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Research Paper

Effects of Friction Stir Processing on Mechanical Properties of AA7075 Aluminum Alloy after Joining by Gas Tungsten Arc Welding

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Abstract
Friction stir processing (FSP) is a method of changing the properties of a metal through intense, localized plastic deformation. The influence of FSP on the mechanical properties of AA7075-T6 aluminum alloy welded by Gas Tungsten Arc Welding (GTAW) was investigated. The original and friction Stir-processed welds were assessed, and their microstructure and mechanical properties were compared. FSP was found to produce a great extent of refinement in microstructure accompany with uniformly distributed fine particles. Using FSP improved the mechanical properties of the welds, particularly those joined by GTAW, through grain refinement in the fusion zone (FZ). The FSP at 1600 rpm and 80 mm/min improved the elongation, tensile strength, and hardness of 7075-T6 aluminum alloy. FSP increased the tensile properties of 7075-T6 GTAW due to grain refinement of the weld zone by 14 percent. Elongation increased about 200 percent for the joint fabricated using WS of 80 mm per min and RS of 1600 rpm compared to unprocessed weld. Hardness decreased from 120 Hv to 60 Hv after welding and then increased to 90 Hv after FSP. Decreasing hardness attributed to welding heat effects, which increase after FSP, is related to grain refinement. This work showed that FSP is an effective method for improving the mechanical properties of fusion welds in 7075 Al-Zn alloy through microstructural modification.

Keywords
FSP, TIG, Grain Refinement, 7075-T6 Aluminum Alloy, Micro-Hardness, Elongation, Ultimate Tensile Strength, Yield Strength

1. Introduction

Good strength-to-weight ratio and natural aging behavior in 7075 aluminum alloy paved the way for the wide use of this alloy in the aircraft and automobile manufacturing industries. The presence of MgZn2 and Al2CuMg precipitate phases makes this alloy very strong. [1-2]. Welding of aluminum alloys is widely used for fabricating structural constructions; however, applying conventional welding methods for welding aluminum 7075 has always troubled designers and technologists. Friction stir welding and processing have proved their capability to improve the properties of joining materials [3]. Gas Tungsten Arc Welding (GTAW) is a popular welding process for aluminum alloys due to its high-quality, more effortless operation, and no need for wire feeding. The GTAW process is immaculate, preventing the atmosphere from polluting aluminum. Past research on structural aluminum alloys showed lower mechanical properties in fusion welds concerning base-metal (BM), which mainly is related to various welding defects such as hot or solidification cracks, segregation, voids and porosity, distortion, and persistent oxide layer, which are related to the melting and following solidification [4]. Friction stir processing of aluminum alloys can boost the modification effect on material properties by incorporating suitable particles [5]. Heat effects on the welding of heat-treatable alloys cause more problems due to softening and phase transformations induced in the alloy [6].

FSP can modify GTA welds' mechanical and microstructural properties by affecting grain size and precipitation strengthening mechanisms at the arc weld nugget [7, 8]. FSP on a Fusion weld of 304L stainless steel has improved mechanical properties by breaking large columnar grains and continuous ferrite, as well as the uniform distribution of ferrite in a fine-grained austenitic matrix [9]. Corrosion and fatigue resistance of FSP welds has increased by FSP through uniform distribution of precipitate and grain refinement [10].

Mechanical and microstructural properties of weldments might be improved by covering the arc weld bead or inducing compressive stresses at the weld zone by shot peening or surface rolling, current pulsing, and magnetic arc oscillating [11]. Still, these methods are expensive and need long operation times. FSP has more straightforward applicability and better economic aspects for improving the mechanical and microstructural properties of Al–Zn alloy fusion welds by modifying the weld microstructure. Friction stir welding and aluminum alloy processing have been surveyed and compared by Kumar et al. [12]. In FSP, a rotating tool with a specific design is pressed into the surface of a workpiece and transfers along a determined direction. Input mechanical energy by tool rotation and compressive stress induced severe plastic deformation and heat input due to friction between the tool and the matrix. After FSP, the stirred zone (SZ) homogenized, and its microstructure was significantly refined [13]. In FSP and FSW, the deformation of materials occurs in the solid state without melting, but in FSP, there is no contact line or interface. FSP has focused on modification of the microstructure and mechanical properties of Al, Mg, Cu, Ni, and Fe based alloy systems [6]. The main parameters affecting frictional heat and plastic deformation flow during the FSP process are the Rotational Speed (RS), the traverse or Welding Speed (WS), and the tool alloy and design [7].

Applying FSP to GTA welds improves the microstructure and mechanical properties of the weld structure. This work showed the FSP effects on microstructural changes of 7075-T6 aluminum alloy joined by GTAW. This work showed that FSP is an effective technique for modifying microstructure and improving mechanical properties in the fusion weld zone of aluminum–zinc alloy.

2. Experimental Procedure

The mechanical properties and chemical composition of Al7075 base metal and Al4043 filler metal are presented in Tables 1 and 2, respectively.

Table 1. Chemical composition of aluminum 7075 and 4043AA Filler metal

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
7075-T6	0.4	0.5	1.2 - 2.0	0.3	2.1 - 2.9	0.18 - 0.28	0.05	5.1 - 6.1	0.2	Bal
AA4043	5.2	0.8	0.25	0.05	0.05	-	-	-	-	Bal

Table 2. Mechanical properties of the base metal and filler

Mechanical properties	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
7075-T6 base metal	450	515	11.06
AA4043 filler	140	210	7

Rolled plates of 5 mm thick were machined to dimensions of 150 mm × 75 mm pieces. The thickness of 5 mm was selected to provide suitable weld penetration and proper welding Figure 1.

Figure 1. Preparing spacemen for GTA welding

GTA welds were performed on 5-mm-thick 7075-T6 Al plates with manual GTAW by Mastering ACDE machine. Welds operated at 160 amps, 27 V, and a WS of 125mm/min with butt joint configuration (150 mm _ 150 mm) and a welding direction perpendicular to the rolling direction of the base metal. Before FSP, the root and reinforcement of welded samples were machined to provide a flat surface—the top surface of welds, friction stir processed by a commercially vertical milling machine Figure 2.

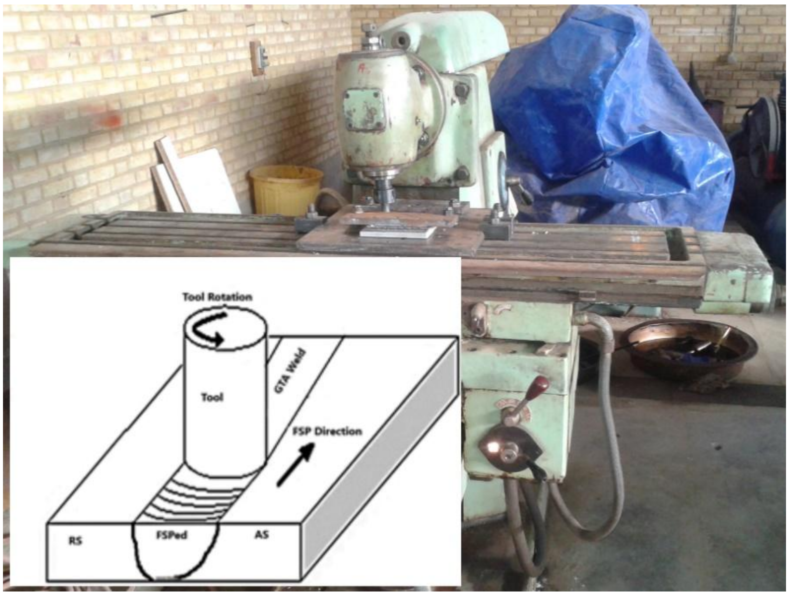

Figure 2. Vertical milling machine and schematic drawing of FSP

Then, these plates were subjected to single passes FSP at three different traverse Speeds, 40, 60, and 80 mm/min, nominally called WS, and three tool RS of 1000, 1250, and 1600 rpm. A hardened high carbon steel tool with a 13-mm Shoulder Diameter (SD) and a 4.5-mm-length conical Pin Diameter (PD) (5.5-mm-diameter tapering to 4.5 mm), as shown in Figure 3, was used to perform FSP. According to ASTM B557, the standard tensile specimens were prepared by a power hacksaw machine from unprocessed and friction stir processed welds Figure 4.

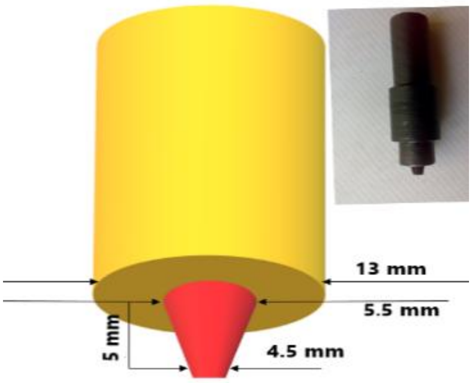

Figure 3. The FSP tool used in the present study

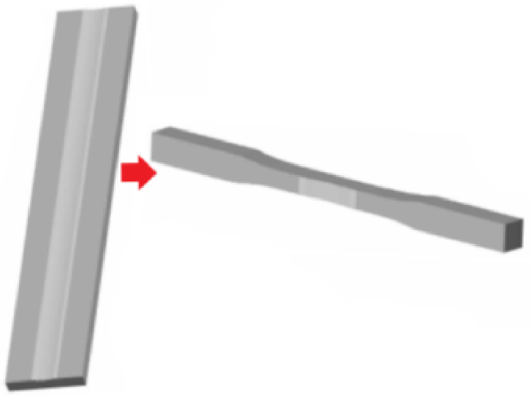

Figure 4. Configuration of Tensile specimens

A tensile test with a strain rate of 1×10^{-3} s $^{-1}$ on three samples was performed by the HOVNSFIELD HSDKS machine. Temperatures were measured using K-type thermocouples inserted in the plates at different locations at a constant distance from the center line. Polishing and etching sample surfaces performed a microstructural examination of sections cut from welds with Keller's reagent. Microstructure was observed using a scanning electron microscope (SEM). The results of Vickers micro-hardness with a load of 100 g and 10s of dwell time along a line perpendicular to the process line are shown in Table 3.

Table 3. Vickers micro-hardness of unprocessed weld and Friction stir processed joints

specimens	Vickers micro-hardness	specimens	Vickers micro-hardness
Unprocessed weld	60	FSP at 1250/60	70
FSP at 1000/40	68	FSP at 1250/80	80
FSP at 1000/60	70	FSP at 1600/40	75
FSP at 1000/80	80	FSP at 1600/60	70
FSP at 1250/40	60	FSP at 1600/80	90

3. Results and Discussion

3.1 Microstructure

In the present work, the 7075-aluminum alloy has been joined with the GTAW process with no macroscopic defects on top and lower welded surfaces, and then the weld top surface was subsequently processed by friction stir. Figure 5 represents the SZ's macrostructure of friction stir processed samples after the first pass with different WS and RS. As can be seen, the smoothest surface developed at RS of 1600 rpm and WS of 80 mm/min resulted in sufficient stirring during FSP. However, the FSP Surfaces of the other specimens have non-uniform and rough appearance that generally show inadequate temperature and plastic flow.

The combination of high RS and low WS caused considerable heat input and slow cooling rates in the SZ, affecting the properties and microstructure of the friction stir processed zone. Optimization and controlling of these parameters are of high importance for having suitable mechanical properties and defect-free joints.

Improper metal flow and insufficient forging in the FSP at low RS and high WS made joints susceptible to defects such as pinholes, tunnels, piping, and cracks. [14].

The microstructure of all joints at different zones was investigated. Generally, in Al–Zn–Mg–Cu alloys, two different precipitates will form, i.e., Mg2Zn and CuAl2. CuAl2 forms as fine precipitates, but Mg2Zn precipitates are coarse [4].

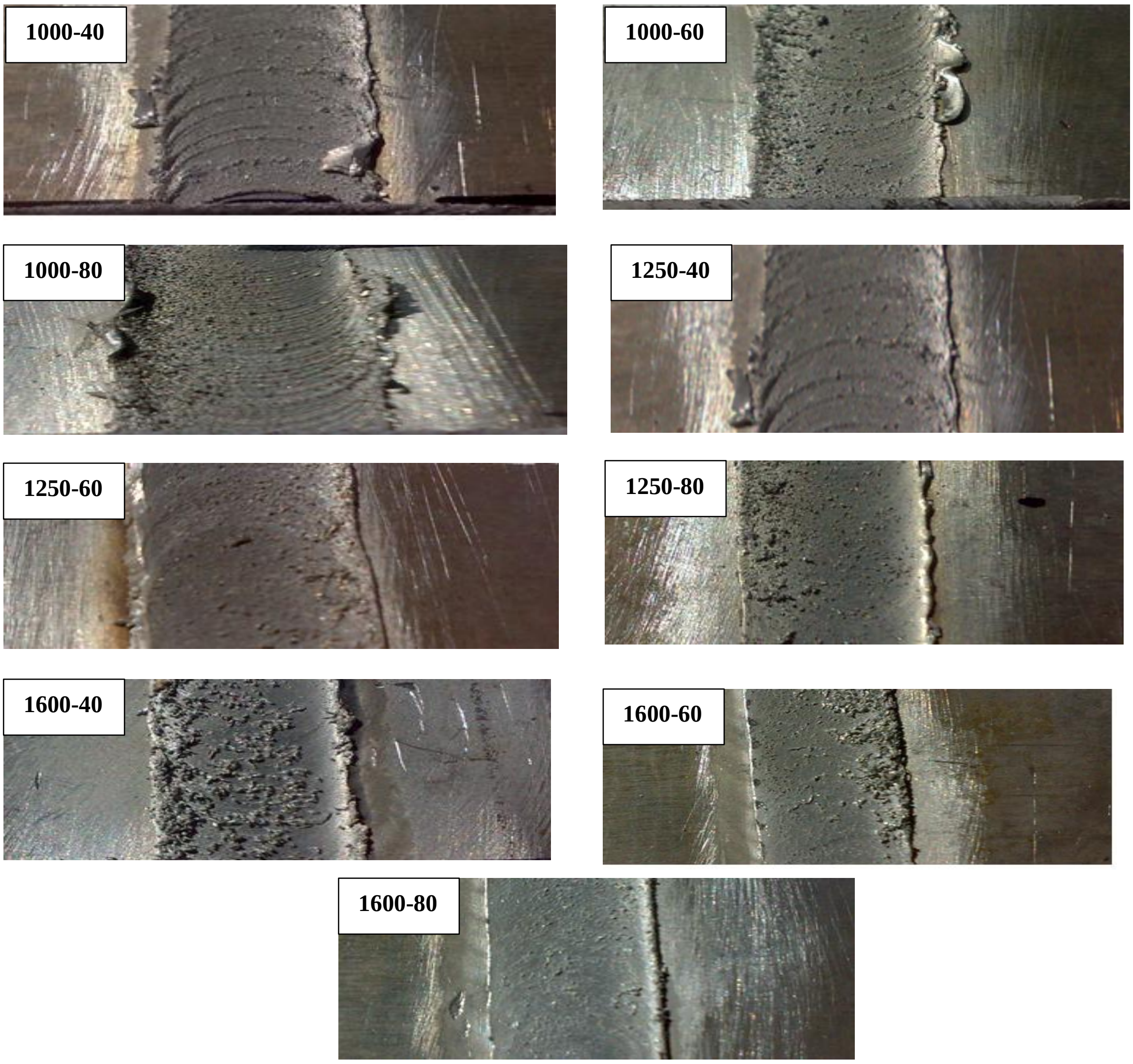

Figure 5. Optical micrographs of friction stir processed samples after the first pass with different RS and WS

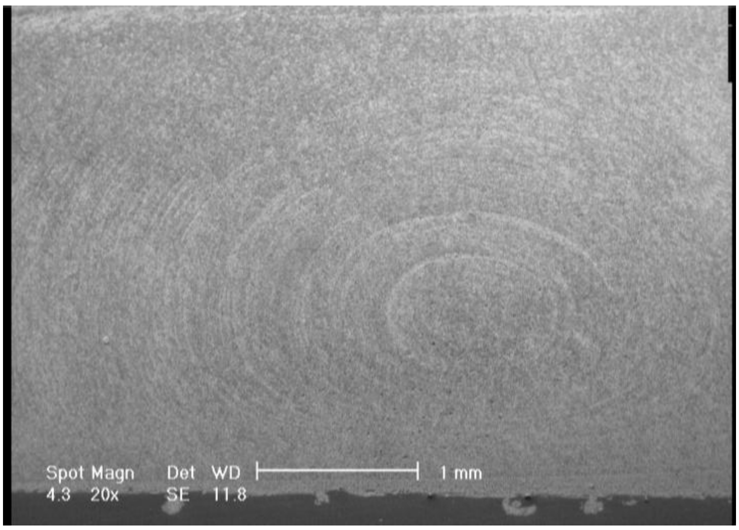

Figure 6. The elliptical 'onion' structure in the center weld

On the other hand, the classical elliptical 'onion' structure [15] was formed in the SZ of friction stir processed samples. The sample related to RS and WS of 1۴00 rpm and ۸0 mm/min showed an apparent elliptical 'onion' structure in the SZ accompanied by fine recrystallized grains (Figure 6). Figures 7 and 8 represent the microstructure of unprocessed weld and SZ in Friction stir processed welds. The microstructure of friction stir processed welds consists of fine and equiaxed grains. Figure 7 displays a few big grains in the weld microstructure of unprocessed weld, but after FSP on welds, very fine grains with uniformly distributed precipitate were generated in Figure 8. The SZ of aluminum alloy with severe plastic deformations in friction stir processed welds resulted in remarkably smaller and equiaxed grains in the microstructure. So, it can be suggested that FSP is a very effective method for FZ grain refinement. Focusing away from the weld center, the grains showed lower equiaxed orientation and remarkably bigger sizes.

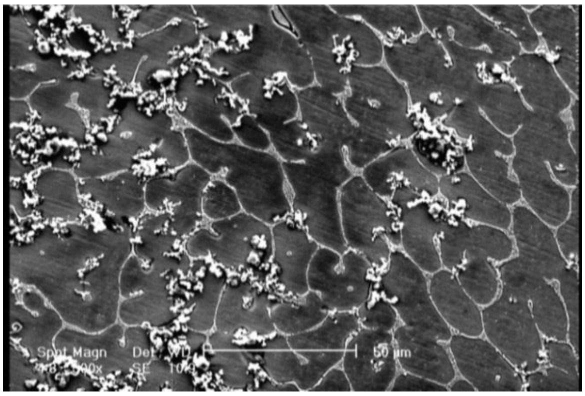

Figure 7. SEM micrographs of unprocessed weld

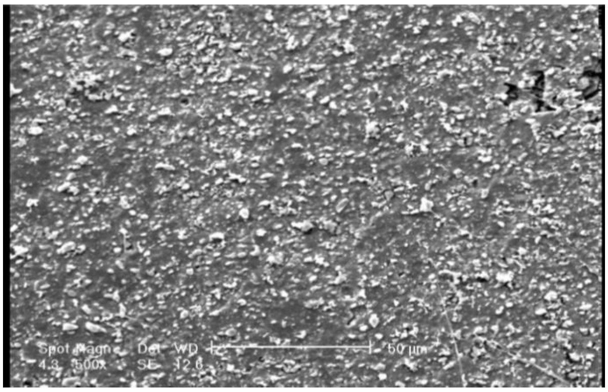

Figure 8. SEM micrographs of nugget zone in FSP weld

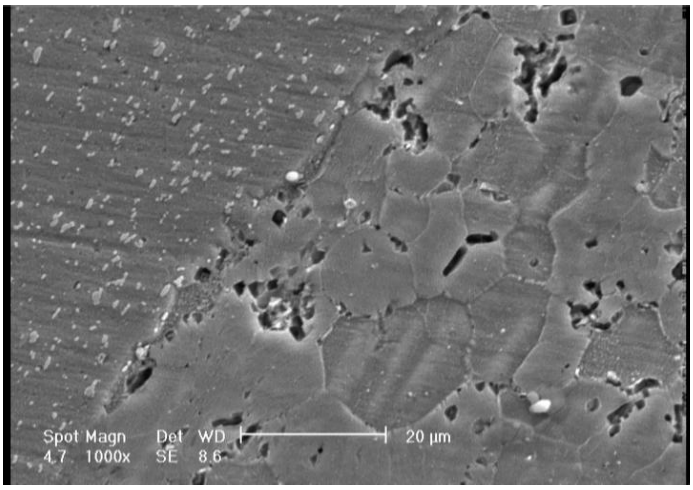

Figure 9. The microstructure of Stir zone (left) with small precipitates and HAZ (right) with bigger grains and precipitates

In particular, at a distance of 5 mm from the weld center related to the Heat Affected Zone (HAZ), raw material grains (Figure 9) and coarsened precipitates can be observed [13]. No obvious recrystallization appeared in the region adjacent to the SZ due to high cooling rate [16].

3.2 Mechanical properties

The results of micro-hardness tests on the unprocessed and friction stir processed weld joints at RS of 1600 rpm and WS of 80 mm/min are shown in Figure 10. According to test results, the hardness of raw material is approximately 120 VH. However, after welding the hardness of weld zone decreased to 60 VH due to welding heat and the lower hardness of filler material.

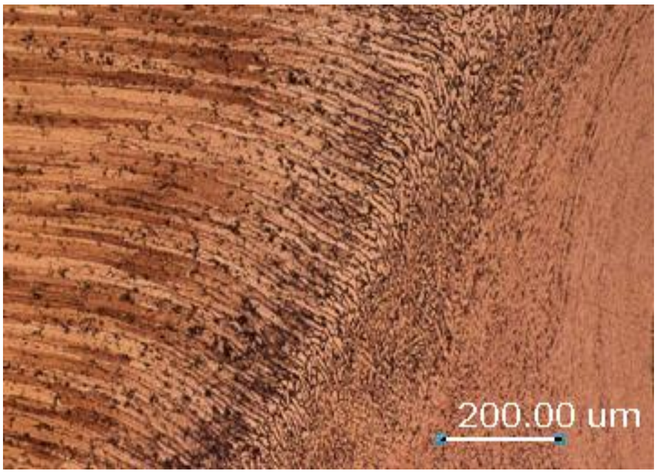

Figure 10. The deformed grains in the TMAZ

Low WS in the FSP at SZ results in higher heat input and temperature, more grain growth, and clustering of Mg2Zn precipitate but a slower cooling rate and lower hardness [16]. However, the results of the present work showed that the hardness level of the weld metal can be regained to some extent by FSP. In the friction stir processed joints, the hardness of weld metal has been increased up to 50% and reached 90 Hv at WS of 80 mm/min and RS of 1600 rpm. So, it can be suggested that Applying FSP can increase the weld metal hardness through grain refinement. In Rajakumar's works on 7075-T6 without previous welding, hardness was about 180 Hv, but all tests showed higher hardness, lower YS and YTS, and smaller grain size for the original sample [17]. The original sample had elongated grains with a mean grain size of 113 micrometers.

In our research, mechanical properties of unprocessed and friction stir processed joints, such as Yield Strength (YS), Ultimate Tensile Strength (UTS), and elongation, have been measured by related tests Table 4. Although YS, UTS, hardness, and grain size showed to change with FSP variables such as WS, RS, Axial Force (AF), Pin Diameter (PD), Shoulder Diameter (SD), Tool Hardness (TH), Tilt angle (TA) and Tool design, but in this study, we evaluated the influence of only WS and RS on the mechanical properties of welds. As the results showed, the strength of friction stir processed joints is influenced by WS and RS. It is also observed that the Friction stir processed joints showed better tensile properties than the unprocessed weld joints.

Table 4. Tensile properties of unprocessed weld and Friction stir processed joints

Mechanical properties	Ultimate tensile strength (MPa)	percentage of elongation
Unprocessed weld	280	2.16
FSP at 1000/40	186.4	4.25
FSP at 1000/60	197.8	4.531
FSP at 1000/80	234.4	5.81
FSP at 1250/40	190.6	4.375
FSP at 1250/60	227.1	5.75
FSP at 1250/80	265.1	6.44
FSP at 1600/40	247.7	6.59
FSP at 1600/60	242	5.13
FSP at 1600/80	320	6.56

The effect of WS on mechanical properties has been shown in Figure 11. Concerning WS, the Friction stir processed joints at a WS of 80 mm/min depicted better tensile properties at any tool RS than other joints. An interesting finding was that the samples' hardness, tensile strength, and elongation increased simultaneously by increasing the WS. This is in agreement with the findings of Rajakumar's Figure 12. Rajakumar, by FSP of Al7075 alloy without initial arc welding, showed that WS and RS can be optimized for optimum properties and defect-free samples (Figures12, 14) by grain size refinement. The best results were obtained at minimum grain size. It could be said that, like other variables, Increasing WS to some extent improves mechanical properties and decreases grain size, but it will break down.

The width of the softened area is narrowed, and the extent of total heat input and mechanical working effects on joint properties are weakened by increasing WS. In lower WS, both heat input and mechanical working were increased. Still, the impact of mechanical work on microstructure and properties is more potent than that of heat input, so dislocation pile-ups provide suitable conditions for dynamic recrystallization, and the grain size will decrease. At higher WS, even though heat input per length, mechanical deformation, and related times were increased, the heat has a more substantial effect than mechanical deformation on microstructure so that recrystallization will decrease and grain growth favored [Figures 11 and 12]. Then, it may be concluded that the tensile strength, yield strength, hardness, and elongation of friction stir processed as welded joints had a direct relationship with WS at the applied range. By increasing the WS from 40 to 80 mm/min, the grain size decreased while the strength and elongation percentage improved. At lower WS, the synergistic effect of higher heat input, grain growth, lower hardness, and reduced tensile strength of the friction stir processed joints.

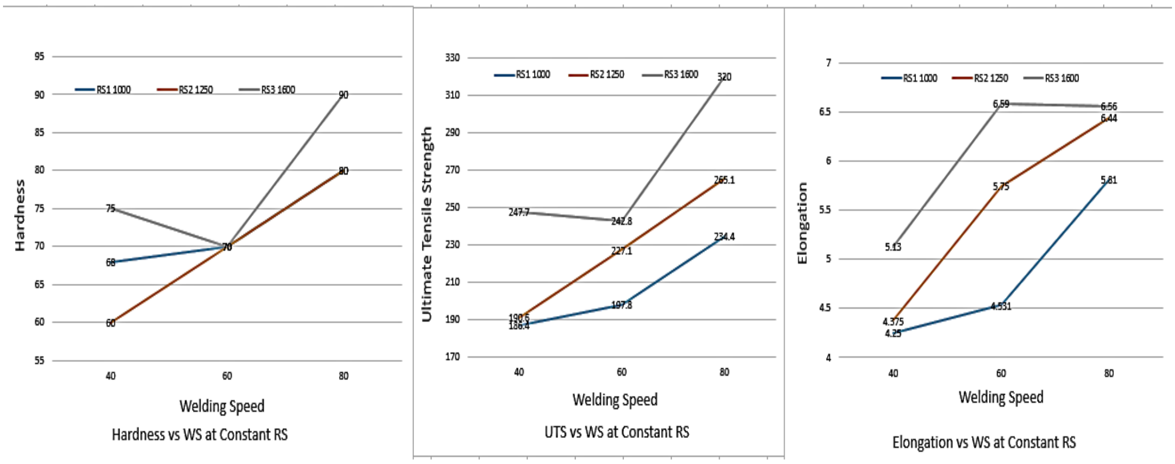

Figure 11. Welding Speed effect on mechanical properties at constant Rotational Speeds on 7075 Al Alloy joined by GTAW

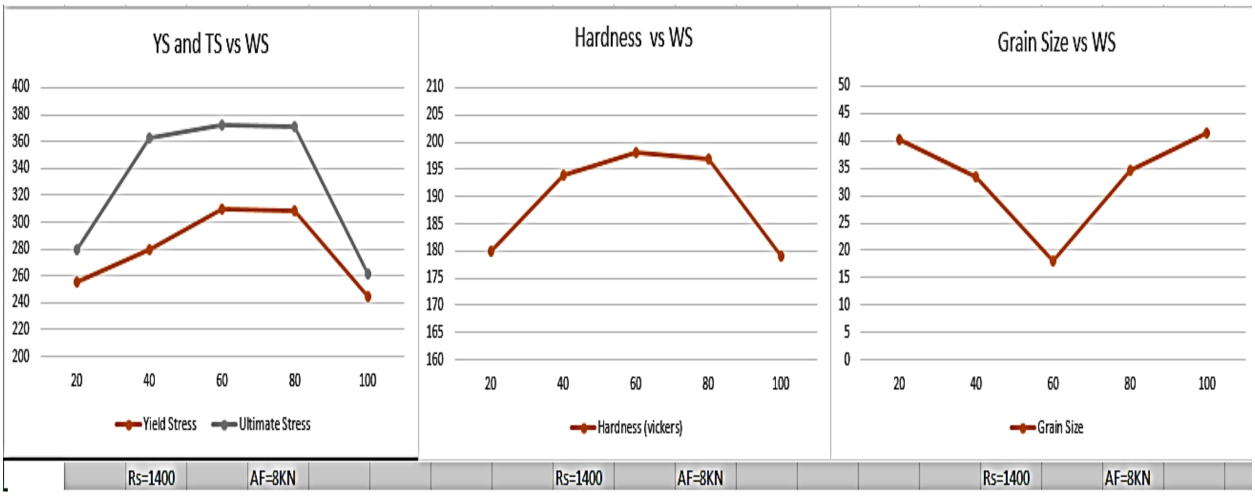

Figure 12. Welding Speed effect on mechanical properties at constant Rotational Speeds of 1400 based on Rajakumar et al. data on bulk 7075 Al Alloy

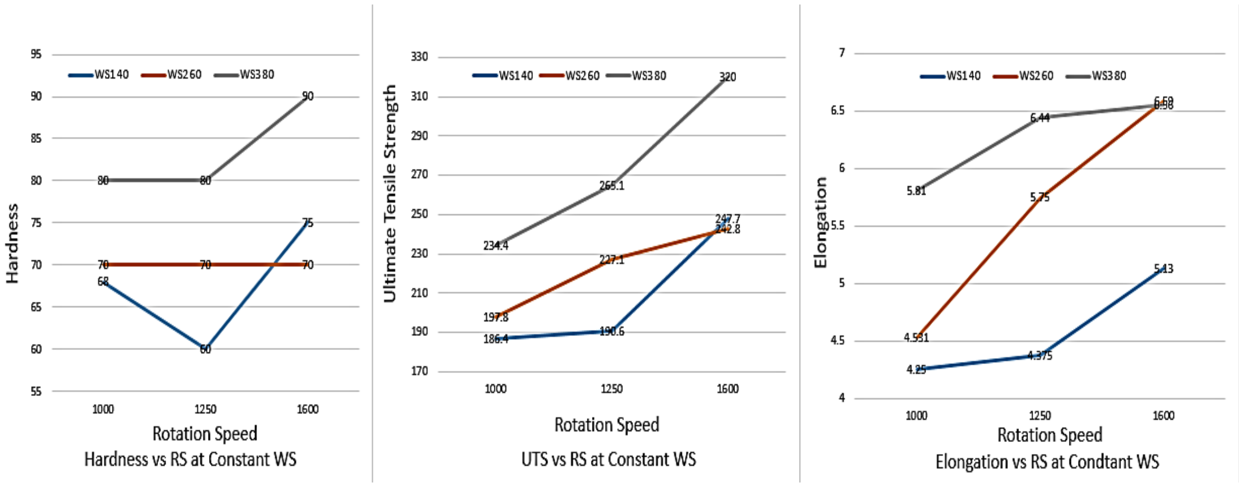

Figure 13. Rotational Speed effect on mechanical properties at constant Welding Speeds on 7075 Al Alloy joined by GTAW

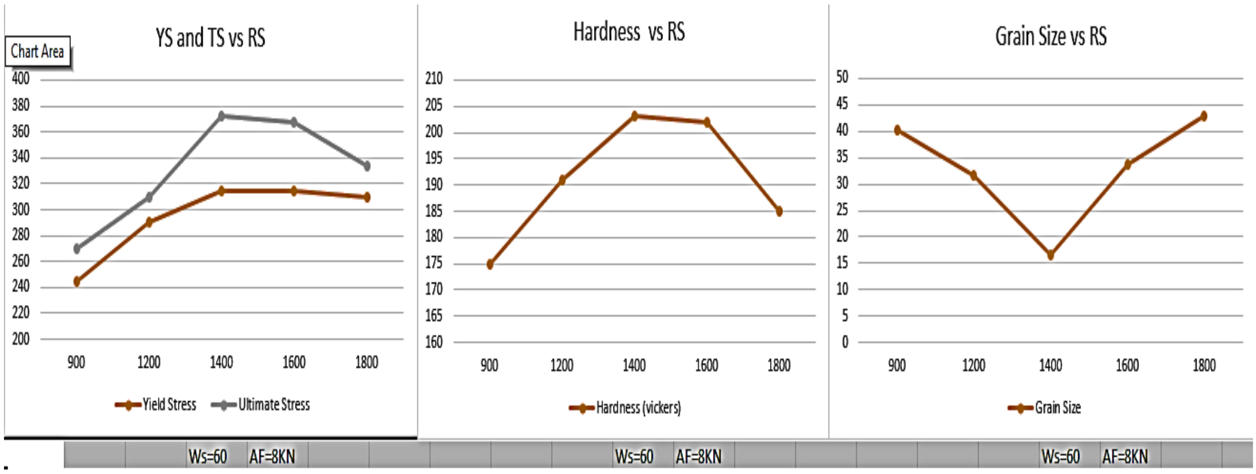

Figure 14. Rotational Speed effect on mechanical properties at constant Welding Speed of 60 based on Rajakumar data on bulk 7075 Al Alloy

The effect of RS on mechanical properties and grain size is shown in Figures 13 and 14. As the RS increased, the grain and particle size in the friction stir processed region decreased, leading to a high-strength friction stir processed area. Thus, the tool RS should be correctly optimized to reach a fined grain FSP region with uniformly distributed particles in the SZ. In Rajakumar's works on mechanical properties and grain size, RS and WS showed similar effects (Figures 12 and 14). Increasing RS makes a high and low pivot in mechanical properties and grain size.

The current study observed that at any WS, the FSP joint, which was carried out at an RS of 1000 rpm, showed the lowest elongation and UTS. In contrast, the joints processed at 1600 rpm depicted superior mechanical properties compared to other joints. It can be concluded that applying more enormous RS than 1600 and WS than 80 may destroy tensile properties and grain size. At RS lower than 1250 rpm and WS lower than 60 mm/min, the Hardness variation does not agree with Rajakumar's work and has a decreasing, increasing, or constant character.

Olga [18] reported that heat input increases in FSW while increasing the RS, and the maximum temperature remains almost constant. It has been reported that some of the produced heat by input mechanical energy is absorbed through the latent heat of the local melted area [17]. Inducing Local melt decreases the friction coefficient and subsequent generated heat input.

In other words, RS has two different effects: heat input and mechanical deformation. At higher RS, heat generated by friction and temperature reaches a constant and maximum value, and higher input mechanical energy induces a higher tendency for mechanical deformation, striation, and homogeneity. At high mechanical deformation or strain rate, the effect of mechanical deformation on grain refinement decreased and grain growth increased, but the relation between grain refinement and friction is unclear. Increasing grain size results in the weakening of the mechanical properties.

Elangovan [19] believed that higher tool RS generates higher heat and more forcing of stirred material to the upper surface, accompanied by lower hardness and coarse grains.

Tensile test results confirmed that the weld zone has the poorest mechanical properties; however, modification by FSP induces a 14 percent increase in tensile strength and a 205 percent increase in elongation for the unprocessed weld. Therefore, applying FSP can locally improve the strength and elongation of GTA welds.

Figure 13 shows that the elongation percentage increases with RS due to grain refinement, thus decreasing the brittleness of the weld nugget [20]. Generally, the tensile strength in FSP samples was less than the base metal, which was confirmed by breaking tensile specimens at the weld zone due to stronger heat effects and reduced dislocation density. Still, the tensile strength of the sample with RS of 1600 rpm and WS of 80 mm/min was higher than the GTA welded sample. Increasing WS and RS changed the effect of mechanical working on dynamic recrystallization and reduced the grain size to values with higher tensile strength. Further changes may be able to increase tensile strength and elongation. Dynamic recrystallization was optimum at distinct RS and WS, so providing suitable heat input and temperature accompanied by mechanical working makes the grain size minimum and elongation, hardness, tensile, and yield strength at maximum values. Higher temperature and heat input by high RS or Low WS may promote local deformation that produces onion structure. More mechanical working concentration on onion boundaries and less concentration on their inner spaces reduce overall grain refinement effects. So, at higher RS or lower WS, the grains became more significant, and mechanical properties related to grain size deteriorated.

4. Conclusions

This study investigated the microstructural modification to improve the mechanical properties of 7075-T6 GTAW weld joints by FSP. The significant findings are:

1. FSP increased the tensile properties of 7075-T6 GTAW due to grain refinement of the weld zone by 14 percent.
2. Both tool WS and tool RS significantly influence the microstructure and mechanical properties through dynamic recrystallization. Still, the best combination of these two parameters with the smallest grain size and maximum mechanical properties, such as tensile and yield stress, elongation, and hardness in every condition of FSP, must be found.
3. Among Friction stir processed joints, the joint fabricated using WS of 80 mm/min and RS of 1600 rpm exhibited maximum tensile strength, higher hardness, and finer grains.
4. Strengthening the unprocessed welds after FSP was attributed to solid solution, grain refinement, and precipitation strengthening.
5. Elongation increased about 200 percent for the joint fabricated using WS of 80 mm per min and RS of 1600 rpm compared to unprocessed weld.
6. Applying GTAW welding before FSP decreased hardness and involved the highest RS and WS necessary for reaching maximum hardness and minimum grain size at SZ compared to Rajakumar results without pre-weld joints.

7- Hardness decreased from 120 Hv to 60 Hv after welding and then increased to 90 Hv after FSP. Decreasing hardness is attributed to welding heat effects, and it increases after FSP is related to grain refinement.

8. Increasing the friction coefficient seems to change the character of mechanical deformation. At constant WS and lower RS, deformation uniformly occurs in very fine sub-layers. Still, at higher RS, only a few thicker layers slide due to easier sliding on paths with local melting. So, grains within these layers with less deformation have a chance to grow due to heat input, and overall grain size increases. Grain size is affected by dislocation generation through mechanical working and atomic movement. Dislocation generation and related stress fields favor recrystallization and fine grain

production, but atomic movement favors the climb and annihilation of dislocation and related stress fields and provides grain growth.

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