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EFFECTS OF TOOL ROTATION AND WELDING SPEEDS ON TOUGHNESS AND TENSILE STRENGTH OF AA 6060 WELDED BY FSW

UTICAJ BROJA OBRTAJA ALATA I BRZINE ZAVARIVANJA NA ŽILAVOST I ZATEZNE KARAKTERISTIKE ALUMINIJUMA AA 6060 ZAVARENOG POSTUPKOM ZTM

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Abstract

Friction Stir Welding (FSW) stands out as an innovative and demanding solid-state welding method gaining traction in modern fabrication. This paper explores the welding of an aluminium-silicone-magnesium alloy using FSW technique with a use of a robot, by utilizing welding speeds of 160 to 250 mm/min. Variation of the tool's rotary and welding speed was conducted to determine the optimal parameters for achieving desirable macro and mechanical properties, including tensile strength and impact energy. It was shown that higher tensile properties and lower impact energies are obtained with lower tool rotation speeds, which can be related to a lower heat input. The highest weld efficiency obtained was 91 %, proving that a relatively effective replacement of precipitation hardening with strain hardening occurred in the welding process.

Rezime

Zavarivanje trenjem sa mešanjem (ZTM) se ističe kao inovativna metoda zavarivanja bez topljenja materijala koja dobija na popularnosti u savremenoj proizvodnji. U ovom radu se istražuje zavarivanje legure aluminijum-silicijum-magnezijum korišćenjem ZTM tehnike uz pomoć robota, koristeći brzine zavarivanja od 160 do 250 mm/min. Varijacija broja obrtaja alata i brzine zavarivanja sprovedena je kako bi se odredili optimalni parametri za postizanje željenih makro i mehaničkih svojstava, uključujući zateznu čvrstoću i energiju udara. Pokazano je da se veće čvrstoće i niže energije udara postižu pri nižim brojevima obrtaja alata, što se može povezati sa manjim unosom toplote. Najveća postignuta efikasnost zavarenog spoja od 91 % ukazuje na to da je tokom procesa zavarivanja došlo do relativno efikasne zamene taložnog ojačavanja deformacionim ojačavanjem.

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1. Introduction

Welding is a fabrication process, used to join materials, typically metals, using heat and pressure. Commonly seen, welding processes include melting of the materials at the joint area in order to create a bond between two parts. Whilst melting the materials, usually consumable material is added, called the filler material that can be in form an electrode or separate from it, depending on the welding process employed. Because of the aforementioned points, evaporation of materials occurs, which results in the formation of welding fumes and vapours.

The composition of these fumes can vary based on factors like the metals being welded and the welding method employed. However, it is crucial to note that inhalation of weld fumes can pose significant risk to both human health and the environment. Proper ventilation and the use of personal protective equipment are essential to mitigate these risks and ensure a safe working environment for welders.

Additionally, managing the evaporation process is vital for minimizing the environmental impact of welding activities. Also, these fusion welding processes are not environmentally friendly, due to high energy consumption and thus a high carbon footprint. Therefore, a safer and greener welding processes occurred, the most notable being friction stir welding (FSW).

1.1 Friction stir welding

Friction stir welding (FSW) is a solid-state joining process used to bond materials, particularly metals, without reaching the melting point [1, 2]. FSW was invented by Wayne Thomas at The Welding Institute (TWI), London, UK, in 1991 [2]. It involves a rotating tool that is plunged into the joint between two pieces of material, creating frictional heat. As the tool traverses along the joint line, it mechanically stirs the softened material, forming a high-strength bond as it consolidates and cools [3]. FSW is renowned for its ability to produce welds with excellent mechanical properties, minimal distortion, and no solidification defects [4, 5].

This technique finds applications in various industries, including aerospace, automotive, and marine, where lightweight, high-performance structures are required. FSW stands out among conventional welding methods due to its environmentally friendly approach. Unlike traditional welding techniques that rely on high temperatures and consumable materials, FSW operates at lower temperatures, thus minimizing energy consumption and reducing greenhouse gas emissions. By avoiding the melting of materials, FSW also eliminates the release of harmful fumes and gases into the atmosphere, contributing to cleaner air and safer working conditions for welders.

Additionally, FSW produces welds with superior mechanical properties and minimal distortion, reducing the need for post-welding treatments and conserving resources. In contrast to fusion welding processes, which often require shielding gases and produce significant amounts of waste, FSW offers a more sustainable alternative with fewer environmental impacts. As industries increasingly prioritize eco-friendly practices, FSW emerges as a viable solution for achieving both high-quality welds and environmental stewardship. In Figure 1, the FSW process is shown.

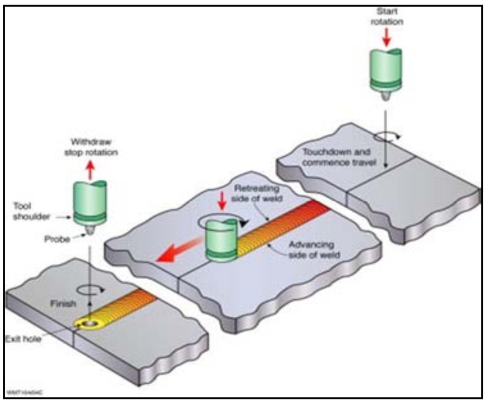

Figure 1. *Friction Stir Welding process [6]*
Slika 1. *Proces zavarivanja trenjem sa mešanjem [6]*

2. Experimental part

In this paper, the effects of rotary and welding speeds of friction stir welding on the mechanical properties of AA6060 are analyzed. In Table 1 and 2 the chemical composition and mechanical properties of the base material are shown, respectively. The chemical composition of the base material was determined using SPECTROMAXx optical emission spectrometer (OES), while tensile properties were tested by VEB ZDM 5/91 machine.

Table 1. *Chemical composition of aluminium 6060 (in mass. %)*

Tabela 1. *Hemijski sastav aluminijuma 6060(u mas. %)*

Mn	Fe	Mg	Si	Cu	Zn	Ti	Cr	Al
0.0545	0.205	0.425	0.532	0.0432	0.0256	0.0158	0.0126	Balance

Table 2. *Mechanical properties of the base material*

Tabela 2. *Mehaničke osobine osnovnog materijala*

Rm [MPa]	Rp [MPa]	A [%]	Z [%]
225	198	32	28

The welding process was done using a KUKA robot (KR 120 R3100-2) to which the FSW tool was attached, while the base plates were fixed in the horizontal plane, as shown in Figure 2.

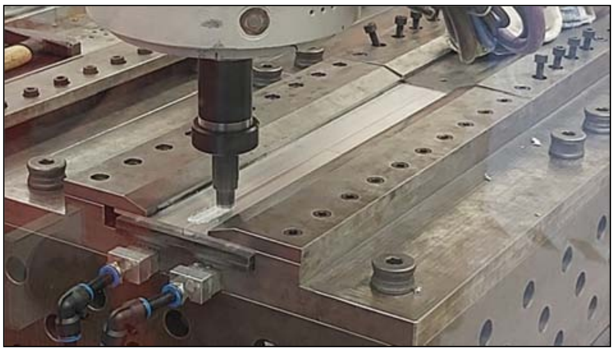

Figure 2. *Setup of the experiment*

Slika 2. *Postavka eksperimenta*

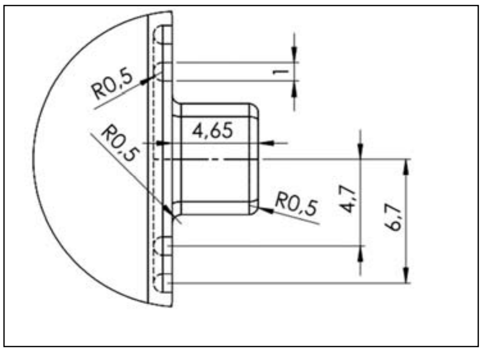

Figure 3. *FSW tool used for the experiment*

Slika 3. *ZTM alat koji se koristi za eksperiment*

In table 3, the weld designations and parameters used during the welding process are shown.

Table 3. *Weld designation and parameters*

Tabela 3. *Oznaka zavara i parametri*

Weld designation	Tool shoulder angle [°]	Tool rotation speed [rpm]	Welding speed [mm/min]	Tool rotary to welding speed ratio
1	2	1400	160	8.75
2		1120	160	7
3		1400	200	7
4		1120	200	5.6
5		1400	250	5.6
6		1120	250	4.48

The tool utilized in the experiment was crafted from X40CrMoV5-1 (also known as AISI H13) hot work tool steel, which underwent quenching and tempering processes to achieve a hardness of 53 HRC. Tool pin and shoulder design is illustrated in Figure 3. For the welding process, AA6060 plates measuring 140 × 60 × 4.8 mm were employed as the base material. Following welding, the plates were sectioned and cut, after which they were prepared for testing.

The testing regime for the samples encompassed metallography analysis, tensile testing and instrumented Charpy impact testing. Metallographic samples were meticulously prepared through a sequence of grinding using abrasive SiC papers ranging from P150 to P2500 grit, followed by polishing with diamond suspensions of 6, 3, 1, and ¼ µm particle sizes. Subsequently, electrolytic etching was conducted using Barker's reagent, with 35 V and 2 minutes time.

Examination of weld defects was carried out using a Zeiss Axio light microscope. Tensile testing adhered to the EN ISO 4136:2012 standard and was performed on a VEB ZDM 5/91 testing machine.

Key parameters such as ultimate tensile strength, proof strength, and cross-section reduction were measured, with average values reported. The Charpy impact test, conforming to the EN ISO 148-1:2016 standard was executed using an instrumented Charpy pendulum JWT450 from Jinan, China, at room temperature. Notably, standard V-notch Charpy specimens were positioned in the nugget zone (NZ) to account for the characteristic V-shape of the weld. Tensile testing of the 6 specimens was performed using the VEB ZDM 5/91 tensile testing machine.

3. Results and discussion

Macrographs of the welded samples are depicted in Figure 5. Within the weld, there are identifiable regions including the nugget zone (NZ) and the thermomechanically affected zone (TMAZ), with the heat-affected zone (HAZ) positioned between the TMAZ and the base metal. Figure 6a illustrates the microstructure of the transition zone, characterized by change in grain size, with smaller grains indicating the NZ. In Figure 6b, highly refined predominantly uniaxial grains are evident within the nugget zone (NZ). The transition zone between the NZ and the thermomechanically affected zone (TMAZ) is depicted also in Figure 6a. The grains in the TMAZ exhibit elongation, attributed to the combined effects of deformation and heat imparted by the FSW tool.

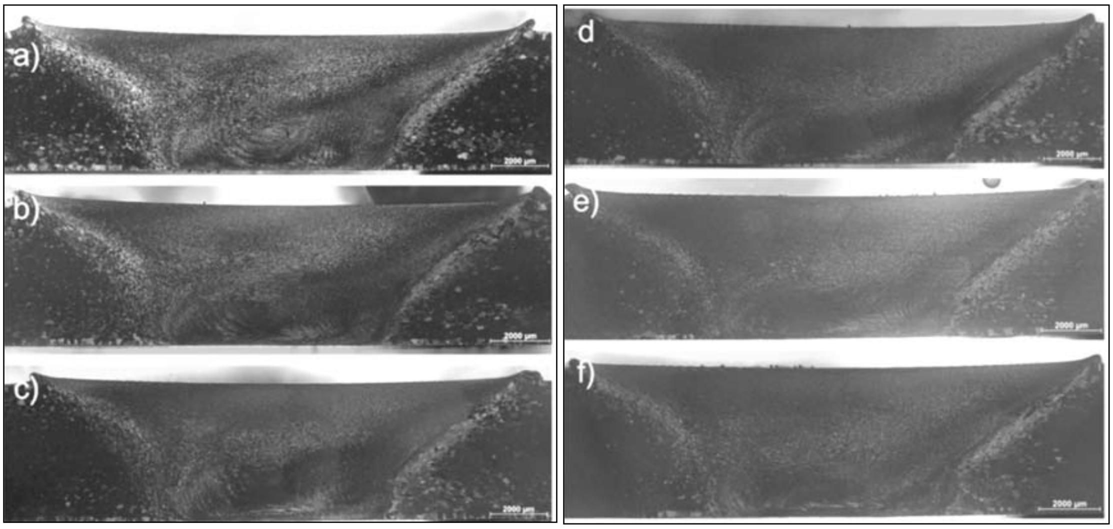

***Figure 5**. Cross-sectional macrographs of the specimens: a) 1; b) 2; c) 3; d) 4; e) 5; f) 6*

***Slika 5.** Makrostrukture poprečnog preseka uzoraka: a) 1; b) 2; c) 3; d) 4; e) 5; f) 6*

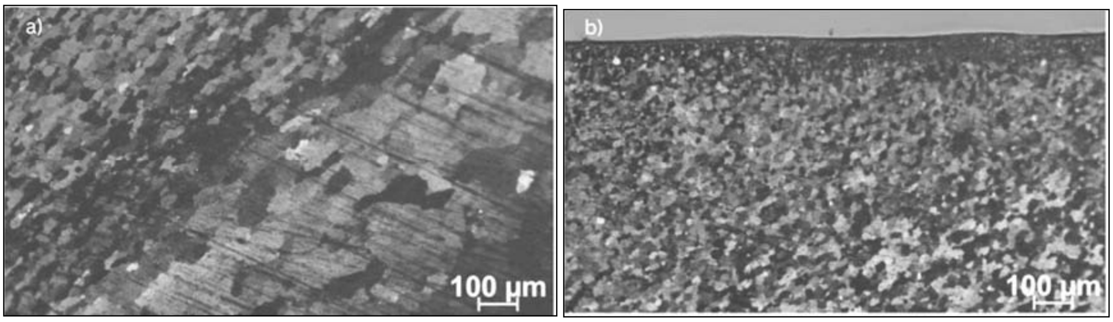

***Figure 6.** Transition NZ/TMAZ (a), nugget zone (b) of specimen 1*

***Slika 6**. Prelaz NZ/TMAZ (a), zona jezgra šava (b) uzorka 1*

Figure 7 represents the impact energy obtained on different specimens during Charpy impact testing. It is visible that the specimen 1 exhibited highest impact energy with the smallest amount of energy required for crack propagation, while specimen 3 exhibited highest energy required for crack propagation.

Compared to the base material, it is visible that the impact energy is lower in the joint area, indication a lesser degree in ductility. This is in contrast to the grain refinement, which is obvious in Figure 5, 6. This may be the result of an excessive temperature during the process, which well exceeds around 200°C, the heat treatment temperature of this alloy. That means, that precipitate hardening is replaced by strain hardening which is apparently not as effective. It can be observed that impact energy is lower for the lower tool rotary to welding speed ratio, or in other words, the lower rotary speed results in the lower impact energy. This is due to crack propagation energies that fully comply to this rule.

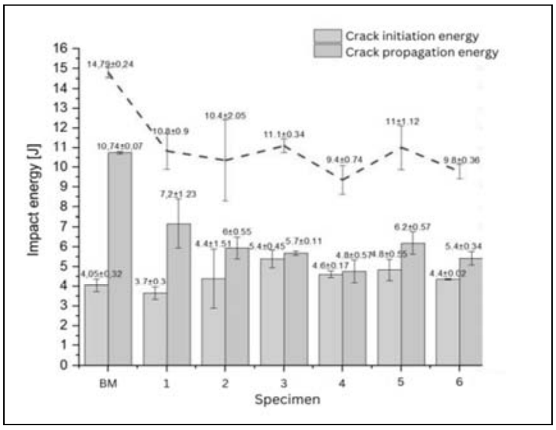

Figure 7. *Impact energy results*

Slika 7. *Rezultati energije udara*

The results obtained after the testing can be seen in Table 4. As can be seen from the aforementioned results, the highest tensile strength was obtained in specimen 2, with the lowest being in specimen 1, both welded with the lowest welding speed. In all three sets of specimens, welded with the same welding speed, a lower rotation speed resulted in a higher weld tensile and yield strengths, due to a more pronounced strain hardening and less intensive heating. Conversely, elongations behave differently, with higher elongations obtained in specimens welded with a higher welding speed (Specimens 3 and 5), which is similar to impact strength results. It can be seen that in the vast majority of specimens, standard deviations in welded specimens are higher compared to base material, probably due to micro imperfections that remain to be determined in the future work. Finally, compared to the base material, a weld effectiveness of 91 % was achieved (Specimen 2), which confirms the effective replacement of precipitate hardening by the slightly less effective strain hardening.

Table 4. *Tensile testing results*

Tabela 4. *Rezultati ispitivanja zatezanjem*

	Rp [MPa]	Rm [MPa]	A [%]
Specimen 1	132±7.57	175±11.99	25±2.27
Specimen 2	143±5.56	206±5.86	21±2.94
Specimen 3	145±10.54	180±13.97	22±9.71
Specimen 4	139±5.27	202±6.08	20±3
Specimen 5	138±5.66	187±8.37	18±5.1
Specimen 6	138±6.38	195±4.85	17±6.35
Base Material	198±4.17	225±4.71	32±2.28

4. Conclusions

Based on the results presented in this paper, and within the limitations of the experiment, the following can be concluded:

4. Zaključci

Na osnovu rezultata prikazanih u ovom radu, a u okviru ograničenja eksperimenta, može se zaključiti sledeće

- Due to the FSW being a solid state welding process, the total carbon footprint of the process is lower than in conventional welding processes.
- V-shape weld can be observed due to the tool having a shoulder only on one side
- Although the grain refinement is observed, a lower impact energies compared to base material were obtained. This can be attributed to replacing of precipitate hardening by the less effective strain hardening.
- Impact energy is lower for the lower tool rotary to welding speed ratio, or in other words, the lower rotary speed results in the lower impact energy**.**
- Tensile testing proved an inverse effect, a lower welding speed and lower rotation speed provided a higher yield and tensile strengths. Elongations behave in a similar manner as impact strengths.

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- Zbog toga što je ZTM proces zavarivanja u čvrstom stanju, ukupni ugljenični otisak procesa je manji nego kod konvencionalnih procesa zavarivanja.
- Zavar u obliku slova V se može uočiti, obzirom na oblik alata
- Iako se primećuje rafinacija zrna, dobijene su niže energije udara u poređenju sa osnovnim materijalom. Ovo se može pripisati zameni precipitacionog ojačavanja manje efikasnim deformacionim ojačavanjem.
- Energija udara je niža za niži odnos rotacije alata i brzine zavarivanja, ili drugim rečima, niža brzina rotacije rezultira manjom energijom udara.
- Ispitivanje zatezanjem pokazalo je inverzni efekat, niža brzina zavarivanja i niža brzina rotacije su obezbedile višu granicu razvlačenja i višu zateznu čvrstoću. Izduženja se ponašaju na sličan način kao i udarna čvrstoća.

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