



## COMPARATIVE STUDY OF DISSIMILAR WELDINGS OF AA6061 AND AA2024 ALUMINUM ALLOYS BY FSW AND GTAW

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### Abstract

In this research weldability of AA6061 and AA2024 aluminum alloys by GTAW and FSW was studied. Friction Stir Welding (FSW) and Gas Tungsten Arc Welding (GTAW) of AA6061 and AA2024 aluminum alloys were carried out with sheet thickness for both alloys was 3 mm. The process parameters used for FSW were 950 rpm tool rotational speed with feeding rate of 50 mm/min. Gas Tungsten Arc Welding of AA6061 and AA2024 aluminum alloys was carried out using ER5356 filler rod to avoid the hot cracking and liquidation in the weld. Comparative study of the joint strength and the microstructure examination showed that the heat affected zone in AA6061 has minimum hardness and strength due to the formation of dark bands of Al-Mg<sub>2</sub>Si eutectic. The joint failure occurred in heat affected zone for both FSW and GTAW welded samples. Results showed that by using Titanium in the filler rod as an alloying addition solve the problem of hot and liquidation cracking and also it refine the grain structure of the weldments. Results also showed that AA6061 and AA2024 aluminum alloys are weldable by GTAW welding using ER5356 filler metal and 80 % more joint strength than that of the FSW welded joint can be achieved.

**Keywords:** Welding of dissimilar aluminum alloys, Microstructure and Mechanical Properties

### 1. Introduction

Alloys of aluminum AA6061 and AA2024 are extensively used in many promising fields like aerospace, marine industry in building of frames, pipelines and storage tanks. Joining of dissimilar alloys is a difficult process one when compared to similar alloys welding method, reason having trouble in joining of 2024 and 6061 aluminum alloys is the differences in chemical composition, metallurgical and mechanical properties [1, 2, 3]. Sadeesh *et al.* [4] reported that most favorable parameters for FSW of 6061 and 2024 (Al alloys) having rotation speed of 1000 revolution per minute (rpm), traverse speed approximately 40mm/min. Enhanced mechanical properties can be attained by placing the harder material

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on advancing side of tool and softer material on retreating side during friction stir welding [5, 6, 7]. Maamar et al. [8] reported that during welding alloys of aluminum are profound to liquidation cracking, hot cracking in heat affected zone (HAZ) and also hot cracking in weld zone. Joint strength of welded aluminum alloys is reduced in heat affected zone (HAZ). This change in properties arises because of different phenomenon which happens during welding. Cheng *et al.* [9] reported that residual stresses produced during the welding also play an important role in reduction of joint strength. Dvornak *et al.* [10] reported that by introduction of grain refiners, such as Zirconium, Titanium, Boron and Vanadium in welding electrodes of aluminum alloys, by introducing grain refiners grain structure of welded metal can be refined, which will result as improved ductility and resistance to hot cracking. Lakshminarayanan *et al.* [11] reported that mechanical properties and microstructural characteristics of friction-stir-welded joints showed that FSW gives rise to softening in joints of heat-treatable aluminum alloys due to the reason of dissolution (growth of strengthening precipitates during the thermal cycle of welding) which results reduction in mechanical properties of joints. Jannet *et al.* [12] studied and compared mechanical properties of welded joints 6061 T6 and 5083 aluminium alloys obtained using friction stir welding (FSW). The results showed that the tensile strength obtained with FSW was higher as compared to conventional fusion welding process. Hussein et al. [13] reviewed and investigated the distinction and characterization of aluminum to steel joints made by this welding method. Diffusion, plunging, and annealing were selected to investigate the results. In this review it was also discussed that steel fragments spattered at the weld zone, weld defects, sharp difference in grain size distribution, and the formed phases of the intermetallic layer.

Purpose of this research is to weld AA2024 to AA6061 by GTAW technique using aluminium filler rod having grain refiner such as Ti, which will refined the microstructure, evade liquidation and hot cracking during fusion welding and enhanced mechanical properties of welded zone, so that a comparative study of the joints (6061-2024) produced by GTAW and FSW can carried out and evaluate the joint strength produced by GTAW technique.

## 2. Materials and Methods

In this work two different aluminum alloy 2024 and 6061 having thickness of 3 mm are used. The standard composition according to American Society of Mechanical Engine (ASME) of both alloys is given in Table 1.

**Table 1. Standard Composition of AA6061 and 2024 aluminum alloys**

<i>Alloy</i> (wt. %)	<i>Fe</i>	<i>Mn</i>	<i>Si</i>	<i>Cu</i>	<i>Mg</i>	<i>Cr</i>	<i>Zn</i>	<i>Ti</i>	<i>Al</i>
6061	0.7	0.15	0.4-0.8	0.15-0.40	0.8-1.2	0.04-0.35	0.25	0.15	Balance
2024	0.5	0.3-0.9	0.5	3.8-4.9	1.2-1.8	0.1	0.25	0.0	Balance

Emission Spectroscopy was applied to compare the composition of sheets with standard composition of aluminum alloys AA6061 and AA2024. The Standard Composition of AA6061 and 2024 aluminum alloys are presented in Table 2.

**Table 2. Spectroscopy Analysis of 6061 and 2024 Aluminum alloys**

<b>Alloy (wt. %)</b>	<b>Fe</b>	<b>Mn</b>	<b>Si</b>	<b>Cu</b>	<b>Mg</b>	<b>Cr</b>	<b>Zn</b>	<b>Ti</b>	<b>Al</b>
6061	0.62	0.02	0.47	0.15	0.53	0.004	0.05	0.001	Balance
2024	0.2	0.8	0.45	4.5	1.5	0.08	0.20	0.0	Balance

Each sheet was cut from the middle in two parts having dimensions of 23x23x3 mm. Cutting of the sheets was done using water cooled hacksaw cutter to avoid any heating during the cutting process and was cleaned by using acetone to remove oil, grease and all other contaminations. After the pre welding cleaning of sheets FSW and GTAW of the alloy sheets 6061 and 2024 was performed using Vertical Miller (XA5040A) Hydraulic machine, having welding tool made of T8-Tool Steel (62 HRC). Work sheets were welded in butt joint configuration with the welding parameters set as 950 rpm rotational speed of the tool and 50 mm/min feeding rate.

Gas Tungsten Arc Welding of the work sheets (6061-2024) were done using WS-200M Delixi machine. EWCe-2 tungsten electrode was used with 120 amp current, hundred percent pure argon (Ar) was used for shielding purpose and ER 5356 filler rod was fed into the weld joint manually. Work sheets were welded in butt joint configuration. Composition of the filler rod ER5356 used for filling in GTAW process is given in Table 3.

**Table 3. Composition of ER5356 Filler Rod**

<b>Alloy (wt.%)</b>	<b>Fe</b>	<b>Mn</b>	<b>Si</b>	<b>Cu</b>	<b>Mg</b>	<b>Cr</b>	<b>Zn</b>	<b>Al</b>
6061	0.62	0.02	0.47	0.15	0.53	0.004	0.05	Balance

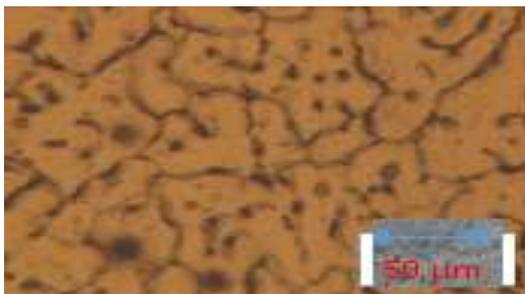
Non Destructive Testing (NDT) was carried out after Friction Stir and Gas Tungsten Arc Welding to check integrity of the welds. Welded sheets were clear in die penetrant and radiography test, there was no indication of any kind of defect in the weld seams for both sheets welded by FSW and GTAW process. The samples were machined from the work sheets for mechanical testing such as tensile test, hardness test and for scanning electron microscopy. Samples were cut from the work sheets by using wire cutting technique to avoid any thermal changes which can affect the properties of the welded and heat affected zone. Samples for tensile testing were made according to the ASTM E8 standards by using wire cutting process. The tensile tests were carried out in standard conditions by using Tinius Olsen 3000KN U series Machine. To evaluate hardness in different zones of base material (2024, 6061), gas tungsten arc welding (Weld zone, HAZ zone) and friction stir welding (Weld zone, HAZ zone and TMAZ zone) micro Vickers hardness test was performed using HM-210/220 series 810 Machine. For microstructure analysis, all samples were hard mounted in Bakelite and grinding of the samples was done at emery papers of grit number ranging from 320 to 2000. The polishing of the samples was performed using 6  $\mu$ m and 1  $\mu$ m polishing papers and etching was done in one percent HF (Hydrofluoric acid). Lica 1000, inverted metallurgical microscope was used to study the microstructure of the samples. After friction stir and gas tungsten arc welding scanning electron

microscopy was performed by using JSM 7600 F machine to see the microstructure and to evaluate the presence of intermetallic layers and precipitates formed in different zones of friction stir and gas tungsten arc welded samples. To find the elemental composition in weld zone, heat affected zone and thermo mechanically affected zone of friction stir and gas tungsten arc welded samples, electron dispersive spectroscopy was performed in conjunction with the scanning electron microscopy.

### 3. Results and Discussion

#### 3.1 Optical Microstructure of GTAW AA6061 and AA2024 Aluminum Alloys

Optical microstructures of GTAW AA6061 and AA2024 were analyzed from different regions. Dendrite structure was found in weld region of samples of AA6061 and AA2024 aluminum alloys welded by GTAW. Figures 1-3 showed that large and fine precipitates were present in HAZ of AA2024 aluminum alloy however dark band like structure was observed in HAZ of AA6061aluminium. Three different regions were observed from optical microstructure study of FSW AA6061 and AA2024. Stir zone (Weld Nugget) in which grains undergo severe plastic deformation adjacent to stir zone there is TMAZ region in which grains undergo plastic deformation but not as severe as in stir zone. There third region is HAZ in which grains does not undergo any deformation but they undergo thermal cycle as shown in microstructures given Figures 4- 8 respectively.



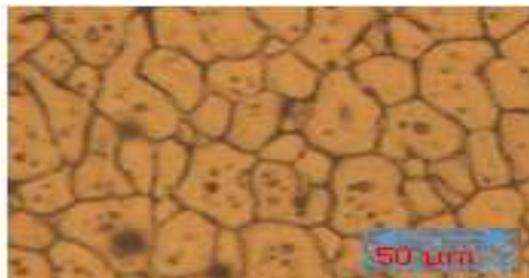
**Figure 1. Weldment of AA6061 and AA2024 by GTAW.**



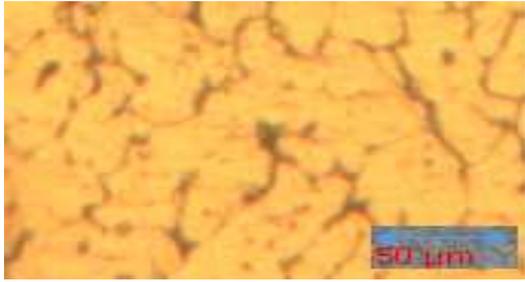
**Figure 2. HAZ of AA6061 Aluminum Alloy.**



**Figure 3. HAZ of AA2024 Alumum Alloy.**



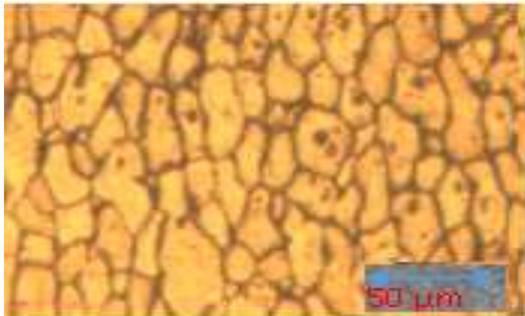
**Figure 4. Weld Nugget of AA6061 and AA2024 by FSW.**



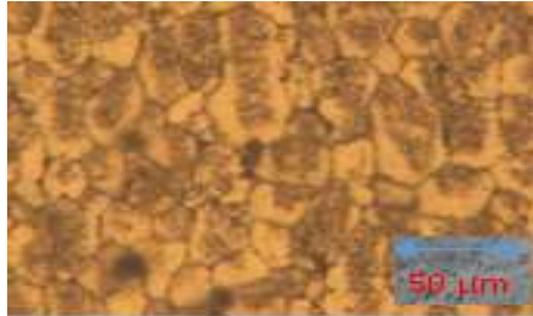
**Figure 5. TMAZ of AA6061 Aluminum Alloy.**



**Figure 6. TMAZ of AA2024 Aluminum Alloy.**



**Figure 7. HAZ of AA6061 Aluminum.**



**Figure 8. HAZ of AA2024 Aluminum Alloy.**

### **3.2 SEM Analysis of GTAW welding of AA6061 and AA2024 Aluminum Alloys**

Microstructure of different regions of dissimilar weld of AA6061 and AA2024 by Gas Tungsten Arc (GTAW) Welding and Friction Stir Welding are shown Figure 9-16 respectively. In GTAW material in weld zone melted and solidify during welding and it consist of dendritic microstructure. The region adjacent to the weld area (HAZ) does not melt during welding but it was influenced by the heat produced during welding in HAZ of 2024 alloy and large particles of  $\text{CuMgAl}_2$  and fine precipitates of  $\text{CuAl}_2$  was observed. However in HAZ of 6061 alloy dark bands of  $\text{Al-Mg}_2\text{Si}$  eutectic was observed as shown in Figures 9, 10 and Figure 11 respectively. In FSW work material does not melt in weld nugget zone due to the vigorous plastic deformation and heat produced by friction of FSW tool and work material grains are deformed. Adjacent to the weld nugget zone is Thermo Mechanically Affected Zone (TMAZ), in this region grains does deformed and experience thermal cycle but not as severe as compare to the weld nugget zone. Heat Affected Zone (HAZ) is near to TMAZ and in this region grains undergo only thermal cycle due to the heat produced during welding, the friction between welding tool and work material. This region also does not deformed plastically.

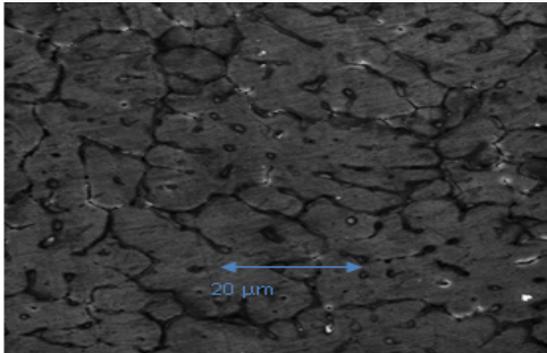


Figure 9. Weld Zone by GTAW.

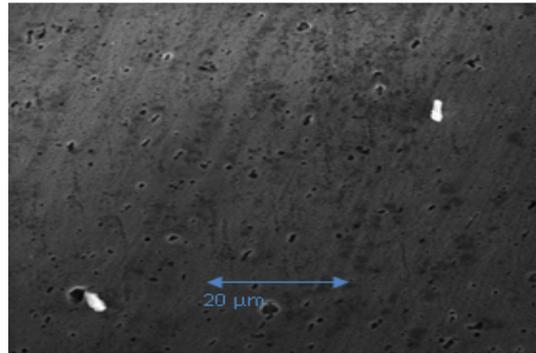


Figure 10. HAZ of AA2024 Aluminum in GTAW.

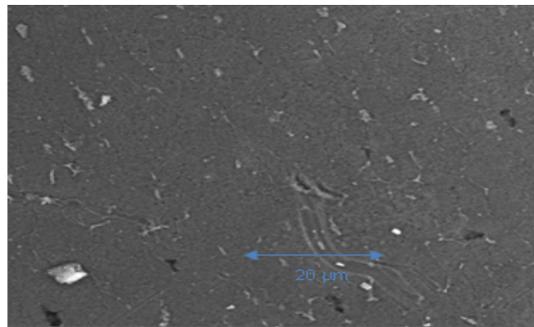


Figure 11. HAZ of AA6061 in GTAW.



Figure 12. Weld Nugget by FSW.

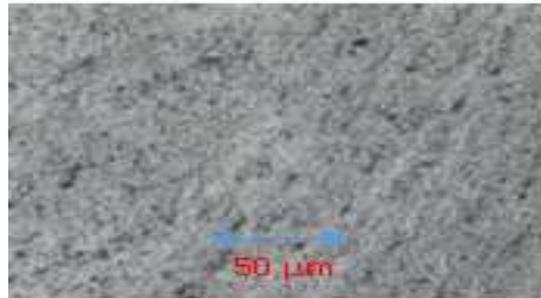


Figure 13. TMAZ of AA6061 Aluminum Alloy.



Figure 14. HAZ of AA6061 Aluminum Alloy.

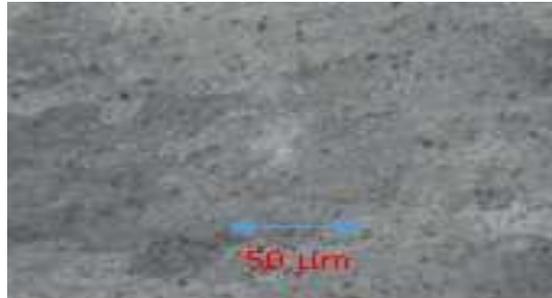


Figure 15. TMAZ of AA2024 Aluminum Alloy.

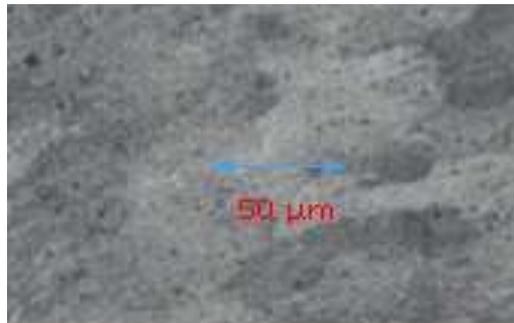


Figure 16. HAZ of AA2024 Aluminum Alloy.

### 3.3 EDS analysis of welding of AA6061 and AA2024 Aluminum Alloys

EDS analysis of GTAW and FSW welding of AA6061 and AA2024 Aluminum Alloys is shown in Figures 17(a, b) and 18 (a, b) respectively. In weld bead of joint fabricated by GTAW technique, interdendritic network of aluminum silicone eutectic structure was observed. In HAZ of 2024 alloy large particles of  $\text{CuMgAl}_2$  and fine precipitates of  $\text{CuAl}_2$  was observed, on the other hand in HAZ of 6061 alloy dark bands of  $\text{Al-Mg}_2\text{Si}$  eutectic was observed. Presence of Al (83.85%) and Cu (8.73%) were prominent in the weld nugget zone of FSW samples and grains were deformed plastically in this region. EDS results shows that there is no change in composition in TMAZ and HAZ of joint fabricated by FSW technique but grains are deformed.

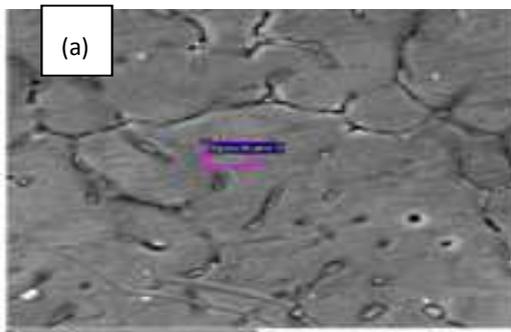


Figure 17. (a) SEM Analysis of GTAW Welding.

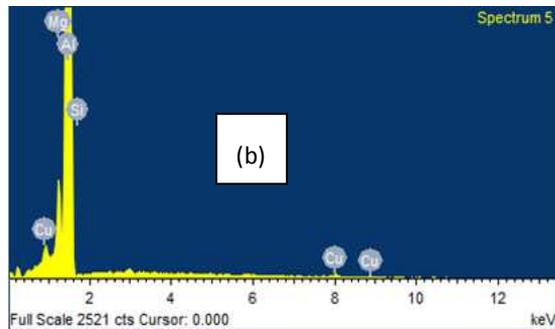


Figure 17.(b) EDS Analysis of GTAW Welding.



Figure 18.(a) SEM Analysis of FSW Welding.

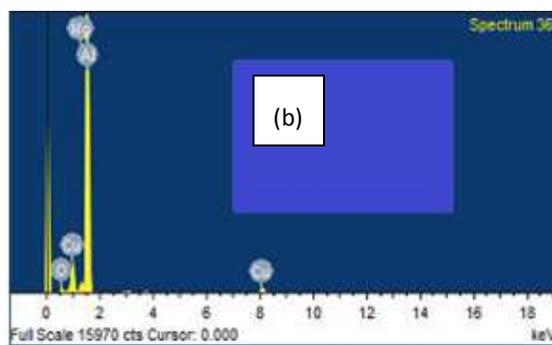


Figure 18. (b) EDS Analysis of FSW Welding.

### 3.4 Tensile Testing of welding of AA6061 and AA2024 Aluminum Alloys

Yield strength and ultimate tensile strength of welded sample for AA6061 and AA2024 aluminum alloys is shown in Figure 19. Maximum weld joint strength was observed in FSW samples because of very severe plastic deformation in welded zone. GTAW sample have shown lesser values of yield strength and tensile strength as compare to FSW samples. The reason behind is the higher temperature of tungsten arc which imparts a larger heat affected zone and due to the formation of dark bands of Al-Mg<sub>2</sub>Si eutectic in HAZ hence results in lower value of joint strength.

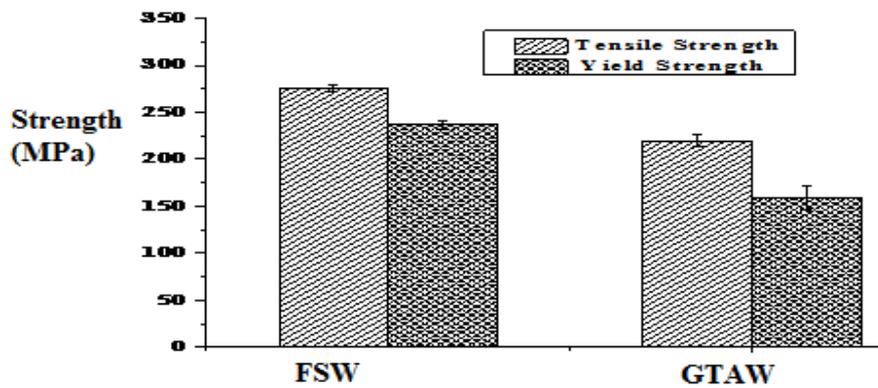


Figure 19. Comparison of UTS and YS of (AA6061-AA2024) FSW and GTAW Samples

Results for percentage elongation of the samples for both FSW and GTAW welded AA6061-AA2024 sample are shown in Figure 20. The trend is same as discussed for yield strength and tensile strength in Figure 19. It can be perceived from these results that more ductility is obtained in FSW as compare to GTAW welded samples. Heat affected zones in GTAW sample served as weak point and fractured first than the rest of the metals. FSW samples have a stronger heat affected zone as compare to GTAW that increased the ability of the sample to deform plastically.

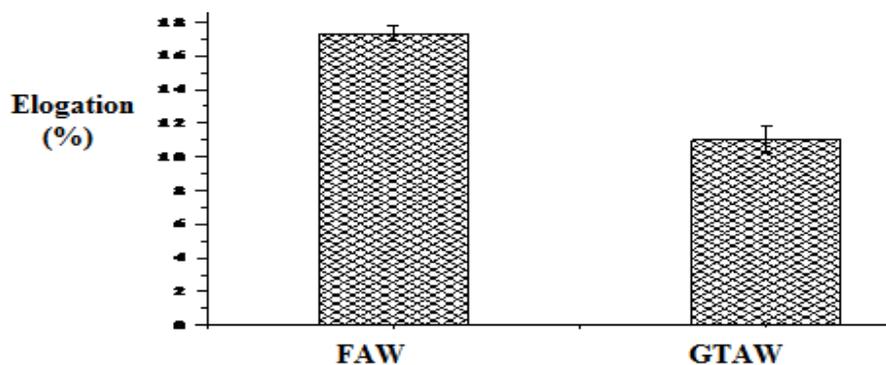


Figure 20. Comparison between elongation of FSW and GTAW (6061-2024) Samples

Results for yield strength and tensile strength are quite inspiring as compare with the values of base metals i.e. AA6061 and AA2024 aluminum alloys from the ASTM standard samples. Yield

strength in this research is more than most of the heat treated base alloys and tensile strength is also comparable. Only very sophisticated and controlled heat treated base metals have more strength as compare to the current study. So it is evident that GTAW process used in this research is economical method to get satisfactory strength after joining the dissimilar aluminum alloys AA6061-AA2024.

### 3.5 Hardness of welding of AA6061 and AA2024 Aluminum Alloys

Figure 21 is displaying the Vicker hardness results of FSW and GTAW welded AA6061-2024 aluminum alloys. It can be observed that in FSW samples, the hardness of HAZ portion and weld bead is more than base alloys. The reason behind this is severe plastic deformation imparted because of high speed stirring which helped in grain refinement and strain hardening of base alloys which inconsequence have shown maximum hardness. However in GTAW welding, the weld bead is weaker as compare to FSW sample. The reason behind this is increase in particle size growth of  $\text{CuAl}_2$  precipitates and also grain coarsening in HAZ zones.  $\text{CuAl}_2$  precipitates when very finely distributed along the matrix of aluminum they are semi coherent with the matrix and in this condition they provide maximum strength and hardness such as in HAZ of AA2024 alloy but if the cooling time or aging time given is prolong after a specific time the precipitates of  $\text{CuAl}_2$  starts growing in size and they become non-coherent with the matrix and become a new phase altogether called as theta double prime this coarsening of  $\text{CuAl}_2$  precipitates is also called over aging and decrease the strength of that zone. On the other hand HAZ of AA6061 had least hardness value and also lesser than AA6061 base metal because of the formation of dark bands of  $\text{Al-Mg}_2\text{Si}$  eutectic which reduced the hardness and strength of this region.

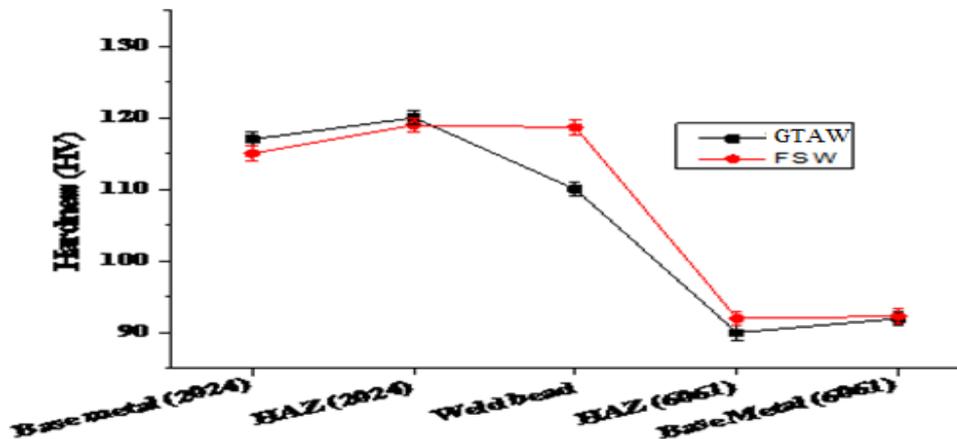


Figure 21. Vicker Hardness of base alloys, HAZ of both alloys and weld bead of FSW and GTAW Samples

## 4. Conclusions

AA6061 and AA2024 aluminum alloys are weldable by GTAW technique using ER5356 filler rod. Joint strength of 80% can be achieved by GTAW technique as that of the joint made by FSW technique which is higher than any joint strength achieved by GTAW Technique reported. Addition of the Titanium into the weld zone avoids the hot cracking and liquidation cracking in the weld zone during GTAW. FSW showed more ductility as compare to GTAW welded

samples. Heat affected zones in GTAW sample served as weak point and fractured first than the rest of the metals. FSW samples have a stronger heat affected zone as compare to GTAW that increased the ability of the sample to deform plastically. It was found that in FSW samples, the hardness of HAZ portion and weld bead was more than base alloys. However in GTAW welding, the weld bead was weaker as compare to FSW sample.

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