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Comparative Study Between Friction Stir Welding and Tungsten Inert Gas Welding Processes

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Abstract

This study compares the properties of the aluminium alloy welded joints prepared by friction stir welding (FSW) to that of tungsten inert gas (TIG). It concentrated on the microstructure, hardness, corrosion resistance, and wear resistance. It has been found that the joints prepared by FSW have fine microstructure while coarse grains microstructure was obtained for joints produced by TIG welding. Also, the lowest Rockwell hardness measured at the centre of the welding line is 52 for joints prepared by FSW and 46 for ones produced by TIG welding. For corrosion resistance the reslt of tests indicated that the welded joints of the TIG process had higher corrosion resistance, the mass loss after 72 hours is 0.2519 grams from TIG joints and it is about double in the case of FSW joints (0.5263 grams). However, TIG joints have lower wear resistance compared to joints produced by the FSW process. It seems that the grain size of the welded joints, in these two considered welding processes, has a great effect on the investigated properties.

Paper type: Research paper

Keywords: Aluminum, welding, Friction stir welding, Tungsten inert gas, hardness, corrosion, wear.

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Introduction

Aluminium is widely used in industry for its desirable characteristics like its lightweight, high strength, versatility in extruding and casting, and corrosion resistance. But there are many challenges in the welding of aluminium and its alloys faced by the industrial and technologies (Kumar *et. al.,* 2020; Ehab *et. al.,* 2010; Li *et. al.,* 2013). Some factors affect the welding of aluminium alloy such as the formation of an oxidation layer during welding, solidification shrinkage, and the solubility of hydrogen in molten aluminium in addition to other gases(Mohamed *et. al.,* 2023). Also, the corrosion resistance of the weldment is affected by the welding process due to phase transformations that occur in alloy structures (Oluwadare *et. al.,* 2024). The present work compares the mechanical and electrochemical properties of aluminium welded joints produced by Tungsten Inert Gas (TIG) and Friction Stir Welding process (FSW). TIG welding uses an inconsumable Tungsten electrode and it was developed in the 1940s in the USA to weld magnesium and aluminium alloys(Yaduwanshi *et. al.,* 2024). Argon or helium gases are used as an inert shield gas to protect the weld pool from oxidation and contamination resulting in clean and stronger welds (Mehdi *et. al.,* 2020). The tungsten electrode is positioned at the center of the gas nozzle. In the TIG welding process, the workpiece is melted by the electric arc formed between the tungsten electrode and the work-piece. However, TIG welding is the most precise and controllable welding process which make it suitable to

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weld thin metal (Mallipudi *et. al.,* 2021). Arc ignition supplied by high-voltage impulse (high-frequency ignition) which takes the form of non-contact ignition, can weld joints with good penetration. Most metals are welded with direct current, only aluminium is generally welded with alternating current. TIG welding can be used for all weldable metals. It is mostly used for welding stainless steel, aluminium, and nickel alloys (Zaho *et. al.,* 2010).

FSW was developed in 1991 in the UK, and it's carried out in a solid state to join aluminium alloys which are unweldable by conventional welding techniques (Cesar, 2008; Li *et. al.,* 2013). Friction stir welding uses a hard unconsumable cylindrical tool which consists of a tool shoulder and pin extending from the shoulder (Cavaliere and Panella, 2008). The FSW process is implemented by moving the rotating tool along the interface between two plates. The tool pin is inserted into the weld line till the shoulder makes surface contact with the weld plates under prescribed pressure. Friction heat is generated due to the relative motion between the rotating tool and the fixed weld plates(Harachai and Prasomthong, 2023). After, ensuring sufficient heat is introduced to the welding zone, where the weld plate reaches the plastic stage, the tool proceeds with its traverse motion at a suitable speed along the weld line. The mixing of the plasticized material by the rotating pin, in the presence of the shoulder and the backing plate constrains the flow of plasticized material producing a welded joint (Senthamaraikannan, 2023).

FSW compared to fusion welding has many advantages such as, there is no filler metals, no shield gas in addition to there is no smoke or dust. Also, the process temperature of the FSW method is always less than the melting point of the weld material. Without melting, less amount of heat is introduced to the welding zone compared with conventional fusion welding(Mosmi and Mbana 2020). Thus, the cast microstructure formed by fusion welding in addition to solidification shrinkages can be avoided. Therefore, the heat distortions are reduced and thereby the amount of residual stresses.

1 Materials and methods

Two plates of commercial aluminium alloy with dimensions 300x150x6mm were prepared for FSW and TIG welding. The chemical composition of aluminium alloy is given in **Table 1**. A special fixture was designed for the vertical milling machine, which makes it capable of handling the friction stir welding process as shown in **Figure 1**. A welding tool with a shoulder diameter of 18 mm, made from high-carbon steel was used in the FSW process. The rotational speed of the tool and welding speed were taken as 1200 rpm and 85 mm/min respectively. A square pin with a 6mm length and 5.8mm height was used in the FS welding process. The above FSW parameters were chosen as an optimum welding parameter used by previous studies (Jawdat *et al,* 2014; Rai *et al,* 2011)

Table 1 Chemical composition percentage of the aluminium alloy.

Elements	Cu	Mg	Si	Fe	Mn	Ni	Zn	Ti	Cr	Al
Wt(%)	0.031	5.49	<0.01	0.29	0.53	<0.01	0.024	0.017	0.067	balance

Similar to FSW plates prepared and welded by the TIG welding process. A tungsten electrode with a 3.2mm diameter was used. Argon is used as a shielding gas with 15L/min, and 110Amp alternate current was used and concentrated on the point to heat the welding area. The welding speed was kept at 100mm/min. These TIG welding parameters are recommended for welding aluminium alloy from previous researchers (Mehdi and Mishra, 2020; Parminder *et al.*, 2012). Microstructure examined under optical microscope. The metallographic samples were cut from the welds of FSW and TIG processes weldment at different points as shown in **Figure 2**. The metallographic samples were prepared by standard metallographic techniques for metallographic examination under a Leitz Wetzler MM6 optical microscope. Keller's reagents were used to reveal the grain structure (Vander Voort, 1984). The Rockwell hardness scale *E* used to measure the hardness of welded joints. A sufficient number of readings have been taken in the transverse section of the welded joints. All specimens have been ground to prepare them for the hardness test. Abrasive wear resistance was carried out using the pin-on-disc machine. Three wear specimens were cut out from the middle area of each weldment that was welded either by FSW or TIG processes. The wear pin has 4mm in diameter*(D)* and length *(L)* of 25mm, is loaded normally against emery paper of 1000 grade attached on the rotating disc. A normal load of 10N was applied as pressing force *(F)* on the tested pin. The pin was put on 38mm track of a disc rotating at speed of 50rpm. The accumulated loss of mass (ALM) was measured by weighing the wear specimen using a digital balance, with accuracy of 0.1mg, before and after carrying out the abrasive wear of each test.

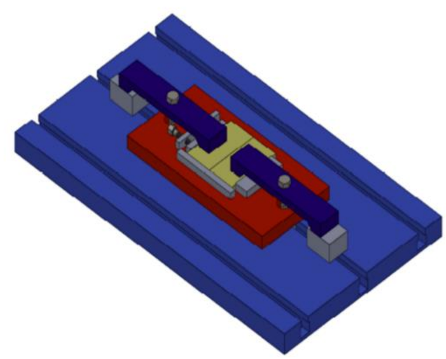

Fig. 1 The special fixture used to handle FSW by vertical milling machine.

The time of the test was running for 20 minutes, where every five minutes the test is interrupted and the pin weighed. Before weighing, the pin was washed and dried. In order to study the corrosion behaviour of the welded joints, specimens with dimensions of 20×40×6mm were used. The corrosion test was carried out regarding to ASTM G31. Each sample was drilled with a 5mm drill bit to provide a hole for the suspension and immersion purpose. Fully immersion technique in an acidic solution was used; namely 0.1M solution of hydrochloric acid (0.1M HCl). Before carrying out the test, samples were washed with ethanol and their mass was measured with an electric balance of 0.1mg resolution, then the samples were immersed in the solution for a period of 72 hours, and each specimen was weighed before being immersed in the solution, then it was weighed every 24 hours, the first reading was taken after 2 hours. The solution temperature (T) was kept between 23-25°C by using a water bath. The mass loss was measured by weighing the samples before and after each test. Five samples were examined for each joint prepared by FSW and TIG process..

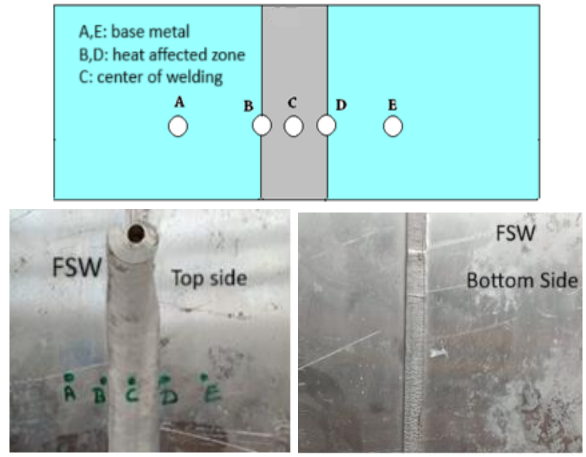

Fig. 2 The distribution of the tested points across the welded joint.

2 Results and Discussion

2.1 Microstructure

Optical microscopy was used to examine the welding joints produced by FSW and TIG process. The microstructure were taken at the center line of the welding zone (point C), at both sides adjacent to the welding zone (points B,D), and at the base metal (points A, E) as shown in **Figure 2**. **Figure 3** shows the microstructure of specimens were taken from the base metal of weldments prepared either by FSW or TIG process. It seems that the base metal microstructure not affected by the welding process. Other microstructure samples were taken at the boundary of the welding zone, for joints produced either by the FSW or TIG process. In FSW process, the welds are produced under the direct action of friction heating introduced to the welding zone, accompany by mechanical deformation due to a rotating of the welding tool. FSW has formally three distinct microstructural regions including the stir zone (SZ) along with the weld centerline, thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) (Janic *et al.,* 2020). The SZ is the region exposed to friction heat and thus plastic deformation occur during FSW process (Khaliq *et al.*, 2023). Thermo mechanically affected zone is adjacent to SZ either on advancing or retreating side. TMAZ has less heat deformation compared to the weld center(Jata *et al*., 1999).

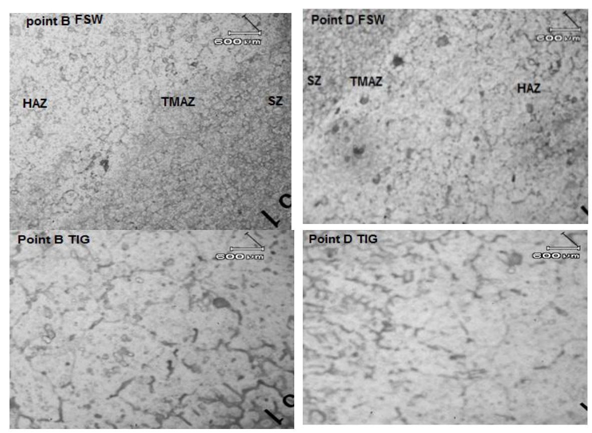

Fig. 3 Microstructure at base material for FSW and TIG welding.

The heat-affected zone has only temperature rise and not affected by mechanical deformation, usually structure of the base materil starts to appear(Leal *et al.*, 2008). **Figure 4** shows the microstructure of FSW microstructure evolution at the boundary of the SZ, which has local thermo-mechanical cycle experienced during welding process (Sun *et al.,* 2022). Microstrutre of point B lies on retreating side of the FSweld, while point D taken at advancing side of the FSweld. The microtructure shows that TMAZ has elongated and coarse grains as compared by SZ grains. However, HAZ zone starts to appear in these microstrucure where the grains of the base metal can be notices at both sides of the weldment. For TIG process, the microstrucure has taken at point B and D at the boundaries of the welding center. During TIG process more heat is introduced to these regions raising its temperature. Thus, the grains posses sufficient time to growth, lefting coarse grain

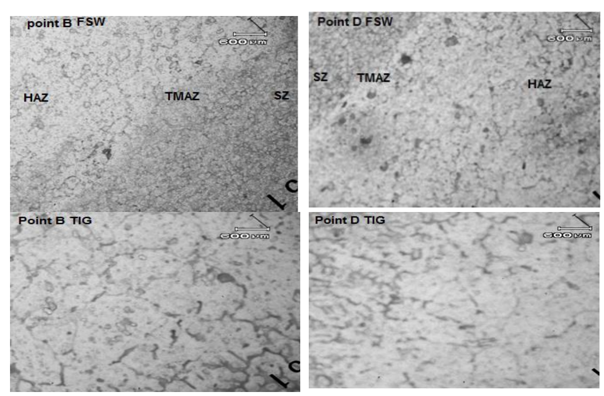

Fig.4 Microstructure of FSW at advancing and retreating side and TIG welding process.

with clear dendrites as shown in **Figure 3**. Due to the fast heating of base metal, the microstructure of aluminium alloy joints prepared by TIG welding contains dendrites structure (Parminder *et al.*, 2012).

Figure 5 shows the microstructure at the centre line of the welding zone for FSW and TIG welding. The heat introduced to the welding region is higher in TIG welding as compared to the FSW process(Mallipudi *et al.*, 2021). So, it can be seen that the microstructure of FSW has fine grains as compared to that of the TIG welding process. These fine grains are the result of recrystallization possible due to the elevated temperatures at the stir zone. During the FSW process, a large amount of plastic deformation occurred for the workpiece through the rotating pin and the shoulder. Such plastic deformation gives rise to subgrains with dislocation at the boundaries. The structure of the base material is completely eliminated and replaced by a fine equiaxed recrystallised grain structure in SZ during the recrystallization process. So that the grain sizes in the centre of the stir zone are smaller than those of the base metal (Jawdat *et al.*, 2014). While the grains have sufficient time to solidify and grow in the case of TIG welding, left a coarse grain size. **Figure 5** shows the forming of the interdendrite with a relatively large second arm space.

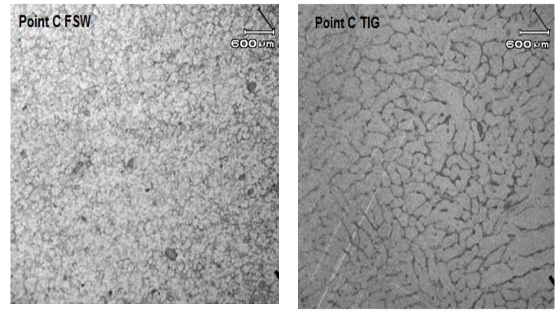

Fig. 5 Microstructure at the centre of the welded joints by FSW and TIG.

2.2 Hardness and wear

The Rockwell hardness HRE ; is measured from the SZ toward the base material from both sides, HRE values of FSW and TIG weldments are shown in **Figure 6**. The figure shows that the hardness values of the TIG and FSW welded joints are the lowest at the center line, where softening occurs at the centre of joints (Zaho *et al.*, 2010). The hardness increases gradually with distance from center line toward the base material. The hardness of SZ joints produced by FSW is higher than that of centre joints welded by the TIG process. The same results were obtained by other researchers (He *et al.*, 2011). It can be noticed that the hardness in the base metal is higher than that of the welded zone for both the TIG and FSW processes. This is due to the high heat applied in the welded zone that coarsens the grains.

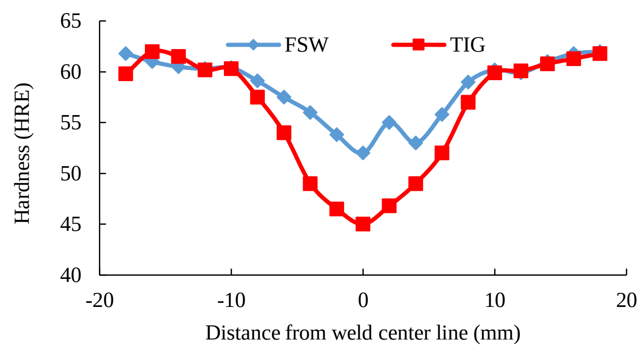

Fig. 6 The hardness profile in the travers direction of the welding line for FSW and TIGwelding joints**.**

The accumulated mass loss for a brasive wear test carried out for base metal, FSW and TIG weldments. Three samples were cut from each of base metal, ceneter line of FSW and TIG joints, and then prepared and tested by a barsive wear machine. The mass loss measured and recorded of each sample and the average value of three reading is shown in **Figure 7**. The accumulated mass loss for TIG specimen is higher than that of base metal and FSW specimens. As it has been discussed earlier, the welded joints by FSW has higher hardness than TIG welded joints, may leads to this results. Also, Fig7 shows that the mass losses of joints prepared by FSW are less than the base metal and TIG specimens. Hardness affects directly the wear behavior of the metals. As it is well known that, the common mechanisms of abrasive wear are ploughing, cutting and fragmentation (Wang and Hutching, 1988). The ploughing mechanism depends on the hardness difference between the abrasive material and the wear specimen. While cutting mechanism depends more on the grain size of the wear specimen, large grain size leads to more cutting which is large in TIG case. Fragmentation happens when crack generated around ploughing

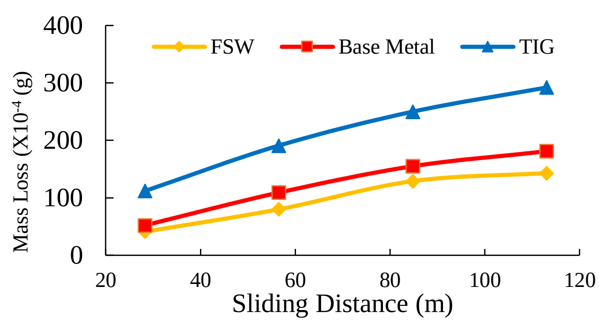

Fig. 7 Accumulated mass loss of abrasive wear for base metal, FSW and TIG weldmen.

grooves propagate creating more mass loss from the worn specimens (Sun *et al.*, 2022). However, the probabilty of crack propagation is higher in coarse grains rather than in fine grains.

2.3 Corrosion

Corrosion test has been carried out for samples taken from the base metal, center of TIG and SZ of FSW weldment. The corrosion resistance of the materials correlated to mass loss of the corrosion samples. **Figure 8** shows that FSW weldment has the lowest corrosion resistance, where mass loss rate is greater than TIG weldment. It is noted that the TIG weldment has the highest corrosion resistance where it shows the lowest mass loss rate. The resistance of the grains boundaries are usually weaker than the grain structure if they are subjected to chemical attack by corrosive agents, as the grain boundaries contain usually many different types of foreign atoms. At the same measured area the total area of the grain boundaries in a fine grain structure is larger than the total grain boundaries area of coarse grain structure as in case of TIG weldment compared by FSW. So, it may be expected that the fine grain structure, will be attacked more severely by the corrosive agents rather than the coarse grain structure. This argument could cause the high mass loss of the fine grain structure of FS weldments compared to less mass loss of the TIG weldments, which have relatively large grains structure. However, a chemical composition analysis has been carried out for samples taken from the center line of weldment welded by TIG and friction stir welding and given in **Table 2**. It has been found that the Mg% content is 5.32 and 2.9 for FSW and TIG samples respectively. Increasing the Mg% content will increase the strength of the aluminum alloy. But, when the percentage of magnesium is more than 4%, the corrosion resistance of the aluminum alloy will gradually decreases. Where the intermetallic particles starts to participate at the grain boundaries. These intermetallic particles are anodic compared by aluminum and thus they cause electrochemical imbalance in the grains that leads to "Inter-Granular Corrosion, (IGC)" (Mehdi and Mishra, 2020). This causes an increase in mass loss during corrosion process.

Table 2 Chemical composition at the centre of FSW and TIG welded joints.

	Element	Cu	Mg	Si	Fe	Mn	Ni	Zn	Ti	Cr	Al
FSW	(Wt%)	0.031	5.32	<0.01	0.29	0.52	<0.01	0.022	0.014	0.066	93.72
TIG	(Wt%)	0.033	2.97	1.51	0.28	0.30	<0.01	0.016	0.12	0.051	94.71

Conclusions

As a comparison between FSW and TIG welding, the ivistiagtion leads to:

1) The grain size produced by fusion welding, TIG, is larger than that of grain size produced in FSW.
2) The hardness at centetr line of the FSW weldment (52 HRE) is higher than the TIG weldments (42 HRE), this is because the grains of the FSW weldments are smaller in size if compared with the grains of the TIG weldments.
3) The wear resistance of FSW weldments (143×10^{-4} grams) is higher than that of TIG weldments (192×10^{-4} grams), where the effect of grain size is prominent in ploughing wear.
4) The corrosion resistant of TIG samples are larger than that of FSW samples, due to Mg% content and the grain size.

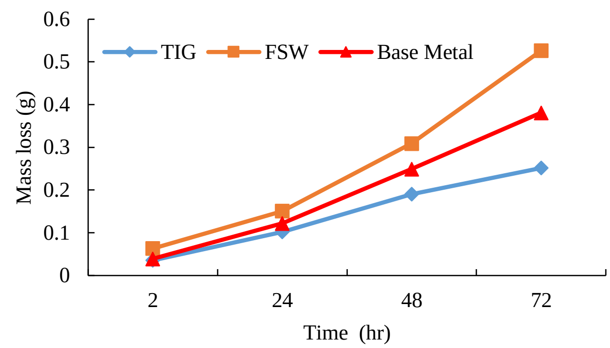

Fig. 8 Corrosion mass loss for FSW, TIG and base metal.

Nomenclature

ALM	=Accumulated mass loss	[gram]
D	=Diameter	[mm]
L	=Length	[mm]
T	=Temperature	[°C]

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