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Effect of rotary friction welding on mechanical properties of 6060 Al alloy

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ABSTRACT: 6xxx series of aluminum alloys are prone to cracking when fusion welded without a proper filler metal. Alternatively, these alloys can be welded by rotary friction welding, a solid-state welding process, without using another material. However, the use of the correct parameters for the rotary friction welding process is a key to get sound welds. In this study, 6060 aluminum alloy was rotary friction welded with various rotation speeds, and the effects of the rotation speeds on the mechanical properties of the welds were studied. The samples were observed under scanning electron microscope, were analyzed using elemental mapping with energy dispersive X-Ray spectroscopy, and tested with micro-hardness and tensile tests. Among the studied samples, the sample welded with the rotation speed of 1700 rpm was found to be much better than the others in terms of the mechanical strength. In the observations made under the microscope, unlike the fusion welding, no cracking or other welding defects or macro segregation was noticed in the sample welded with the speed of 1700 rpm.

KEYWORDS: 6060 Al; Friction welding; Mechanical properties; Rotation speed; Solid state welding

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RESUMEN: *Efecto de la soldadura por fricción rotativa sobre las propiedades mecánicas de la aleación Al 6060*. Las aleaciones de aluminio de la serie 6xxx son propensas a agrietarse cuando se sueldan por fusión sin un metal de relleno adecuado. Alternativamente, estas aleaciones se pueden soldar mediante soldadura por fricción rotatoria, un proceso de soldadura en estado sólido, que no utiliza otro material. Sin embargo, el uso de los parámetros correctos para el proceso de soldadura por fricción giratoria es clave para obtener buenas soldaduras. En este estudio, la aleación de aluminio 6060 fue soldada por fricción rotatoria utilizando diferentes velocidades de rotación, y se estudiaron los efectos de las velocidades de rotación en las propiedades mecánicas de dichas soldaduras. Las muestras se caracterizaron utilizando microscopía electrónica de barrido, se analizaron realizando un mapeo elemental utilizando espectroscopía de rayos X por dispersión de energía, y se caracterizaron mecánicamente realizando microdurezas y ensayos de tracción. Entre las muestras estudiadas, la muestra soldada con la velocidad de rotación de 1700 rpm resultó ser mucho mejor que las demás en términos de resistencia mecánica.

En las observaciones realizadas bajo el microscopio, a diferencia de la soldadura por fusión, no se notó agrietamiento u otros defectos de soldadura o macro segregación en la muestra soldada a la velocidad de 1700 rpm.

PALABRAS CLAVE: 6060 Al; Propiedades mecánicas; Soldadura de estado sólido; Soldadura por fricción; Velocidad de rotación

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1. INTRODUCTION

Aluminum (Al) alloys are widely used as structural materials for their good mechanical and metallurgical properties, excellent corrosion resistance and significant low density (i.e., good for light weight applications). Furthermore, the mechanical properties of Al alloys can be improved with work hardening or heat treatment. However, the high heat input can cause a decline in the mechanical strength of these alloys when they are joined with fusion welding processes (Kou, 2020). In addition, Al alloys are sensitive to hot cracking when fusion welding is used (Soysal, 2020; Soysal, 2021) due to the solidification shrinkage (liquid density > solid density) and the thermal contractions. Thus, usually a proper filler alloy is needed to change the chemical content of the weld to avoid the cracking issue (Coniglio and Cross, 2009; Soysal and Kou, 2019). A solid-state welding process can be an alternative solution for these problems because the joining occurs under the melting temperatures of the materials, and it can offer a lower heat input. For example, the rotary friction welding (RFW), as a solid-state welding process, can be used for various materials, bring smaller heat affected zones compared to the fusion welding processes, and save materials and energy (Dey *et al.*, 2009; Teker and Karakurt, 2020).

RFW is performed rotating one of the two workpiece relative to the other stationary one and applying a compressive axial friction pressure. The friction between the two workpiece produces heat and causes the interfacial portions of the material to plasticize. The plasticized material is displaced by the axially applied pressure from the interface, and this knocks the interface oxide layers and other contaminants to allow joining. As a result of this deformation process, a flash collar is formed, and the axial length of both workpiece is shortened. When the desired shortening (burn-off distance) is managed, the rotation is stopped, and a forging pressure is used for a period of time to assist consolidation of the joint (Teker, 2013).

Welding conditions and welding parameters of RFW have still been investigated for aluminum alloys to obtain sound welds. Li *et al.* (2018) has observed the friction behavior of RFW while welding 6061-T6 Al alloy by changing the rotation speed from 500 to 2100 rpm and indicated that an unbounded area appears in the weld after exceeding the rotation speed of 1500 rpm. Etesami *et al.* (2015) has also studied the friction welded 2014 Al samples with various rotation speeds, and they showed that increasing the rotation speed decreased the weld defects and increased the hardness and the strength of the material. Kimura *et al.* (2006) used friction welding process and studied the influence of the welding conditions on the mechanical properties of 5052 Al alloy to increase the joint efficiency by keeping the rotation speed the same, and changing the friction pressure and friction time. The effect of rotation speeds have also been studied for joining dissimilar metals by friction welding, and the speed range of 1400 to 1600 rpm or 1700 rpm were reported as proper speeds to have sound welds (Sun *et al.*, 2018; Teker *et al.*, 2018). Furthermore, the effect of rotation speeds on the microstructure (deformed zones) of the joint of alumina/6061 Al alloy was investigated, and it was reported that increasing the rotation speed increases the size of fully plasticized deformed zone (Ahmad Fauzi *et al.*, 2010).

Al alloys welded with friction welding are expected to show good mechanical properties (Kimura *et al.*, 2005; Threadgill *et al.*, 2009; Dursun and Soutis, 2014; Fu *et al.*, 2015) but the optimum welding parameters should be used to obtain sound welds with superior mechanical properties. The mechanical properties of 6061 Al alloy are improved with the heat treatment of T5 which is artificially aging process applied (at a temperature between 150 and 300 °C) on the material cooled from the elevated extrusion temperatures (without solution treatment) (ASM Handbook, 1981). In this study, 6060 Al alloy was selected and welded by RFW, and mechanical tests have been conducted on the welds made with various rotation speeds to study the mechanical properties of the alloy.

2. MATERIALS AND METHODS

Pairs of 6060-T5 Al cylindrical rods with the size of 12 mm diameter and 75 mm length were joined with the RFW using three different rotation speeds: 1500, 1600 and 1700 rpm. The welded rods were grouped as S1, S2 and S3 regarding the rotation speeds. The process parameters used to weld these rods are shown on Table 1 with respect to the groups. The chemistry of the 6060-T5 Al alloy is given on Table 2. Mechanical properties of the 6060-T5 Al materials are shown in Table 3 (provided by Metalreyonu.com), Metalreyonu (2021).

Table 1. RFW process parameters

Sample Nº	Friction Pressure (MPa)	Friction Time (s)	Forging Pressure (MPa)	Forging Time (s)	Rotating Speed (rpm)
S1	40	6	90	4	1500
S2	40	6	90	4	1600
S3	40	6	90	4	1700

Table 2. Chemistry of the material (wt.%)

Alloy	Mg	Si	Fe	Zn	Cu	Ti	Mn	Cr	Al
6060-T5	0.39	0.46	0.15	0.15	0.1	0.1	0.1	0.05	Bal.

Table 3. Mechanical properties of the 6060-T5 Al materials (Metalreyonu, 2021)

Materials	Tensile Strength (MPa)	Yield Srength (MPa)	Elongation (%)	Hardness (HB)
6060-T5	215	175	12	60

The welded rods were cut perpendicular to the joint line to study the weld zones. First, the samples were rough grinded and polished (Al_2O_3 particles of 0.25 μm used for final polishing step), and then etched using the Keller's etching solution (2.5 mL HNO_3, 1.5 mL HCl, 1 mL HF and 95 mL distilled water) for 3-5 s to be able clearly observe the joint. After that, the samples were observed using optical microscopy (OM: LEICA DM750) and scanning electron microscopy (SEM: ZEISS EVO LS10). They were analyzed with energy dispersive x-ray spectroscopy (EDS) using point analysis and elemental mapping. Vickers micro-hardness measurements were taken under 100 g loading for 5 s by the ONESS Q10 test device. Tensile test specimens were machined in a way that the joint line located at the middle of the specimens. The tensile test specimens were prepared with respect to ASTM E8-E8M (2013) standards. Figure 1 shows the front view of the round tensile specimen with the dimensions. The tensile tests were performed with the drawing rate of 0.5 mm·min^{-1} using the UTEST UTM-8050 test device with the load capacity of 50 kN. After the tensile tests, the fracture surfaces were examined under SEM.

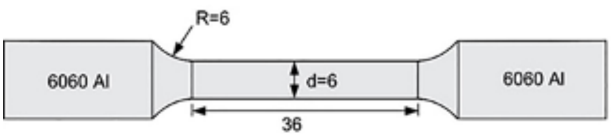

Figure 1. Schematic front view of the round tensile test specimen.

3. RESULTS AND DISCUSSION

3.1. Macrograph of the welds

The surface and cross-section macrographs of the welds made with different rotational speeds are shown in Fig. 2(a-b). As it can be seen from the figure, more flash produced in the sample S3 compared to the other two samples due to the use of a higher rotational speed. The bonding between the two welded 6060 Al rods seemed better in the sample S3 because the shape of the flash was rounder than the other two. These can be attributed to more heat generated during the welding process of the sample S3. The heat caused the material around the interface to be viscous and move

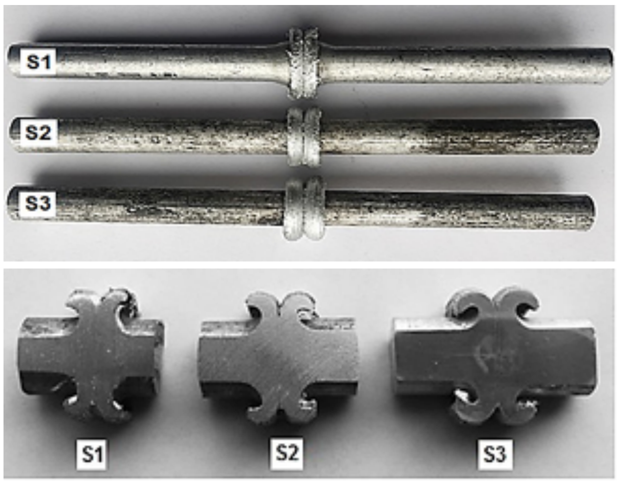

Figure 2. Macrograph of the weld joints.

out when the forging pressure was applied at the terminal stage of the RFW (Etesami *et al.*, 2015). On the other hand, the heat input in the sample S1 was the lowest among all. This caused the formation of the flash zone with the conical shape because the forging pressure on the rods resulted in a visible plastic deformation and hence indicated a weak bonding between them. The sample S2 indicated a transition between these two samples. None of these samples had cracks at the joints, unlike the reported cracks in the fusion welding (Soysal and Kou, 2019). After welding, the amounts of shortening (burn-off) in the samples were detected as S1= 3, S2= 5 and S3= 7 mm.

3.2. Mechanical tests

The micro-hardness measurements undertaken in the transverse cross-sections of the samples with error bars are given on Fig. 3. All the samples had a similar trend. The hardness increases from the base metal to the joint line, as Fig. 3 shows. Around the joint line, although it was difficult to separate the data points from each other in the figure, it was observed that the sample S3 had slightly higher hardness values. On the other hand, the hardness values of the samples S1 and S2 seemed greater than that of the sample S3 in the heat affected zone. The high hardness values of these two samples could be related to the plastic deformation and the heat input generated during welding. Perhaps, when the heat input was low, the plastic deformation generated with forging action could cause the hardening of the samples in the heat affected zones. Although at some points there were some fluctuations in the hardness values as it ca be observed in the graph, the hardness measurements overall show that there was no visible softening from the weld interface to the base metal.

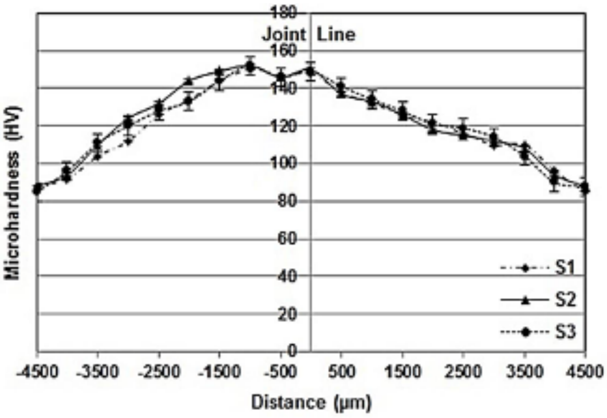

Figure 3. Micro-hardness measurements of the samples.

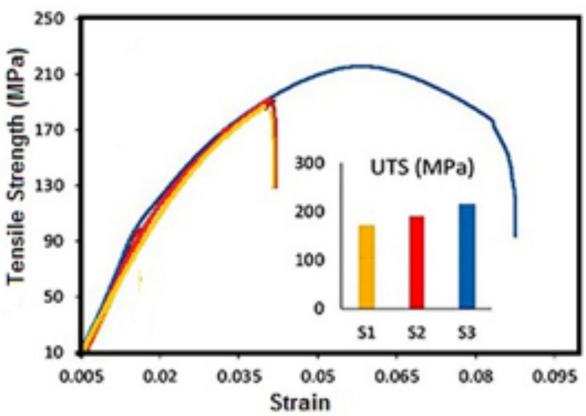

Figure 4. Tensile test results of the samples. The inset bar plot provides the value of the ultimate tensile strength (UTS) measured for each sample.

Figure 4 shows the tensile test curves and the bar chart (inset) represents the ultimate tensile strength (UTS) of the samples. The tensile test curves of the samples S1 and S2 failed after exceeding the linear elastic region. However, the sample S3 had a typical ductile tensile test curve of 6xxx series of aluminum alloys (Jha *et al.*, 2015). As can be seen from the bar chart, the UTS values of the samples S1, S2 and S3 were respectively found as 190.5, 197.7 and 217.7 MPa. Both the UTS and the tensile test curves of the samples showed that the mechanical properties of the sample S3 were much better than those obtained for the other two samples. When a comparison was made among the UTS of all the welds and the UTS of the base metal (215 MPa from Table 3), it could be seen that the UTS values of the samples S1 and S2 were under the UTS of the base metal, but the UTS of the sample S3 was slightly higher. The tested tensile test specimens are shown in Fig. 5. While the samples S1 and S2 showed brittle fracture characteristics (no obvious necking), the sample S3 showed ductile fracture characteristics by having a conical fracture geometry. Although the samples S1 and S2 fractured at the middle (most probably at the weld interface), the sample S3 fractured a bit far away from the middle. Figure 6, SEM fracture surface images of the sample S3. As it can be seen from the figure, the surface morphology of the fracture had dimples, which are typical of ductile fractures.

3.3. Characterization of microstructure

The OM images of S1 and S2 samples are displayed in Fig. 7(a-c) and Fig. 8(a-c). SEM images

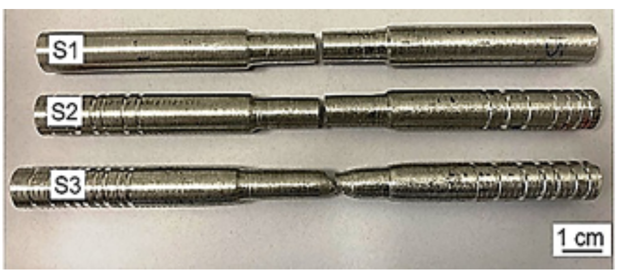

Figure 5. Macrograph of the samples after tensile testing.

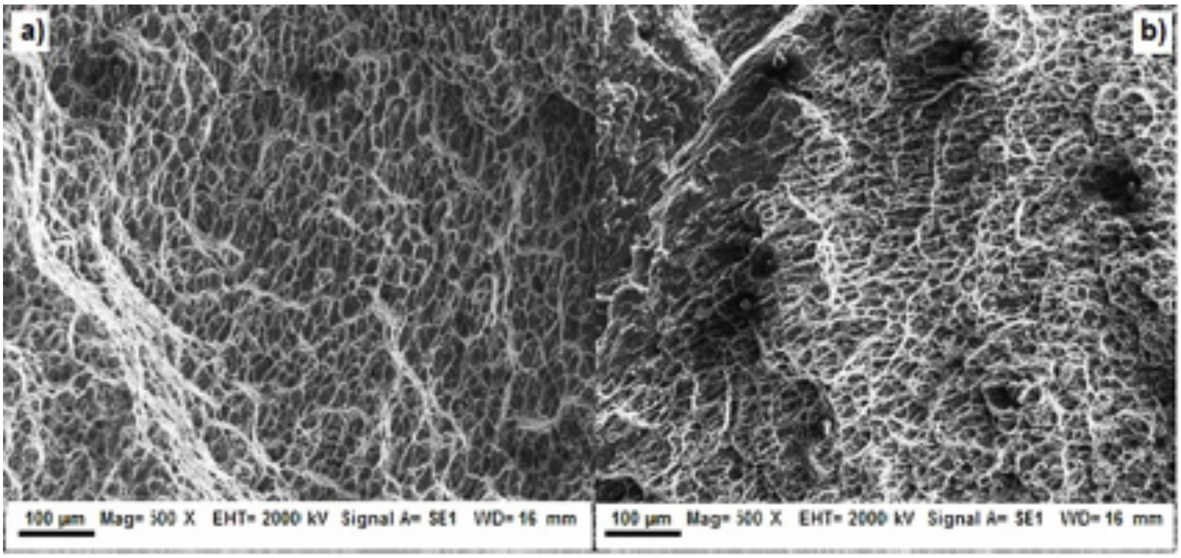

FIGURE 6. SEM fracture surface images of the sample S3.

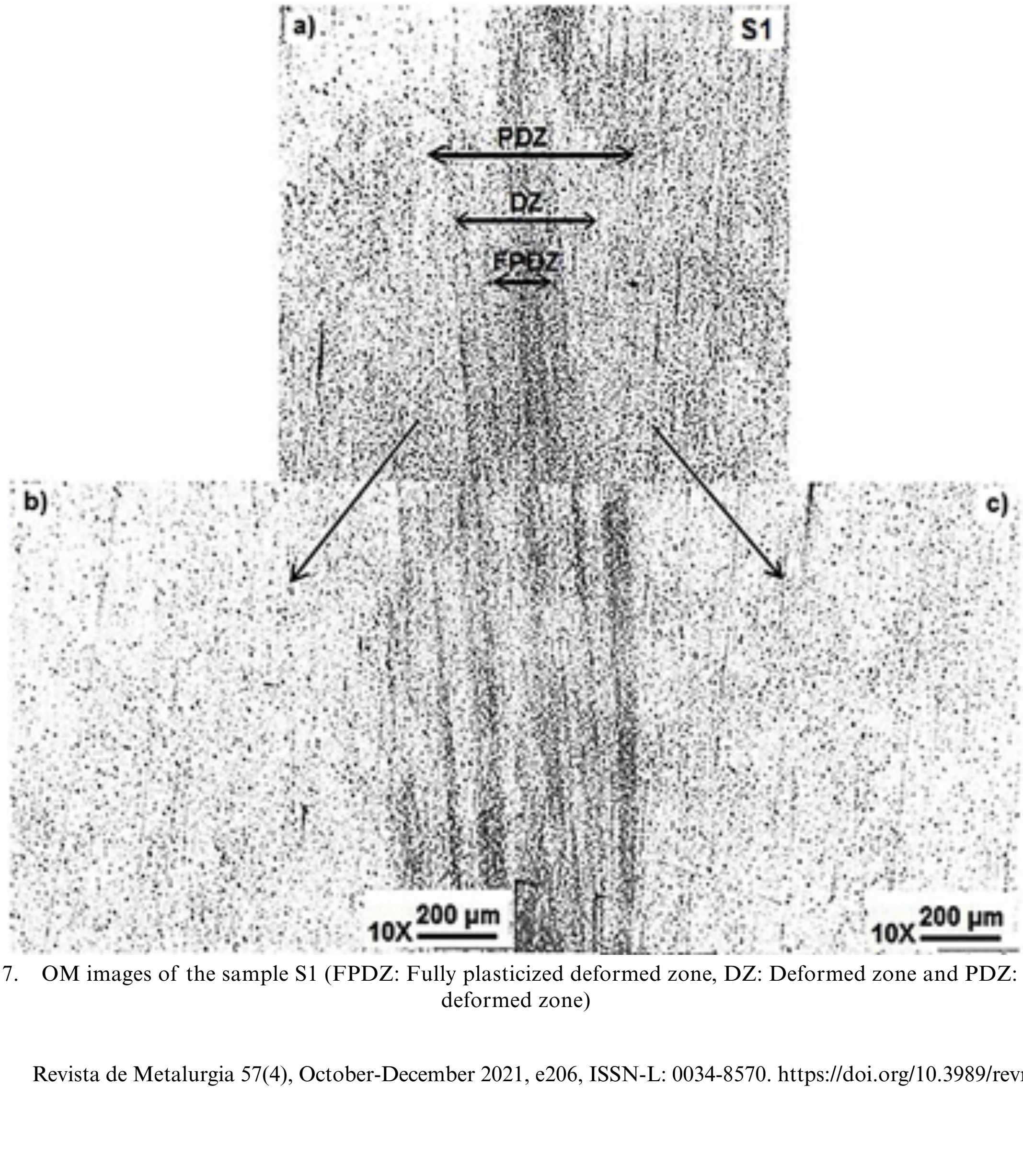

FIGURE 7. OM images of the sample S1 (FPDZ: Fully plasticized deformed zone, DZ: Deformed zone and PDZ: Partially deformed zone)

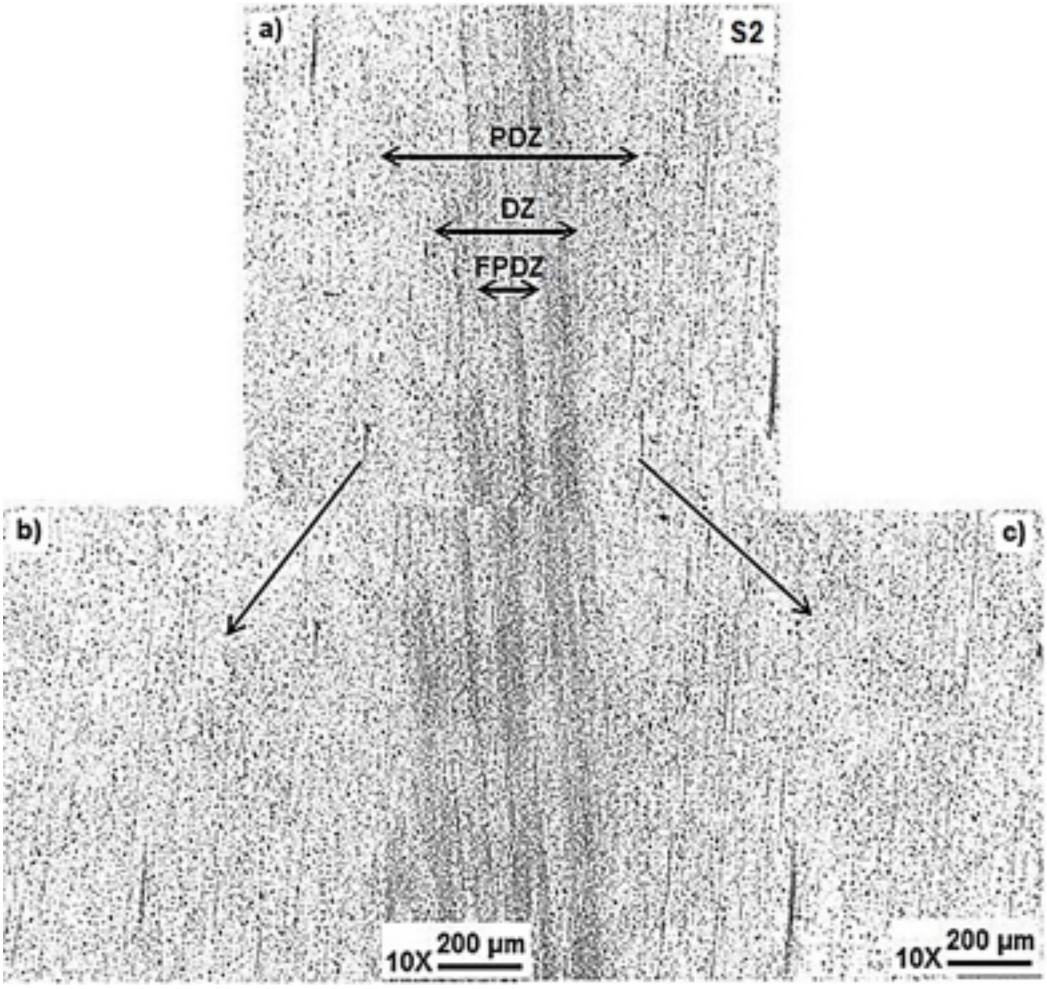

FIGURE 8. OM images of the sample S2 (FPDZ: Fully plasticized deformed zone, DZ: Deformed zone and PDZ: Partially deformed zone).

of the sample S3 are given on Fig. 9(a-c). Figures respectively show the left side, the center, and the right side of the weld zone. Unconnected zones (Li *et al.*, 2018) cracks or other weld defects were not seen in these images. The joint line or weld interface has been indicated on Fig. 9. The typical zones for the rotary friction welding (Ahmad Fauzi *et al.*, 2010; Teker, 2013) were identified and showed in the figure. The fully plasticized deformed zone (FPDZ), the deformed zone (DZ) and the partially deformed zone (PDZ) were formed as a result of friction and forging pressures and the heat generated during welding. From the comparison of Figs. 8 to 9, it can be suggested that the increase in the rotation speed resulted in the widening of the zones: FPDZ, DZ and PDZ.

EDS point analyses were done on the sample S3 at three different locations, as shown in Fig. 10. The local composition measurement at the middle corresponds to the weld interface. While the measurement on the left side was taken from the partially deformed zone, the one on the right side was taken from the deformed zone. The amount of Al, Si and Mg which are the main alloying elements of this alloy did not fluctuate much in all the three measurements. This indicated that the joining process did not cause any major composition gradients in the weld zone, unlike the fusion welding.

Elemental EDS mapping of the weld zone of the sample S3 is given on Fig. 11. Overall elemental mapping and the elemental mapping for each element of the weld zone are demonstrated in the figure. The alloying elements in the aluminum matrix were homogenously distributed all around in the weld zone. Unlike the welds made with fusion welding, it seemed that there was no clear macro-segregation in the weld zone. Therefore, the sample 3 carries the desired characteristics of the microscopic examination.

This study clearly indicated that the rotational speed of 1700 rpm was the ideal speed (among all the conditions investigated) to weld 6060 Al alloy with the rotary friction welding. Since this speed was at the upper border of the recommended speed

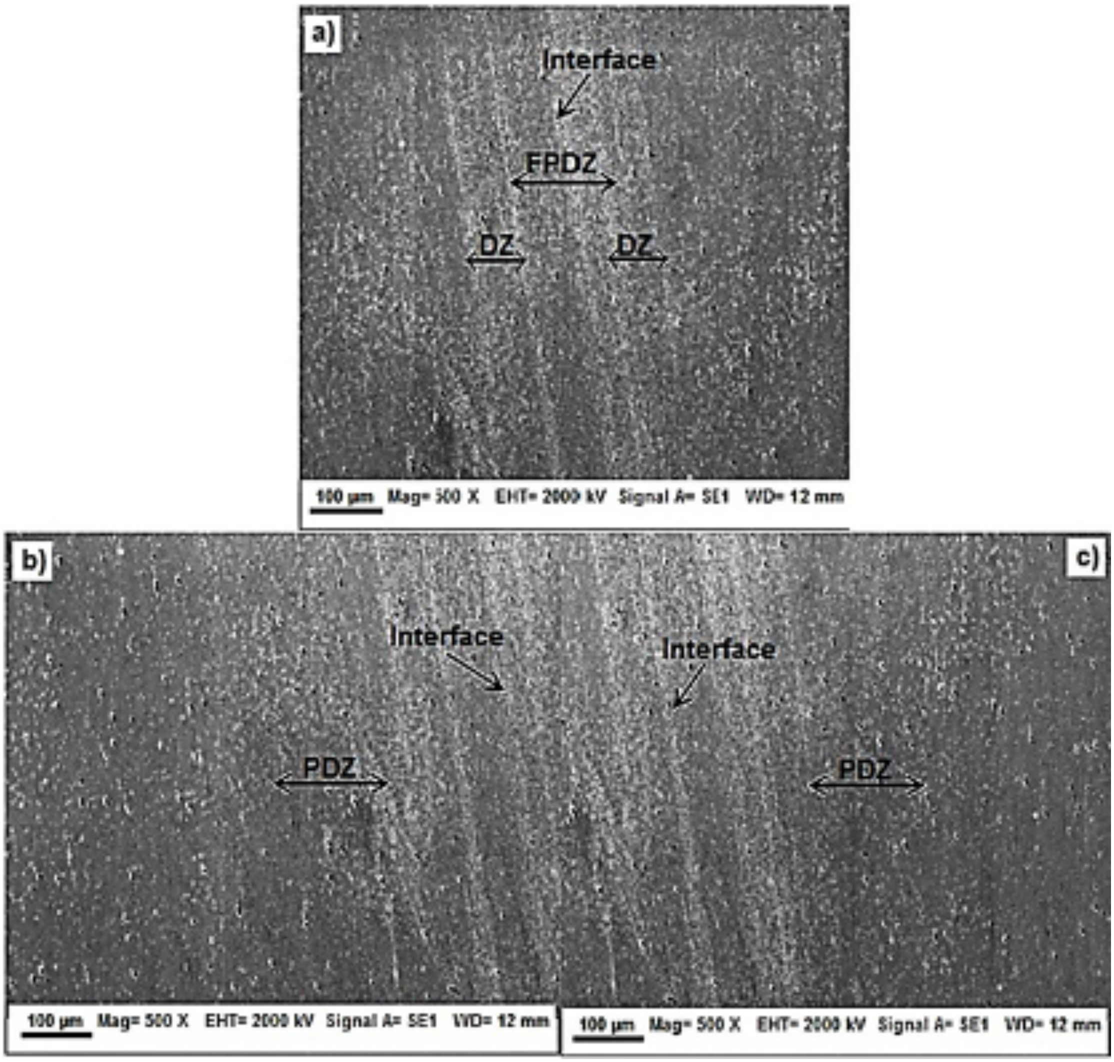

FIGURE 9. SEM images of the sample S3: a) the weld zone; b) left side of weld zone; c) right side of the weld zone (FPDZ: Fully plasticized deformed zone, DZ: Deformed zone and PDZ: Partially deformed zone).

range of the friction welding (Sun *et al.*, 2018; Teker *et al.*, 2018), higher speeds were not studied not to have unbounded areas in the weld zone (Li *et al.*, 2018). The mechanical tests used in this study showed that the rotary friction welding of 6060 Al alloy with the rotation speed less than 1700 rpm resulted in brittle and hard joints. On the other hand, the mechanical properties of the sample made with the rotation speed of 1700 rpm were found desirable. Furthermore, the UTS of the sample S3 can be comparable to the UTS of the base metal. Thus, the friction welding with the 1700 rpm rotation speed actually did not cause a significant reduction in the strength of the joined portion of the material. None of the welding defects observed in the fusion welding has been seen in the joint, as shown with the microscopy images. Thus, the rotation speed of 1700 rpm can be a good choice to friction weld the 6xxx series of aluminum alloys which are prone to cracking when they are welded by fusion welding without dissimilar filler metals (Soysal and Kou, 2019). Since dissimilar filler metals reduce the mechanical properties of the base metal (Othman *et al.*, 2010), using friction welding with the optimum parameters can offer quality welds and good mechanical properties.

4. CONCLUSION

The aluminum alloy 6060-T5 was welded by rotary friction welding with three different rotation speeds: 1500, 1600 and 1700 rpm. The mechanical properties of the welded samples were studied with hardness and tensile tests. The following conclusions were drawn.

- The UTS of the sample welded with the rotation speed of 1700 rpm was measured as 217.7 MPa, which was comparable to the base metal and higher than that of the others.

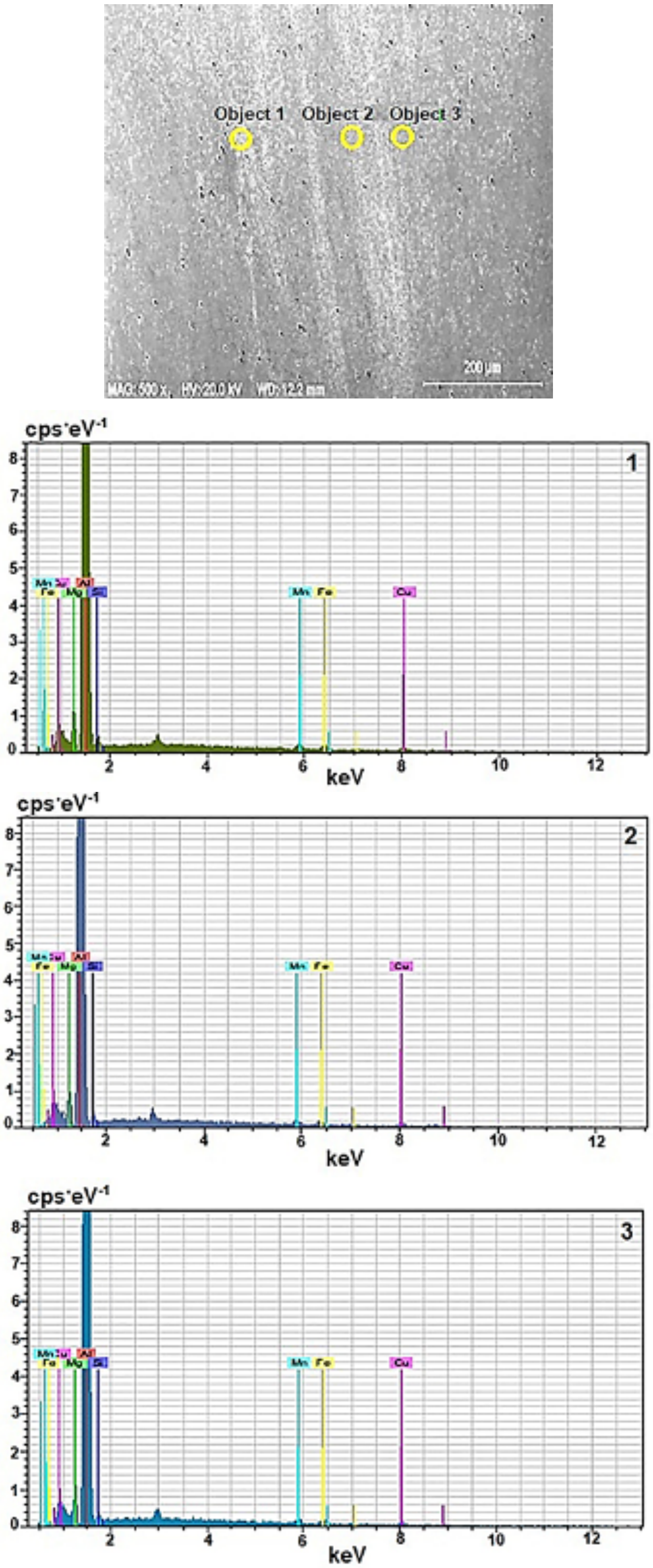

FIGURE 10. EDS analysis of the sample S3.

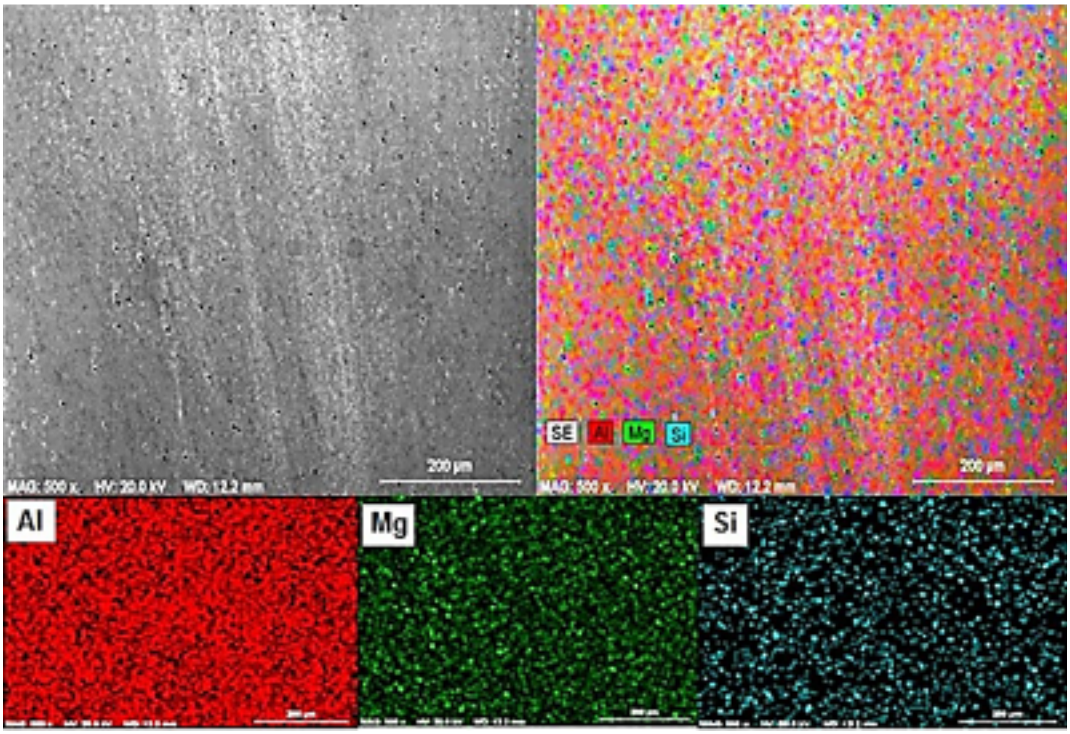

FIGURE 11. Elemental mapping of the weld zone of the sample S3.

- The sample S3 had ductile fracture characteristics while the others failed in a brittle manner.
- Hardness of all the samples had a similar trend across the joint.
- No cracking or other welding defects or macro segregation was noticed in the microscopic analysis of the joint made with the speed of 1700 rpm.
- The alloying elements in the aluminum matrix were homogenously distributed all around in the weld zone.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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