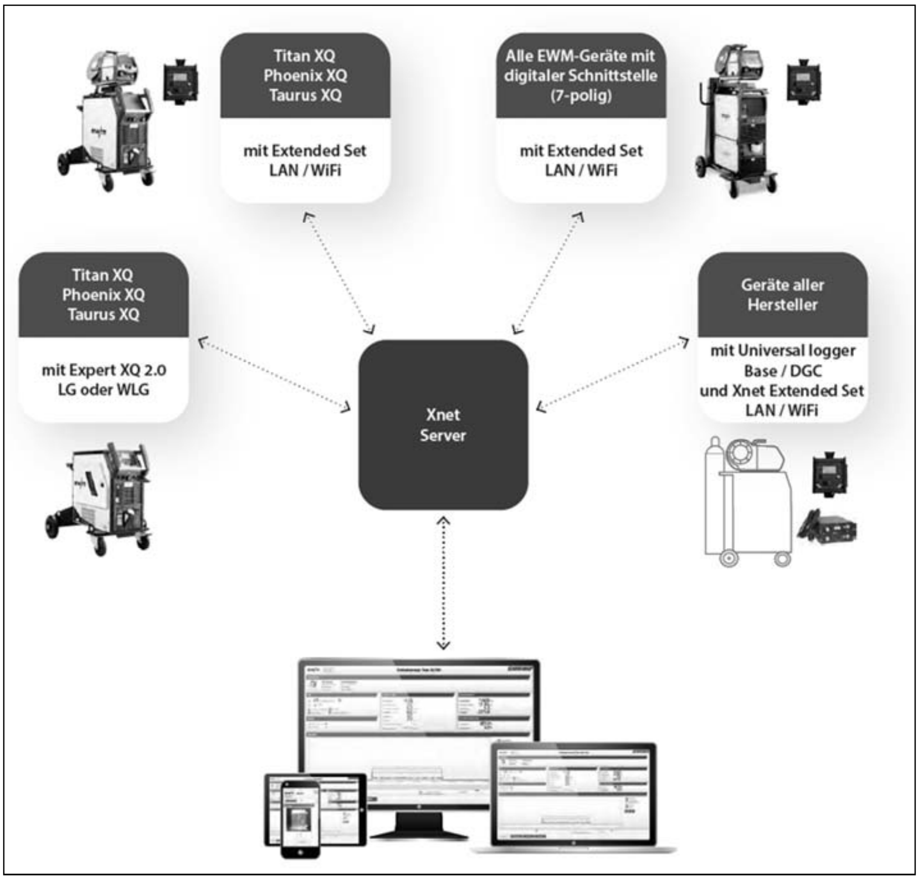

Figure 5. *The Xnet connection to welding machines with integrated networking options and innovative welding process controls*

Slika 5. *Xnet veza sa aparatima za zavarivanje sa integrisanim opcijama umrežavanja i inovativnim kontrolama procesa zavarivanja*

Conclusion

EWM Xnet is easy to use and operated intuitively, but will still meet all requirements for complex production sequences, including implementation of Industry 4.0. Transparent display of production sequences discloses ineffective work times and results in optimum work processes, leading to savings potential. Quality is also assured as each weld can be monitored on a continuous basis.

Optimised work processes and high quality standards mean more money coming in. Both small firms and big corporations who use EWM Xnet thus remain competitive.

Zaključak

EWM Xnet je jednostavan za korišćenje i njime se upravlja intuitivno, ali će i dalje ispunjavati sve zahteve za složene proizvodne sekvence, uključujući implementaciju u Industriju 4.0. Transparentan prikaz proizvodnih sekvenci otkriva neefikasna vremena rada i dovodi do optimalnih radnih procesa, što dovodi do potencijala uštede. Kvalitet je takođe osiguran jer se svaki zavar može kontinuirano pratiti.

Optimizovani radni procesi i visoki standardi kvaliteta znače više novca. I male firme i velike korporacije koje koriste EWM Xnet na taj način ostaju konkurentne.

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[1] https://www.EWM-group.com (2023)

UPUTSTVO AUTORIMA I SARADNICIMA

Časopis **ZAVARIVANJE I ZAVARENE KONSTRUKCIJE** (***ZZK***) je naučno-stručni časopis čiji je zadatak afirmacija naučnih istraživanja, razmena stručnih saznanja i praktičkih iskustava, kontinualno obrazovanje i sveobuhvatno informisanje svih onih koji imaju interesovanje za tehniku i tehnologiju zavarivanja, termičkog rezanja i lemljenja. Autorski radovi podležu recenziji i mogu da budu svrstani u jednu od sledećih kategorija:

Originalni naučni rad (Original scientific paper) je neobjavljeni rad koji doprinosi naučnom saznanju ili shvatanju, a omogućava da se na osnovu datih informacija može: ponoviti eksperiment i postići prikazane rezultate sa istom tačnošću ili unutar granica eksperimentalne greške prema navodima autora i ponoviti autorova zapažanja, proračune ili teorijske navode i doneti slične zaključke.

Prethodno saopštenje (Preliminary communication) je rad koji sadrži nova naučna saznanja ili rezultate čiji karakter zahteva hitno objavljivanje. Rad obavezno sadrži jedan ili više novih podataka, naučnih informacija, ali bez dovoljno pojedinosti koje bi omogućile čitaocu proveru iznesene informacije na opisan način.

Pregledni rad (Review) izveštava o nekom posebnom pitanju o kome je već objavljivana informacija, samo je to ovde sakupljeno, analizirano, pogodno prikazano i raspravljeno. Autor preglednog rada dužan je da se u tekstu poziva na svu literaturu koju je koristio u svom radu, i da literaturu navede redosledom onako kako se pojavljuje u tekstu.

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Izvod (Abstract) treba da je kratak i informativan i može da sadrži najviše 500 slovnih mesta. On upozorava na zaključke za svaku novu informaciju koju donosi rad. Za radove koji ne daju bitno nove rezultate (pregledni radovi, referativni radovi) dovoljno je napisati indikativni izvod u kojem se kratko opisuje predmet rada. Preko izvoda čitalac treba da lako i brzo oceni da li ga taj rad zanima. Izvod, kao i integralni tekst, se pišu u trećem licu.

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Rezultati - Rezultate treba dati pregledno, u obliku tabela ili dijagrama. Suvišno je koristiti oba načina prikaza rezultata. Na dijagrame treba uneti sve rezultate dobijene eksperimentima. Preporučuje se da se rezultati obrade statistički. Ilustrovanje rezultata fotosima (npr. fotosi mikrostrukturnih analiza) treba ograničiti na karakteristične primere, značajne za zaključak ili za poređenja stanja. Poželjno je da autor tekstovi uz tabele i slike daje dvojezično, na srpskom i engleskom.

Diskusija - Analiziraju se dobijeni rezultati, upoređuju sa ranije publikovanim podacima, pronalaze se zakonitosti i granično područje zakonitosti, komentarišu se greške i tačnosti merenja. Daju se eventualne sugestije za dalja istraživanja.

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