

ORIGINAL ARTICLE

Mechanical characterization of friction stir welded joint of dissimilar aluminum alloys AA6061 and AA7050

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Article Information

Received: 11 May 2021

Revised: 14 June 2021

Accepted: 24 June 2021

Available online: 28 June 2021

Keywords:

Tensile strength;
Microhardness;
Aluminum alloys;
Microstructure;
Grain Size

Abstract

Friction stir welding (FSW) process has gained attention in recent years because of its advantages over the conventional fusion welding process. These advantages include the absence of heat formation in the affected zone and the absence of large distortion, porosity, oxidation, and cracking. Experimental investigations are necessary to understand the physical behavior that causes the high tensile strength of welded joints of different metals and alloys. This paper focuses on the effect of welding parameters on microstructure and mechanical properties of welded joint by friction stir welding. In this work, the fabrication of AA6061 and AA7050 was successfully done by friction stir welding, the confidence interval has shown that tensile strength and hardness increased with increasing tool rotation. The maximum tensile strength and % strain at SZ was observed 269 MPa, and 21.5 HV at TRS of 1000 rpm, and TS of 60 mm/min, and the maximum hardness at SZ was observed 135 HV at TRS of 750 rpm, and TS of 80 mm/min. The grain size in the SZ at higher tool rotation (1000 rpm) was much finer than the lower tool rotation (800 rpm). The FSWed portion at 500 rpm shows the big and deep dimples, while equiaxed fine dimples were observed at TRS of 1000 rpm.

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1. Introduction

Friction-stir welding (FSW) technology invented at The Welding Institute, UK, in December 1991 is a solid-state joining process for joining aluminum alloys and used increasingly in aerospace, transportation and car manufacturing industries [1, 2]. This technology that is a solid state joining technique can be utilized to produce sound joints in aluminum alloys [3, 4]. Fig. 1 show the schematic diagram of FSW. In the process of FSW, the tool rotational speed, welding speed (travel speed) and pin geometry essentially determine the material plasticization around the pin, weld geometry and consequently mechanical properties of the joints

[5]. Lately, substantial work has been reported about the FSW process for similar and dissimilar metal joining due to its ability to eliminate local casting defects of the conventional fusion welding techniques [6]. The joining of such dissimilar materials by fusion welding techniques is quite challenging due to their different chemical, mechanical and thermal properties. Based on the above background, FSW is an effective technology for the reduction in defect in aluminum alloys. Some researchers tried to weld dissimilar alloys using the process of FSW. For example, Carlone et al. [7] examined the microstructural aspects in aluminum–copper dissimilar joining by FSW. Also, Habibnia et al. [6] investigated the effects of different operating conditions on FSW of dissimilar

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<https://doi.org/10.36037/IJREI.2021.5503>.

sheets of 5050 aluminum alloy and 304 stainless steel. They found that tool welding speed had a negligible effect on tensile strength of the joint and increasing welding speed increased the tensile strength.

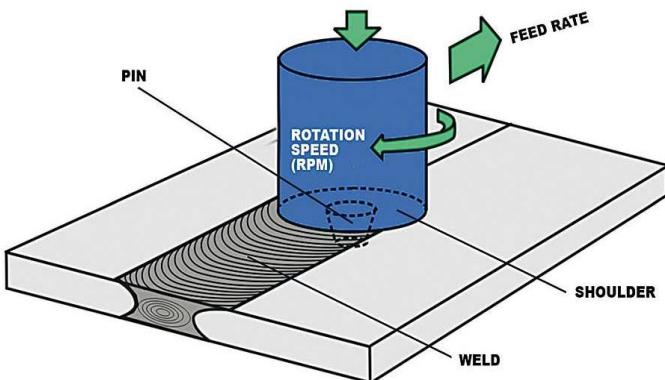


Figure 1: Friction stir welding

Guo et al. [8] discovered that the highest joint strength was obtained when welding was conducted at highest welding speed. New welding approach has been introduced to improve the welding quality of TIG welded joint, the influence of friction stir processing on TIG welded joint have been analyzed and they observed that mechanical properties and heat transfer of TIG+FSP welded joint [9-15]. Due to their high strength-to-weight ratio, good machinability, and high resistance to corrosion [16], aluminum alloys are an attractive lightweight metals for structural applications in the aerospace, automotive, and naval industry. However, the joining of Al alloys by conventional fusion welding techniques is known to be problematic [17], where some of these issues include the formation of secondary brittle phases, cracking during solidification, high distortion, and residual stresses [17]. Among aluminum alloys, the heat treatable 6XXX Al–Mg–Si and 7XXX Al–Mg–Zn systems [16] are some of the most widely advanced and used alloys. The AA6061 class have been extensively employed in marine frames, pipelines, storage tanks and aircrafts [18]. On the other hand, the AA7050 alloy is widely used in the aerospace industry and is known to have an improved toughness and corrosion resistance when compared to other alloys from 7XXX series [19]. The strengthening of these alloys is achieved by producing hard nanosized Mg-rich precipitates via solution heat treatment, and subsequent artificial aging [20-22]. Although the AA6061 alloy can be joined by conventional fusion welding, the AA7050 alloy is considered to be “unweldable” by these methods [23]. However, multiple studies have demonstrated the effectiveness of friction stir welding (FSW) for the joining of the AA6061 [24-27] and the AA7050 [28, 29].

2. Materials and Methods

Butt friction stir welds were produced using 6 mm thick rolled plates of AA6061 and AA7050. The chemical composition for

both the materials is summarized in Table 1. The aluminum alloys were welded at three different tool rotational speeds ranges lie between 500 to 1000 rpm, while the welding transverse speed was fixed was lie between the 40-80 mm/min. The processing parameters was opted from the design expert software. The FSW of AA7050 and AA6061 Al-alloy was performed experiments using H13 tool steel of 6 mm diameter and 5.5 mm length of square pin with shoulder diameters of 19 mm. After the welding was completed, the top and bottom surfaces of the welded plates were machined down to a 3 mm of thickness. This was done to eliminate the stress raisers produced due to the flash material at the top of the weld.

Table 1: Chemical composition of Al-alloys

Material	Si	Cu	Fe	Zn	Mg	Cr	Ti	Al
AA6061	0.7	0.2	0.6	0.3	0.8	0.2	0.15	Bal.
AA7050	0.05	1.9	0.08	5.8	2.3	0.05	0.03	Bal.

Flash material is produced on top of the welded plates due to the direct interaction of the tool shoulder and the underneath material that is been extruded and stirred around the pin. Then, specimens for microstructural and mechanical characterization were cut perpendicular to the welding direction by milling cutter. Microstructural characterization of the welds was carried out using optical (OM) and scanning electron microscopy (SEM). The transverse and longitudinal sections of the welds were prepared as per ASTM E8 standard. Vickers microhardness measurements were performed in the transverse cross section of the FSWed samples. To characterize the mechanical properties of the welds, monotonic tensile testing was performed on the FSWed coupons at room temperature.

3. Results and discussions

3.1 Tensile strength

The tensile sub-test specimens were cut with the help of a milling machine as per ASTM E8 standard. A universal testing machine was used to perform these test at room temperature. Three test specimens were tested for each parameter and the average value have been taken as shown in table 2-4. The experimental results of tensile strength of the FSWed joint of AA6061 and AA7050 AA7050 are significantly varied when the TRS varies from 500 to 1000 pm. The maximum tensile strength of 269 MPa was observed at TRS 1000 rpm, TS 60 mm/min, while minimum tensile stress of 171.2 MPa was found at TRS of 500 rpm with a TS of 40 mm/min.

The maximum joint efficiency of 78.43% was observed at TRS of 1000 rpm, TS of 60 mm/min, and the minimum joint efficiency of 49.91% was found at TRS of 500 rpm with a TS of 40 mm/min because a lower TRS i.e. 500 rpm experience a lower temperature distribution along with poor stirring action by the square pin and observed inadequate consolidation of FSWed material by the tool shoulder [30]. Hence the minimum joint efficiency or lower tensile strength was observed.

Table 2: Tensile strength of FSW welded joint of AA6061 and AA7050

Processing Parameter		Tensile Strength (MPa)			Mean Tensile Strength MPa	Standard Deviation	Standard error	95% Confidence Interval	
TRS (rpm)	Traverse speed (mm/min)	Specimen 1	Specimen 2	Specimen 3				Minimum	Maximum
750	60	223.1	222.8	221.9	222.60	0.62	0.36	221.89	223.31
1000	80	250.2	252.4	250.8	251.13	1.14	0.66	249.85	252.42
500	40	172.2	170.5	170.8	171.17	0.91	0.52	170.14	172.19
500	80	199.2	196.8	197.6	197.87	1.22	0.71	196.48	199.25
500	60	191.1	190.2	189	190.10	1.05	0.61	188.91	191.29
750	40	211.4	210.4	211.2	211.00	0.53	0.31	210.40	211.60
750	80	239.3	237.6	238.6	238.50	0.85	0.49	237.53	239.47
1000	40	241.7	244.3	243	243.00	1.30	0.75	241.53	244.47
1000	60	267.8	269.2	270	269.00	1.11	0.64	267.74	270.26

Table 3: % Strain of FSW welded joint of AA6061 and AA7050

Processing Parameter		Strain (%)			Mean Strain	Standard Deviation	Standard error	95% Confidence Interval	
TRS (rpm)	Traverse speed (mm/min)	Specimen 1	Specimen 2	Specimen 3				Minimum	Maximum
750	60	17.3	16.2	16	16.50	0.70	0.40	15.71	17.29
1000	80	18.9	20.6	19.3	19.60	0.89	0.51	18.59	20.61
500	40	15.2	13.4	14.3	14.30	0.90	0.52	13.28	15.32
500	80	16.2	18	16.5	16.90	0.96	0.56	15.81	17.99
500	60	14.9	15.8	16.7	15.80	0.90	0.52	14.78	16.82
750	40	20	18.2	19.4	19.20	0.92	0.53	18.16	20.24
750	80	18.4	16.8	18.2	17.80	0.87	0.50	16.81	18.79
1000	40	18.6	17.2	18.5	18.10	0.78	0.45	17.22	18.98
1000	60	22.1	20.8	21.6	21.50	0.66	0.38	20.76	22.24

Table 4: Micro-hardness of FSW welded joint of AA6061 and AA7050

Processing Parameter		Hardness (HV)			Mean Hardness (HV)	Standard Deviation	Standard error	95% Confidence Interval	
TRS (rpm)	Traverse speed (mm/min)	Specimen 1	Specimen 2	Specimen 3				Minimum	Maximum
750	60	124	124.6	123.4	124.00	0.60	0.35	123.32	124.68
1000	80	132	129.8	131.2	131.00	1.11	0.64	129.74	132.26
500	40	114.5	113.5	114	114.00	0.50	0.29	113.43	114.57
500	80	119.8	120.2	120	120.00	0.20	0.12	119.77	120.23
500	60	122.6	123.2	123.2	123.00	0.35	0.20	122.61	123.39
750	40	110.8	109.2	110	110.00	0.80	0.46	109.09	110.91
750	80	134.6	135.2	135.2	135.00	0.35	0.20	134.61	135.39
1000	40	128.4	126.4	126.2	127.00	1.22	0.70	125.62	128.38
1000	60	128.2	127.2	128.6	128.00	0.72	0.42	127.18	128.82

When the TRS increased, the welded joint's heat input also increased, due to this a fine and equiaxed grain structure was observed which enhanced the mechanical properties. when the TRS increases from 1000 rpm it may experience as excessive stirred welded material on the top surfaces of the base plate, which causes the microvoids in the SZ. The increase in temperature as well as coarsening of grains and cooling rate at more than preferred temperature may decrease the tensile strength of the FSWed joints at high TRS. Some defects were also observed while the material flow around the AS of the weldment [31]. The percentage strain of the welded joint at 500 rpm was lower than 1000 rpm. The tensile stress-strain diagram of welded joints with different processing parameters was shown in fig. 2. At low TRS, the frictional heat that

observed from the rotating tool and the base plate will not have produced adequate plasticized flow, leading to a defects in the FSWed joints., whereas at low TS, frictional heat produced high temperature in the welded region then have a possibility of excess heat flow in the FSWed joint due to this defects were observed in the welded region. Standard deviation, standard error and 95% confidence interval were investigated for FSWed joint of AA6061 and AA7050 as shown in tables 2-4. The confidence interval shows that the tensile stress increased when TRS increased. These values may be calculated as

$$\text{Standard deviation (SD)} = [\sum(Y_i - K)^2 / (M - 1)]^{1/2}$$

$$\text{Standard error (SE)} = \frac{\text{standard deviation}}{M^{1/2}}$$

Where M: Number of observations, and K: Mean

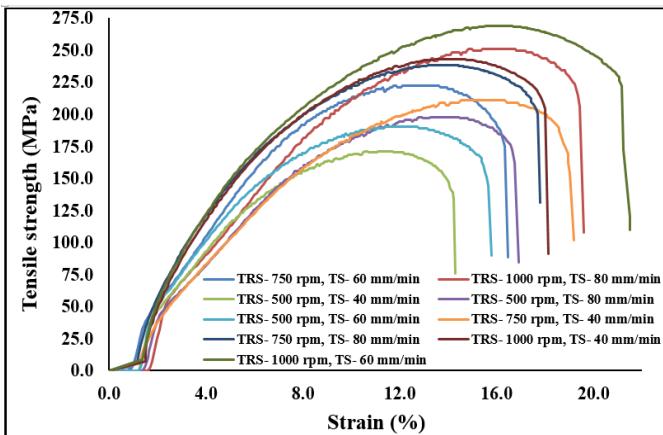


Figure 2: Comparison of stress-strain diagram of FSW welded joint of AA 6061 and AA7050 with different rotational speed

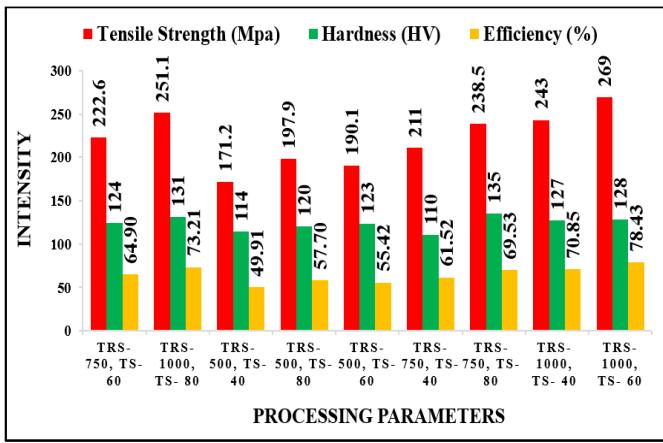


Figure 3: Variation of tensile strength and hardness to processing parameters FSWed joint of AA 6061 and AA7050

3.2 Microhardness

The microhardness directly affects by the dislocation density and phase dispersion microstructure. The micro-hardness values are less significant in affecting the mechanical properties of FSWed joint [32]. Due to the cooling rate, and solidification of FSWed joints, the hardness values at the bottom and the middle of the weldment observed the major effect. For recognizing the metallurgical phase, the hardness number plays a significant role. The maximum hardness value of 131 HV was found at TRS of 1000 rpm and TS of 80 mm/min, whereas the minimum hardness value of 110 HV was obtained at TRS of 750 rpm and TS of 40 mm/min as shown in fig. 3.

The hardness test was performed from 1st base metal (AA6061) to 2nd base metal (AA7050) included welded region. At each point, three hardness values were observed and mean value were taken. The hardness value at the SZ was higher than the TMAZ zone because very fine and equiaxed grains structure was observed at SZ. Due to coarsening of grains and precipitates in the HAZ, the lower hardness value was observed. Whereas due to dissolution of precipitate, the

decreasing trend of hardness was observed at TMAZ as shown in fig. 4 [33]. When the TRS increased, hardness value at the SZ also increased due to low heat concentration and fine microstructure [34].

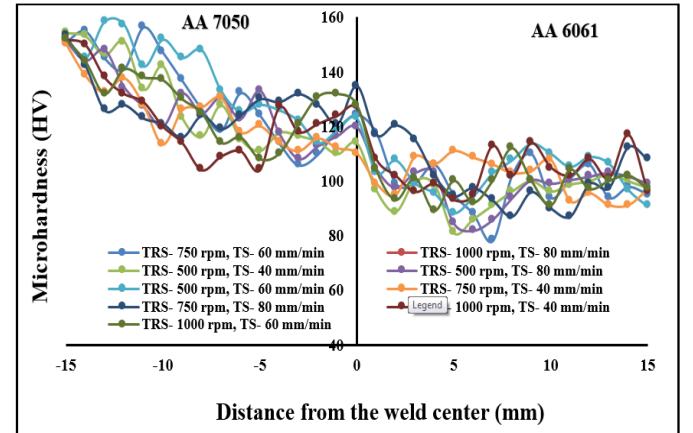
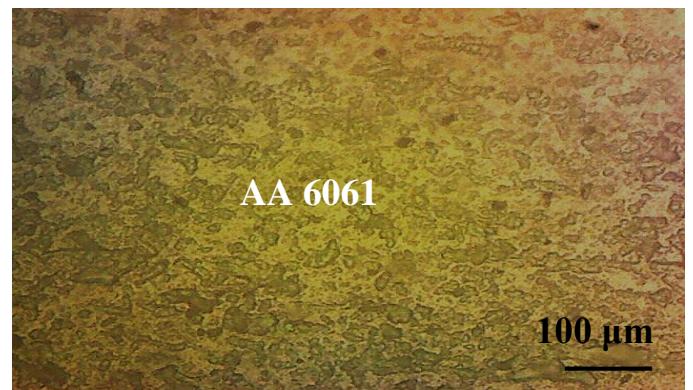


Figure 4: Distribution of micro-hardness of FSW welded joint of AA 6061 and AA7050 with different rotational speed

3.3 Microstructure analysis

The microstructure of FSWed joints of AA6061 and AA7050 were examined in details. FSW joint microstructure consists of parent metal (AA6061 and AA7050), HAZ, and TMAZ zones. The HAZ and TMAZ zone consisting of coarse grains structures. These structures changed depending on processing parameters of FSWed joint. A wide gap was observed between the grains structure when the microstructure at TRS of 500 rpm with different TS ranges from 40-80 mm/min was examined. Besides, When the microstructure at TRS of 750 rpm with different TS ranges from 40-80 mm/min was examined, less porosity occurred at the joining zones, and the base metal was observed better extruded to join. Whereas, when the microstructure at TRS of 1000 rpm with different TS was examined, it was observed fine and equiaxed grains structure in the SZ as shown in fig. 5-8.



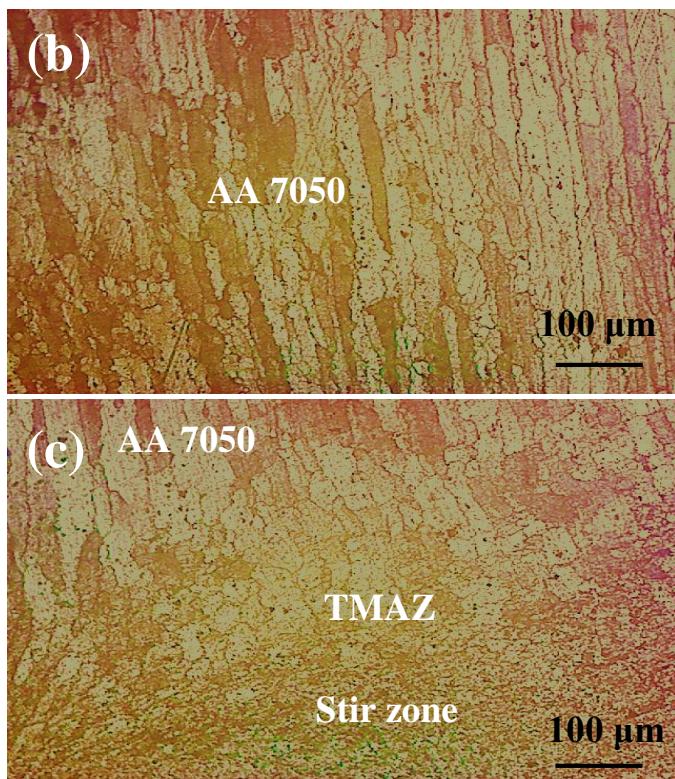


Figure 5: Optical images of base metal, (a) AA6061, (b) AA7050, (c) FSWed joint of AA 6061 and AA7050



Figure 6: Optical images of FSWed joint of AA6061 and AA7050 at TRS of 500 rpm, (a) 40 mm/min (b) 60 mm/min (c) 80 mm/min

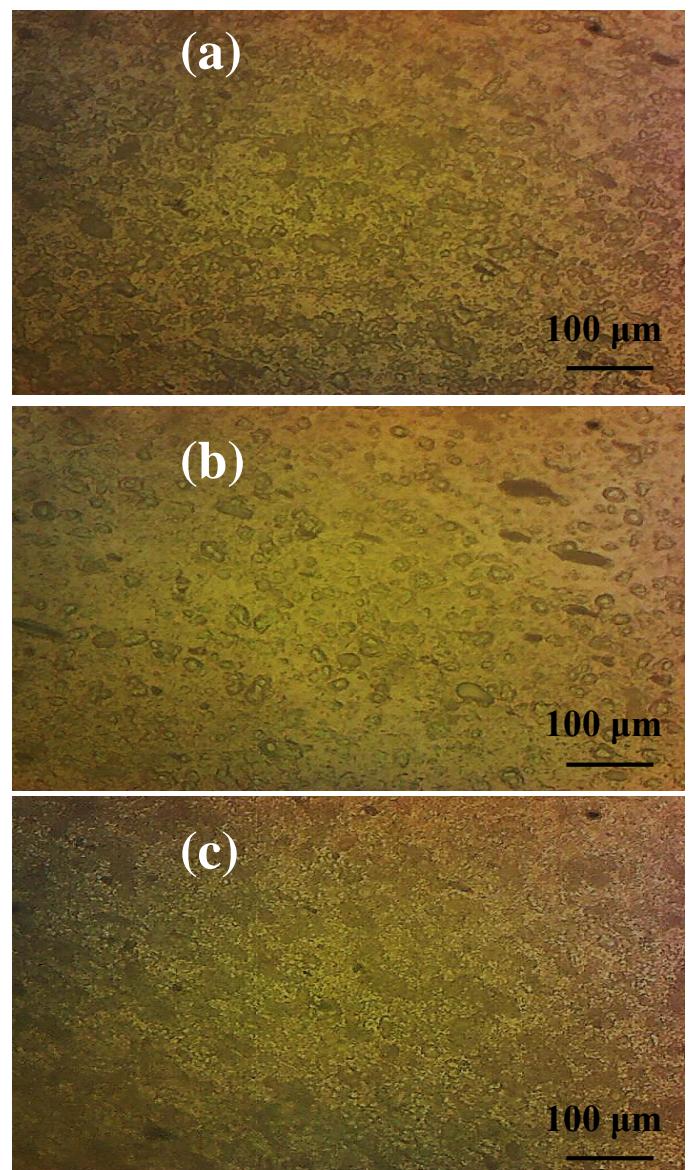


Figure 7: Optical images of FSWed joint of AA6061 and AA7050 at TRS of 750 rpm, (a) 40 mm/min (b) 60 mm/min (c) 80 mm/min

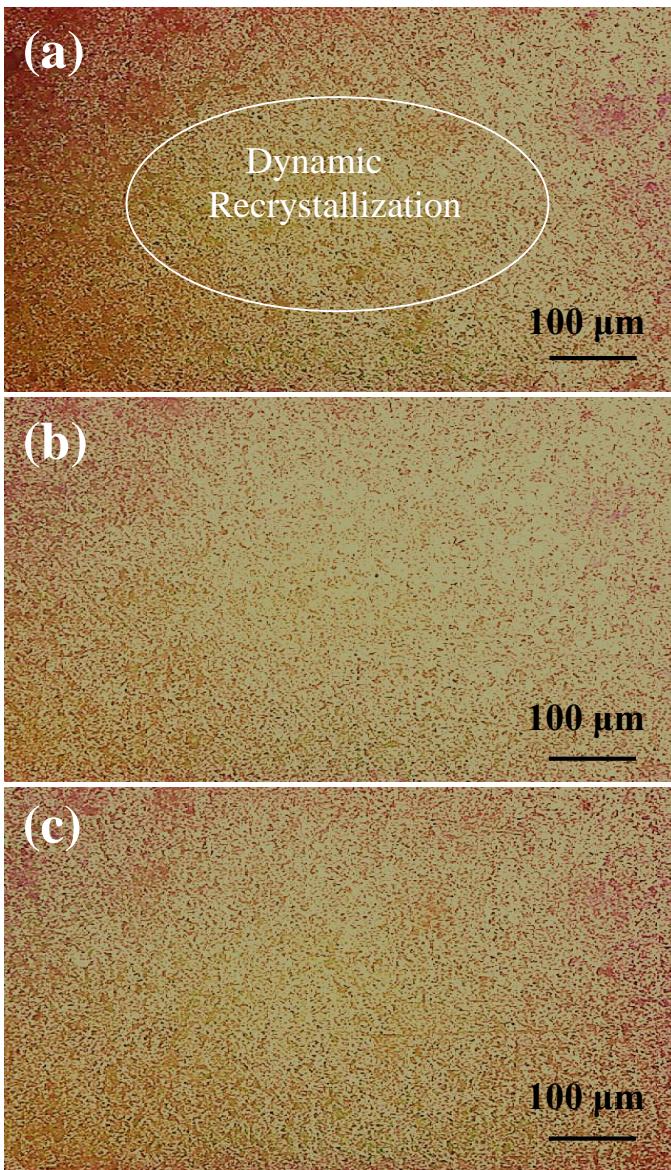


Figure 8: Optical images of FSWed joint of AA6061 and AA7050 at TRS of 1000 rpm, (a) 40 mm/min (b) 60 mm/min (c) 80 mm/min

That situation clearly showed that the grain size and amount of gaps between the grains decreased with increasing the TRS and TS. The increase of welding defects was predicted to be caused by insufficient plasticity temperature and a decrease in temperature [35]. The welding quality of samples at TRS of 1000 rpm with different TS were observed very well and occurred very less welding defect related to increasing TRS and TS. Fig. 6-8 shows the effect of TRS (500-1000 rpm) and TS (40-80 mm/min) on the microstructure of the FSWed joints of AA 6061 and AA7050. The temperature ranges at the SZ zone for all the specimens were observed 395-432°C but the thermocouple. It is reasonable to predict that the temperature in the SZ was greater than the TMAZ and HAZ region. At high TRS, the adequate frictional heat and extensive plastic deformation generate fine and recrystallized equiaxed grains in the SZ [36] as shown in fig. 8. The fine grain size was found at

TRS of 1000 rpm as compared to 500 and 750 rpm. The average grain size in the SZ was found as 10.8 μm at 1000 rpm, whereas 30.5 μm and 22.6 μm grain size were observed at TRS of 500 rpm and 750 rpm respectively.

3.4 Fractured surface analysis

The fractured specimen's high magnifications were investigated as shown in fig.9. When the tensile force was applied to the FSWed joints of AA6061 and AA7050, the stress concentration take place in the low strength region or part of the FSWed joints, and subsequently the FSWed joints were failed in that region [37, 38]. If the welded joints were defects free, the joints were failed on the A.S instead of R.S, which means the strength of R.S region is higher than the A.S region [39]. Fig. 9 clearly reveals that the large and deep dimples were observed at low TRS (500 rpm), while equiaxed tiny dimples were observed at high TRS (1000 rpm). This was the evidence of crack nucleation and growth 4 mm away from the weld line [40].

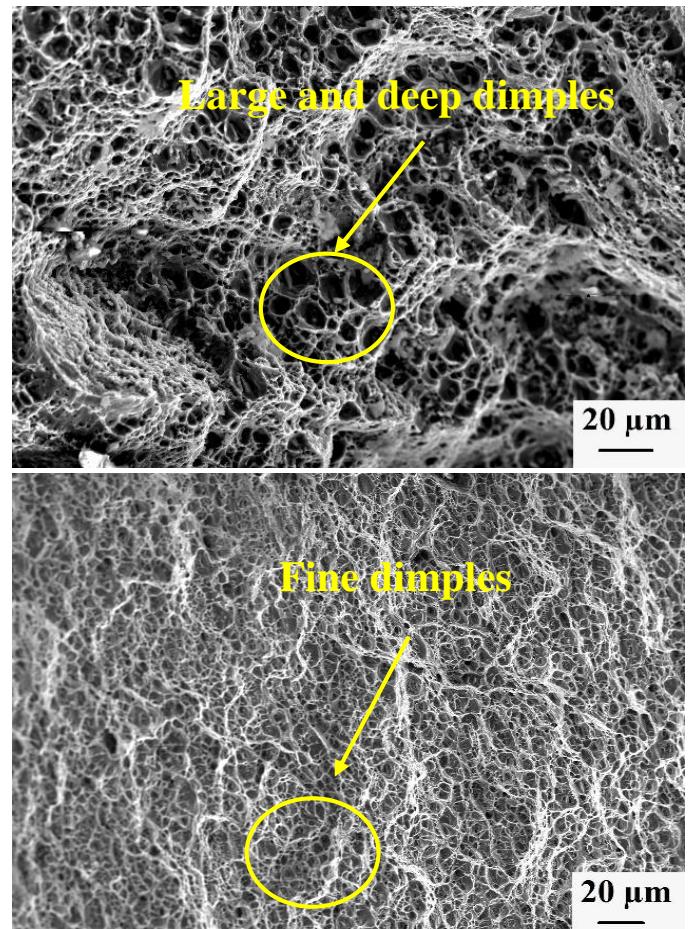


Figure 9: SEM images of tensile fractured specimen, (a) 500 rpm, (b) 1000 rpm

4. Conclusions

The study of FSWed joints of AA6061 and AA7050 was successfully analyzed and the following conclusions have been observed.

- The confidence interval has shown that tensile strength and hardness increased with increasing tool rotation.
- The maximum tensile strength and % strain at SZ is 269 MPa, and 21.5 HV at TRS of 1000 rpm, and TS of 60 mm/min.
- The maximum hardness at SZ was observed 135 HV at TRS of 750 rpm, and TS of 80 mm/min.
- The grains size in the SZ at higher tool rotation (1000 rpm) was much finer than the lower tool rotation (800 rpm).
- The FSWed portion at 500 rpm shows the big and deep dimples, while equiaxed fine dimples were observed at TRS of 1000 rpm.

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Cite this article as: Masood Saeed, Ubaid Khan, Mechanical characterization of friction stir welded joint of dissimilar aluminum alloys AA6061and AA7050, International journal of research in engineering and innovation (IJREI), vol 5, issue 5 (2021), 236-243. <https://doi.org/10.36037/IJREI.2021.5503>.

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