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A Comparative Study Between Friction Stir Welding And Metal Inert Gas Welding Of Aluminum Alloys

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Abstract. The present work was undertaken to compare the mechanical characteristics of AA6061-O aluminum plates welded using friction stir welding (FSW) and metal inert gas (MIG) techniques. Plates from AA6061-O plates were welded using the aforementioned techniques using different process parameters. A comparison between the impact toughness and tensile strength of FSW and MIG was carried out. Moreover, the effect of FSW and MIG process parameters on these properties was investigated.The results revealed that the FSW samples exhibited significantly higher impact toughness and tensile strength when those welded using MIG technique.For FSW, increasing the tool rotational speed reduces slightly the impact toughness, but increases the tensile strength of AA6061-O weldments. While increasing the welding speed increasing slightly both of the tensile and the impact toughness of FSW specimens. For MIG welded specimens, increasing the welding current reduces the impact toughness, but increases the tensile strength of the AA6061-O weldments. However, increasing the welding voltage reduces slightly both of the tensile strength and impact toughness of the AA6061-O weldments.

KEYWORDS: Friction stir welding, Aluminum Alloys, Metal inert gas welding, Mechanical properties.

1. INTRODUCTION

Aluminum alloys are widely used in aerospace and automobile industries, due to their light weight, higher strength to weight ratio, corrosion and fatigue resistances. Welding of aluminum alloys still represents a great challenge due to the high thermal conductivity, high chemical reactivity with oxygen and high hydrogen solubility at high temperature [1,2]. All these factors can cause the presence of defects on the weld bead.

Friction stir welding (FSW) is a solid-state joining process that was developed by the TWI, UK in 1991 [3]. FSW is a relatively new and promising welding process that can produce low-cost and high-quality aluminum weld joints. During FSW, a non-consumable tool with a special designed pin and a shoulder is plunged in the abutting edges of the plates to be joined to a preset depth and then moved along the weld joint. Heat is generated due to the frictional between the rotating tool shoulder and abutting material surface. The FSW joint is created by friction heating with a severe plastic deformation of the weld region material. The stirring action of the tool minimizes the risk of having excessive local amounts of inclusions, resulting in a homogenous and void-free weld [4].

Metal inert gas (MIG) welding or Gas metal arc welding (GMAW) is a welding process in which an electric arc forms between a consumable wire electrode and the work piece metal, which heats the work piece metal, causing them to melt, and join. Along with the wire electrode, a shielding gas feeds through the welding gun, which shields the process from contaminants in the air. The MIG is the most widely used process for welding aluminum and its alloys [5-10].

The present investigation aims to compare the MIG process with an emerging welding technique like FSW to assure best quality welds as much as possible. Plates from AA6061-O aluminum plates were joined using FSW and MIG using different process parameters. The tensile strength and impact toughness of the weldments fabricated using FSW and MIG were compared. For FSW, the effect of the tool rotational and welding speeds process parameters on the aforementioned mechanical characteristics was determined. While for MIG, the effect of the welding voltage and current process parameters on these mechanical characteristics was determined.

2. EXPERIMENTAL PROCEDURES

In the present investigation, the AA6061 (Al-Si-Mg) wrought aluminum alloy was used as a base material (BM). The AA6061 was heat treated to O-condition (Annealed) before welding. The chemical compositions of the AA6061 alloy are listed in Table (1).

Table (1). Chemical composition of AA6061 wrought aluminum alloy (wt. - %).

Alloy	Si	Mg	Fe	Zn	Cu	Cr	Mn	Ti	Al
AA6061	0.9	0.8	0.13	0.015	0.27	0.35	0.001	0.1	Bal.

Several 6 mm (thickness) × 50 mm (width) × 150 mm (length) plates of AA6061-O were joined using FSW. The FSW process was conducted using different tool rotational speeds of 800, 1100 and 1400 rpm and different welding speeds of 60, 80 and 100 mm/min. The tilt angle and the tool plunging depth were kept constant at 3^o and 0.1 mm, respectively. Before FSW the plates were cleaned using Methyl alcohol. The FSW was carried out using conventional milling machine. The FSW was performed using a steel tool. The tool made from H13 steel. The tool has a cylindrical shape with 6 mm pin diameter, 25 mm shoulder diameter, and pin length of 5 mm. The rotating pin travelled along the butt line between the two plates. Figure 1 shows a photograph of the FSW process carried out in the present investigation. After welding the test pieces were cut along the transverse direction and mounted to analyze their microstructures and mechanical properties.

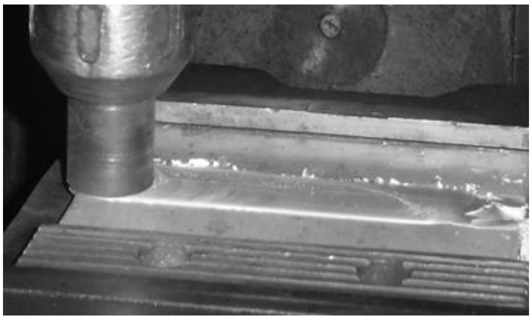

Fig (1). The FSW process.

Figure 2 shows a schematic illustration of edge preparation performed on AA6061-O plates before MIG welding. The edges of the plates were machined to V-butt joint configuration. Before welding, the v-grooves were cleaned using steel wire brush and after that with Methyl alcohol to remove grease and oxide layer found at the surfaces to be welded.

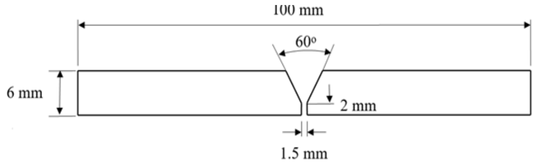

Fig (2). V-butt joint configuration of MIG welding samples.

The MIG welding process was carried manually using HELVI MAXIMIG 288 welding machine. The material used as a filler was ER4030 (Al-Si5) wires with the chemical compositions are listed in Table 2. The welding process was performed using AC current at different voltages of 14, 16 and 18 V and different welding currents of 140, 160 and 180 A. During the welding process, argon shielding gas (99.97 % pure) was used to provide a protective atmosphere. The gas flow rate was about 12 lit/min.

Table (2). Chemical composition of the (ER 4043) Al-Si5 filer wire.

Elements wt.-%	Si	Fe	Cu	Mn	Mg	Zn	Al
Nominal value	4.5-6	<0.6	<0.3	<0.15	<0.2	<0.1	Bal.

The microstructures of the FSW and MIG welded joints were investigated using an Olympus GX-41 optical metallurgical microscope equipped with high resolution digital camera. Welded samples were ground using SiC abrasive papers of increasing fineness up to 1200 grit under pure water. After that, the FSW and MIG welded samples were polished using 10 μm alumina and 3 μm diamond suspensions. The size of the α-Al primary phase grains was determined by means image-analyzing techniques using MIAS Metallurgical images analysis software.
Chirpy impact specimens were machined from the transverse directions of the welded plates. The standard specimen size is 10 mm×10 mm×55 mm with a V notch of 2 mm deep, 45^o angle degree and 0.25 mm root radius. To evaluate the impact toughness of the weld metal, the notch is placed (machined) at the weld metal (weld center). Impact testing was conducted at room temperature using semi-automatic pendulum-type impact testing machine with a maximum capacity of 300 J. The amount of absorbed energy or impact toughness (J) in fracture was recorded. From each condition three samples were tested, and the average value was recorded.
The tensile tests were conducted at room temperature using *Schimadzu* universal testing machine having a capacity of 200 kN at constant cross head speed of 1 mm/min. Tensile specimens were machined from the FSW and MIG welded plates from the transverse direction. The tensile specimens have the dimensions shown in Fig. 3. Three replicates for tensile testing were prepared and the average value of the ultimate tensile strength (UTS) was determined.

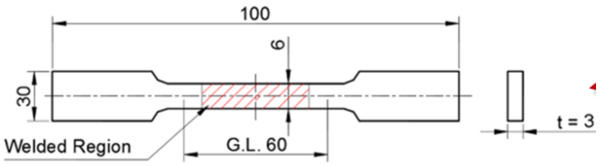

Fig (3). The tensile specimen. (Dimensions In the present investigation, the full factorial (3^2) design of experiments approach was adopted. For FSW experiments, the independent factors are the tool rotational speed and the welding speed (two-factors). While for MIG experiments, the independent factors are the welding voltage and welding current. Each of the independent factors has three levels representing the minimum (level 1), average (level 2) and maximum (level 3) values. For both experiments the impact energy and the ultimate tensile strength are the dependent factors.

The analysis of variance (ANOVA) statistical analysis was performed to determine the most influence of FSW and MIG process parameters under investigation on the tensile and impact properties of the AA6061-O welded joints. ANOVA calculations were performed using MiniTab commercial statistical software.

3 . RESULTS AND DISCUSSION

3.1. General Appearance of FSW AND MIG Joints

Figure (4) shows sample photographs of the surfaces of FSW and MIG AA6061-O welded plates. It is clear that surface friction stir (FS) welded plates are smoothers than those welded using MIG welding process. However, the surfaces of FS welded plates have flashes of the AA6061-O Al alloy on the sides of the welded regions. These flashes can be easily removed using steel wire brush. In fact, the MIG welded plates need to be machined to make the surface of the welded region smooth. This increases the cost of the manufacturing process. According to the above results, it can be concluded that the machining cost of the FS welded plates is lower than the MIG plates.

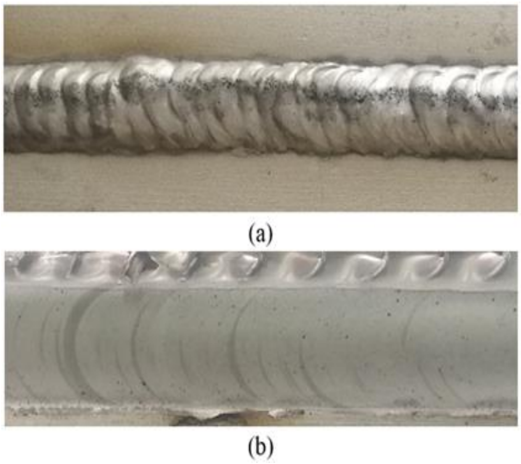

Fig (**4).** Photographs of the (a) MIG and (b) FSW welded plates.

3.2. Macro- & Microstructure of The FSW and MIG Welded Regions

Figure (5) shows sample macrographs of the cross-sections of the FS welded and MIG welded plates. The FSW specimen was welded using 1100 rpm and 80 mm/min. While the MIG sample was welded using 16 V and 160 A. All FS welded plates are free from defects such as cavities and tunnel defects. Also, the MIG welded plates are free from fusion welding defects such as lack of fusion and solidification cracks. The macrostructure of FS welded region mainly of three distinct zones, typically, (i) fine grained dynamically recrystallized zone DRZ or sometimes called the stirred zone (SZ), (ii) thermo-mechanically affected zone (TMAZ) and (iii) heat-affected zone (HAZ).The macrostructure of the MIG welded sample consists mainly of three distinct regions in the weldment are the fusion zone (FZ), the heat-affected zone (HAZ), and the unaffected base metal (BM).

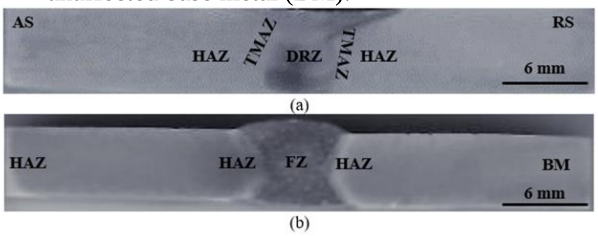

Fig (5). Photographs showing the macrostructure of the (a) FSW sample welded using 1100 rpm and 80 mm/min; and (b) MIG sample welded using 16 V and 160 A.

The microstructure at the center of the DRZs for AA6061-O samples FS welded at several tool rotational and welding speeds is shown in Fig. 6. Figure 7 shows optical micrographs for the microstructure of the AA6061-O at the center of the FZs for regions welded using MIG technique at several voltages and currents. The microstructure of both FSW and MIG welded regions consists mainly of α-Al grains. The grains are equiaxed in shape in both cases. However, it is clear from microstructural observations that FS welded regions exhibited much lower grain size than those regions welded using MIG technique.

For FS welded regions, it was noticed that, at constant welding speed, increasing the tool rotational speed increases the size of α-Al grains. This may be attributed to the increase in heatinput due to increase in rotational speed. High tool rotational speed resulted in a higher temperature and slower cooling rate in theDRZ zones[3]. It has been found that, within the investigated range, the welding speed has no significant effect on the size of α-Al grains. While, for MIG welded regions, the results revealed that increasing the welding current tends to increase slightly the size of α-Al grains. Increasing the welding voltage has practically no effect on the size of α-Al grains.

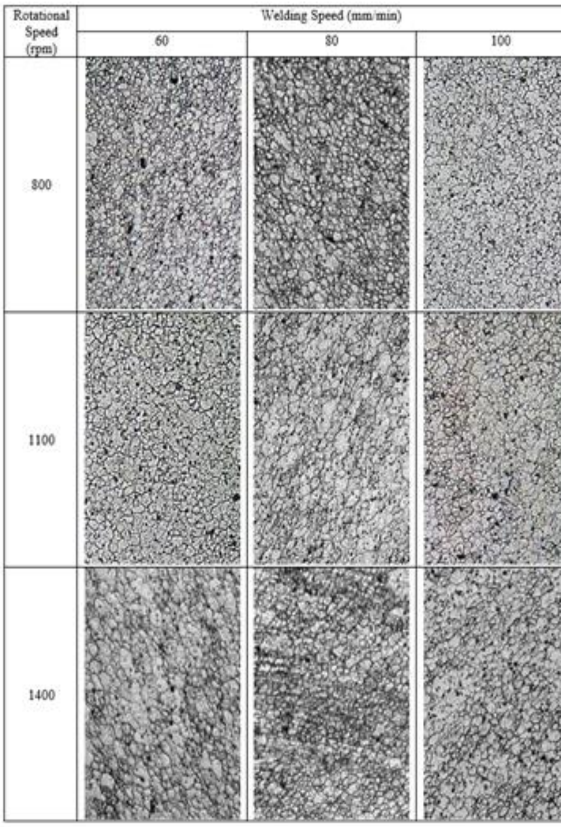

Fig (6). Microstructure at the center of DRZ for AA6061-O samples FS welded using different tool rotational and welding speeds (×100).

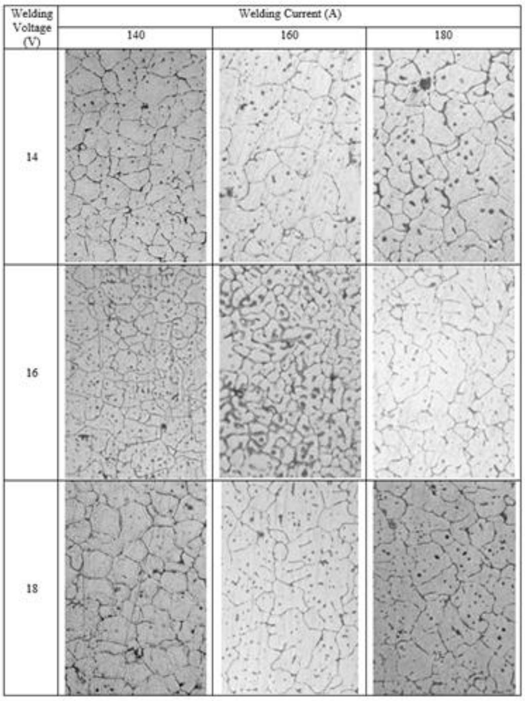

Fig (7). Microstructure at the center of FZ for AA6061-O samples MIG welded using different voltages and currents (×100).

3.3. Impact Toughness of FSWand MIG Joints

Figure 8 shows the variation of the impact energy with the welding speed for samples FS welded at different tool rotational speeds. Figure 9 shows the variation of impact energy for samples welded using MIG technique at different welding voltages. Generally, the results revealed that the FSW samples exhibited significantly higher impact toughness when those welded using MIG technique. The maximum impact toughness for FS welded samples was about 24 J for samples welded at 800 rpm and 100 mm/min. While the maximum impact toughness for MIG was about 10 J for samples welded at 16 V and 140 A.

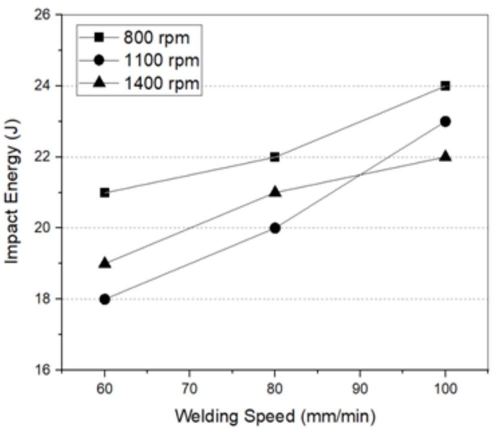

Fig (8). Variation of the impact energy with welding speed for samples FSW using different tool rotational speeds.

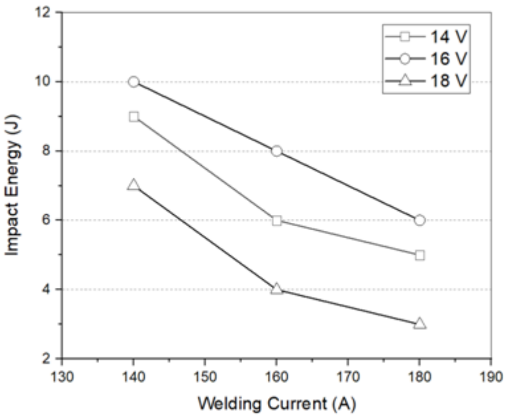

Fig (9). Variation of the impact energy with welding current for samples MIG technique using different welding voltages.

For FSW samples, increasing the tool rotational speed reduces slightly the impact toughness of AA6061-O weldments. For example, increasing the tool rotational speed from 800 rpm to 1400, at constant welding speed of 60 mm, reduces the impact toughness from 21 J to 19 J. In contrast, at constant tool rotational speed increasing the welding speed increasing slightly the impact toughness of FSW specimens. For example, at constant tool rotational speed of 800 rpm, increasing the welding speed from 60 mm/min to 100 mm/min increased the impact toughness from 21 J to 24 J.

It has been found that, for MIG samples, increasing the welding current tends to reduce the impact toughness of the AA6061-O weldments. For example, at constant welding voltage of 18 V, increasing the welding current from 140 A to 180 A reduced the impact toughness from 7 J to 3 J. Also, increasing the welding voltage was found to reduce slightly the impact toughness of the AA6061-O weldments.

For FSW, ANOVA results showed that welding speed (υ) has higher statistical and physical significance on the impact toughness than tool rotational speed (ω). The welding speed (υ) and tool rotational speed (ω) showed F-values of 22.75 and 7.75, respectively.For MIG, ANOVA results showed that welding current (A) has higher statistical and physical significance on the impact toughness when compared with the welding voltage (V). The welding current (A) and welding voltage (V) showed F-values of 112 and 76, respectively.

3.4. Tensile Characteristicsof FSWand MIG Joints

Figure 10 shows the variation of the tensile strength (UTS) with the welding speed for samples FS welded at different tool rotational speeds. Figure 11 shows the variation of tensile strength for samples welded using MIG technique at different welding voltages.

The results revealed that, the FSW specimens exhibited higher tensile strength when compared with the MIG specimens. The maximum ultimate tensile strength for FS welded samples was about 145MPa for samples welded at 1400 rpm and 100 mm/min. While the maximum tensile strength for MIG specimens was about 124 MPa for samples welded at 14 V and 180 A. This about 17% improvement in the tensile strength. It has been noticed that increasing the tool rotational speed and/or the welding speed increase(s) slightly the tensile strength of AA6061-O FS welded specimens. For example, at constant tool rotational speed of 1400 rpm, increasing the welding speed from 60 mm/min to 100 mm/min increased the tensile strength from 140 to 145 MPa.

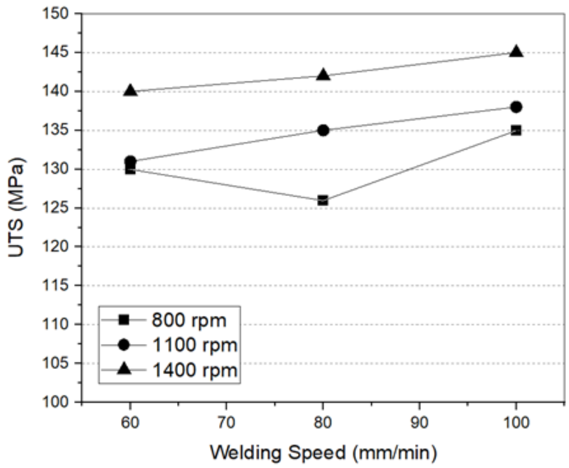

Fig (10). Variation of UTS with welding speed for samples FSW using different tool rotational speeds.

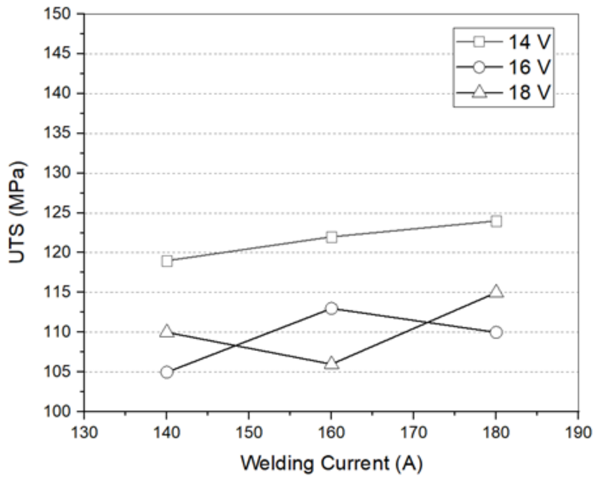

Fig (11). Variation of UTS with welding current for samples MIG technique using different welding voltages.

For MIG tensile specimens, increasing the welding current increases slightly the tensile strength of AA6061-O welded specimens. For example, at constant welding voltage of 14 V, increasing the welding current from 140 A to 180 A increased the tensile strength from 119 to 124 MPa. In contrast, increasing the welding voltage tends to reduce the tensile strength of AA6061-O welded specimens.

For FSW, ANOVA results showed that tool rotational speed (ω) has higher statistical and physical significance on the impact toughness than welding speed (υ). The tool rotational speed (ω) and welding speed (υ) showed F-values of 21.37 and 5.63, respectively. For MIG tensile specimens, ANOVA results showed thatwelding voltage (V) has higher statistical and physical significance on the tensile strength when compared with the welding current (A). The welding voltage (V) and welding current (A) showed F-values of 11.62 and 1.55, respectively.

CONCLUSIONS

The conclusions of significance are drawn as follows:-

1. The welding of AA6061-O aluminum alloys using friction stir welding provides better mechanical properties than using metal inert gas welding. The friction stir welded AA6061-O Al joints exhibited higher tensile strength and impact toughness when compared with those welded using metal inert gas technique.
2. For plates joined using FSW, increasing the tool rotational speed reduces slightly the impact toughness, but increases the ultimate tensile strength, of AA6061-O weldments. Whereas increasing the welding speed increases slightly both of the tensile and the impact toughness.
3. For plates joined using MIG welding, increasing the welding current reduces the impact toughness, but increases the tensile strength, of the AA6061-O weldments. However, increasing the welding voltage reduced slightly both of the tensile strength and impact toughness of the AA6061-O weldments.
4. The ANOVA calculations showed that,for FSW, the welding speed has higher statistical and physical significance on the impact toughness than tool rotational speed. While, for MIG, that welding currenthas higher statistical and physical significance on the impact toughness when compared with the welding voltage.
5. The ANOVA calculations for tensile strength (UTS) showed that,for FSW, the tool rotational speed has higher statistical and physical significance on the impact toughness than the welding speed.For MIG, ANOVA results showed that welding voltage has higher statistical and physical significance on the tensile strength when compared with the welding current.

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