

ELECTRICAL CONDUCTIVITY AS AN INDICATOR OF FRICTION STIR WELDED ALUMINIUM LAP JOINT QUALITY

ELEKTRIČNA PROVODLJIVOST KAO POKAZATELJ KVALITETA ALUMINIJUMSKOG PREKLOPNOG SPOJA DOBIJENOG ZAVARIVANJEM TRENJEM SA MEŠANJEM

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Adresa autora / Author's address:

¹⁾ Academy of Applied Studies Polytechnic, Belgrade, Serbia

Đ. Đurđević <https://orcid.org/0009-0001-8263-188X>,

*email: djdurdjevic@politehnika.edu.rs

A. Đurđević <https://orcid.org/0009-0000-7233-5748> ;

B. Ivljanin <https://orcid.org/0009-0008-3551-6409>

²⁾ MESSER, Tehnogas, Bor, Serbia

³⁾ Goša FOM, Smederevska Palanka, Serbia

Keywords

- electrical conductivity
- macrostructure
- friction stir welding (FSW)
- non-destructive testing (NDT)

Abstract

Friction stir welding has proven to be a good process for joining materials because the welded joint has good mechanical properties. The aim of the study is to examine the electrical conductivity of the welded joint, because of its effects on quality of a welded joint, i.e., on the homogeneity of the structure. By experimentally welding two aluminium plates of thickness 3 mm, AA5754-H111, a lap joint is obtained. The paper provides a description of technological parameters for experimental welding, the macrostructural images of the joint and electrical conductivity of the joint. The joint is successfully welded with the selected technological parameters. The macrostructural images clearly show the nugget zone as well as the joint without defect type bonding line (kissing bond). Measurements that are made show that electrical conductivity is almost constant over the entire section of the joint, from the base metal zone to the weld zone which indicates that the mixing in that part is excellent and that a homogeneous material is obtained in the weld zone.

INTRODUCTION

Friction stir welding (FSW) is a relatively recent solid-state joining technique that demonstrates higher efficiency compared to conventional methods for joining aluminium alloys. The application range of aluminium in various industries is expanding due to its numerous inherent properties, such as low density, high ductility, and excellent thermal and electrical conductivity.

Friction stir welding is performed by utilising a non-consumable cylindrical tool that rotates and advances in the material to be welded. These movements produce heat through friction and mix the softened material to produce the weld. The tool comprises a shoulder that generates heat and exerts downward forging force and a probe that transports plasticised material along the joint. It also presents numerous advantages over conventional fusion welding methods, since it occurs at temperatures below the melting point of the material, such as minimising distortion in the workpiece and reducing porosity and cracking when com-

Ključne reči

- električna provodljivost
- makrostruktura
- zavarivanje trenjem sa mešanjem
- ispitivanje bez razaranja

Izvod

Zavarivanje trenjem sa mešanjem pokazalo se kao efikasan postupak za spajanje materijala zato što zavareni spoj ima dobra mehanička svojstva. Cilj ovog rada je ispitivanje električne provodljivosti zavarenog spoja, zato što ona govori o kvalitetu spoja, tj. o homogenosti strukture zavarenog spoja. Eksperimentalnim zavarivanjem dve aluminijumske ploče debljine 3 mm, AA5754-H111, dobijen je preklopni spoj. U radu se daje opis tehnoloških parametara za eksperimentalno zavarivanje, makroskopske slike strukture spoja i vrednosti električne provodljivosti spoja. Preklopni spoj je uspešno zavaren sa odabranim tehnološkim parametrima. Makrostrukturne slike jasno prikazuju zonu grumenja, kao i spoj bez grešaka tipa linije vezivanja (kissing bond). Merenja pokazuju da je električna provodljivost gotovo konstantna na celom preseku spoja, od zone osnovnog metala do zone metala šava, što ukazuje da je mešanje u tom delu odlično i da se dobija homogen materijal u zoni metala šava.

pared to traditional welding techniques. Additionally, FSW stands out as an environmentally conscious technology and is often regarded as a ‘green’ solution due to its reduced energy consumption compared to fusion processes. It does not require filler material or the use of solvents, /1/.

To fully characterise friction stir welding, several techniques are required, mainly destructive, as e.g., hardness or metallographic testing. However, there is still a need for developing dedicated methods, preferably non-destructive. Electrical conductivity, based on a different physical principle, may constitute an alternative. The present study aims to characterise the electrical conductivity in friction stir welded joint and to investigate the correlation between this and the welded joint quality observed in different zones of a weld metal. A close match between the electrical conductivity field and the microstructure is observed, suggesting that non-destructive testing has the potential to complement or replace destructive methods such as hardness testing, /2, 3/.

Electrical conductivity σ , is the reciprocal of electrical resistivity ρ , according to the relation $\sigma = 1/\rho$. The electrical

resistivity of most metals increases approximately linearly with temperature T . This characteristic is particularly relevant for aluminium alloys, as it influences both heat generation and current-carrying capacity during friction stir welding, affecting the resulting joint quality and structural integrity, /3/.

In friction stir welded (FSW) joints of AA5754-H111 aluminium alloy, electrical conductivity is closely related to the thermomechanical conditions imposed during the welding process. As a non-heat-treatable Al-Mg alloy, AA5754-H111 does not undergo precipitation reactions during welding; instead, the dominant mechanisms influencing electrical conductivity are solid-solution effects of magnesium and changes in dislocation density caused by severe plastic deformation and thermal exposure. Within the stir zone, the material experiences intense plastic deformation accompanied by elevated temperatures, leading to dynamic recrystallisation and significant grain refinement. Although grain boundary scattering may increase due to the refined microstructure, this effect is partially compensated by recovery processes that reduce dislocation density. As a result, electrical conductivity variations within the stir zone of AA5754-H111 are typically limited, reflecting the balance between these competing mechanisms. In the thermomechanically affected zone (TMAZ) and heat-affected zone (HAZ), the absence of melting and the relatively moderate thermal cycles characteristic of FSW promote microstructural stability. Local recovery and partial annealing may slightly modify the dislocation structure without substantially altering the magnesium distribution in solid solution. Consequently, electrical conductivity values in these regions often remain close to those of the base material, provided that the welding parameters are properly selected. Because AA5754-H111 exhibits minimal conductivity changes associated with thermal exposure, deviations in electrical conductivity across the FSW joint can be primarily attributed to weld imperfections or local inhomogeneities, such as insufficient material flow or internal defects. Therefore, electrical conductivity measurements represent a particularly effective non-destructive tool for evaluating the quality, uniformity, and integrity of friction stir welded AA5754-H111 joints, /4-8/.

WELDING PROCESS AND JOINT STRUCTURE

Welding is done on a tool milling machine. The geometry and material selection of welding tools, clamping tool

and backing plate are made on the basis of theoretical knowledge and acquired practical experience /9, 10/. The experimental setup and the working table of the machine are given in Fig. 2. The plates that need to be welded are made of aluminium alloy 5754-H111, which is a typical Al-Mg alloy. The lap joint is produced by welding two plates in one pass of the tool. Dimensions of working plates are $80 \times 200 \times 3$ mm. The length of the produced weld metal is 170 mm.

Speed of translator movement is called the welding speed, $v_{wel} = 15$ mm/min. The tool rotates at the constant speed during this movement with $v_{rot} = 950$ min⁻¹. Tool tilt-angle is $\alpha = 0^\circ$, and tool-plunge depth is 5.6 mm. The overall welding duration is 11 minutes.

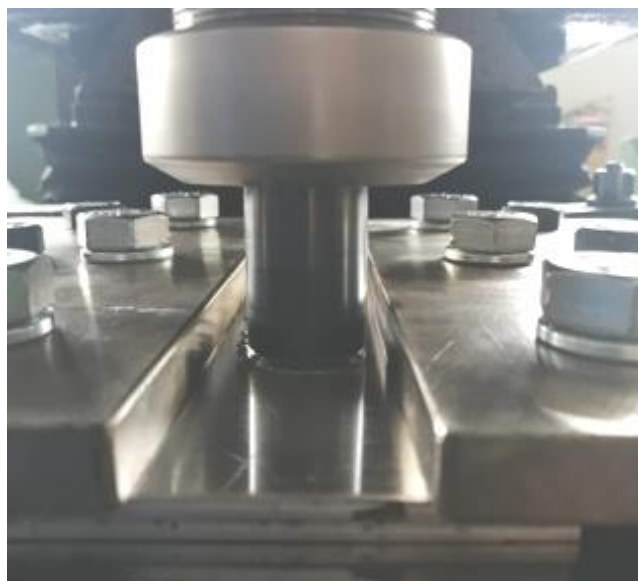


Figure 2. The experimental setup.

A preliminary macroscopic examination is conducted to precisely locate the regions for electrical conductivity measurements. Sample preparation for macrostructural analysis involves sectioning and etching the surface with a suitable reagent. The sample is taken from the lap joint, and Fig. 3 shows the cross-sectional surface of the joint exposed to the reagent. The cross-sectional plane is perpendicular to the tool translational direction (welding direction). To enhance the visibility of the structural zones, Tucker's reagent is employed.



Figure 3. Cross-sectional surface of the joint.

Figure 4 shows the characteristic macrostructure of the cross-section of the joint, perpendicular to welding direction, at a magnification of 12.5. The stirred zone is clearly visible and symmetric with respect to the joint's axis of symmetry. Within the stirred zone, a fine equiaxed grain structure is observed due to the most intensive material stirring in this region. The grain structure in the thermomechanically affected zone (TMAZ) is similar to that of the base material,

although slightly coarser due to the influence of heat. Distinct material flow lines indicate the direction of material movement during the stirring process. The position, extent, and clarity of these flow lines depend on the welding parameters. By appropriately selecting the welding process parameters, as well as the tool, clamping system, and welding machine, defects such as tunnel voids, lack of bonding lines, and lack of root fusion are avoided in the welded joint.

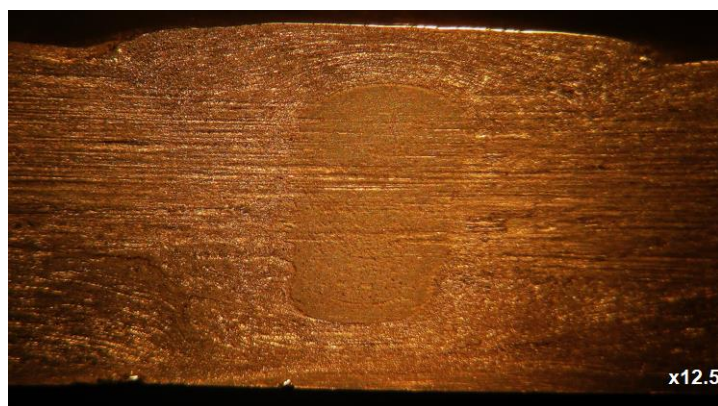


Figure 4. Macroscopic view of the cross-section of the joint.

A slight surface bulge is observed on the weld metal. It appears in the region beneath the tool shoulder, resulting from material stirring around and beneath the tool pin. The tool pin used in this welding process has a conical shape with a helical groove.

In the FSW, both primary and secondary material flows occur. The primary flow refers to the movement, i.e., the transport of softened material around the tool pin (red arrows, Fig. 5). A sufficient amount of softened material must be transported by the rotating pin from the retreating side toward the advancing side of the weld to ensure a defect-free joint. The secondary material flow involves the movement of softened material along the vertical axis, generated by the action of pin and tool shoulder. Pin thread geometry is designed to push the softened material downward, toward the root of the weld metal. Material located near the weld surface on the retreating side is transported toward the weld surface on advancing side, while the material near the weld surface on the advancing side is moved downward, /11/.

The advancing side (AS) is where directions of tool rotation and welding velocity vectors coincide, while the retreating side (RS) is where these vectors are opposite. The primary and secondary material flows are schematically illustrated in Fig. 5.

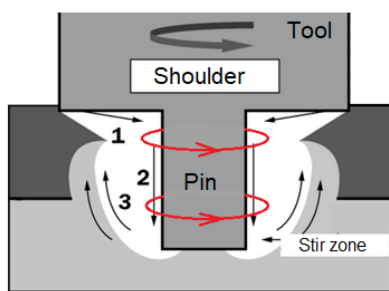


Figure 5. Schematic representation of primary (red arrows) and secondary (black arrows 1-3) material flows.

ELECTRICAL CONDUCTIVITY

Electrical conductivity measurements are performed using the 'Institute Dr. Förster Sigmatest 2.063' device, which determines this property on materials by measuring the impedance response of the measurement electrode. Prior to each measurement, the device is calibrated using reference plates with known electrical conductivities of $8.4 \text{ MS}\cdot\text{m}^{-1}$ and $58.05 \text{ MS}\cdot\text{m}^{-1}$. Measurements are carried out directly

by placing the measurement electrode on the sample surface, and the conductivity values are read from the device. Electrical conductivity is determined for specific zones: Zones 1 and 3 correspond to the base metal, while Zone 2 represents the weld metal. Measurement locations are indicated by 'x' markings in Fig. 6. The obtained results are presented in Table 2.



Figure 6. Measurement of electrical conductivity on the sample.

Table 2. Results of electrical conductivity measurements.

	Electrical conductivity ($\text{MS}\cdot\text{m}^{-1}$)
Zone 1	31.46
Zone 2	31.27
Zone 3	31.3

The obtained measurement results indicate that electrical conductivity is almost uniform across the entire cross-section. Interestingly, in /3/, the authors report on the electrical resistivity of the welded joint, noting that it is higher than that of the base metal. They also explain how this method can be utilised for the evaluation and characterisation of the weld itself.

The underlying principle is that electrical conductivity depends on the movement of electrons through the material. Therefore, if the welded joint is well-executed and homogeneous, electron flow will be nearly identical to that in the base metal. Conversely, if the weld is inhomogeneous, containing defects such as tunnel voids, lack of bonding lines, porosity, or similar imperfections, electron scattering will occur at these locations, resulting in reduced electrical conductivity. Hence, this measurement method can serve as a useful tool for assessing quality and uniformity of the weld.

CONCLUSIONS

Electrical conductivity of a friction stir welded aluminium alloy can be significantly impacted by the welding process,

though often remains high. The final conductivity depends on factors like the original alloy, the welding parameters (such as speed and tool rotation), and the resulting microstructure, which can include the formation of precipitates or intermetallic compounds. Using optimal friction stir welding parameters can lead to joints with high conductivity and improved mechanical properties.

The macroscopic image of the cross-section of the overlap joint shows a weld free of defects such as tunnel voids or lack of bonding lines. The stirred zone and its fine-grained structure are clearly visible, as well as the material flow lines. Electrical conductivity measurements provide valuable insight into the quality of the welded joint and the weld metal, reflecting the structural homogeneity. The measurements presented in this study indicate that electrical conductivity is almost uniform across the entire cross-section, from the base metal zones to the weld metal zone, suggesting excellent material mixing and the formation of a homogeneous weld. The lowest conductivity value is observed in the weld metal zone; however, it differs by only 0.1 % compared to Zone 3, and 0.6 % compared to Zone 1.

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