Effect of Friction Stir Welding Process Parameters and Post-Weld Heat Treatment on the Microstructure and Mechanical Properties of AA6061-O Aluminum Alloys

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Abstract: The aim of the present work is to study the effect of the welding conditions and T4 and T6 post-weld heat treatments (PWHT) on the microstructure and hardness values of AA6061-O aluminum plates joined using friction stir welding (FSW). The welding was conducting using three rotational speeds of 400, 500 and 630 rpm and two welding speeds of 25 and 40 mm/min. After FSW, the AA6061 joints were subjected to T4 and T6 heat treatments. Microstructural characterization was examined using optical and scanning electron microscope (SEM) equipped with energy dispersive x-ray spectroscopy (EDS). The results showed that the grain size of the stir zone increased by increasing the rotational speed or by decreasing welding speed. Hardness significantly decreased as rotation speed increased and the values of hardness for the welded joints after artificial aging (T6) are greater than solution heat treatment (T4).

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Keywords: Friction stir welding, AA6061 aluminum alloy, microstructures observations, Hardness measurement.

1.Introduction.

Friction stir welding (FSW) is a relatively new joining technique invented at The Welding Institute in 1991 for mainly welding Al alloys [1]. The high quality Al welds produced by this technique encouraged researchers to extend its application to include other alloys such as copper, magnesium, steel and dissimilar alloys. Since FSW is carried out in the solid state, all problems from solidification process are eliminated. Also, compared with the conventional fusion welding processes, the residual stresses and distortion are very low due to low heat input [2-4]. Aluminum and its alloys are used in many industrial applications due to high strength to weight ratio, excellent corrosion resistance and high electrical and thermal conductivity. AA6061 is a typical alloy of 6xxx series and includes some alloying elements such as Al-Mg-Si [5]. It used in ship and aircraft structures, transportation and utensils [6]. The solidification problems and formation of intermetallic compounds in the welded joints have prohibited the use of fusion welding processes for joining these heat treatable 6061 aluminum alloys for long time [2,7,8]. Due to its great advantages mentioned above, FSW is extremely very attractive for joining 6061 heat treatable alloys.

Concerning the welding of AA6061 by FSW process, it was found that the microstructure and mechanical properties of welded joints are markedly affected by the welding parameters such as rotational and welding speeds as well as welding tools geometries [9–10]. The effect of the FSW process parameters on the microstructure and mechanical properties of friction stir welded aluminum joints were studied by many workers [11-14]. For example*, H. J. Liu et al.* [11] investigated the effect of welding speed on microstructure and mechanical properties of friction stir welded 6061-T6 aluminum alloy. It was observed that as the welding speed increased, the grain size of the stir zone decreased and the micro hardness in the welded zones is strongly increase and observed that the tensile strength increases with increase of welding speed. *F. Fadaeifard el al.* [12] investigated the effect of welding rotational speed on microstructure of friction stir lap joints of AA 6061-T6 aluminum alloy. They observed that the grains of stir zones became finer and smaller than the grains of base metal. *F.F. Wang et al.* [13] investigated the effect of tool rotational speed on microstructure and mechanical properties of friction stir welded Al–Li alloy. They observed that the grain size of the stirred zone increases by increasing the rotational speed and by increasing rotational speeds from 600–1000 rpm, the hardness rises above 104 Hv within the SZ *W. Boonchouytan et al.* [14] obtained the highest mechanical properties (179.80 MPa) of AA 6061-T6 welded joint at a welding speed of 160mm/min and rotating speed of 1400 rpm. It has been reported that the microstructure and mechanical properties of FS welds can be improved by several treatments after or during the welding [15-16]. for example, *P. Vijaya Kumar et al.* [15] investigated the effect of post weld heat treatment, viz., retrogression and reaging (RRA) and peak aging (T6) on the microstructure and mechanical properties of friction stir welded AA7075 aluminum alloy with 8mm thickness. They observed that in T6 condition, the microstructure has relatively coarse and closely spaced precipitates along the grain boundaries and fine precipitates in the grains and in case of RRA condition, the grain boundary precipitates are discontinuous and coarser than that in T6 condition. It was observed that the hardness is high in T6 condition compared to other post weld heat treatments. *Jitlada boonma et al.* [16] studied the hardness of both as welded and as quenched samples of friction stir welded AA6061. They observed that, the hardness profile of the FSW specimens after PWHT higher than the hardness of as welded samples. Therefore, the present work aims to study the effect of the FSW process parameters, typically, the tool rotational and welding speeds as well as the post weld heat treatment, typically, T4 and T6 heat treatments on the microstructure and mechanical properties of friction stir welded AA6061 joints.

2. Experimental Procedure.

AA6061-O aluminum alloy plates having 8 mm thickness were Friction Stir butt welded using conventional vertical milling machine. The chemical composition of the AA6061 alloy is: 0.52% Si, 0.025% Fe, 0.005% Mn, 0.871% Mg, 0.259% Cu, 0.2% Cr, 0.008% Zn, 0.04% Ti, and 98.08% Al. A non-consumable welding tool is made of H13 alloy steel and composed of 30mm diameter shoulder and 12mm diameter threaded probe, 1.75 mm pitch and 7.8 mm height was used to weld the AA6061 Al plates. FSW was carried out using three different tool rotational speeds of 400, 500 and 630 rpm and two welding speeds of 25 and 40 mm/min. The tool tilt angle was kept constant at 2 degrees. The surface of the plates was cleaned with acetone before welding.

Post weld heat treatment PWHT was carried out immediately after welding and the samples were heated in furnace at 550^{o}C for 2 hrs, and then quenched in water (T4). Half of samples were tested after quenching and the other half were artificially aged at 177 ^{o}C for 6 hrs (T6). Then all samples were cut to analyze their microstructure and mechanical properties on base metal and weld zones. Samples were cut out from the T4 and T6 heat treated conditions using an electric discharge wire cutting machine for metallographic evaluations and hardness measurements. Metallographic samples were ground using emery paper of increasing finesse up to 1200 grit followed by polishing using 0.3 µm alumina suspension and then etched using solution of 1 ml HF +1.5 ml HCl +2.5 ml HNO_3 + 95 ml distilled water for 240 s at ambient temperature. Microstructural investigations were carried out using optical microscope and Scanning Electron Microscope (SEM) equipped with Energy Dispersive x-ray Spectroscopy (EDS). The microstructural measurements of the size of the α-Al grains were performed using image analyzing techniques. Hardness measurement was carried out at the mid thickness along the cross section transverse to the welding direction with an internal spacing of 0.5 mm under the load of 4.903 N for a 15 s of loading time.

3. Results and Discussion.

3.1 Microstructural Observations

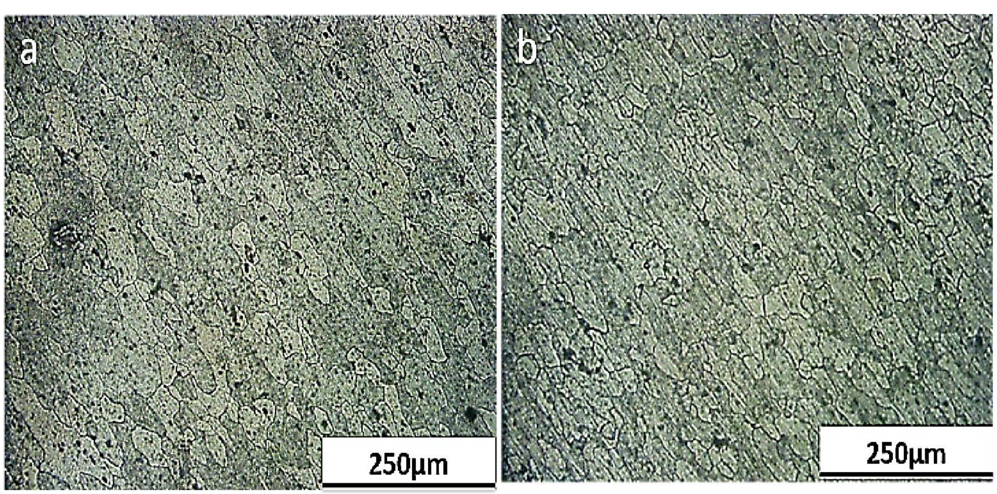


Fig. 1. Microstructure of base metal after (a) T4 and (b) T6 heat treatments.

Figure 1 shows typical micrographs of the microstructure of the AA6061 Al alloy base metal (BM) after T4 and T6 heat treatments. In both cases, the microstructure of BM consists of elongated α-Al primary grains with an average size of 30±4 µm. Figures 2 and 3 show typical micrographs of the microstructure in the center line of the stir zones FS welded using different tool rotational and welding speeds after T4 and T6 heat treatments, respectively.

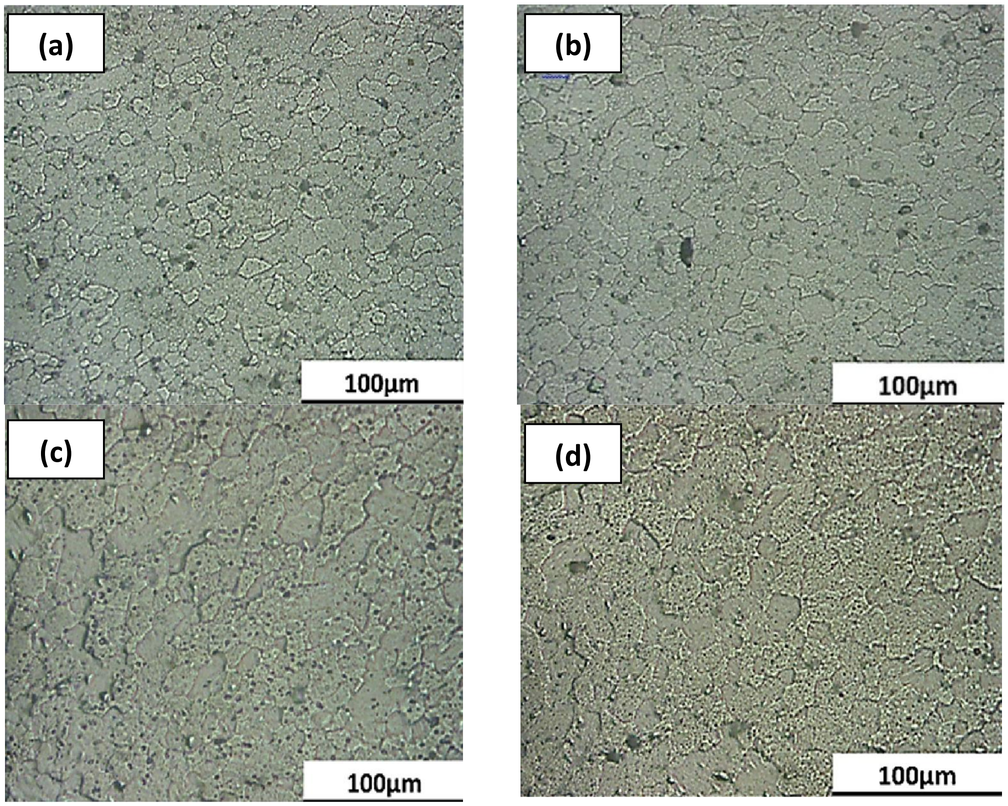
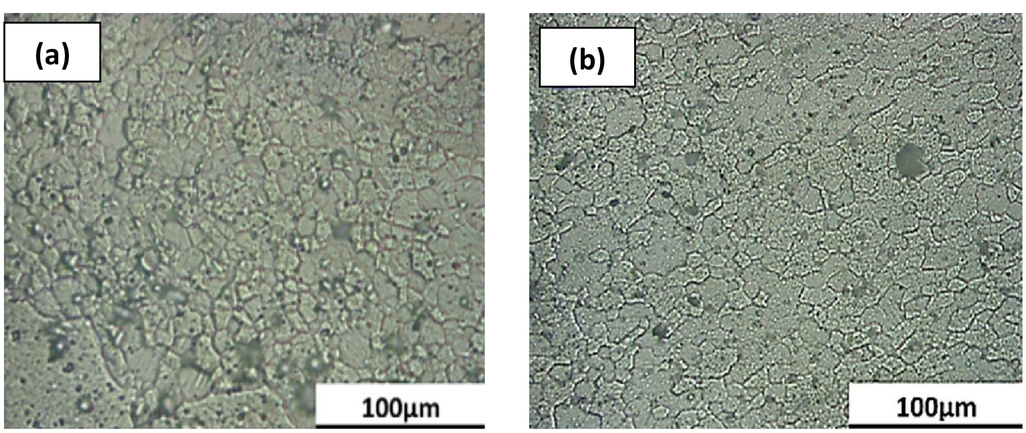


Fig. 2. Microstructures at the centers of the stir zones of joints after T4 heat treatment. The joints FS welded using tool rotational and welding speeds of (a) 400 rpm and 25 mm/min (b) 400 rpm and 40 mm/min, (c) 630 rpm and 25mm/min and (d) 630 rpm and 40 mm/min.



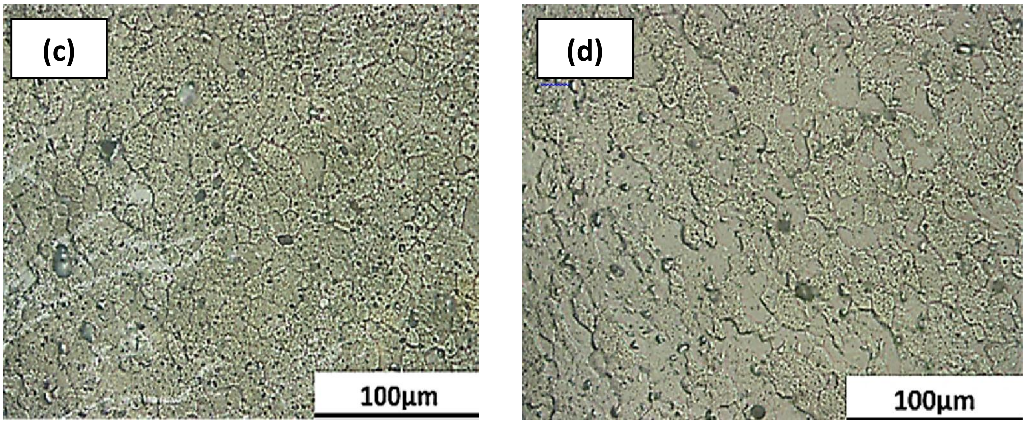


Fig. 3. Microstructures at the centers of the stir zones of joints after T6 heat treatment. The joints FS welded using tool rotational and welding speeds of (a) 400 rpm and 25 mm/min (b) 400 rpm and 40 mm/min, (c) 630 rpm and 25 mm/min and (d) 630 rpm and 40 mm/min.

It is clear that, the microstructure of the stir zones consists of finer equiaxed grains due to the dynamic recrystallization occurred during FSW. Quantitative analysis of grain size revealed a clear dependence of grain size on the tool rotational and welding speeds. Figure 4 shows the variation of the average grain size at the center of the stirred zones with tool rotational speed at different welding speeds and post-weld heat treatments. The average grain size was found to be increased with increasing rotational speed and/or reducing the welding speed as a result of increasing heat input. The stirred zones heat treated at T6 exhibited slightly higher average grain size when compared with those heat treated at T4.

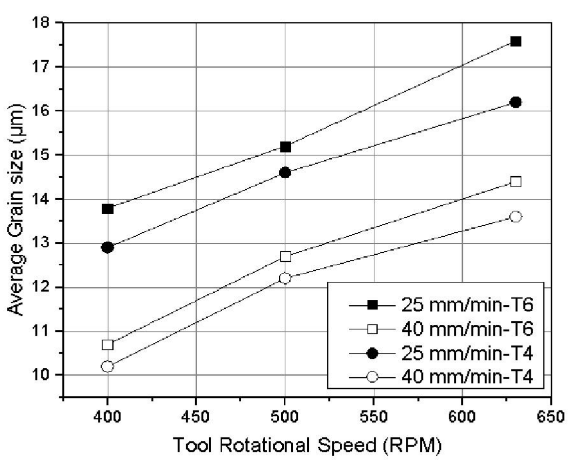


Fig. 4. Variation between the average grain size at the center of the stirred zone with the tool rotational speed at different welding speeds and post-weld heat treatments.

3.2. SEM-EDS analysis for the second phase particles.

Scanning Electron Microscope (SEM) equipped with Energy Dispersive x-ray Spectroscopy (EDS) was also used to investigate the microstructures of the 6061 aluminum alloy base metal and stir zone of welded specimens after T6 and T4 treatments. Examples of the microstructures of the base metal are shown in Figure 5. SEM microstructures of the base metals of T6 and T4 condition are similar and representing elongated grains with random distribution of second phase particles. It can be seen that, the grain sizes approximately the same by the comparison between solution treatment and artificial aging for the base metals. On the other hand, Figure 6 represents examples of the microstructures of the stir zones for the samples with conditions (a) (400rpm, 25mm/min, T6), (b) (630rpm, 40mm/min, T6), (c) (400rpm, 25mm/min, T4), (d) (630rpm, 40mm/min, T4). The microstructures consisted of equiaxed grains with small sizes compared to the large elongated grains of BM as a result of the dynamically recrystallization occurred during friction stir welding. Grain size increases with increasing rotation speed. These results are in good agreement with the previous works done by *F.F. Wang et al.* [13].

Examination of the compositions of the second phase particles in the stir zones of the samples with condition (400rpm, 25mm/min, T6) and (630rpm, 40mm/min, T4) was carried out using EDS spots analysis. The results are listed in Table 1. The analysis of point 1 contains high percentages of Al, Ti, O and Mg indicating that the small white particles were Ti-O containing precipitates. Analysis of point 2 showed high percentages of Al, Fe, Si, Cr and Mg indicating that the elongated white particles were Al-Fe-Si-Cr-Mg-containing precipitates. Analysis of point 3 showed high percentages of Si, Al, and Mg indicating that the small rounded grey particles were Mg_2Si precipitates. Analysis of point 4 showed high percentages of Al, Fe Cr, and Cu indicating that the small irregular shape grey particles were Al-Fe-Cr – Cu containing precipitates. On the other hand, Si and Al were only the dominant elements in the EDS spot analysis of point 5, indicating that these large irregular shape grey particles were Al-Si precipitates. All these precipitates were also observed in the EDS maps analysis of base metal and stir zones as shown in Figures 7 to 10.

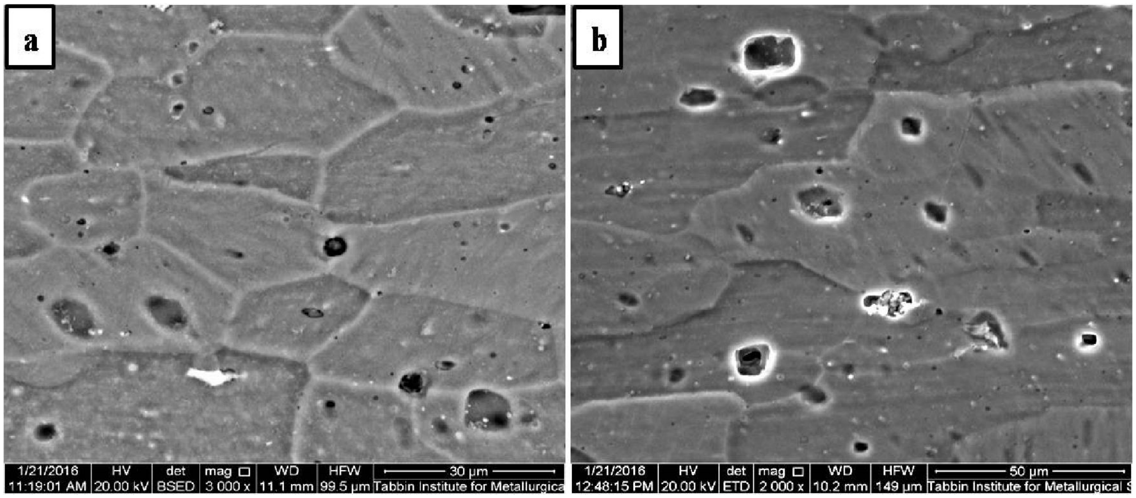


Fig. 5. SEM images of the base metal: (a) T6 and (b) T4.

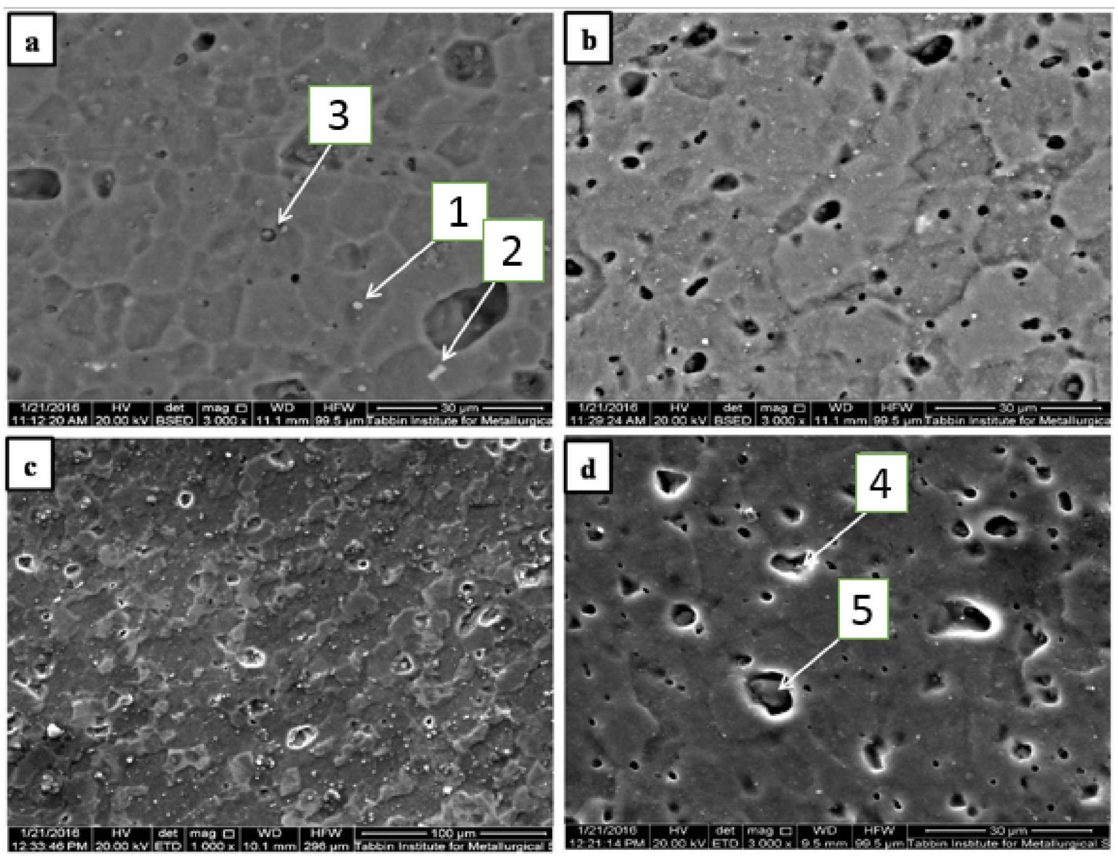


Fig. 6. SEM images of the stir zones: (a) (400rpm, 25mm/min, T6), (b) (630rpm, 40mm/min, T6), (c) (400rpm, 25mm/min, T4), and (d) (630rpm, 40mm/min, T4).

Table. 1. EDS spot quantitative analysis of the five points shown in Figure 6.

Element	Wt. %				
	Point 1	Point 2	Point 3	Point 4	Point 5
Al	73.27	72.53	33.14	76.17	44.78
Si	-	5.55	36.99		53.48
Fe	-	14.48	-	13.21	-
Ti	18.13	-	2.29	-	-
O	6.75	-	-	-	-
Mg	1.39	2.29	25.9	1.7	0.55
Cu	0.45	0.58	1.16	2.44	1.19
Cr		4.58	1.33	6.48	-

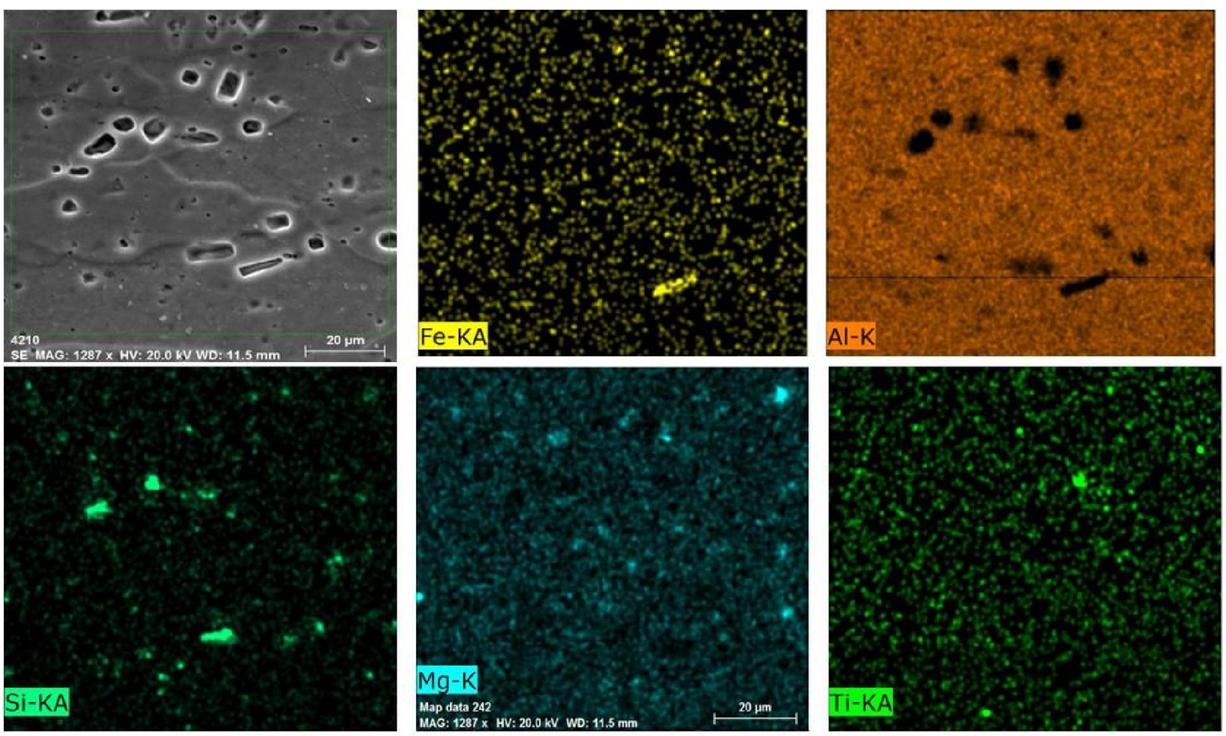


Fig. 7. EDS map analysis of the base metal with T6 condition.

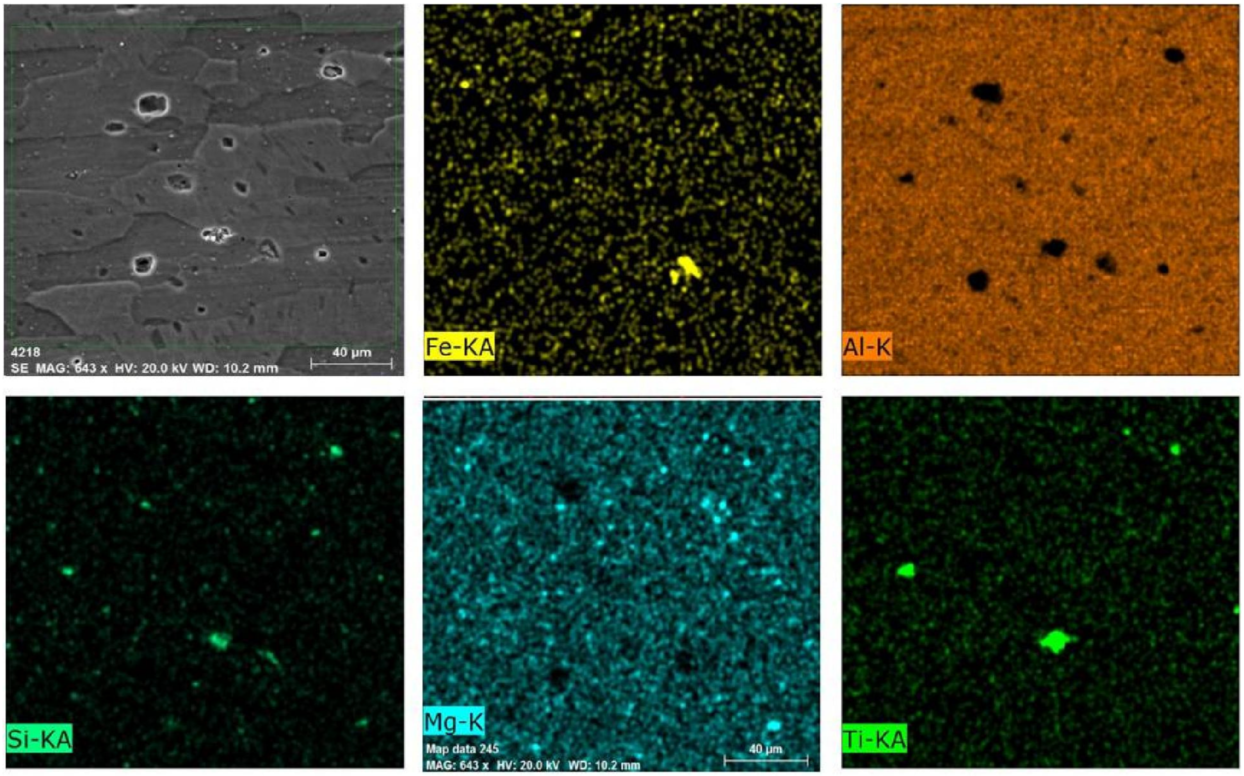
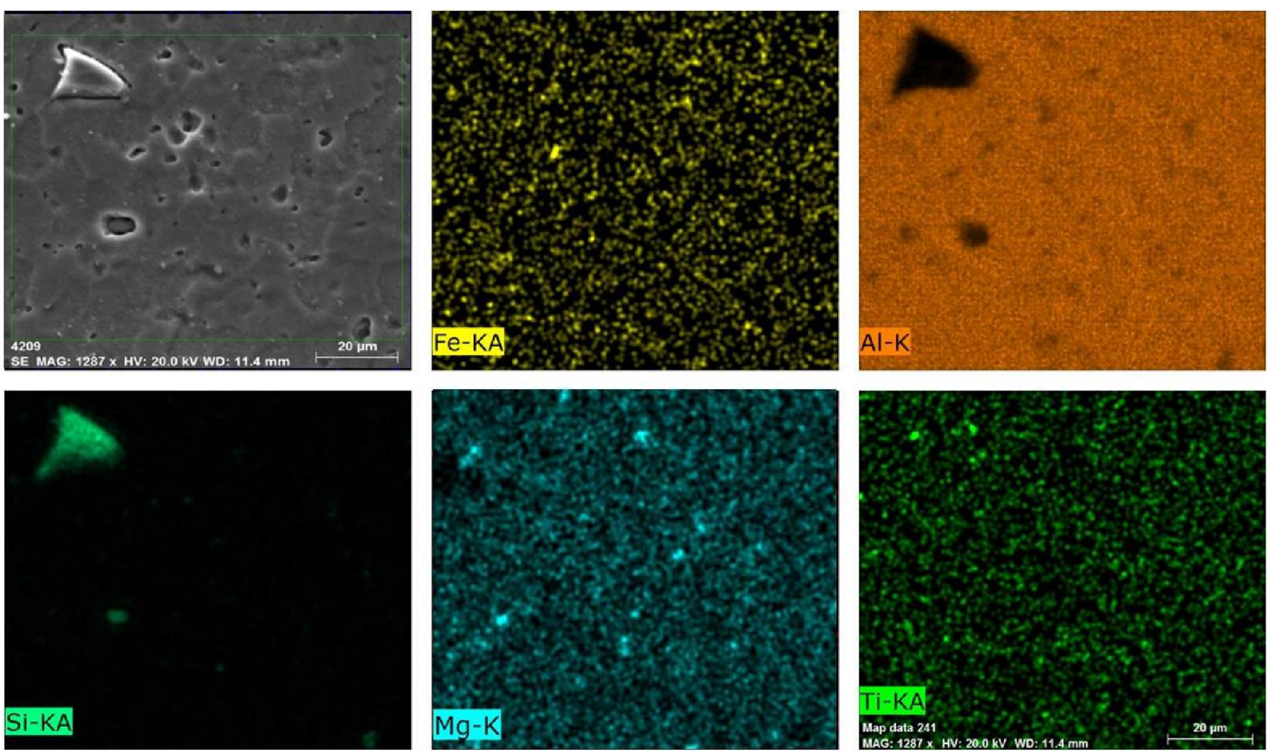


Fig. 8. EDS maps analysis of the base metal with T4 condition.



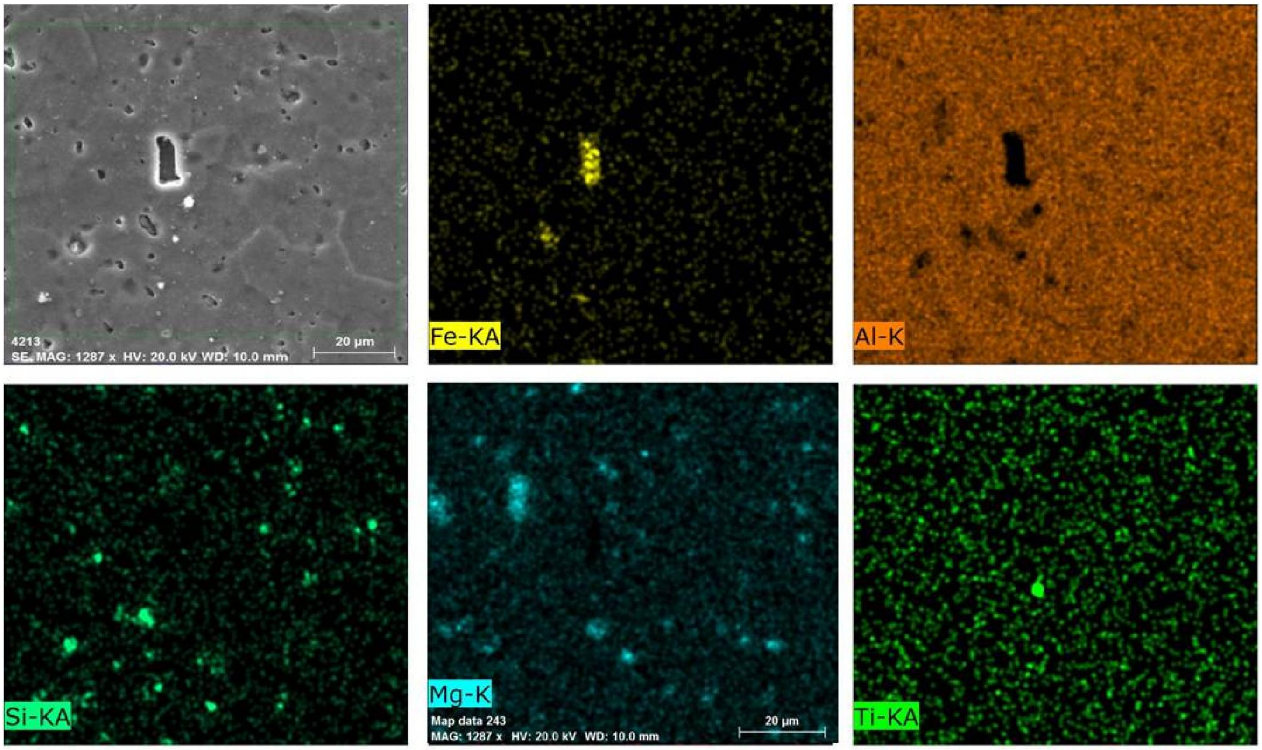


Fig. 10**.** EDS maps analysis of the stir zone of sample with condition 630rpm, 40mm/min, T4.

3.3. Hardness of AA6061 Al Friction Stir Welded Joints.

Hardness profiles of the FSW welded joints for both T4 and T6 conditions were measured at mid thickness of the cross sections transverse to the welding direction in order to detect if there is any remaining welding effect on the joints after heat treatments.

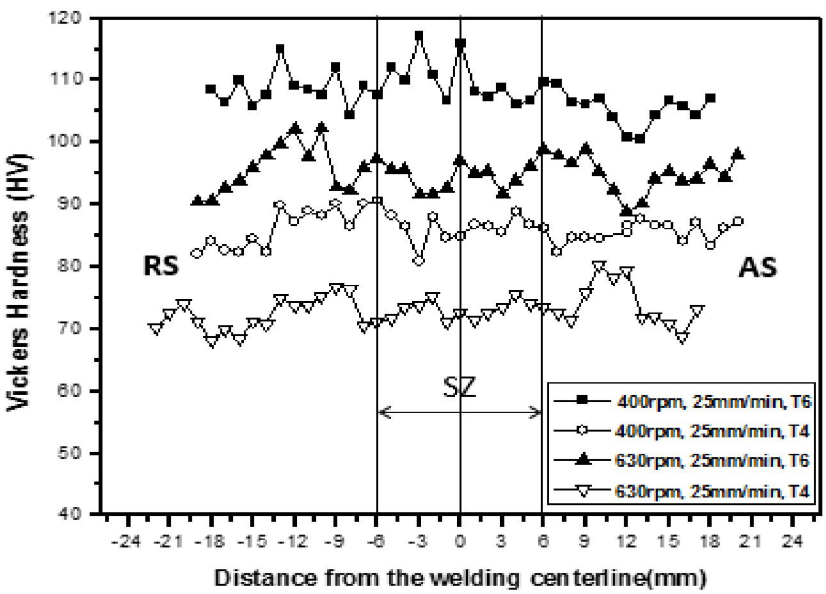


Fig. 11. Effect of rotational speed at constant welding speed 25mm/min on the micro hardness distribution for some joints at T4, T6 treatment.

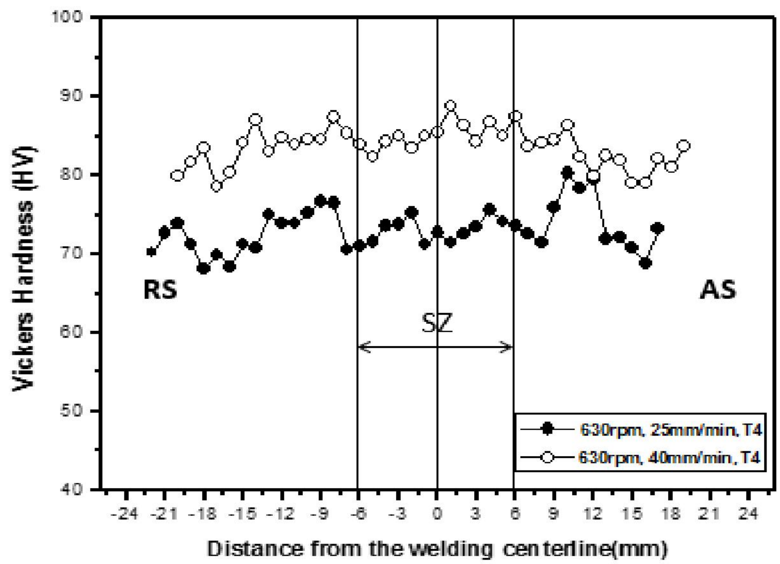


Fig. 12**.** Effect of welding speed at constant rotational speed 630rpm on the micro hardness distribution for the joint at T4 treatment.

Figure 11 shows the hardness distributions of some FSW joints welded at constant welding speed of 25mm/min and two rotational speeds of 400, 630rpm after T4 and T6 treatment conditions. Hardness values for the BM, HAZ and SZ are similar. However, the slight decrease in hardness values with increasing rotation speed for all joints indicates the remaining welding effect after both treatment conditions. These results are in good agreement with the previous works done by *M. Ilangovan* [17] and *Y. Chen et al.* [18]. Effect of the welding speed on the hardness distribution of welded joints after T4 treatment is shown in Figure 12. Hardness is slightly increased with increasing welding speed indicating also, the remaining effect of welding process after T4 treatment. Generally, from figure 11 hardness distribution for joints after T6 treatment is higher than T4 ones. This could be attributed to the fine precipitates (GPZ) formed after artificial aging (T6). During solutionization, the precipitates are dissolved in the matrix and form super saturated solid solution upon cooling. Further aging leads to the precipitation of a secondary phase which reinforces the strength of aluminum alloy. Since AA6061 is a heat treatable aluminum alloy, the hardness is mainly attributed to the presence of precipitates. These results are in good agreement with the previous works done by *M. Movahedi et al.* [9] and *B.K.B. Nadikudi et al.* [10].

4. Conclusions

From the analyses, we can summarize the results as follows:

1. Equiaxed grain size of the SZ increased with increasing rotation speed. Increasing rotation speed resulted in finer and homogenous distributions of second phase particles in the SZ. On the other hand, grain size decreases with increasing welding speed.
2. Hardness distributions are almost homogenous through the welded joints and showed remaining effected of welding process after T4 and T6 treatments. Hardness decreased as rotation speed increased and vice versa for welding speeds. and the values of the hardness after artificial aging (T6) are greater than solution heat treatment (T4).

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