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A Survey on Post-Weld Modification of Microstructural and Mechanical Properties of GTAWed Aluminum Butt Joints Through FSP and T6 Heat Treatment

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ABSTRACT

Fusion welding is a commonly applied manufacturing process in all fields of industry. Some imperfections (formation of coarse-grained microstructure, decrease in mechanical property, etc.) can occur especially in the fusion welding-based fabrication of aluminum alloys which have specific features, such as having high thermal conductivity, expansion coefficient, high hydrogen solubility in the liquid state, and oxide layer on the surface. Therefore, the enhancement of microstructure and mechanical properties in terms of the lifespan and strength of the fusion-welded joints is crucial for most applications. In the study, the effects of friction stir processing (FSP) and T6 heat treatment, applied as post-weld processing, on the weld zone properties of the gas tungsten arc welded (GTAWed) AA6082 plates were investigated. The effects of the post-weld processings (FSP and T6 heat treatment) on mechanical and microstructural features were analyzed via microstructural examination and microhardness measurements and tensile strength testing. It was observed that the dendritic microstructure in the processed region (stir zone) of the weld bead was destroyed and fine-grained microstructure was formed via FSP. Additionally, the findings showed that heat input occurred during FSP led to broaden of heat affected zone (HAZ) and decrease the hardness in a wider region. It was also determined that the mechanical characteristics of the GTAWed joint were increased but in contrast, the toughness was decreased through T6 post-weld heat treatment.

Keywords: GTA welding, aluminum alloy, Butt welding, friction stir processing, T6 heat treatment

Tig Alın Kaynaklı Alüminyum Birleştirmelerin Mikroyapı ve Mekanik Özelliklerinin SKP ve T6 Isıl İşlemi Yoluyla Kaynak Sonrası Modifikasyonu Üzerine Bir Araştırma

ÖZ

Ergitme kaynağı ile birleştirme endüstrinin her alanında yaygın olarak uygulanan imalat yöntemlerindendir. Özellikle yüksek ısıl iletim ve genleşme katsayısına sahip, sıvı halde hidrojen çözünürlüğü yüksek olan ve yüzeyinde rijit oksit tabakası bulunan alüminyum alaşımlarının ergitme kaynağıyla imalatında iri tane oluşumu, mekanik özelliklerde düşüş vb. olumsuzluklar gerçekleşebilmektedir. Bu nedenle ergitme kaynaklı birleştirmelerin ömürleri ve mukavemetleri açısından kaynak sonrası işlem ile kaynak bölgesinin iç yapı ve mekanik özelliklerinin iyileştirilmesi çoğu uygulama için önemli rol oynamaktadır. Çalışmamızda, tungsten inert gaz (TIG) kaynağı ile birleştirilen AA6082-T6 plakaların kaynak bölgesi özelliklerine kaynak sonrası işlem olarak uygulanan sürtünme karıştırma prosesi (SKP) ve T6 ısıl işleminin etkileri araştırılmıştır. SKP ve T6 ısıl işleminin mekanik özelliklere ve iç yapıya etkileri çekme testi, mikrosertlik testi ve mikroyapı incelemeleri ile araştırılmıştır. SKP ile kaynak dolgusunun işlem gören bölgesindeki (karıştırma bölgesi) dendritik tanelerin parçalanarak ince taneli iç yapının elde edildiği tespit edilmiştir. Bununla birlikte, SKP'nin malzemede oluşturduğu ısıl girdi ile ısıdan etkilenen bölgenin (IEB) genişlemesine ve sertliğin daha geniş bölgede düşmesine sebep olduğu gözlemlenmiştir. Kaynak sonrası uygulanan T6 ısıl işlemi ile kaynaklı birleştirmenin mekanik özelliklerin arttırıldığı ancak tokluğunun azaldığı gözlemlenmiştir.

Anahtar Kelimeler: TIG kaynağı, alüminyum alaşımı, alın kaynağı,sürtünme karıştırma prosesi,T6 ısıl işlemi

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1. INTRODUCTION

The heat-treatable 6XXX Al alloys with their superior properties, such as high specific strength, good deformability, and significant corrosion resistance are commonly used engineering materials in aerospace, automotive, and shipbuilding in order to reduce weight and fuel consumption [1-6]. By considering the application areas, gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) are extensively employed methods for joining aluminum alloys due to their high productivity, applicability, and excellent versatility features [3, 7- 9]. Even though the 6XXX Al alloys have good weldability properties, some discontinuities or defects, such as hot cracking, distortion, porosity, lack of fusion, residual stress, etc. can occur in the weld zone of fusion welded materials, by its very nature [10, 11]. Additionally, high heat input occurred in arc welding methods [12-16] causes remarkable grain coarsening in the heat-affected zone (HAZ). Especially in the welding of precipitate hardened Al alloys such as 6XXX-T6 the formed grain growth in HAZ leads to decrease hardness, strength, and ductility properties [17, 18]. Within this context, the quality of arc welded joints that particularly result in high heat input to the workpiece has an important effect on the mechanical properties of the fabricated structure.

In order to improve the mechanical and microstructural characteristics of the welded joints mechanical deformation methods, such as ultrasonic impact treatment and shot peening can be used. However, these types of methods cannot totally modify the microstructure of the material (shallow deformation) and prevent the defects, such as porosity, microcrack, etc. formed in the weld bead. Thus, these methods are not accepted as efficient enough by researchers due to their drawbacks. Recently, various studies have been carried out on the application of FSP which is a commonly used solid-state method to enhance the lifespan and properties of the welded joints [3, 5, 18-21].

In friction stir processing which is simple, clean, low cost, and environmentally friendly [22], a non-consumable rotating tool with a specific pin and shoulder profiles is plunged into the surface of the workpiece. The occurred friction-based heat between tool and workpiece increases the deformability of the material. Severe plastic deformation (also named stirring) comes true in the processed zone of the material through the traveling of the rotating tool along a specific path in the surface of the workpiece [23-25]. Thereby, the microstructure and mechanical properties of the locally processed zone of material is enhanced via dynamic recrystallization (DRX) [26, 27]. Borrego et al. [28] stated remarkable findings by using this method that identified as green energy in their study on the fatigue strength enhancement of the butt-welded aluminum alloys. In the research, the fatigue strength of the manufactured welded joints was significantly improved through the reduction in stress concentration and refinement of the microstructure.

The research done in the literature emphasizes that the enhanced properties in fusion welded joints by employing a post-weld process are crucial in the way of performance and lifespan of the manufactured structure. In the study, the applicability of the FSP and T6 heat treatment as post-weld processing was investigated to improve the mechanical and microstructural properties of the weld zone of gas tungsten arc welded (GTAWed) 6082-T6 Al plates. The effects of the methods applied as post-weld processing on the joint quality were analyzed in comparison.

2. EXPERIMENTAL DETAILS

2.1 Gas Tungsten arc Welding (GTAW)

EN AW 6082-T6 alloy with a thickness of 5 mm were used as base material. The chemical composition and mechanical properties of the wrought alloy are given in Tables 1 and 2, respectively. The plates were cut to obtain workpieces with the dimensions of 200×100 mm. The edges of workpieces were prepared considering EN ISO 9692-3:2016 standard and afterward, they were fixed on a steel table with pneumatic clamps (Fig 1.a). Before the welding process, the V-groove was brushed to remove the oxide layer, and then the possible contaminants such as oil were cleaned with acetone. The EN ISO 18273:S Al 5356 filler wire (Table 1) with a diameter of 1.2 mm and as a

Table 1. The Chemical Compositions of The Base and Filler Materials

	Si	Mg	Mn	Fe	Cr	Cu	Zn	Ti	Al
EN AW 6082-T6	0.9	1	0.52	0.39	0.04	0.08	0.08	0.03	Balance
S Al 5356	<0.25	5	0.3	<0.4	-	-	-	-	Balance

Table 2. The Mechanical Properties of The AA6082-T6 Alloy

	σ_{YS} (MPa)	σ_{UTS} (MPa)	Strain (%)	Hardness (HV)
AA6082-T6	268	326	16	106

Table 3. GTAW and FSP Parameters

Parameter	
Welding current (A)	240
Welding voltage (V)	26
Welding speed (mm/min)	130
Shielding gas flow rate (L/min)	18
Wire feed rate (mm/min)	120
FSP tool rotation speed (rpm)	900
FSP tool travel speed (mm/min)	20
Tilt angle	2°

Table 4. Sample Designations in The Study

Sample	Sample ID
Welded sample	GTAWed
Friction stir processed sample following welding	GTAWed+FSPed
T6 heat treated sample following welding	GTAWed+T6

shielding gas pure argon were used in the joining process. The GTAW parameters are presented in Table 3. The single V-butt joints were fabricated throughout the rolling direction of the AA6082-T6 plates with a double pass from one side of the plates.

2.2 Post-Weld Processing

Friction stir processing (FSP) and T6 heat treatment were carried out to GTAWed samples as post-weld methods. The methods were applied separately to different samples that are fabricated with the same welding parameters. The manufactured samples were denoted as shown in Table 4 from now on. FSP was done by using a vertical milling machine. A non-consumable ISO X40CrMoV5-1 steel tool (55 HRC) was used with a cylindrical shoulder of 20 mm in processing. The conical pin, 3 mm in length, had a 6 mm diameter at the top while 5 mm at the bottom. The weld bead was FS processed with two overlapped passes (Fig 1.c). The overlapped ratio was 0.33 and determined considering [29]:

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

Where l designates the distance between pin axes in passes and d is the top diameter of the pin (Fig 2). 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.

T6 heat treatment that sequentially consists of solution heat treatment, quenching, and artificial aging was carried to welded samples. Solution heat treatment was done at 540 ^{o}C for 4 hours and then aged at 180 ^{o}C for 8 hours following water quenching.

2.3 Metallographic and Mechanical Testing

Metallographic examinations were performed via optical microscope at the cross-sections of the samples to characterize the weld region macro and micrographically considering the effects of the FSP and T6 heat treatment. The sample cross-sections were ground and then polished with respect to the standard metallographic methods. Afterward, samples were chemically etched with Keller's reagent consisting of 190 ml distilled water, 5 ml HNO_3, 3 ml HCl, and 2 ml HF. Additionally, Tucker's reagent

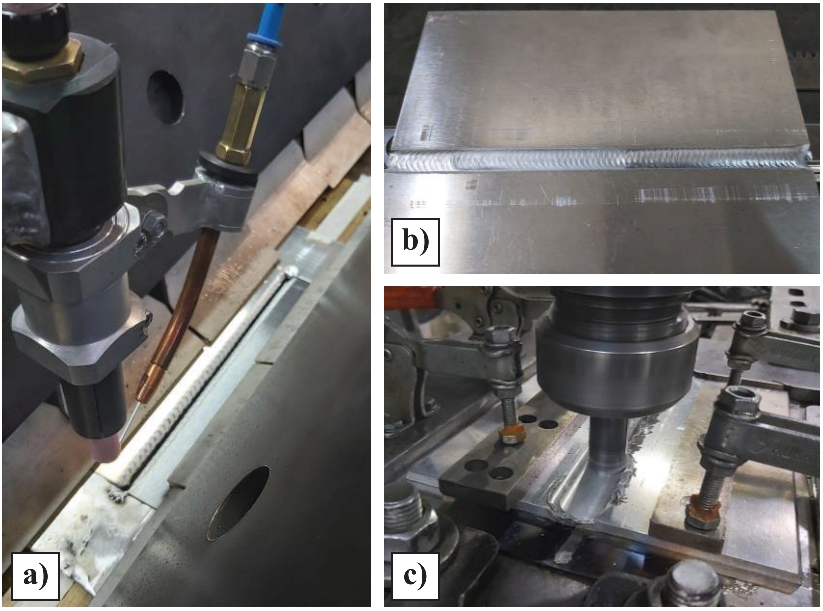


Fig 1. Process Images of (a) GTAW, (b) GTAWed Aluminum Plate, (c) FSP of GTAWed Plate

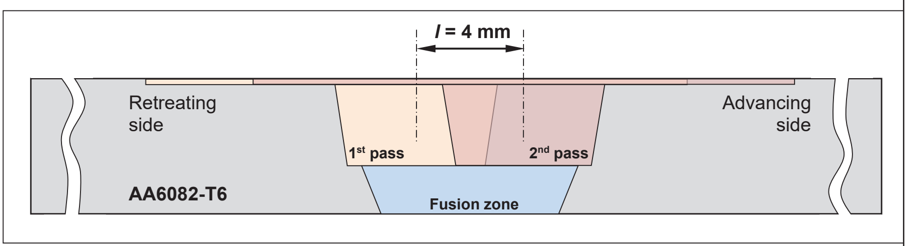


Fig 2. Schematic Cross-Section Representation of Overlapped FSP of GTAWed AA6082-T6 Joint

(45 ml HCl, 15ml HF, 15 ml HNO_3, 25 ml H_2O) was used to reveal the macro images of the weld regions.

The Vickers microhardness measurements were carried out to observe the hardness profile of the cross-sections. The indentations were made throughout a line that was 2 mm below the upper surface of the Al alloy plate. The indentations were made with a 0.2 kg load and a dwell time of 15 sec and the hardness profile of the samples was precisely obtained by arranging 0.5 mm spacing between indentations.

To evaluate the effect of post-weld processings on the tensile properties of GTAWed,

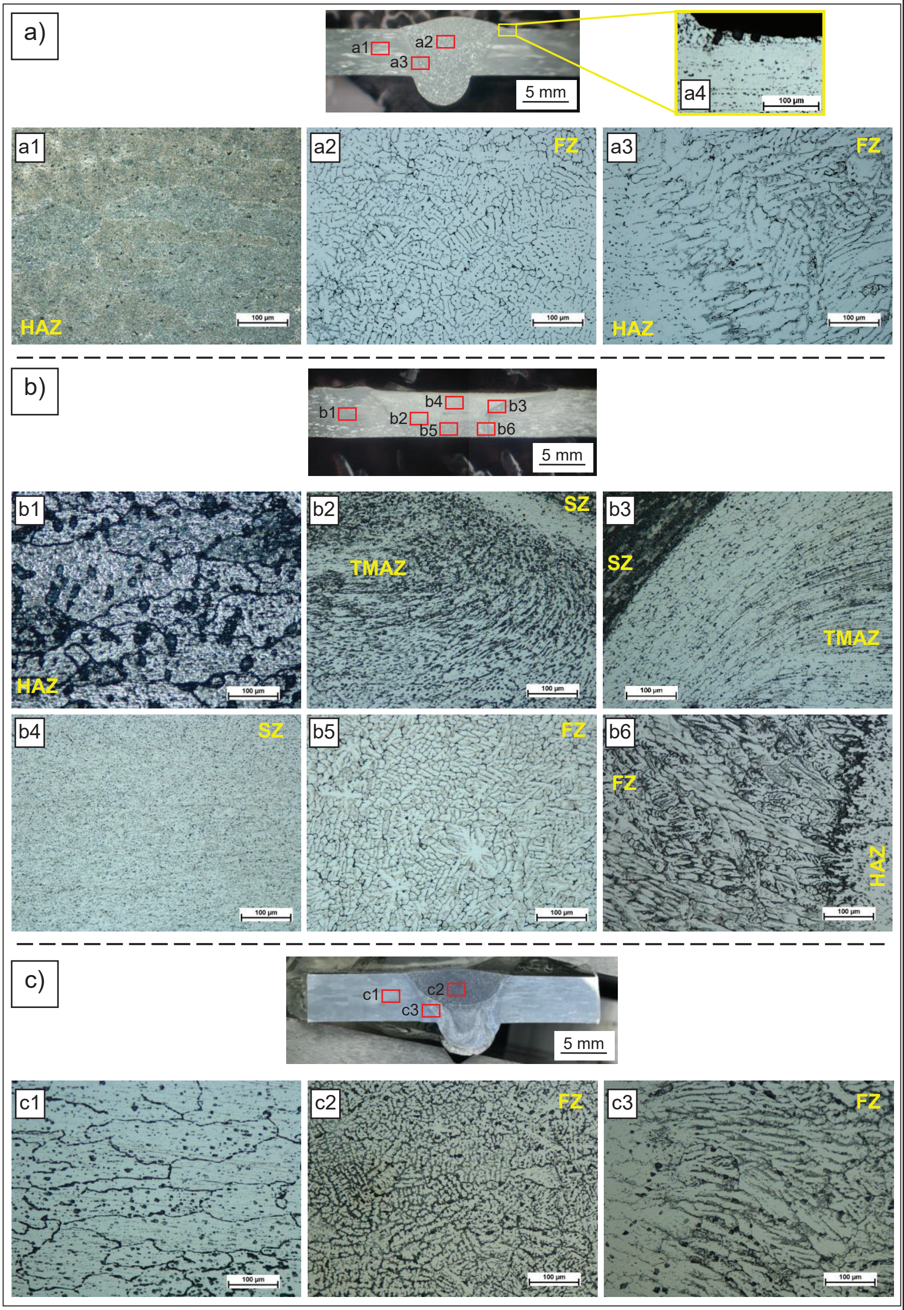


Fig 3. Metallographic Examinations of the Samples; a) GTAWed, b) GTAWed+FSPed, c) GTAWed+T6

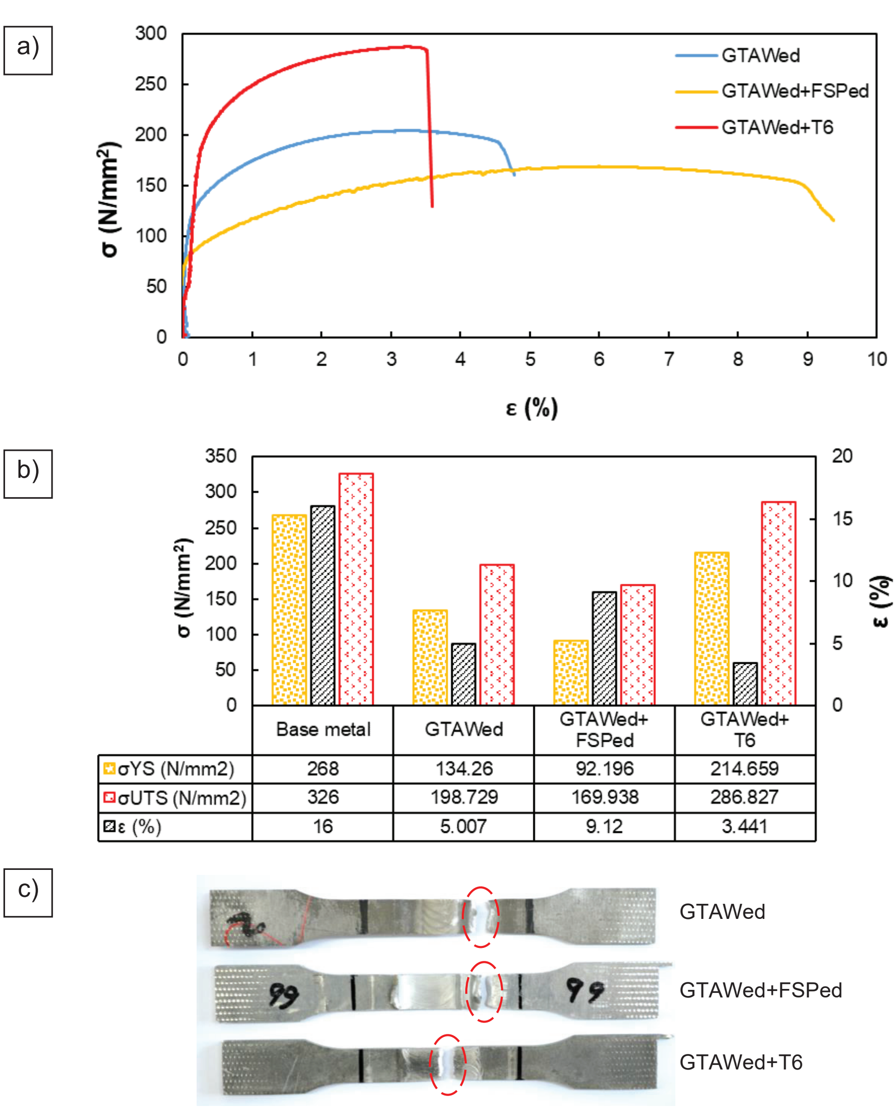
GTAWed+FSPed and GTAWed+T6 samples, tensile testing was performed. The tensile specimens were extracted through the water jet from the normal direction of the joint line. Test were carried out at room temperature by using a constant testing speed of 1 mm/min.

3. RESULTS AND DISCUSSION

3.1 Macro and Microstructural Analysis

Fig 3. illustrate the cross-section macro and micrographs of the processed distinct zones of samples. It can be observed from the macrographs that there are no visible macro discontinuity/defects present in the joint (porosity, lack of fusion for GTAWed sample; tunnel defect for GTAWed+FSPed sample). However, microporosities were found at the weld toe of the GTAWed sample (Fig 3.a4). Cerit et al. [30] emphasized in their research that discontinuities at the weld toe result in local stress fields and thus, increase the stress concentration in materials. Consequently, these kinds of discontinuities at the weld toe reduce the load-bearing capacity of the welded structures. According to the research done, the elimination of defects in this region has a great effect on improving the service life of welded joints. It was determined that a high solidification rate in the weld zone increased the nucleation sites and thus, the equiaxed dendritic microstructure was obtained in the fusion zone (FZ) of the GTAWed sample (Fig 3.a2). This cast microstructure formed in the weld bead became elongated and coarsened along the heat transfer direction at the fusion line during the welding (Fig 3.a3). It can be clearly seen that the cast microstructure in the fusion zone was modified as fine equiaxed grains in the stir zone (SZ) via FSP following GTAW (Fig 3.b4-b5). The grain refinement in the stir zone comes true as a result of dynamic recrystallization caused by adequate heat input and severe plastic deformation formed in the workpiece [31]. Therefore, the low ductility of the cast structure in the processed zone was inhibited via FSP. Fig 3.b3 shows another distinct region known as thermo-mechanically affected zone (TMAZ) where the plastically deformed and thus elongated grains were obtained. Additionally, it was also observed that FSP removed micro porosities at the weld toe of GTAWed sample with the effects of high pressure and plastic deformation.

The apparent HAZ in the GTAWed sample cannot be observed after T6 post-weld heat treatment (Fig 3.c). The macrograph of GTAWed+T6 sample demonstrated two distinct zone consisted of weld bead and base material. In comparison with the GTAWed sample, there was not any obvious difference determined in the weld bead microstructure of GTAWed+T6 sample as expected (Fig 3.c2). This finding is a result of employing a non-heat treatable filler metal was used for joining.



	Base metal	GTAWed	GTAWed+ FSPed	GTAWed+ T6
σYS (N/mm2)	268	134.26	92.196	214.659
σUTS (N/mm2)	326	198.729	169.938	286.827
ε (%)	16	5.007	9.12	3.441

Fig 4. Tensile Test Results of the Samples; a) Stress-Strain Curves, b) Average Tensile Property Values, c) Fracture Areas Occurred in The Samples

3.2 Tensile Testing

The tensile stress-strain curves and results of the samples are given in Fig 4. The presented values are averages of the three samples for each group and curves are representations of the average values. The tensile test findings indicate that the tensile strength and ductility of the GTAWed sample significantly decreased in comparison with the base material. The reduction in ultimate tensile strength was 39.04% while it was measured as 68.75% for the strain. It is a known phenomenon that the homogenous distribution in the structure as finer-sized β'' precipitates of the Mg5Si6 compound formed by alloying elements of Mg and Si existing in the 6082-T6 aluminum alloy enhances the strength of the base metal remarkably [32]. Starink et al. [33] stated that the most effective strength increasing mechanism for heat treatable aluminum alloys is obtained by precipitation hardening. Therefore, the mechanical behavior of such alloys after welding is directly related to the properties of the precipitates. The heat input during GTAW caused over-aging in the HAZ that resulted in a decrease in the mechanical properties of the joint. The cross-section hardness profile verifies this weakening in HAZ. To prevent solidification cracking defects that may form in the fusion zone of the arc welded 6XXX Al alloy, the related standards recommend using 4XXX and 5XXX Al alloys as filler materials [34]. The strength enhancement of these aluminum series is not possible by heat treatment. Besides, the dilution in base material in the fusion zone inhibits or significantly decreases the formation of β'' precipitate which consequently led to strength reduction in this zone. Thus, the mechanical property decrease following GTAW with respect to the base material is an expected fact.

It was observed that T6 post-weld heat treatment improved the mechanical characteristics of the GTAWed joint markedly however the percentage of elongation decreased to 3.44%. The reprecipitation was ensured in HAZ and base metal of GTAWed+T6 sample via post-weld heat treatment. However, a similar trend in the strength of fusion zone was not achieved through T6 due to the usage of non-heat treatable filler wire (S Al 5356). Thus, the fracture was occurred at the fusion zone that is the most mechanically critical point of the GTAWed+T6 sample. In GTAWed+FSPed sample, a large part of the weld bead was locally treated via FSP. By obtaining fine equiaxed microstructure as a result of dynamic recrystallization, FSP as a post-weld treatment enhanced the ductility of the sample in the ratio of 82.14% in comparison with GTAWed sample. It can be clearly denoted that the high heat input formed during double passed FSP (consecutively) affected the mechanical properties negatively in the HAZ by causing over-aging. Therefore, the rupture was observed at the HAZ of the GTAWed+FSPed samples as in GTAWed sample.

3.3 Hardness Measurements

Fig 5. illustrates the cross-section hardness profiles of the samples. The hardness profile showed abrupt fluctuation in the weld zone of the GTAWed sample. While the mean hardness value of the fusion zone was 76 HV, it was measured as 101 HV in the HAZ side of the fusion line. It can be seen from the profile that the distinct increase in hardness throughout the transition from FZ to HAZ then gradually decreased to a minimum value of 63.5 HV in HAZ.

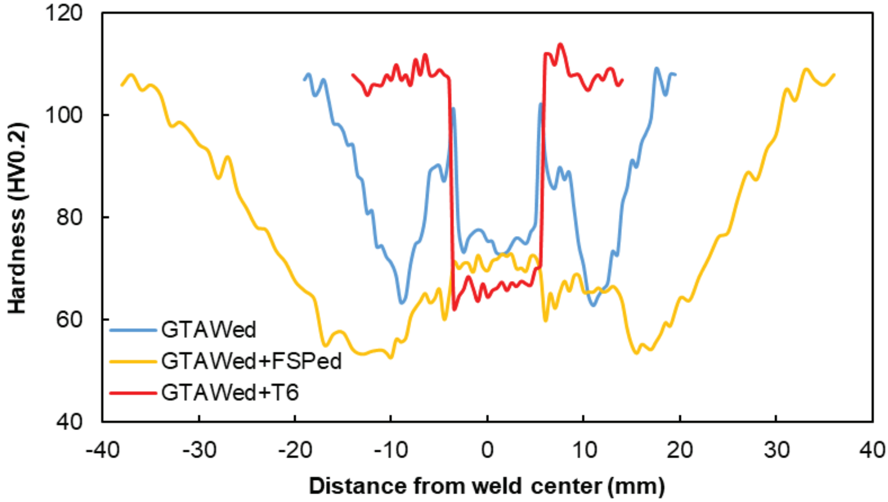


Fig 5. Cross-Section Hardness Profiles of GTAWed, GTAWed+FSPed and GTAWed+T6 Samples

The maximum hardness value in the processed zone of the GTAWed+FSPed sample was measured in the stir zone as 71 HV. Although the hardness profile did not change as abruptly as the GTAWed sample, a remarkable difference was also determined between the stir zone and HAZ of the GTAWed+FSPed sample. The hardness value has decreased to 53 HV in HAZ due to the applied consecutive heat inputs (GTAW and double pass FSP) to the workpiece. In parallel with the results of the study performed by Aliakbari et al., intense heat input coarsened the precipitates in Al alloy and thus, led to over-aging in HAZ [1]. It is obvious that the total heat input caused to widen HAZ in this sample with respect to the GTAWed sample. The hardness profiles of GTAWed and GTAWed+FSPed samples showed a similar tendency throughout the transition from HAZ to base metal and gradually increased up to base material hardness. Even though the cast microstructure in the fusion zone was refined via double pass FSP, it is apparent that the hardness in the stir zone was not changed markedly.

T6 heat treatment following GTAW gave rise to reprecipitation and thus, ensured to obtain an average hardness value of 107 HV regularly in the cross-section except for fusion zone. Consequently, the minimum hardness value (66.4 HV) was measured in the fusion zone of the GTAWed+T6 sample. The underlying reason is that the main hardness increment mechanism of S Al 5356 filler metal can be achieved by plastic deformation [28].

3.4 Fracture Surface Analysis

To get insight into the failure modes of the samples, fracture surfaces after tensile

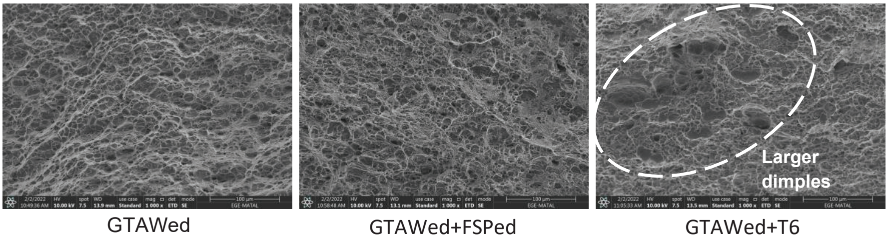


Fig 6. Fracture Surface SEM Images of Tensile Test Specimens

testing are analyzed (Fig. 6). Although relatively finer dimples were observed in the GTAWed+FSPed sample as a slight difference, the SEM fractography showed that similar fracture modes were occurred both in GTAWed and GTAWed+FSPed samples. This situation can be attributed to the occurrence of fractures in HAZ for both samples. It is evident from the SEM fractography that larger and shallower dimples were determined in the fracture surface of the GTAWed+T6 sample. In compliance with the findings, the GTAWed+T6 sample also demonstrated a ductile fracture mode in the fusion zone. However, the observed dimples in the GTAWed+T6 sample resulted in low elongation in comparison with the GTAWed and GTAWed+FSPed samples.

4. CONCLUSION

In the study, a comparative experimental survey was carried out to observe the effects of FSP and T6 heat treatment as post-weld processing on the microstructural and mechanical properties of the GTA welded AA6082-T6 butt joints. Three sample group was taken into consideration in the research: GTAWed, FSPed following GTAW, and T6 heat-treated following GTAW. The obtained conclusions can be summarized as:

- The dendritic microstructure was refined and equiaxed grains were successfully obtained via overlapped friction stir processing in stir zone that increase the ductility of the GTAWed sample by 82.14%.
- Over-aging occurred in HAZ of the GTAWed sample led to decrease hardness and thus, minimum hardness value was measured in this region of cross-section (63.5 HV).
- It was observed that consecutive heat inputs through GTAW end FSP were enlarged the HAZ in GTAWed+FSPed sample and thereby the over-aged area. The intense heat inputs caused to decrease in the hardness down to 53 HV.
- T6 post-weld heat treatment increased the hardness in the HAZ of the GTAWed sample up to 107 HV. By precipitation hardening via T6 heat treatment, the mechanical property of the GTAWed butt joints was enhanced but ductility was decreased.

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