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JOINING OF AA2014 AND AA5059 DISSIMILAR ALUMINIUM ALLOYS BY FRICTION STIR WELDING

SPAJANJE RAZNORODNIH LEGURA ALUMINIJUMA AA2014 I AA5059 ZAVARIVANJEM TRENJEM SA MEŠANJEM

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Keywords
- friction stir welding
- dissimilar aluminium alloys
- microstructure
- heat affected zone
- thermo-mechanically affected zone

Abstract

AA 2014T3 and AA 5059H11 are two dissimilar aluminium alloys friction stir welded. The joint has been examined in terms of hardness, microstructure, and mechanical properties. The microstructure of the weld area is characterized by using optical microscopy. Seven diverse regions of the microstructure in the joint can be illustrious. It has been noticed that a structure of fine grain is formed in the nugget region as a consequence of recrystallization. The thermo-mechanically affected and heat affected zones of aluminium alloy 2014 are characterized by the lowest hardness values in spite that there is a general hardness decrease through the weld zone, compared to both base metals. The ultimate tensile strength values of the dissimilar joint are found to be varying between 54 to 66 % those of the base metal. The outcomes display that friction stir welding can be effectively applied for joining dissimilar aluminium alloys.

Ključne reči
- zavarivanje trenjem sa mešanjem
- različite legure aluminijuma
- mikrostruktura
- zona uticaja toplote
- zona termomehaničkog uticaja

Izvod

Dve različite legure aluminijuma AA 2014T3 i AA 5059H11 su zavarene trenjem sa mešanjem. Ispitivanje zavarenog spoja obuhvatilo je tvrdoću, mikrostrukturu i mehaničke osobine. Karakterizacija mikrostrukture oblasti zavarenog spoja izvedena je optičkom mikroskopijom. Razlikuje se sedam specifičnih oblasti u mikrostrukturi spoja. Primećuje se formiranje strukture finog zrna u oblasti šava, kao posledica rekristalizacije. Zona termomehaničkog uticaja i zona uticaja toplote legure aluminijuma 2014 su karakteristične po najmanjim vrednostima tvrdoće, uprkos opštem padu tvrdoće u oblasti zavarenog spoja, u poređenju sa oba tipa osnovnog materijala. Zatezne čvrstoće različitih materijala u spoju variraju između 54 i 66 % vrednosti osnovnog materijala. Pokazuje se da se zavarivanje trenjem sa mešanjem može efikasno primeniti za spajanje raznorodnih legura aluminijuma.

INTRODUCTION

Friction stir welding (FSW) has illustrated very extraordinary suitability for the joining of aluminium alloys. It is a solid state joining process, invented by The Welding Institute (UK) in 1991, /1/. FSW can prevent many problems, namely porosity, compaction cracks, and vacancies, /2/. This process progresses in a solid state where temperature throughout the welding is comparatively lower than the melting point of the welded metal, /3/. At this time, the FSW study has largely focused on joining Al alloy plates, which has the greatest demand in the aerospace, aircraft, electronic, missile, nuclear and commercial fields /4/. It has appeared in many applications and has mainly aroused the interest of the automotive industries, aerospace aircraft, and owing to its ability of producing sound joints in aluminium alloys difficult to fusion weld, /5/. Friction between the welding tool and weld metal causes heat generation that softens the material around the tool and permits the tool to move along the joint line, /6/. The fact that the FSW joining takes place with the base materials remaining in the solid state, gives a considerable possibility to produce joints between the alleged difficult-to-weld heat treatable aluminium alloys, /7/. Dissimilar joints of 2014-T3 to 5059 Al alloys are obligatory for some application to enhance chemical and mechanical properties. Though there are few publications available in literature about dissimilar joining, there is no information about the influence of welding conditions on the mechanical properties and microstructure of stir welded joints. This work aims to investigate the microstructure and mechanical properties achieved by FSW of butt joints, namely of dissimilar sheets of 2014-T3 to 5059-H11 Al alloys by bonding the two materials perpendicular to their rolling directions.

EXPERIMENTAL PROCEDURE

Dissimilar sheets of aluminium alloys 2014 in condition T3 and 5059 in condition H11 are welded by FSW. Table 1 demonstrates the chemical composition of both aluminium alloys.

Table 1. Chemical composition of AA 5059 and AA 7075 (wt. %).

Material	Zn	Mg	Cu	Fe	Cr	Mn	Ti	Other	Al
AA2014	0.25	0.5	4.4	0.7	0.1	0.8	0.15	0.81	balance
AA5059	0.46	5.2	0.01	0.09	0.003	0.77	0.02	0.16	balance

The two plates are manufactured with the same dimensions of 275×150×6 mm (length, width, thickness) by rolling. The direction of the friction stir welding line is longitudinal and parallel to the rolling direction of the 2014 and 5059 alloys. The tool used in this study is composed of a 12 mm shoulder diameter and a pin of 4 mm diameter and 5.7 mm length. The fixed FSW tool is tilted 3° from the normal direction of the plate and rotated clockwise. The translational motion and simultaneous rotation of the welding tool thru the welding process generates a characteristic irregularity between the adjoining sides. The advancing side (AS) of the tool is the side where the tool's rotation synchronizes with the direction of translation of the welding tool, whereas, the other side, where the two motions, rotation and translation counteract is the so-called retreating side (RS), /8/. Throughout FSW, the 2014 aluminium alloy plate is fixed so as to be in the advancing side (AS) and 5059 to be in the retreating side (RS), as shown in Fig. 1. The welding is achieved in three steps, the first two are alike, as joining 2014 to 2014, and 5059 to 5059, whilst the third step is the welding of 2014 to 5059, as shown in Fig. 2. After the welding, the joints are cross-cut vertical to the welding direction for metallographic analysis. Metallographic specimens are cut and polished with alumina suspension; two diverse etching solutions are utilized in order to obviously establish the grain structure differences in dissimilar joints. In the foremost stage, the polished sample is etched by 3 ml nitric acid and 1 ml hydrofluoric acid solution for 20 s at 0 °C in 150 ml water, and the 5059 aluminium alloy side has been examined for microstructural variations. Then, the re-polished sample is etched with 9 g of 40 % phosphoric acid (H_3PO_4) solution, for 4 min. at 50 °C in 100 ml water, to detect the microstructural variations in the 2014 aluminium alloy side. An optical microscope is used to investigate the microstructural features of the welds. Furthermore, EDS analyses has achieved in revealing the concentricity of alloying elements inside the weld region. The Vickers indenter with 0.85 N loads for 10 s is used to obtain the Vickers micro hardness profiles in the cross section of the welded zones. Hardness measurements are achieved along the middle section and transverse to the welding direction of the joints. Tensile tests are done at a crosshead rate of 1 mm/min using a computer-controlled testing machine at room temperature to estimate the mechanical properties of the welded joints. Tensile tests are carried out at room temperature. The tensile samples are cut out vertical to the weld axis. Tensile tests are achieved according to the ASTM E8-95a standard code.

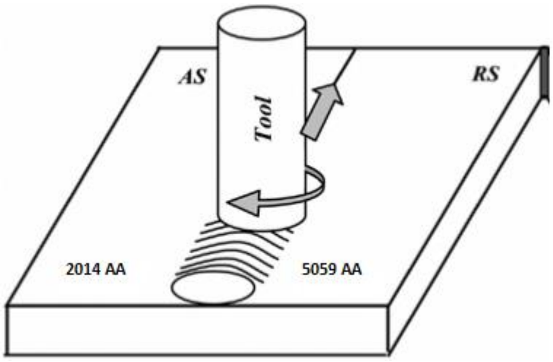


Figure 1. Arrangement of plates for the FSW process.

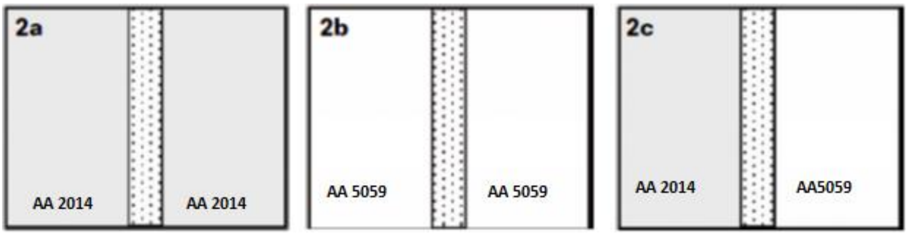


Figure 2. Shape of friction stir welded joints: a) similar AA 2014; b) similar AA 5059; and c) dissimilar AA 2014-AA 5059.

RESULTS AND DISCUSSION

Microstructure

In the current study, dissimilar aluminium alloys 2014 and 5059 are effectively joined by using the friction stir welding process and no noticeable macroscopic defects or porosity has been observed in the weld cross-section. The FSW process used on dissimilar 2014 and 5059 aluminium alloys exposed the first-rate formation of the onion ring 'elliptical' structure to some extent in the thermo-mechanically affected zone (TMAZ) and entirely in the nugget zone (NZ); this is assured by the concentricity of diverse alloying elements in the rings of the onion shaped structure, as will be illuminated later. Figure 3 shows the microstructure of the weld cross-section, etched by two different etching solutions. Contrary to the friction stir welding of similar alloys, where four distinct regions are noticeable, namely the heat affected zone (HAZ); nugget zone (NZ); thermo-mechanically affected zone (TMAZ); and the parent material, also called base material (BM), dissimilar welds show seven distinct regions as shown in Fig. 3. The nugget region is the zone that undergoes the highest strain and experiences recrystallization. The mechanical action of the tool probe is responsible for the formation of such microstructure that generates a continuous dynamic recrystallization process. Severe plastic deformation and the higher temperature during the welding in the NZ results in a renewed fine grain structure, /9/. Figure 3d displays the nugget region in the welded 2014 and 5059 aluminium alloy. By moving in the direction to the base metal neighbouring the nugget region, there lays the TMAZ (Fig. 3c for AA 2014 and Fig. 3e for AA 5059) where no recrystallization is noticed The zone neighbouring the TMAZ is the HAZ (Fig. 3b for AA 2014 and 3f for AA5059), where the grain size is alike the BM. Together, the HAZ and TMAZ experience an uttermost temperature which results in the decrease of hardness. Neighbouring the HAZ lies the BM (Fig. 3a for AA 2014 and Fig. 3g for AA 5059). Because of the different etching response of each material, the AA 2014 looks darker than AA 5059.

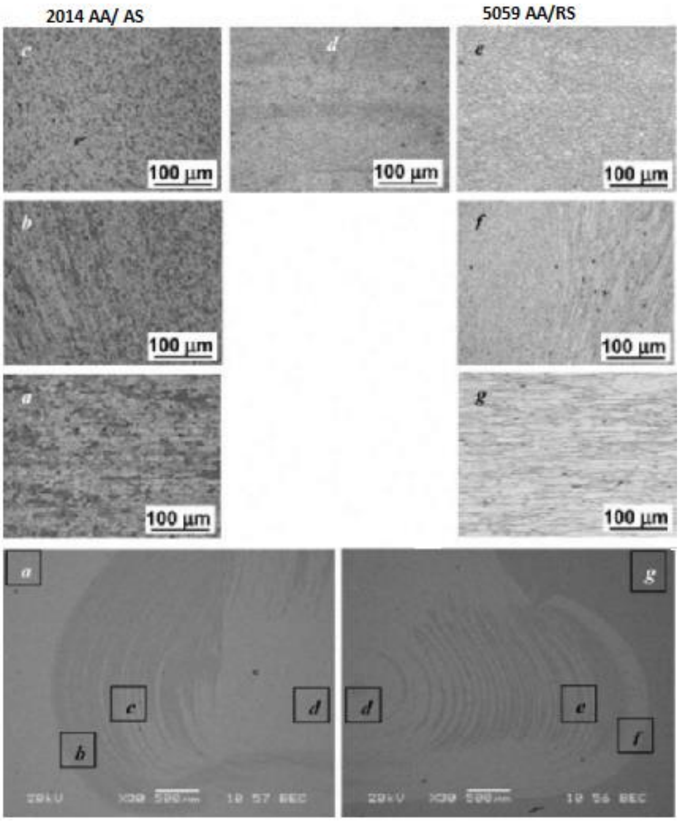
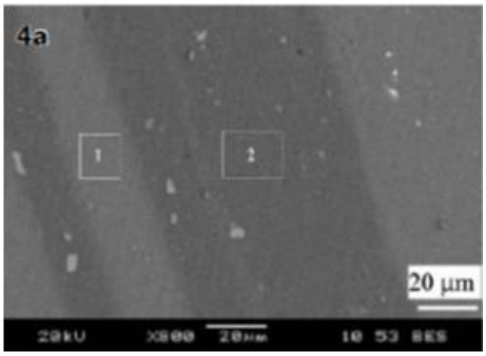


Figure 3. Weld region microstructures: a) BM AA 2014; b) HAZ AA 2014 / AS; c) TMAZ AA 2014.

The EDS examination conducted thru the weld zone of AA 2014 and AA 5059, Fig. 4, has exposed that in both alloys, the rings forming the onion-shaped structure are rich in Mg in light coloured ones, while the darker ones are rich in Cu. Table 2 provides the Mg and Cu content in nugget zones of AA5059 and AA 2014. It has been noticed that the quantity of Mg has increased in the NZ of AA 2014 after welding. This can be well thought-out as an indication of a good friction stir welding procedure.



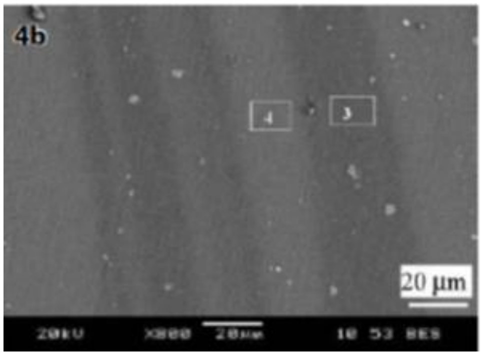


Figure 4. EDS examination results in the NZ close to the BM of: a) AA 5059; b) AA 2014.

Table 2. EDS analyses results of the weld region microstructure.

Materials	Light coloured area		Dark coloured area	
	% Mg	% Cu	% Mg	% Cu
AA5059	5	2	0.9	4.6
	zone 1 in Fig. 4a		zone 2 in Fig. 4a	
AA2014	4.8	2.2	1.2	4.5
	zone 4 in Fig. 4b		zone 3 in Fig. 4b	

Hardness

The microhardness distribution over the weld cross section, of the welded dissimilar aluminium alloys 2014 and AA 5059, is shown in Fig. 5.

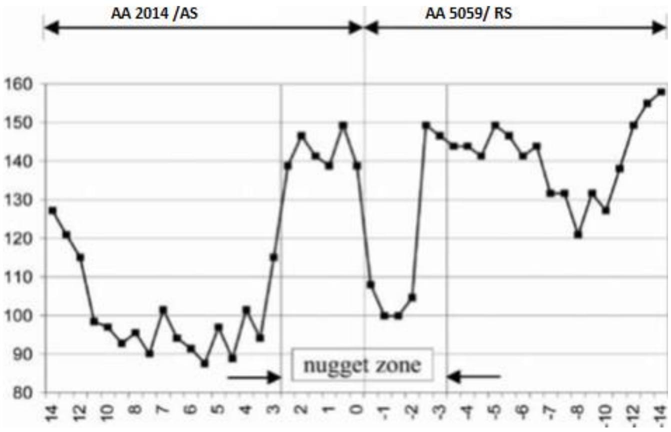


Figure 5. Hardness deviation in the weld cross-section.

BM hardness values of the AA 2014 and AA5059 are around 128 HV and 158 HV, respectively. In general, the hardness reduces within the weld region composed of TMAZ and HAZ, due to the softening of the material in the welding process that coarsens by thermomechanical conditions, while the recrystallization owing to great plastic deformation causes hardness increase in the NZ. On the other hand, the variation of hardness values, for dissimilar FSW in the nugget zone, can be attributed to the variation of the alloying elements in this zone, as in agreement with Chen and Kovacevic, /10/. In the nugget region area equal in width to pin diameter, both hardness values decrease (on the AA 5059 side) and increase (on the AA 2014 side), as noticed in this study. Recrystallization of a very fine grain structure effects the hardness recovery in the nugget for AA 2014; this is in agreement with the classical behaviour of aluminium alloys welded by FSW, /11/. Nonetheless, at the

AA 5059 side in the nugget zone, as close to the AA 2014 side, there is a decrease in hardness, and while moving in the direction of the TMAZ side the hardness increases. The lowest hardness values are measured in the TMAZ and HAZ on the AS side (AA 2014 side), around 87 HV.

Tensile properties

Three tests were conducted to obtain the average values as the minimum tensile property. Tensile properties (ultimate tensile strength-UTS and yield strength-YS) of the BM and similar/dissimilar FSW are presented in Table 3. The fracture takes place at HAZ, or in the TMAZ for all similar welded specimens. While for the dissimilar joints, the welded specimens have fractured similarly at the HAZ or the TMAZ on the AS side (AA 2014 side). The cause for this could be attributed to the extreme decrease in hardness at these zones, as revealed in Fig. 5. The ultimate tensile strength efficiency for joint of similar welding of AA 2014 and AA 5059 was 60 % and 62 %, respectively. While, for dissimilar welding, the joint efficiency for AA 2014 has increased to 66 %, while for AA 5059 it has decreased to 54 %, compared to their base metal values. Although the dissimilar joint revealed lower tensile properties related to both base metal values, the outcomes can be considered fairly satisfactory taking into account the drastic conditions the materials undertake thru the friction stir process, in agreement with Cavaliere et al. /11/.

Table 3. Tensile strength of BM and dissimilar/similar welded joints AA2014 - AA5059.

Materials	YS (MPa)	UTS (MPa)	Total elong. (%)	Joint efficiency
BM AA2014	260	388	11.7	-
BM AA5059	381	471	13.9	-
FSW AA2014	190	239	3.4	60
FSW AA5059	262	300	0.8	62
FSW AA5059-AA2014	236	263	2.0	54-66

CONCLUSIONS

AA 2014 and AA 5059 are two dissimilar aluminium alloys friction stir welded by using a rotation speed of 1600 min^{-1} and welding speed of 100 mm/min. The following can be concluded from this study:

– friction stir welding is applied successfully to dissimilar AA2014 and AA5059 joint with no visible macroscopic defects or porosity in the weld cross-section,
– seven different microstructural zones are recognised for the dissimilar joint. EDS examination exposed that after welding, the Mg content of AA 2014 has increased from the base metal value of 0.5 % to 4.8 % in the weld region. This can be considered as evidence of a good friction stir welding procedure,
– the variation in concentration of alloying elements and the recrystallization of a very fine grain structure may be the main reasons for variation of hardness values within the nugget zone,
– the lower tensile properties obtained compared to both base metal values can be considered quite satisfactory by taking into account the drastic conditions to which the materials are exposed to in the friction stir process.

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