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IMPROVEMENT OF HEAT AFFECTED ZONE OF GTAWed 5754 ALUMINUM ALLOY WITH FSP

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Highlights

- Defect-free weld seam with low heat input value
- Fine-grained micro structure in the heat-affected zone
- Eliminated welding brittleness and uniform hardness distribution
- Enhanced elongation for approximate ultimate tensile stress values
- Breaking in the base material instead of the weld seam

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ABSTRACT: In this study, post-weld friction stir processing (FSP) was applied to eliminate the grain coarsening disadvantages encountered in the heat-affected zone when joining AA5754 aluminum alloy with Gas Tungsten Arc Welding (GTAW). As a result of welding in two passes and with the low heat input by selecting the appropriate welding parameters, all welding seams were produced without macro defects. Despite all these precautions, grain coarsening has occurred in the Heat Affected Zone (HAZ), as expected. Significant amounts of grain refinement were detected as a result of the FSP applied to the regions with grain coarsening. Consequently, the grain refinement in the HAZ, the tensile strength increased slightly, in contrast with ductility has significantly increased (around from 6% to 19%). In the tensile tests, the rupture occurred in the HAZ in the GTAWed specimens, while the rupture occurred in the base material close to the HAZ in all FSPed specimens. In addition, the high hardness values of HAZ of the GTAWed samples were reduced to the base material hardness values in all FSPed samples, resulting in a more homogeneous hardness distribution.

Keywords: *AA5754, Gas Tungsten Arc Welding, Friction Stir Processing, Mechanical Properties, Microstructure*

1. INTRODUCTION

Energy consumption and air pollution are important problems to be overcome for today's automotive industry. The studies carried out for this purpose in literature especially focus on the development of vehicles that operate more efficiently [1-4]. Applications for the reduction in fuel consumption are generally aimed to reduce vehicle weight. This situation has led to the increasing use of aluminum alloys in the automotive industry in recent years, due to their high strength compared to their low density. However, there are very important problems in joining aluminum alloys with fusion welding methods. The fusion welding behavior of aluminum alloys differs significantly from conventional materials such as steel [5-6]. The properties that affect the weldability of aluminum alloys are high thermal conductivity, high solidification shrinkage, oxide formation on the surface, high coefficient of thermal expansion, the high solubility of hydrogen in the molten state, and relatively wide solidification-temperature ranges [7-9].

As it is well known, friction stir welding (FSW), which is one of the solid-state welding methods, is recommended by many researchers for welding these materials due to the limited weldability of aluminum alloys by arc welding methods [10-13]. However, this welding method requires special equipment depending on the base material being welded, and the shape and geometry of the part. In addition, the welding process becomes more difficult, especially as the materials having high thickness values. For this reason, the use of solid state welding methods such as FSW in industrial production applications is still very inadequate [14-16].

Due to these factors, traditional welding methods such as Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) are generally used for aluminum and its alloys, which have high power density and use inert gas as shielding gas atmosphere. In general, it has been reported by many researchers that coarse-grained microstructures occur in the fusion zone (FZ) and the heat-affected zone (HAZ) after the welding process is performed with arc welding methods [17-19]. Grain coarsening after welding is an important issue, especially for non-heat treatable aluminum alloys. For this reason, methods having higher

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energy density such as laser welding have been used to prevent coarse grain formation in the welding process of these alloys. However, even though this method that has a higher energy density is used, a dendritic grain structure is formed in the fusion zone increasing the risk of hot crack formation, although a finer grain structure can be obtained [20-22].

One of the most common methods used to prevent hot crack formation is preheating in the welding of aluminum and there are many studies in the literature. As given in these studies, preheating increases the risk of coarse grain formation. The coarse-grained structure formed in the weld zone adversely affects the strength of the weld joint as given above [23-25].

As it is well known, grain refinement significantly increases both the strength of the material (this is especially important at low temperatures) and its ductility. Therefore, in recent years, there have been many important commercial attempts at the development of fine-grained materials for various applications. In particular, controlling the grain refinement by processing is preferred instead of alloying due to being cheaper, simpler, and recycling advantages [26-27].

Welding wire manufacturers produce welding wire with a suitable chemical composition, taking into account the defects such as hot cracks, grain coarsening, etc. that may be encountered in the weld filler. However, only the use of welding wire is generally insufficient to prevent the formation of hot cracks [28-30]. Therefore, in aluminum fusion welding, it is preferred the pre-annealing treatment before the welding. The pre-annealing process used supports grain coarsening especially in the heat-affected zone (HAZ), making the grain coarsening problem in this region even more critical. Unfortunately, grain refiners in the welding wire have no effect on this grain coarsening in HAZ. Therefore, ensuring grain refinement in HAZ has critical importance in the fusion welding of aluminum alloys [31].

In this study, friction stir processing (FSP) application after welding is proposed to solve the grain coarsening in the HAZ that is encountered in joining aluminum alloys with arc welding. AA5754 aluminum alloy which is one of the most widely used alloys in the automotive industry was chosen for experimental studies. This alloy was joined with ER5356 welding wire without preheating by GTAW and then FSP was applied in the weld area for beneficial grain refinement.

2. EXPERIMENTAL DETAILS

2.1. Gas Tungsten Arc Welding

In the experimental studies, AA 5754 alloy, whose chemical composition is shown in Table 1 and mechanical properties are shown in Table 2, with a thickness of 5 mm was used. After the V-shaped welding groove was formed on the edge of the plates with dimensions of 200x100 mm, according to EN ISO 9692-3:2016 standard, the surfaces were degreased and welding processes were carried out using GTAW process. The used GTAW process parameters were given in Table 3. ER 5356 with a diameter of 1.2 mm, the chemical composition of which is presented in Table 1, was used as filler wire, and pure argon gas was also used as a shielding gas in the welding process, which was carried out in a total of two passes, on both surfaces.

Table 1. The chemical compositions of the base material and filler wire

	Si	Mg	Mn	Fe	Cr	Cu	Zn	Ti	Al
AA 5754	0.124	2.789	0.355	0.397	0.068	0.059	0.037	0.017	Balance
ER 5356	<0.25	5	0.3	<0.4	-	-	-	-	Balance

Table 2. The mechanical properties of the AA5754 alloy

	σ_{YS} (MPa)	σ_{UTS} (MPa)	Strain (%)
AA5754	112.2	208.8	15.8

Table 3. GTAW and FSP parameters

Parameter	
Welding current (A)	235
Welding speed (mm/min)	130
Shielding gas flow rate (L/min)	18
FSP tool rotation speed (rpm)	900
FSP tool travel speed (mm/min)	20
Tilt angle	2°

2.2. Friction stir processing

After the welding processes were completed, FSP was performed with predetermined process parameters (Table 3) on a plate while another plate was directly used as-welded for the testing. From now on, the sample names are referred to as GTAWed and GTAWed+FSPed for arc welded and friction stir processed following arc welding, respectively. FSP was carried out using hot work tool steel with AISI H13 (X40CrMoV5-1) material. Having a hardness of 55 HRC, the tool also has a cylindrical shoulder and a conical pin. The pin, which has a diameter of 5 mm at the bottom and 6 mm at the top, has also a 3 mm length. The FSP, having 0.33 overlapping ratio [32] is given in the Figure 1.

$$Overlap\ Ratio = 1 - \left[\frac{l}{d_{pin}}\right] \quad (1)$$

Where l designates the distance between pin axes in passes and d is the top diameter of the pin. In FSP, the tool was plunged 0.4 mm to welded sample and initial preheating was achieved by keeping the penetration speed constant at 1 mm/min.

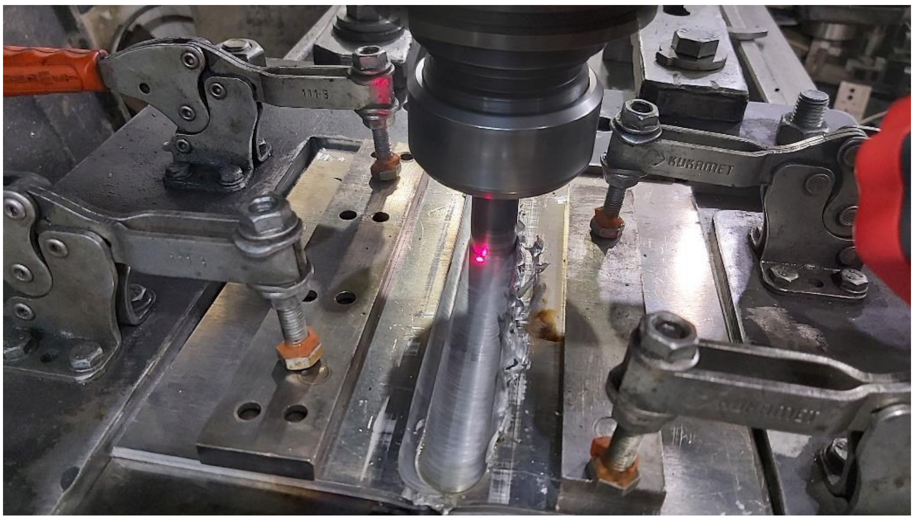

Figure 1. Friction stir processing of GTAWed AA5754

2.3 Microstructural Charactarization and Mechanical Testing

Tucker etchant (25 ml of water, 15 ml HF, 25 ml HCl, 15 ml HNO_3) was used for macro examinations and Keller etchant (50 ml of water, 10 ml HF, 15 ml HCl and 25 ml of HNO_3) was also used for micro examinations of the fabricated samples. In order to determine the hardness distribution of the samples, Vickers test examinations were carried out on the line with a depth of 2 mm from the surface. The tests carried out with a load of 200 grams were also repeated on the same line at 0.5 mm intervals. Tensile tests of the samples were also carried out at a testing speed of 1 mm/min.

3. RESULTS AND DISCUSSION

AA5754 aluminum alloy was first joined with ER5356 welding wire by GTAW without preheating. As a result of the macro examination carried out after the welding process, no macro defect was detected in the structure (Figure 2). The macrograph of the GTAWed+FSPed sample also shows the proper processing was performed via FSP. Any defects, such as wormhole and porosity which are particular with FSW/FSP were not observed.

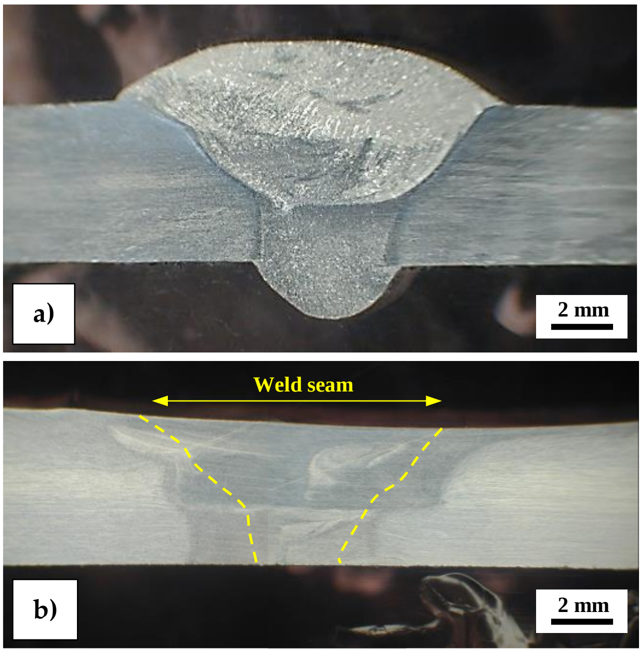

Figure 2. Cross-sectional macrographs of the samples; a) GTAWed sample, b) GTAWed+FSPed sample

It can be also seen that the HAZ is not relatively wide compared to the base material with high thermal conductivity. Keeping the HAZ narrow is ensured by the selected welding parameters (higher welding speed in addition to higher current and voltage values). A high increase in the heat input was prevented by selecting the current and voltage higher values, and by keeping the welding speed also higher. Thus, the 5mm thick plate was welded in two passes, trying to prevent the expansion of the HAZ. This welding process with a lower amount of heat input is also preferred to prevent grain coarsening in the FZ [33, 34].

Welding with low heat input, chosen to prevent grain coarsening, causes the formation of pores in the welding of aluminum alloys having high thermal conductivity. For this reason, the using heat input should be low enough not to cause grain coarsening, it should also has a value that will not cause porosities in the weld due to rapid solidification [35]. As can be seen from Figure 2, there was no porosity in the seam after the fusion welding process.

The metallographic examination of the weld seams was obtained after the welding process as can be seen in Figure 3. Although partial grain growth occurred in HAZ, this area could be kept narrower as much as possible. This is another important point that shows that the selected welding parameters are suitable for the process.

After the welding process, FSP was applied in order to obtain grain refinement in the weld zone. As can be seen in Figure 4, grain refinement has occurred in the coarse-grained weld seam and oriented-grained HAZ resulting from the FSP.

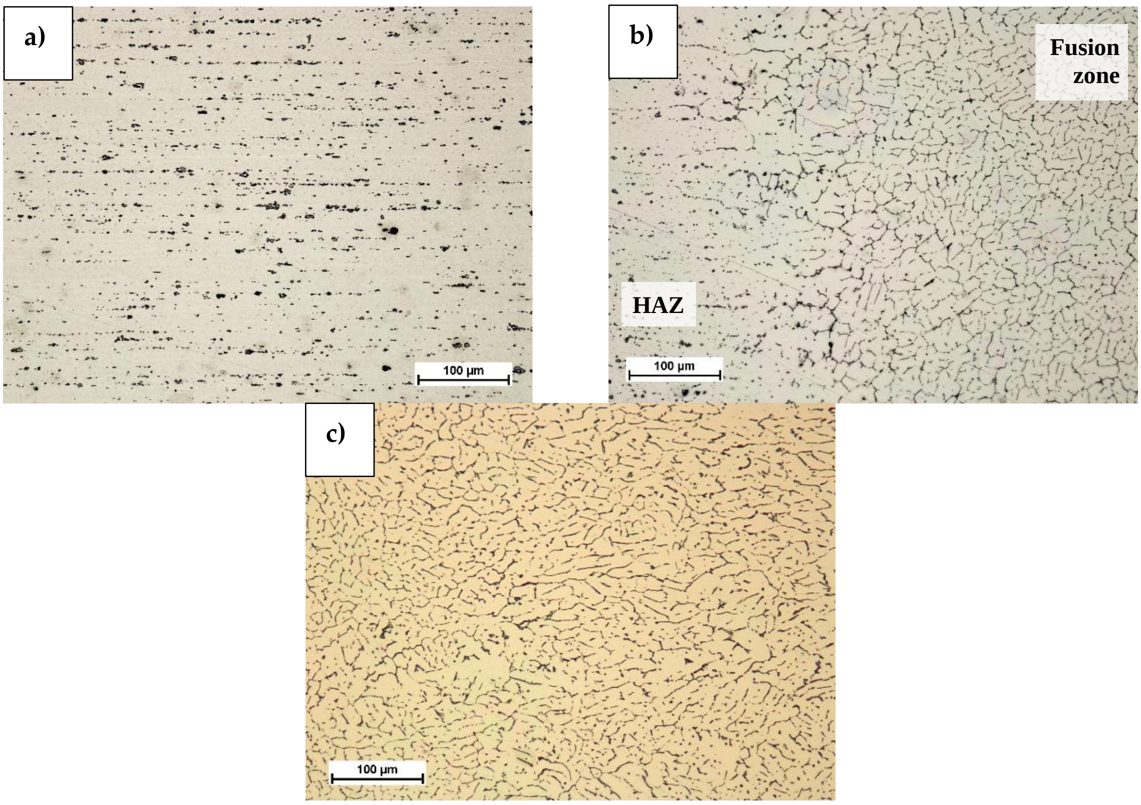

Figure 3. The microstructural zones of the GTAWed sample; a) Base material, b) Transition zone (weld metal-HAZ), c) Fusion zone

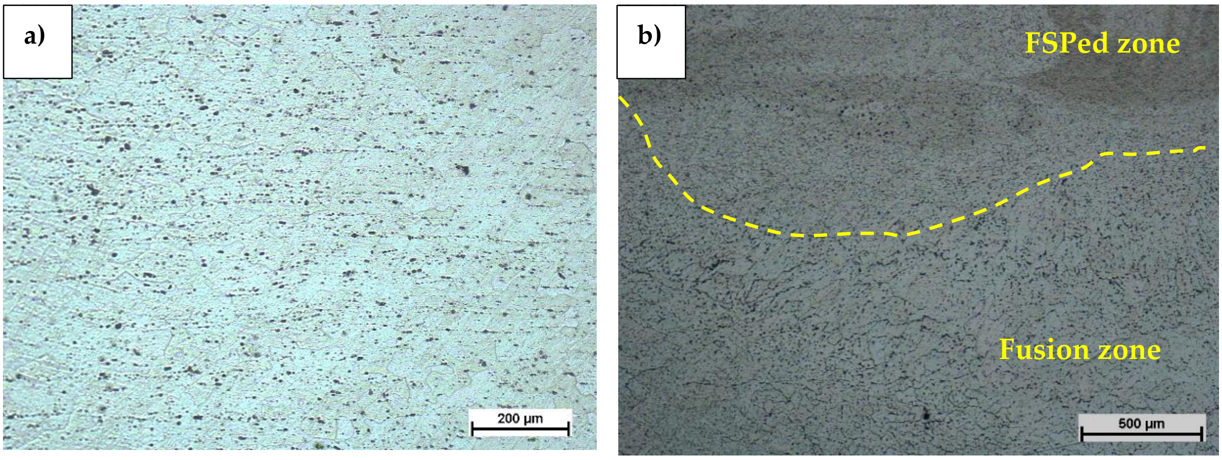

Figure 4. Grain refinement after FSP treatment applied to the heat affected area of the welded sample. a) Base material b) Transition zone between the FSPed area and weld metal

The onion ring microstructure and thus the material flow form can be clearly seen in the areas where the FSP has been applied (Figure 5). It was also determined that any porosity and cracks did not occur in the areas where FSP was applied. The onion ring forms occurring in the microstructure also clearly show adequate bond strength resulting from the grain refinement and dynamic recrystallization [36-38].

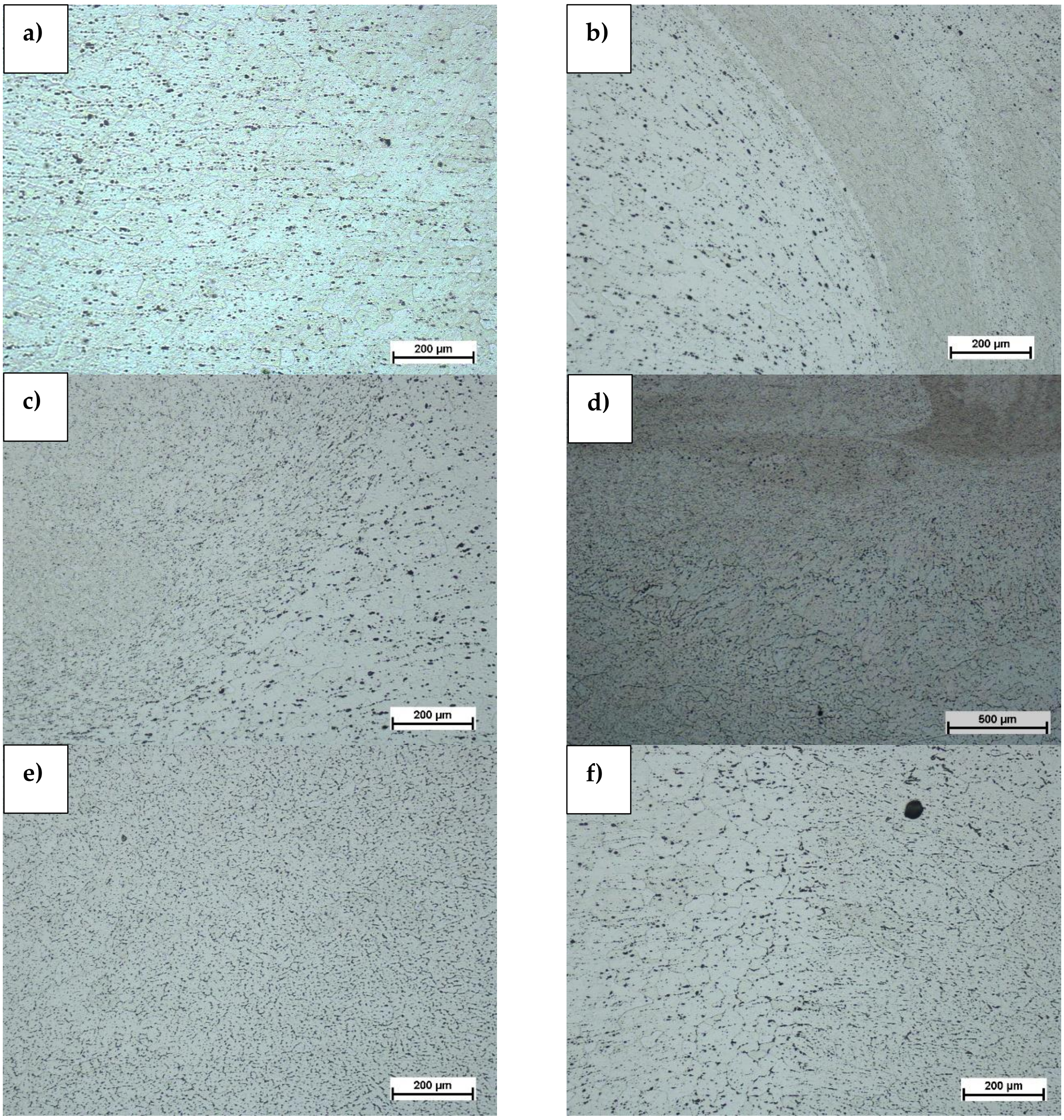

Figure 5. Onion ring microstructure and material flow in the FSP-ed areas a) base material b) TMAZ advancing side c) transition zone between the FSPed area base material d) transition zone between FSPed area and weld metal, e) Weld metal, f) transition zone between the weld metal and base material

When the tensile test results were examined (Figure 6), it was determined that the mechanical strength of the GTAW specimen was compatible with the values in the literature. However, it is also seen that higher elongation values are obtained compared to the low ductility values expected in fusion welding methods. This situation is attributed to the formation of a fine-grained structure in the weld metal due to the fact that the FSP was made with two passes and the low heat input is used in the passes [39, 40]. As well-known, fine-grain structure increases the strength and ductility of metallic materials. Following the FSP, it was determined that the average grain size in HAZ was measured between 60-90 µm.

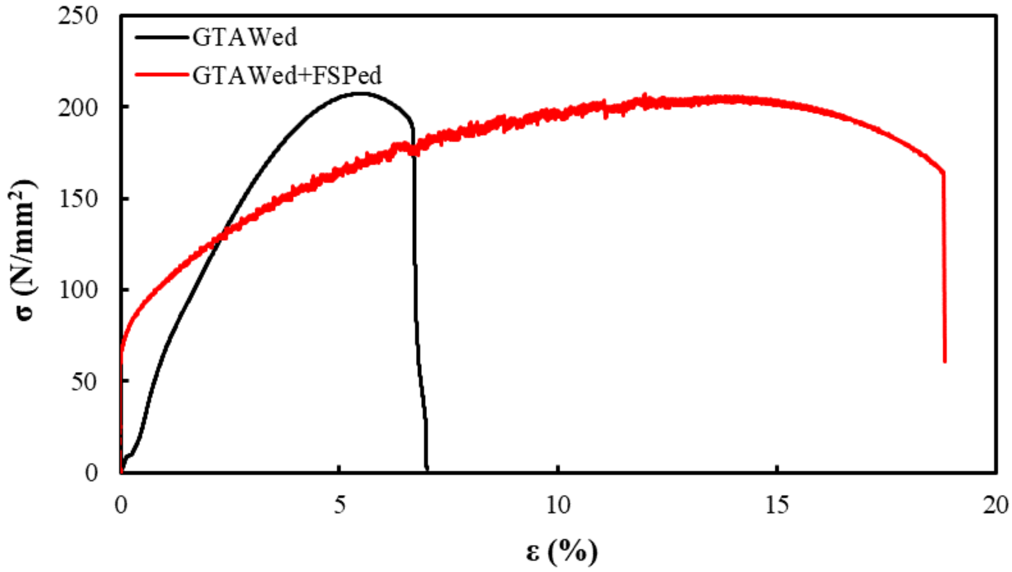

Figure 6. Representative tensile test results of the samples

When Figure 6 is examined, it is seen that the tensile strengths are slightly higher than the base material (Table 2). According to the tensile test results of welded joints without FSP, it has been observed that the welding parameters selected for GTAW welding provide acceptable weldability and strength values. This result also shows that it is possible to obtain sufficient tensile strengths for welded joints of 5xxx series (Al-Mg) aluminum alloys by the GTAW method. The FSP process applied after the welding process did not significantly change the strength values of the joins. However, the ductility of welded joints has increased remarkably. This situation can effectively contribute to the elimination of the brittleness/low toughness problem, which is a major disadvantage, especially for welded joints [41-43]. With the increase in ductility, the elongation values of the base material were regained for the welded structure.

During the tensile tests, none of the specimens broke from the weld fill and each specimen ruptured in base materials regions close to the HAZ (Figure 7). When the elongation results of the FSPed samples are examined, a significant increase in ductility was achieved compared to the as-welded sample. FSPed samples' elongation have a slight decrease (almost the same) in elongation values can be obtained compared to the base material. As it is known, it is an expected result that the ductility of welded joints will decrease significantly due to the negative effects of the thermal effect that given during the welding process [44]. This is a very important gain, especially for aluminum alloys joined by fusion welding, where the ductility is expected to decrease further as a result of the thermal effect.

Figure 7. Failure zones of the GTAWed samples after tensile testing

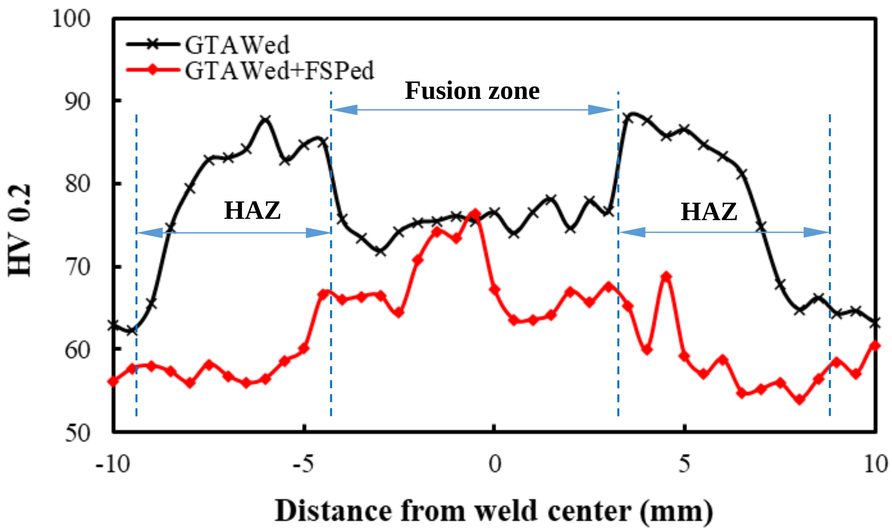

Figure 8. Cross-sectional microhardness profiles of the samples

When the hardness distribution is examined, it is clearly seen that the hardness distribution of the GTAWed sample has characteristically high hardness values from the sides of the weld seam to the base material throughout the HAZ (Figure 8). The highest hardness values were measured as 88 HV including this region in HAZ. It can be given the main reasons for high hardness in HAZ as grain coarsening (Figure 3b), and residual stresses due to rapid cooling after welding resulting from thermal shrinkage caused by the heating-cooling cycle. Because of the high residual stresses, these areas are the weakest region of the welded joint. For this reason, the FSP was applied to these areas of GTAWed parts as given in the experimental studies section of this study. The applied FSP resulted in a stress relief effect as well as grain refinement. With the FSP, both thermal stress and mechanical stress relief occurred and the hardness values decreased in the HAZ. The stress-relieving effect of the FSP is adequately efficient in that the high hardness values formed in HAZ can be reduced to the hardness values of the base material. As given before, another effect of the FSP is the increase in ductility as given in the tensile test. This is an important desired result in welded samples [45].

4. CONCLUSION

In this study, AA5754 alloy was joined with GTAW and then FSP was used in order to modify the coarse grain structure formed in the HAZ. The results obtained after the FPS performed in two passes for enhancing the HAZ grain structure on both sides of the weld seam are as follows;

- The microstructure, which did not have any welding defects after GTAW, had a fine-grained structure with dynamic recrystallization after the applied FSP.
- The low ductility that occurred after the GTAW was eliminated thanks to the fine-grained microstructure created in the microstructure. While approximate ultimate tensile strength values were obtained after the GTAW and FSP, a remarkable improvement was achieved in the elongation values after the FSP.
- All FSPed specimens ruptured in base materials regions close to the HAZ due to the significant increase in ductility. FSPed samples' elongation is almost the same as the elongation values of the base material.
- The hardness tests demonstrated that the grain coarsening and the harmful effects that occurred after the thermal cycle during the GTAW were eliminated efficiently. Characteristic high hardness values in the HAZ were reduced to base material hardness values because of the FSP's stress relief effect. After the FSP, approximately uniform hardness distribution was obtained clearly.

Declaration of Ethical Standards

Authors declare to comply with all ethical guidelines, including authorship, citation, data reporting and original research publication.

Credit Authorship Contribution Statement

Fatih Kahraman: Methodology, writing, reviewing, supervision
Gökçe Mehmet Gençer: Methodology, experiments, writing, editing
Coşkun Yolcu: Experiments, writing

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

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Data Availability

The datasets collected during the current study are not publicly available but are available from the corresponding author on reasonable request.

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