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MECHANICAL AND MICROSTRUCTURAL PROPERTIES OF AL 5754 ALLOY JOINED BY GMAW AND GTAW

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Abstract

The purpose of this study is to examine the effect of double pulse Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) on metal droplet transfer, weld bead geometry, weld pool profile and to examine the mechanical properties of the Al 5754 alloy weld joints. Al 5754-Al 5754 aluminum alloy plates were welded with ER 5356 welding wire. No significant defects were found, and full penetration joints were created. The effect of arc welding parameters on the speed and appearance of welding were investigated by means of macrostructure and microstructure characterization of fusion zone. Also, the characters of tensility and micro-hardness being of the welded specimens were measured.

Keywords: Gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), Al 5754 aluminum alloy, mechanical properties, microstructural properties

1. Introduction

Aluminum alloys are widely used in structural materials in automotive and aerospace industries because of their characteristics such as low density, strength to weight ratio, corrosion resistance, ductility, and recyclability. The 5000 series Al–Mg non-heat treatable alloys have especially deep drawing and sheet forming characters enabling them appropriate to be used in automotive tailored blanks [1–4].

Aluminum is among the lightest construction metals. However, joining of these alloys may cause severe problems. For this reason, various traditional welding methods including Gas Tungsten Arc Welding (GTAW) [5, 6] are used for Aluminum and Mg alloys. These techniques are revealed coarse-grained and inter metallic (both large and continuous) zones in the welding area followed by a prominent heat affected zone (HAZ) and the base material (BM) [7-9]. There are also some other welding alternatives [10, 11] such as cold metal transfer welding [12, 13] and conventional MIG (Metal Inert Gas) and TIG (Tungsten Inert Gas) welding [14–16]. Intermetallic compounds are seen during the solidification of metal due to the usage of weld Al to Mg alloy. The final formation of different types of inter metallic compounds (IMCs) in the welding zone undermines the integrity of the weld. Moreover, the distribution control, size and type of the brittle IMCs are challenging. In addition, it has a significant effect on the strength of the weld [17].

Argon is frequently used in Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) welding techniques as a shielding gas and increases the stability of the process and the number of good results in terms of bead appearance and content of porosity. The magnesium content of the filler is found to be higher than the content of the weld aluminum to cover the magnesium leak during welding [4].

Gas Metal Arc Welding (GMAW) and Gas Tungsten Arc Welding (GTAW) welding processes are commonly used in order to join different aluminum alloy components. On the other hand, such welding techniques can cause various problems such as porosity, lack of wetting, hot cracking and decrease in strength, distortion and tensile residual stresses. Several studies in aluminum alloy welds have shown that the strength reduction, stress concentration and weld defects may cause monotonic properties decrease and a crucial fatigue strength loss [18–23].

It is noteworthy to state that the 5xxx aluminum alloys are not heat-resistant. In addition, they may have plastic deformation for the mechanics in these alloys. It will be sufficient to apply the same procedure used in the 6082-T651 alloy to these alloys [24-26].

GTAW (or TIG welding) is one of the well-known technologies for the aluminum alloy welding. Due to the high heat input in GTAW, microstructure coarsening in the fusion zone (FZ) of aluminum alloys would be formed regarding the welding process [27] resulting in an apparent decrease of mechanical properties of the joints. Menzemer et al. examined the microstructures of TIG welded 5083 and 6061 aluminum alloy joints and revealed that microstructure coarsening was clear in the fusion zone because of the slow dissipation of heat generation during welding [28]. Lakshminarayanan et al. also stated that coarse columnar grains were shown typically in the fusion zones of 6061 alloys resulted in a sharp decrease of joint strength compared to base metal [29]. It could be noted that most of the previous studies focused on the TIG welded joints of traditional aluminum alloys. The microstructure characteristics of Al–Mg–Mn–Er alloy joints are not known today [30].

Regarding the productivity improvement and cost-effectiveness in mechanical production, high speed welding plays an important role. GMAW (or MAG welding) is one of the most commonly used welding methods due to its relatively high productivity and reasonable cost. On the other hand, it was firstly reported by Bradstreet [31] that high speed Gas Metal Arc Welding (GMAW) welding could not be accomplished through simply increasing welding speed and welding current proportionately. The further study of Lucas [32] and Tusek [33] suggested that a number of appearance defects typically including undercut and humping weld were easily formed and thus limiting the further improvement of productivity. Furthermore, instabilities presented as spatter and weld bead roughness also found in high-speed MAG welding. Previous research has suggested various changes on either the method or the process in order to fulfill high speed Gas Metal Arc Welding (GMAW) welding in various aspects of shielding gas, welding current or arc voltage waveform and hybrid welding being the most common industrial application. Ueyama et al. [34] have suggested a tandem Gas Metal Arc Welding process in order to enable sound weld bead in high-speed welding where heat input was deconcentrated and metal flow in weld pool was controlled by the leading and trailing arcs. Li et al. [35]

proposed a double electrode (DE-GMAW), utilizing a non-consumable tungsten electrode to by-pass part of the melting current in a conventional Gas Metal Arc Welding process [36].

Al 5754 alloy was joined by two welding methods namely GTAW and GMAW welding in butt joint geometry in the present study. The relationship between welding parameters and the mechanical properties such as tensile properties, micro-hardness and microstructures were also examined. The microstructure and phase composition of the joints were analyzed by optical microscopy as well.

2. Experimental procedures

The welded samples were exposed to tensile-test in a KONDI-A X1150 AB type testing machine at room temperature with 1 m/s speed. Test specimens were prepared in accordance with the TS 287 standard. Moreover, ER 5356 wire electrode having 1.2 mm diameter was used as the filler metal. The spectrometric analysis of the specimens was carried out by means of a Beirth Spectrometer and the chemical compositions of both base-metal and wire electrode and mechanical properties were presented in Table 1 and Table 2, respectively. Micro-hardness values of welded Al alloys were found by using HMV2 SHIMADZU type machine. An ER5356 filler wire was used and its chemical compositions were presented in Table 3.

Table 1. Chemical composition regarding Al 5754 alloy and ER 5356 wire electrode (wt %)

Material	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Base metal	0.40	0.40	0.10	0.50	2.6	0.30	0.20	0.15	Balance
Wire electrode	0.25	0.40	0.05	0.15	4.9	0.16	0.10	0.15	Balance

Table 2. Mechanical properties of the 5754-aluminum alloy

Tensile strength, σ_{uts} (MPa)	237.1
Yield strength, σ_{ys} (MPa)	123
Elongation, e_r (%)	19.1
Young Module, E (GPa)	103

GMA welding processes were carried out using a DAIHEN Model DR Series ARK ROBO 1100 welding robot with an operating capacity between 0–500 A and 0–50 V. The welding opening was fixed as 0.8 mm and the torch was centered. The welding robot and the apparatus have been presented in Fig. 1. Aluminum is one of the lightest structural metals and joining and it may have various challenges. Therefore, gas tungsten arc welding (GTAW) has been used to weld Al alloys by using ESAB 4300i welding machine.

Figure 1. The welding robot and its apparatus used in MIG weld experiments.

The constant parameters during welding process were as follows; the thickness of base-metal was 2.5 mm and wire electrode diameter was 1.0 mm. Protective gas was 82 wt% Ar + 18 wt% CO_2 mixture, nozzle opening was 10 mm and the free wire length was 15 mm. Wire feeding rate was 12 m/min and arc distance was 3 mm and the torch angle was 5°. The variable parameters were as follows; welding current (I) as 105A, arc voltage (V) as 22, 24 and 26 V, the welding speed (S) as 0.6/min selected for the welding experiments.

After the completion of the welding, the specimens were dissected perpendicularly to the welding direction by using a closed circuit saw cooled by boron oil in order to measure the penetration depth. The dissected surfaces were grinded and etched. The macro- and micro-structure images have been received from these surfaces via Nikon Stereo Zoom optical microscope in 10x magnification.

The penetration calculation was carried out on macro-structure images by using a new vision program. Bead penetration in welding applications was presented in Fig by means of an image. 2. Vickers hardness tests were performed in order to provide some information on the mechanical properties of the welding zone. Micro hardness profiles on the cross-section of joints welded at a speed of 0.6 m/min were shown in Fig. 2.

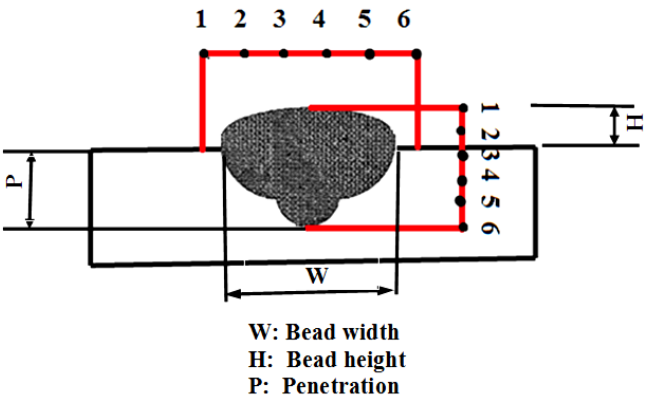


Figure 2. A schematic illustration of bead geometry

3. Results and discussion

3.1 Tensile Test Results

The relevant standards were considered for the preparation of the tensile test specimens. Then they were exposed to tensile test. The yield strength and ultimate tensile strength of base metal were measured as 123 MPa and 237.1 MPa in un-welded original specimens, respectively. Its yield strength values decreased to 110 MPa and 104 MPa in GTAW and GMAW welded joint of Al 5754 sample, respectively. When the neck point was reached (i.e. maximum tensile strength), the strength values increased to 183 and 178 MPa values for GTAW and GMAW welded samples, respectively.

Figure 3. Tensile test fracture surfaces Al 5754 base material

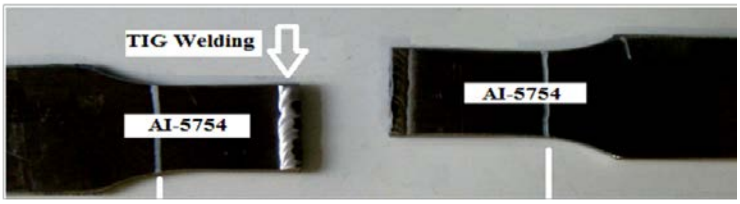


Figure 4. Tensile test fracture surfaces Al 5754 GTAW weld material

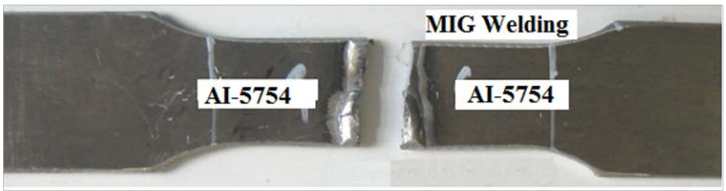


Figure 5. Tensile test fracture surfaces Al 5754 GMAW weld material

The fractured tensile test specimens were shown in Figures 3-5. The un-welded, original specimen was presented in Fig. 3. The ductile fracture was shown in Fig. 4. Fracture was observed in heat-affected zone (HAZ). In Fig. 5, failure was more detrimental than GTAW welded one since the fracture was observed between weld zone and HAZ in GMAW welded specimen. This proves that the lower strength values of yield strength and ultimate tensile strength values of GMAW welded samples than GTAW ones.

Figs. 6, 7(a) and 7(b) showed the yield strength, tensile strength and the elongation percentage for all welded samples and the base metal. Accordingly, the base metal (Fig. 6) was found to be stronger and ductile compared to the welding spots.

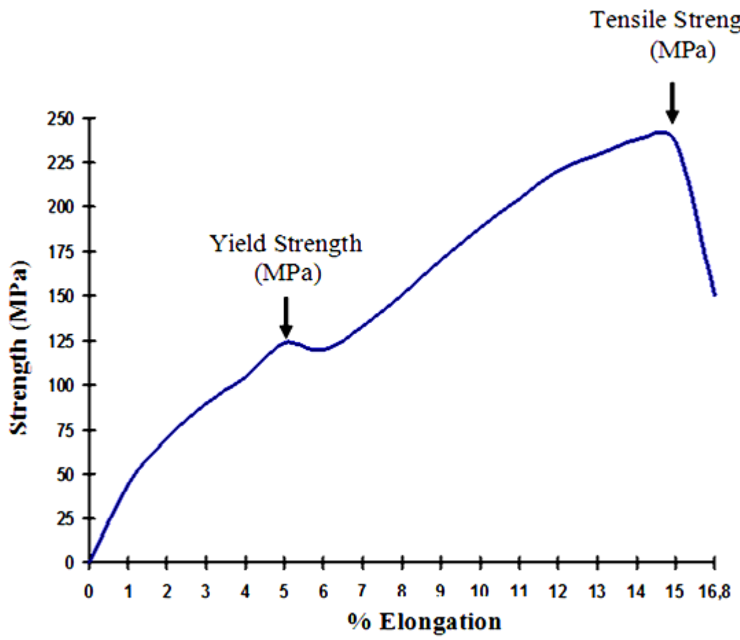
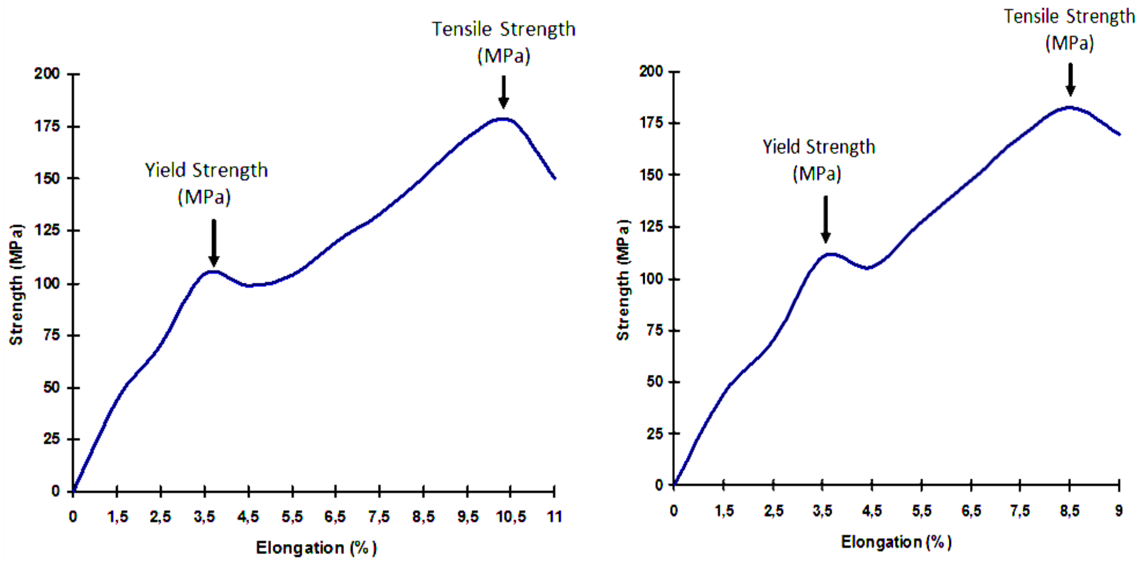


Figure 6. Tensile test values Al 5754 base metal

Fig. 7(a) showed tensile tests specimen GMAW welded. Its yield and tensile strength values were obtained as104 MPa and 178 MPa in GMAW welded joint of Al 5754 sample, respectively.



(a) (b)

Figure 7. Tensile test results of Al 5754 (a) GMAW welded, and (b) GTAW welded.

The ultimate tensile strength of GTAW welded sample was measured as 183 MPa and the yield strength value was found as 110 MPa. Minor irregular and spherical pores located in the bottom side of the weld can be identified throughout the specimen section. Mechanical properties of specimens revealed welds having a more volume of geometric failures and porosity reduced tensile strength and percent elongation. The mechanical property values of base metal samples were found to be better than that of welded ones. Compared to the base material, a slight reduction in yield strength, ultimate tensile strength and elongation were observed. The reason could be the porosity for the low tensile property found in the study. The similar results were detected by Casalino et. al [4].

3.2. Micro-hardness measurements

The hardness results of joint welded by GTAW method were shown in Fig. 8. The micro-hardness value of base metal increased to 74.1HV0.1 0.1 in heat- affected zone was measured as 75 HV0.1. The highest value was found as 72.9 HV0.1 in the center of weld fusion zone as measured in horizontal line (Fig.8). The hardness value decreased to 70 HV0.1 in weld zone and again increased to 71 HV0.1 in heat-affected zone (HAZ) was measured as 72 HV0.1 in base metal as seen in Fig. 8 in vertical direction.

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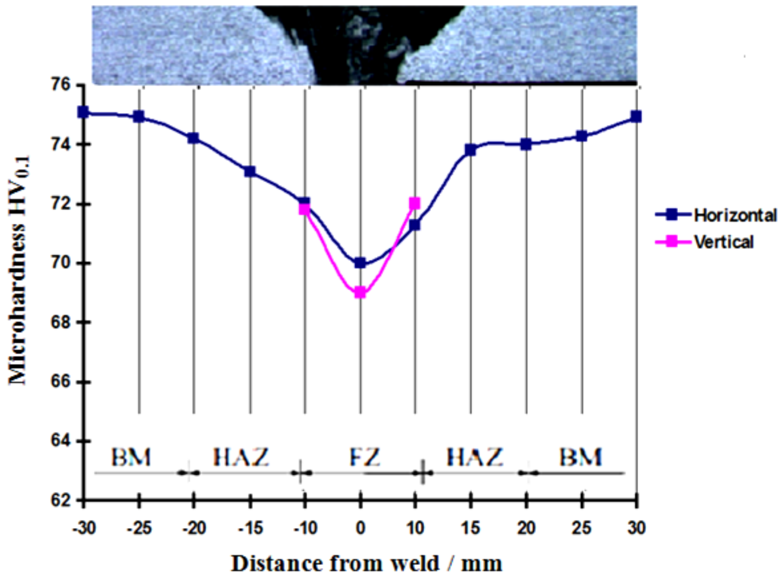


Figure 8. AI5754-AI5754 specimen GTAW welding hardness values

The hardness in this region was found to be more than of the level in base metals implying that fracture would be seen in the heat affected zone (HAZ). In the weld nugget, hardness was approximately constant as 68-69 $HV_{0.1}$ in the direction of the vertical line (Fig. 9). The hardness results of joints welded by GMAW method were shown in Fig. 9 as the horizontal line. Mean hardness of base metal, weld joint and HAZ was measured as 72.1, 69.8 and 71.8 $HV_{0.1}$, respectively. The hardness profile was not found to be fully uniformed in the Al5754 processed zone although it was slightly higher than that in the base material. The hardness profile was mainly affected by the dislocation density in this zone due to the major hardening mechanism of Al5754 being strain hardening. The similar results were also found by Shojaeefard et. al [37].

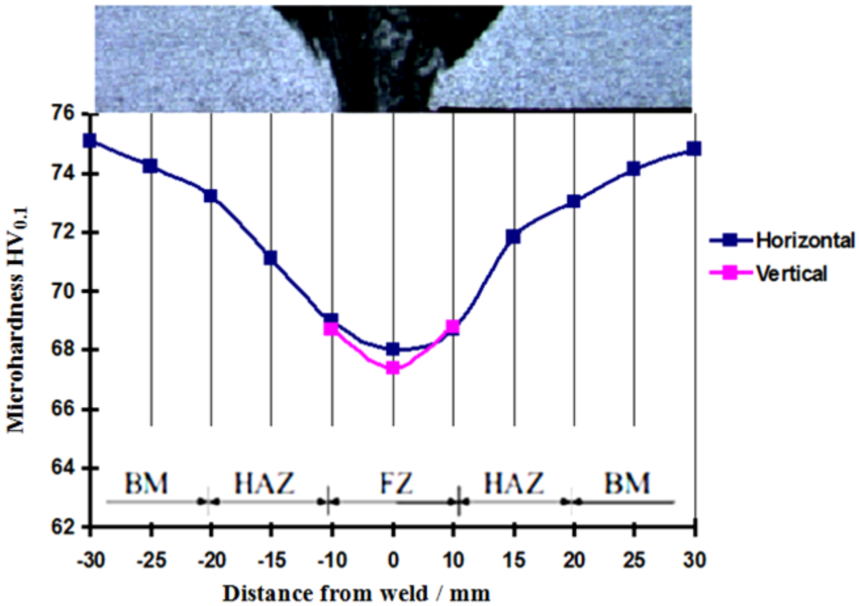


Figure 9. AI5754-AI5754 specimen GMAW welding hardness values

3.3. Macrostructure and microstructure appearances

The microstructure and mainly macrostructure appearances of GMAW and GTAW welded specimens were examined by optical microscope where the penetration was also measured. The height for the lead and depth for the penetration have been calculated via a new vision program as shown in Fig. 10 and Fig. 11.

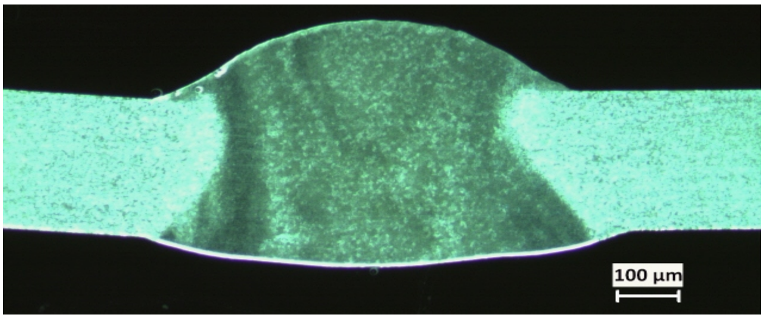


Figure 10. AI5754-AI5754 TIG welding specimen penetration zone

In the light of macro-structure photos of GTAW and GMAW welded specimens, the following results could be stated; reliable bead heights and depth of penetration values were obtained in configurations shown in Fig. 10 and 11. Depth of penetration was in the range of 298 and 2.93 mm for GTAW and GMAW welded joints, respectively. Over-penetrated specimens were given in Fig. 12. Over-penetration is not a very significant issue and waste of material and the cost effectiveness of production decreases. In other words, weight increase in construction and structure is found to be higher. These are undesired events and therefore it is necessary to prevent over-penetration. The similar results were also identified by Karadeniz et. al [38].

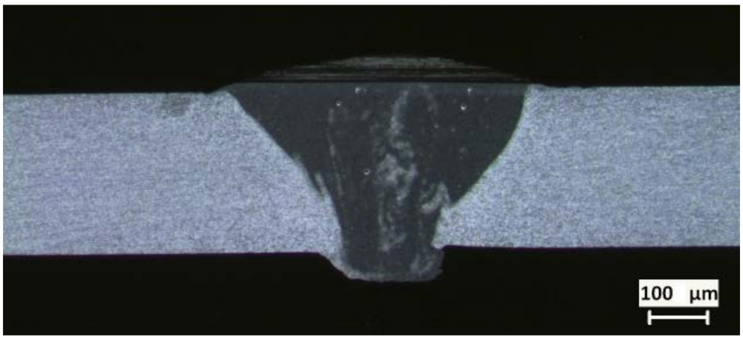
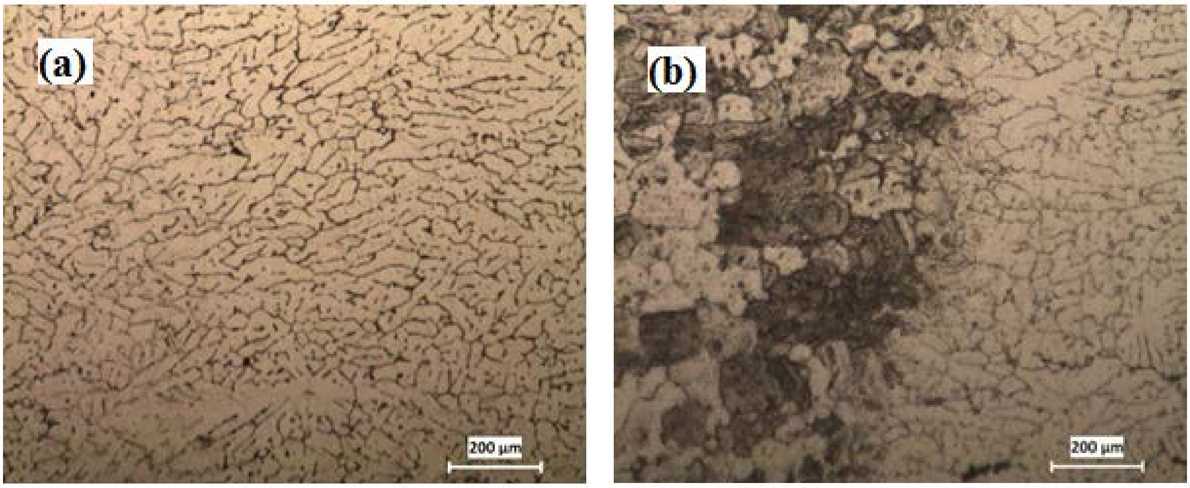


Figure 11. AI5754-AI5754 MIG welding specimen penetration zone

Fig. 12(a) presented the microstructure in fusion zone of samples welded by MIG. The microstructure was mainly composed of dendrite grains and precipitations were observed at the boundaries of the grain. When the voltage increased, there was a parallel increase in fine dendrite grains in fusion zone. Therefore, it could be stated that the amount of the fine grains increased due to the rise of weld voltage. The temperature increase adjusted in the GMAW can improve the fluidity of the weld pool and inhibit the growth of grains [39]. The microstructure in heat-affected zone and base metal were presented in Fig. 12(b). The base metal was rolled with a typical deformation texture property [40] and the grain orientation was found to be parallel to the rolling direction. On the other hand, the rolled grains could not be seen and the coarse grains were clearly observed in the heat-affected zone (Fig. 12c). It has been revealed that the recrystallization occurred close to the fusion zone during welding process. The similar results were also found by Liu et. al [41]. The microstructure of the foundation substance of the 5754-aluminum alloy was shown in Fig. 12(d). The grains have an elongated morphology consistent with the rolling process of the plates prior to welding.



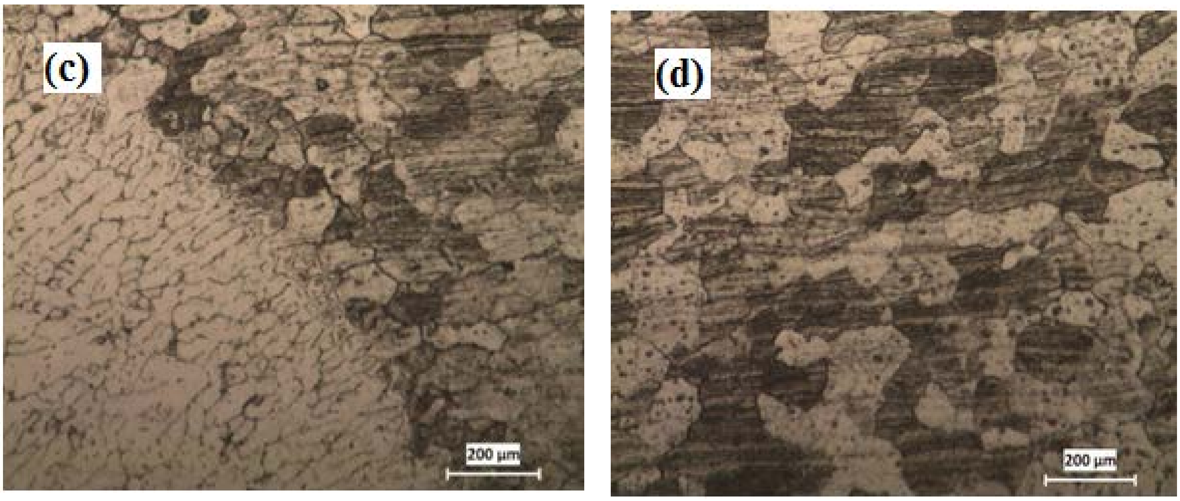


Figure 12. (**a**) AI5754-AI5754 GMAW welded specimen fusion zone (FZ), (**b**) HAZ-BM interface, (**c**) AI5754-AI5754 GMAW welded specimen HAZ-FZ interface zone, (**d**) base metal (BM)

Fig.13. reveals the microstructure for the non-defect less joint at different positions such as a, b, c and d representing the microstructure of weld zone encoded as FZ (fusion zone), HAZ-BM boundary, heat affected zone (HAZ)-FZ interface and BM (base metal) of the alloy welded by GTAW method.

Fig. 13(a) presents partial melting at the grain in the fusion close to the boundary generally associated with liquation cracking in these alloys. Similar results were also presented by Preston [42] et al. In Fig. 13(b), the base metal and HAZ boundary acted as homogeneous solid solutions similar to the next HAZ where dissolution was complete. The result could be accepted since the highest level of residual stress is seen in the HAZ rather than the weld metal. The stresses were not found to be too sensitive for hot and low strength accepted for the solidified weld metal. The estimated stress and the hardness have to be considered carefully HAZ-FZ interface was shown in Fig. 13(c). The grains of aluminum matrix become coarser before welding process. The base metal of Al 5754 alloy was presented in Fig. 13(d). The homogeneous grains having less retained stress were formed due to the fact that base metal was not so close to weld zone and did not affect high heat input. Similar results compared to our results were also noted by Preston et. al [42].

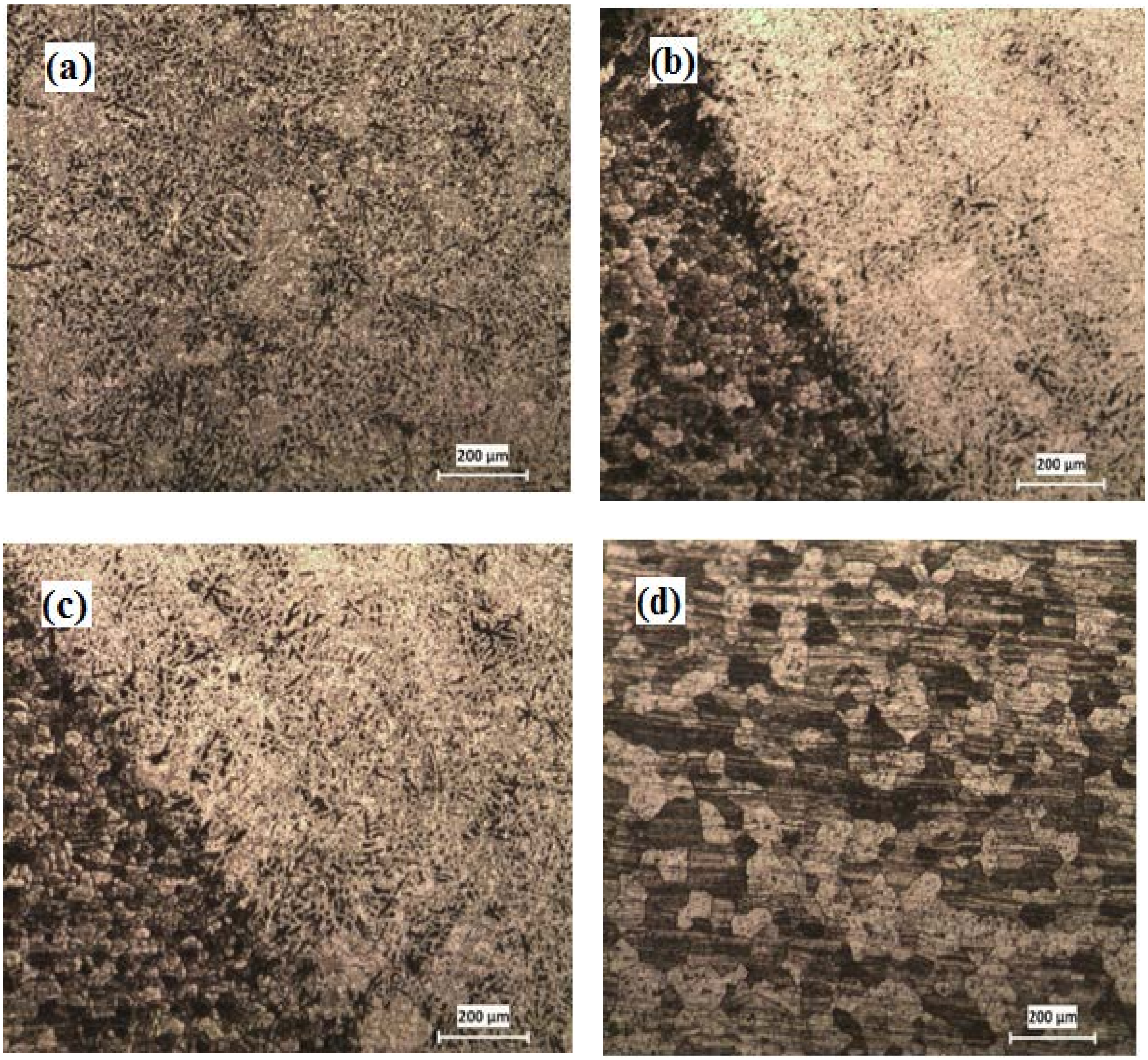


Figure 13. (**a**) AI5754-AI5754 TIG Welded specimen weld zone, (**b**) HAZ-BM boundary, (**c**) AI5754-AI5754 GTAW Welded specimen HAZ-FZ interface zone, (**d**) base metal (BM)

4. Conclusions

In the study, the mechanical and microstructure properties of Al-5754 alloys welded with GTAW and GMAW welding processes were comparatively analyzed using tensile tests, hardness measurements, optical microscopy and macrograph methods. The results of the study are stated as follows:

- Strengths for yield and tensile for unwelded Al-5754 alloys were found as 123 MPa and 237.1 MPa. The yield strength values of the Al 5754 samples in GTAW and GMAW welded joints decreased to 110 MPa and 104 MPa, respectively, and the maximum tensile strength values to 183 and 178 MPa, respectively.

- As expected, it was observed that the mechanical characteristics of the base metal samples were better than the welded ones. Accordingly, a slight decrease in yield strength, ultimate tensile strength and elongation was observed. This can be attributed to the heat affected zone (HAZ) and very small pores.

- GTAW welded joints of aluminum alloys having the height of the beads and penetrating depth at a reasonable level. The range of depth of penetration was between 2.98 and 2.93 mm for GTAW and GMAW welded joints, respectively. Over-penetrated specimens were obtained in some specimens. Over-penetration is not a significant case. It also increases the cost of the formation. In other words, weight increase in construction is seen more.

- The hardness profile was found to be rarely well-compiled in Al5754 area. However, it has been observed to be more compared to the level in the material of the basis. The hardness has been influenced due to the density of dislocation in the zone since the higher hardening of Al5754 is to be strain.

- As GTAW and GMAW welded joints have finer grains at the boundary of the fusion, it causes higher mechanical characteristic. Dendrite grains were forming the microstructure. In addition, at the level of grain boundaries in GMAW welded specimens, the precipitation could be observed. It could be noted that the homogeneous grains having less retained stress were generated in GTAW samples.

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