A Novel Approach for Improving Mechanical Properties in Friction Stir Butt Welded AA6061 Aluminum Plates by Using Preheat

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Abstract

In this paper, the effect of preheating on the mechanical properties and micro structure of similar friction stir welded AA 6061aluminum alloys sheets was investigated. Aluminum alloy 6061 sheets with a thickness of 5 mm and threaded cylindrical pins were used. Rotation and traverse speeds were 1200 rpm and 75 mm/min, respectively. The results of tensile tests performed on the welded samples showed that compared to the non-preheated samples, preheating had increased the strength and elongation of the joints by 58% and 46%, respectively. In the present study, during the welding process preheating cause emerged heat with lower slope from stir zone. This phenomenon may result in Increase the deformation resistance of material and consequently decrease of grain size. This grain refinement can improve the mechanical properties of welds. Accordingly, hardness and strength of the material will be increased.

Keywords

Friction stir welding, aluminum alloy, Preheating, Mechanical properties, microstructure

1. Introduction

FSW is a solid-state welding invented by Thomas et al[1,2] at TWI in 1991, but some problems were found with aluminum alloy welding, especially with 2000 and 7000 series [3-5] after a few years of much work performed on other aluminum alloys including 6000 series [6,7]. Due to sufficient amount of magnesium and silicon available for the production of magnesium silicide, this group of aluminum alloys is heat treatable. Since these alloys are used in architecture, transportation, and structures, many researches have been carried out on the optimization of their mechanical properties and welding parameters [9]. Investigating the corrosion behavior and fatigue of the joints [10, 11]; measuring the residual stresses in the joints [12]; and modeling the tensile behavior and the effect of welding parameters on the strength of the joint [13-15] are a number of activities performed by researchers on these alloys.

Although there are numerous reports on friction stir welding of 6000 series Al-alloy plates, most of these works concentrated on the determination and the effect of welding parameters on microstructural and mechanical characterization of the joints produced[16-19]. This implies that the different FSW process parameters of the welds lead to different material flow behavior such as rotational speed and traverse speed, thus influencing the microstructures and mechanical properties of the joint [20-22]. Therefore, there is still a need for further research on friction stir welding of AA6061 Al-alloy plates, particularly for works aiming at the determination of the ways to improve mechanical properties of the joints regardless of welding parameters. In this paper, AA 6061-T6 Al-Alloy plates were joined by friction stir welding using constant sets of weld parameters in 5 different temperatures. The correlation between preheating and mechanical properties on similar friction stir butt welded joints of aluminum alloy plates were investigated. The novelty of this work is employing the preheating for similar joint of aluminum sheets.

2. Experimental method

This experiment used commercially produced AA6061 aluminum alloy plates with a thickness of 5 mm cut to 100 mm by width 70 mm using wire cut. Specifications and chemical compositions of the experimental materials are listed in Table 1.

Table 1
Nominal chemical composition of welded material (wt. %)

Elements	Si	Fe	Cu	Mn	Ng	Zn	Cr	Ti	Al
AA6061	0.62	0.33	0.28	0.06	0.9	0.02	0.17	0.02	Bal.

A stirring tool with a M6 threaded cylindrical pin (its length being 4.8 mm) was used. The tool had a concave shoulder with a diameter of 18 mm. it was made of AISI H13 hot work steel and heat treated to a hardness of 52 HRC after machining to increase its wear resistance. The dimensions given in Table 2.

Table 2
Tool parameters

Material	Shoulder diameter [mm]	Pin diameter [mm]	R/r	Pin height [mm]	Pin length [mm]	Holder length [mm]
H13	18	6	3	18	4.8	50

The other details of the stirring tool used in this study are illustrated in Fig.1.

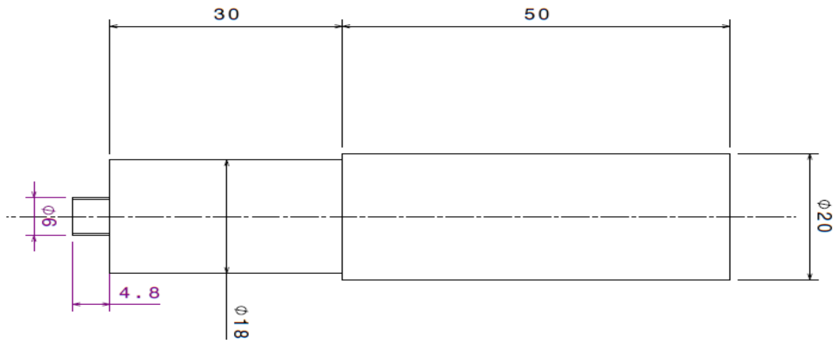


Fig.1 The tool dimensions

The welding trial were conducted using a universal CNC vertical machine with the usual clamping and steel backing-plate. The plates were joined perpendicular to the rolling direction.

All the joints produced using a rotation rate of 1200 rev/min and a traverse speed of 75 mm/min. and 3 degree for tilting angel of the stirring tool was employed.

The aim of this study was to investigate the effect of preheating on mechanical properties of the AA6061 aluminum alloy plates, joining of aluminum sheets was done by putting the samples in furnace at 75 and 125˚C. Then, a comparison was made with the joint at room temperature. Welding conditions of the aluminum sheets are given in Table 3.

Table 3
FSW parameters and tool dimensions used in this investigation

Process parameters	Values
Tool pin geometry	Threaded cylindrical pin
Tool rotational speed (rpm)	1200
Traverse speed (mm/min)	75
Tilt angle	3˚
Tool offset	0

A metallography specimen and three standard tensile test specimens according to ASTM E8/E8M-13a were extracted from each joint produced by wire cut technique. Tensile tests were conducted using a universal tensile test machine with a load capacity of 100 KN at a loading rate of 1mm/min. metallography specimens extracted from the joints were etched for 110 s using Keller's solution consisting of 150 mL distilled water, 3 mL HNO3, 6 mL HCL and 6 mL HF at room temperature. Detailed optical microscopy was carried out on these metallographic specimens for microstructural characterization. The Vickers hardness profile of the weld zone was measured on the cross section perpendicular to the welding direction using an indenter with a load of 100 gf for a dwell period of 20 s while data were taken from several locations in order to determine the hardness profile of each joint. The shape and dimensions of the tensile test specimen are shown in Fig.2.

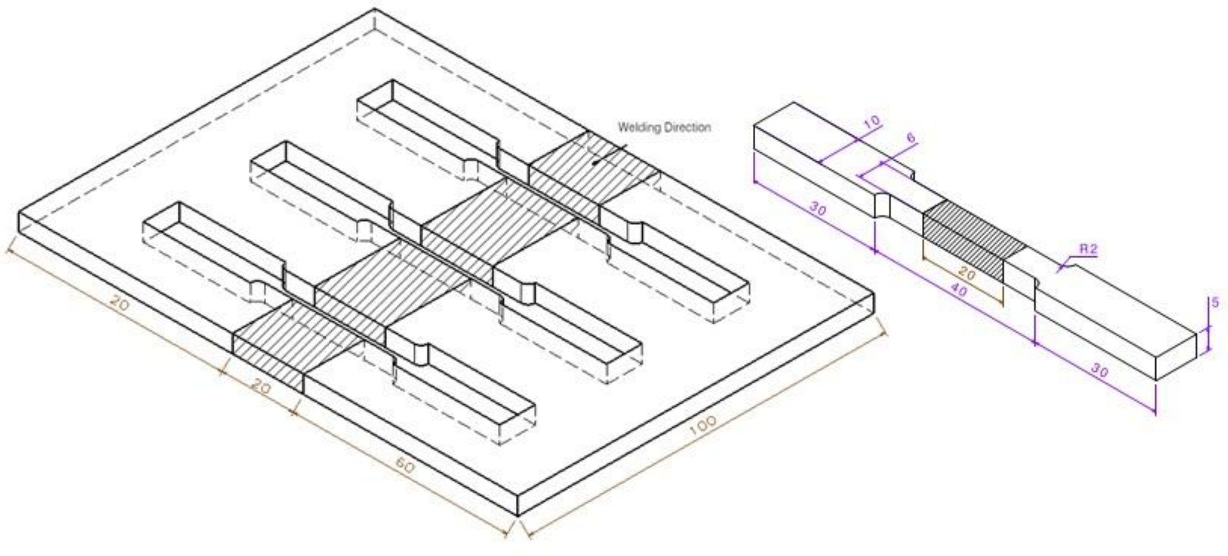


Fig. 2 Schematic view of tensile test specimens prepared from welded plates

3. Results and Discussion

3.1 Macrostructure and microstructure of the joints:

Optical micrographs showing the microstructures of the base plates and the macrographs illustrating the transverse cross-section of the joints produced are given in Fig 3 Respectively.

The weld surface without any kind of defect and onion ring structure is clearly observable. The nugget can be easily identified since the "onion-ring" structure is mainly visible on the center of the nugget (Fig.3). The material in this region had undergone the most severe plastic deformation during FSW.

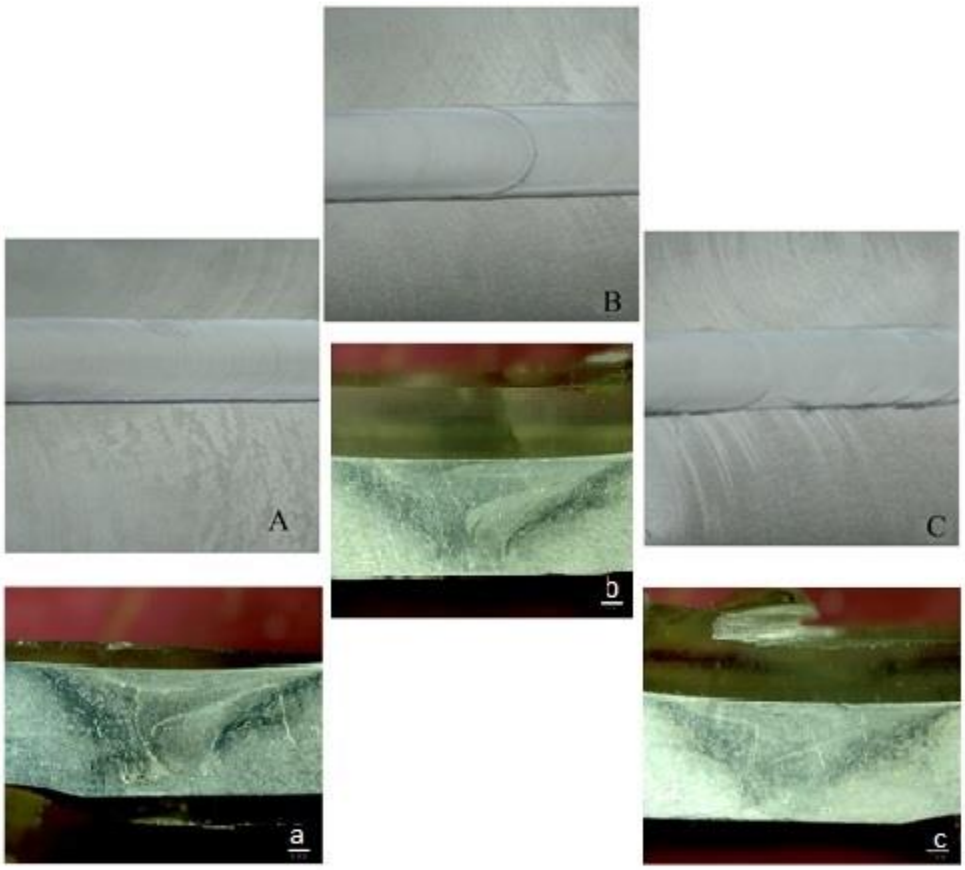


Fig3. Weld surface and the cross-section in different conditions of welding (a) room temp (b) 75 ˚C (c) 125 ˚C

Optical microscopy also revealed that no weld defect formation took place in the weld regions of the joints of AA6061-O plates, except the joint produced with a parameter set of 1200 rpm and 75 mm/min at room temperature. as seen from (Fig3-a) there is a weld defect in the lower part of this joint, which is believed to occur due to the insufficient plasticization of the alloy during joining resulting from the insufficient weld parameters. The worm holes in the bottom corner of the nugget suggest that the pin is not moving enough Material vertically (Fig3a). Further, the shoulder is letting material escape the tool before it can bring it around behind the pin. The heating of the aluminum definitely played a part in helping solve these defects. With the material already warm, the FSW tool is logically able to create more stirring (Fig3b, c). However, the defects in this particular experiment are believed to be effectively eliminated with the use of a different tool design. Heat input is therefore highest near the tool shoulder edge and zero at the center of the probe tip with the total heat input equal to the weld power.

FSW is a process in which the material deforms excessively thus leading to an evolution of fine grains and inhomogeneous grain size distribution across the cross-section. The plastic deformation is higher in some regions of the weld cross-section. i.e., in the shoulder zone.

It is also very common to study etched metallurgical cross-sections of friction stir Welds. There are four noticeable regions created by the FSW tool separated by how much heat and deformation the material was exposed to. In the center where the pin has Passed is the weld nugget, characterized by the greatest deformation and as a site of Recrystallization. Surrounding the nugget is the thermal mechanically affected zone (TMAZ), which contains grains of the original material in a deformed state. The third Layer, affected by the heat of the weld but lacking the deformation of the more central Zones, is referred to as the heat affected zone (HAZ), similar to conventional fusion Welding. Finally, the unaffected original material is often called the parent material or the unaffected zone; both names are relatively descriptive. Figure 4 shows the microstructure of the sample welded by friction stir method and preheated at 75 ˚C.

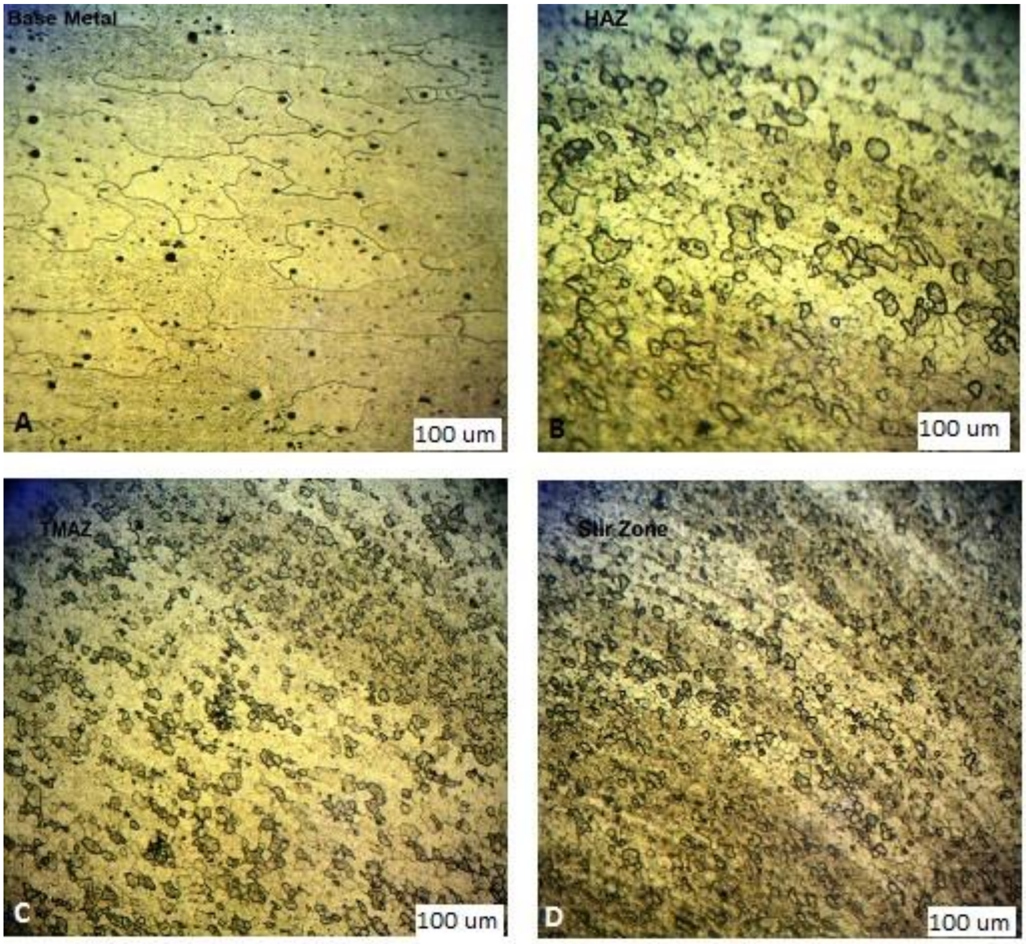


Fig4. Microstructure of aluminum 6061: a. BM, b. HAZ, c. TMAZ and d. SZ (welding condition of ω =1200 v =75 & preheated in 75 ˚C)

Three zones of 1.SZ, 2.TMAZ, and 3.HAZ are shown in this figure. The grain size in the stir zone has become greatly fine and homogenous compared with the base metal. This phenomenon results from the effect of recrystallization taking place following intense plastic deformation in this zone. The grains in the TMAZ zone enjoy special orientation elongated lengthwise in the boundary between the stir zone and the HAZ zone. The structure change in the boundary between the stir zone and TMAZ zone on the advancement side relative to the retreating side, has taken place at a faster pace. This fact shows the asymmetry present in the friction stir welding process. No specific change has also taken place in HAZ from the view of the grain size and it seems that only the size of the precipitations has coarsened a little.

It was also observed that the coarse precipitates existing in the microstructure of the base plate segregated to the boundaries of the abnormally grown grains and lined up along these boundaries (Fig 4-a). This can be attributed to the fact that if the driving force for grain growth is not high enough for the grain boundary to by-pass the existing particles and dissolve them, these particles tend to segregate to the grain boundaries [23].

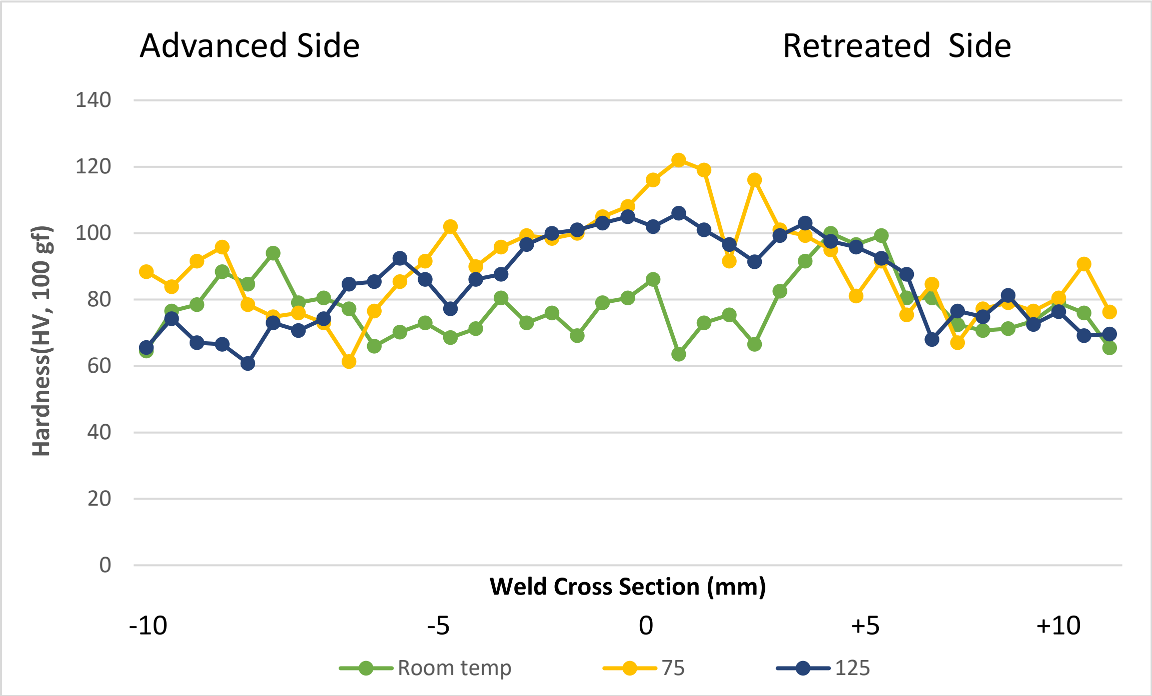
similar to this finding, it is also reported by several researchers that the grains evolving during hot working of materials tend to be corrugated when the density of dislocations entering the grain boundaries exceeds their absorption capacity or when the process of lattice dislocation absorption requires an incubation time(requires long time)[24].

3.2 Hardness:

The most important phenomenon in FSW process reducing the size of the grains and increasing the rate of strength and hardness at the weld section is the crystallization process. The welding process in aluminum alloys has been precipitation hardened resulting in the softening of the zone around the weld center and in the reduction of the hardness in these zones relative to the base metal. Hardness changes in these types of alloys are greatly dependent on temperature changes during the process. An increase in temperature results in the dissolution and/or growth of precipitations in different zones of the weld affecting the microstructure and mechanical properties of the joints. Figure 5 shows the hardness profiles obtained from all the joints produced. The joints produced in the different temper conditions exhibit different hardness values in the weld region, namely hardness increase and hardness loss, respectively. This is due to the difference in their original microstructures prior to joining.

As seen from Fig5, there is a hardness increase in the weld regions of all the joints produced. Similar results were also reported for other age hardenable Al-alloy FS welded in O temper condition [25, 26]. The reason for this hardness increase is the fact that the as-received base material (O temper condition) was in the homogenized condition wherein all strengthening precipitates are dissolved, thus, the material has a low strength prior to joining and the grain refinement takes place in the stir zones of the joints produced in this temper condition.

As it is observed in Fig 5, hardness distribution in different points of the weld especially in the stir zone is affected by the HAZ heat in a heterogeneous manner. Heat treatment, mechanical properties, and hardness of the welded pieces are intensively affected by rate of distribution evenness of the precipitations, suitable size of the alloy hardening precipitations, grain size, and intermetallic compounds in aluminum alloys of capable of being heat treated. The grain size in the stir zone is finer than that in other zones like TMAZ and HAZ. This is believed to be due to the difference in the grain size within weld region resulting from different heat inputs involved.



Distance from weld center/mm

Fig. 5 Hardness profiles measured on cross-section of Al (ω = 1200 v = 75)

It is therefore expected that the hardness in the stir zone enjoys more values compared to those of the zones around it. Hardness loss in TMAZ and HAZ zones is also present due to coarseness and dissolution of precipitation particles due to high temperature and plastic deformation. Of course, due to the fact that temperature in the TMAZ zone has not increased sufficiently, the dynamic recrystallization has not taken place in this zone and as a result, it encounters the loss of the hardness value relative to that in the stir zone weld center. Also, the high rate of cooling in these zones leads to an acceleration in re-precipitation of the strengthening phases.

The reason for this(hardness loss) is the higher heat inputs(in 125˚C) involved in the joints produced resulting in a higher degree of precipitate dissolution and the difference in the amount of coarse particles in the weld zones of the joints produced in higher and lower heat inputs.

It is also well demonstrated that the hardness of the weld zone of friction stir welded joints is determined not only by the grain size but also by the volume percentage of precipitates and dislocation density in the weld zone [27, 28].

3.3 Tensile properties:

Table 4 gives the summary of the tensile test results obtained from all the joints produced, and Fig6 gives a column graphic summarizing average values of elongation and the tensile test results obtained. It can be seen that by an increase in the preheating temperature, the strength increases up to a maximum strength at 75˚C. The elongation data of the samples shows a significant growth with an increase in temperature. However, the preheating temperature must be perfectly monitored to obtain optimized mechanical properties, but it can be concluded that even at 125˚C which is a deviation from the optimized condition by the excessive heat in the weld, the strength of the joint is still higher than that at room temperature.

Table 4
Tensile tests Results obtained from experiments

Temperature condition		Aluminum 6061 joint			
		Specimen 1	Specimen 2	Specimen 3	**Average**
Room temperature	UTS (MPa)	90.7	85.7	76.5	**84**
	Elongation (%)	4.088	4.113	3.297	**3.83**
75° centigrade	UTS (MPa)	161	124.5	114.5	**133**
	Elongation (%)	7.84	4.863	4.158	**5.62**
125° centigrade	UTS (MPa)	102.6	97.8	88.3	**96**
	Elongation (%)	4.83	3.85	3.68	**4.12**

This results are in a good agreement with the hardness measurement conducted on these joints, which exhibited a hardness increase in the weld area as seen from Fig 5.

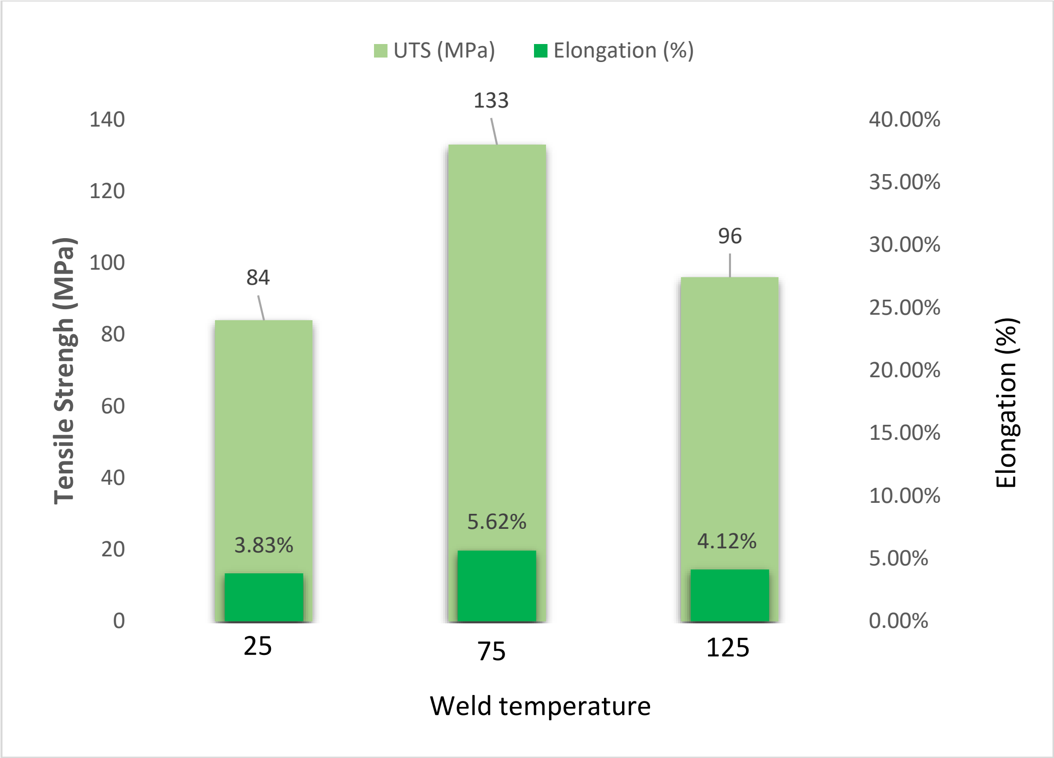


Fig 6. The results from strength and elongation of welded samples.

Precipitation hardening is one of the mechanisms cause increase the hardness and strength of the materials in which alloying elements combine with each other and form fine precipitates. These precipitates like as strong obstacles increase the deformation resistance of material. Accordingly, hardness and strength of the material will be increased. In the present study, intermetallic compounds and the precipitates are moved to the grain boundaries during the welding process. This phenomenon may result in locking of grain boundaries and consequently decrease of grain size. This grain refinement can improve the mechanical properties of welds. Locking of grain boundaries decreases the grain growth and grain boundary movement during the plastic deformation which in turn delays the occurrence of recrystallization. Moreover, in this condition, the recrystallization temperature is probably higher than the temperature at which the precipitates are formed. Another possible explanation during recrystallization process is that the amount of time which is not provided during the welding process is not considered. Driving force for precipitates to move to the metallurgical defects such as grain boundaries and prevent the grain growth during the welding process will be the result of Preheating of the specimens at 75 ^{o}C.

In this paper, preheating the AA6061-O aluminum alloys increased the strength of the joint by 58% compared to the joint strength at room temperature. This phenomenon can be related to a decrease in the temperature gradient between the weld joint and the base metal where the heat gets out of the nugget with a gentle gradient. On the other hand, preheating the samples makes more uniform structures in the alloy bringing about an increase in the strength and ductility simultaneously; while an increase in preheating improves mechanical properties. Excessive heat at the weld zone affects the mechanical properties of joints whether it is due to the higher rotational speed, the lower traverse speed, or a combination of the welding parameters [29]. A joint with the desired mechanical properties can be made by preheating and lower rotational speed or at higher linear speeds, i.e. higher welding processes. The results from experiments show that apart from strength, preheating can also increase the ductility of the joints. An impressive growth in elongation of similar aluminum joints by 46% proves this claim. In FSW, heat plays the main role in joining the joints. This is because it affects microstructure, internal strains, and material transferring as well as physical processes like heat transfer and temperature increase in the weld zone, so these factors affect the appearance and structure of the weld zone. The heat plays a significant role in welding the joints through its effects on residual stresses produced by different independent parameters [30].

However, the excessive heat in the weld joint reduces the strain rate and plastic deformation which are the main properties of FSW [31]. The results of microstructure change include grain size, grain boundary properties, solutioning, coarsening and a change in mechanical properties. To optimize the mechanical properties and monitoring the microstructure of the weld, good mechanical and thermal perception are needed.

4. Conclusion

In this study, the effect of preheating on the joints of AA6061-O aluminum alloy plates with a thickness of 5mm was investigated. After placing the samples in a furnace at 75 and 125˚C and comparing them with the joints at room temperature, the following results were obtained:

1. WFSW is a brand new method to change mechanical and metallurgical properties at joints, because the distribution of particles at the stir zone is an important goal which can be reached by the use of this process.

2. Preheating temperature causes a uniform temperature increase throughout the sample which apart from making more uniform microstructure; it can lower the difference between the stir zone and the base metal temperature bringing about better final mechanical properties.

3. Preheating must be perfectly monitored in WFSW to obtain optimized values; however, all the joints obtained in this research work showed significantly higher UTS and elongation after performing the preheating when compared with the sample prepared at room temperature.

4. Preheating the AA6061-O aluminum alloy increased the joint strength by 58% and elongation of the joint by 46% compared to the joint at room temperature.

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