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Correlation between Microstructure and Bending of FSW and TIG Welded Mg-Rich Aluminium Alloy Joints

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Abstract. This paper reports on the mechanical properties in relation to the microstructure of the Mg-rich aluminium alloy joints fabricated through friction stir welding (FSW) and tungsten inert gas (TIG) welding techniques. The microstructure, tensile, and bending tests were conducted on friction stir, and TIG welded joints. Most coarse grains (27.81µm) dominated the joint produced using the TIG welding technique, while the refined grains (11.26 µm) mostly dominated the joint made through the FSW technique. The ultimate tensile strength (UTS) of the joint fabricated using the FSW technique was higher (379 MPa) compared to the TIG-welded joint (260 MPa). However, the inverse behaviour was observed when looking at the tensile elongation of the very same joints. The bending results correlated with UTS results, and this phenomenon was attributed to the microstructural grain size.

Introduction

Aluminium alloys are generally used in producing engineering structures used for different purposes. These structures are made through joining dissimilar materials, and the joining procedure is usually chosen based on various properties in relation to the materials to be joined. Aluminium alloys have been joined using tungsten inert gas (TIG) welding until the discovery of friction stir welding (FSW). TIG welding requires the melting of filler material to join materials successfully, yet friction stir welding softens the materials to be welded through the specially designed tool. The FSW technique, a solid-state method, offers an advantage over fusion welding [1-4] as it eliminates the problems observed in fusion welding of aluminium alloys, such as porosity formation [5-8]. Failure of structures, especially those with joints, usually occurs at the joints. This is because joints typically possess different micro-defects that are unintentionally caused by the nature of the joining techniques. These post-defects are the ones that are encouraging many researchers to either look into new joining techniques or improve the existing methods so that they produce joints and structures with better performance.

Numerous works have been conducted to optimise friction stir welding and TIG welding techniques when welding similar and dissimilar materials. Hazari et al. [9] have investigated the deformation behaviour of the AA6082 and AA8011 joints produced through the TIG welding technique. The gas flow rate, welding current, and filler diameter were the only varying parameters among the parameters used. It was discovered that the gas flow rate and the current increase significantly influenced the joint's ultimate tensile strength (UTS). However, the filler diameter did not contribute substantially to the microhardness and the UTS. Kumar et al. [10] have conducted a comparative analysis of the tensile and fatigue behaviour of AA5082 and AA7075 joints produced through TIG and FSW techniques. It was discovered that the specimens made using FSW exhibited higher fatigue cycles and high tensile properties compared to those produced through TIG welding.

The microhardness of the TIG welded specimens was lower than that of the specimens made through the FSW technique. Munoz et al. [11] have investigated the microstructural and mechanical behaviour of Al-4.5Mg-0.26Sc joints fabricated using FSW and TIG welding techniques. It was discovered that the strengthening precipitates were significantly reduced post-TIG welding technique. The decrease in strengthening precipitates was attributed to the high heat involved during the TIG welding procedure. The loss in precipitates consequently resulted in a loss in the joint's mechanical properties. Deng et al. [12] have studied the influence of Sc and Zr additions on Al-Mg-Zn joints produced with FSW and TIG welding techniques. Sc and Zr's addition increased joints' tensile properties produced through FSW and TIG. However, friction stir welded joints exhibited higher tensile properties than joints produced using TIG welding. This behaviour was attributed to the high heat input involved during the TIG welding procedure.

The available literature on the subject indicates that the mechanical behaviour of joints created using Friction Stir Welding (FSW) and Tungsten Inert Gas (TIG) welding techniques varies depending on the specific aluminium alloy used. This variation in mechanical behaviour is primarily attributed to different alloying elements in each aluminium alloy, each of which has a unique sensitivity to various factors. Furthermore, it has been noted that there is a lack of research on joints created from magnesium-rich aluminium alloys. As a result, this study aims to investigate the impact of microstructural arrangement on the bending properties of FSW and TIG welded magnesium-rich aluminium alloys. This research is particularly relevant because the magnesium-rich alloy is a relatively lightweight metal with an excellent strength-to-weight ratio, making it a desirable material for various industries. Understanding how the microstructure of FSW and TIG welded magnesium-rich aluminium alloys affects their mechanical properties will provide insights into how these alloys can be further optimized for various applications. The outcomes of this study could potentially have significant implications for the design and fabrication of lightweight structures for aerospace, automotive, and other industries.

Experimental Procedure

The 6 mm thick Mg-rich aluminium alloy (H321) plate was prepared into 250 x 75 mm, and the dimensioning was based on the fixture capacity of friction stir welding machine. The chemical composition of the material utilized in this study is presented in Table 1. Two sets of plates were prepared, i.e. friction stir welded and TIG-welded plates. The prepared plates were then friction stir welded using semi-automated milling machine, and the other set of plate was welded using TIG machine. The full details of the machines can be accessed in the literature [13,14]. The hexagonal tool pin profile with a 20 mm shoulder diameter, 7 mm probe diameter, and 5.8 mm pin length was used in conducting the FSW procedure (see figure 1 (a)). The tool profile was adopted from the literature [15]. The rotational tool speed of 1000 rpm and the traverse speed of 40 mm/min were adapted from previous studies [15,16]. The TIG welding was conducted on a 60º V-groove welding using ER5356 filler, and the parameters used are adopted from the literature [15]. Figure 1 (b) show the TIG-welded plate while figure 1 (c) shows the friction stir welding of the plates.

Table 1: Chemical composition of Mg-rich aluminium alloy

Material	**Al**	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**
Mg-rich aluminium alloy	Balance	0.148	0.163	0.015	0.684	4.022	0.040	0.011	0.017

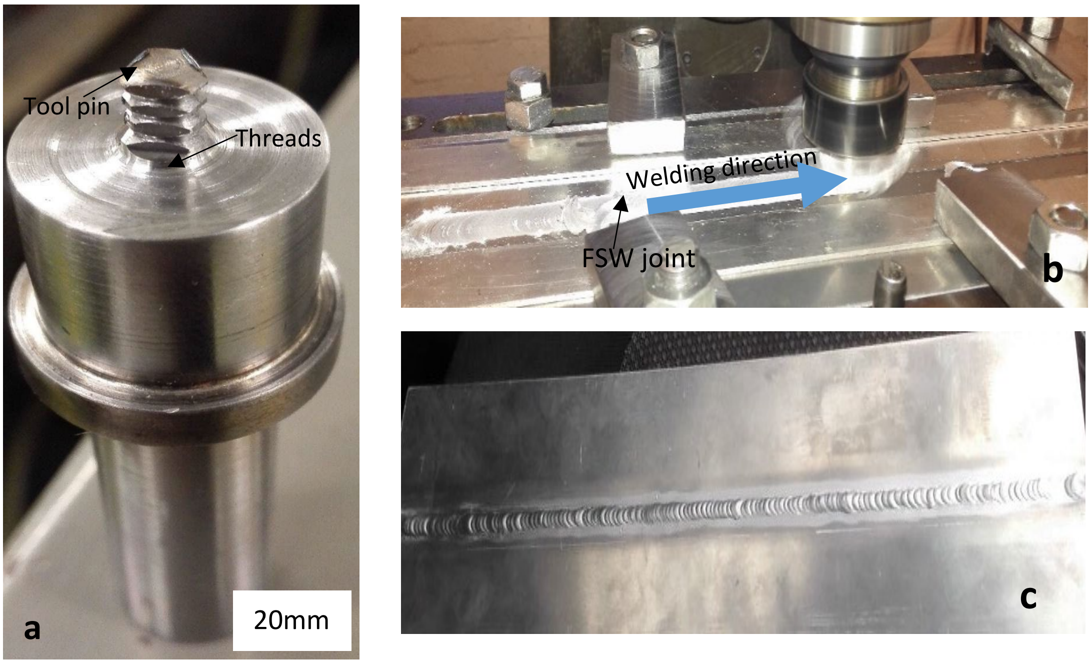
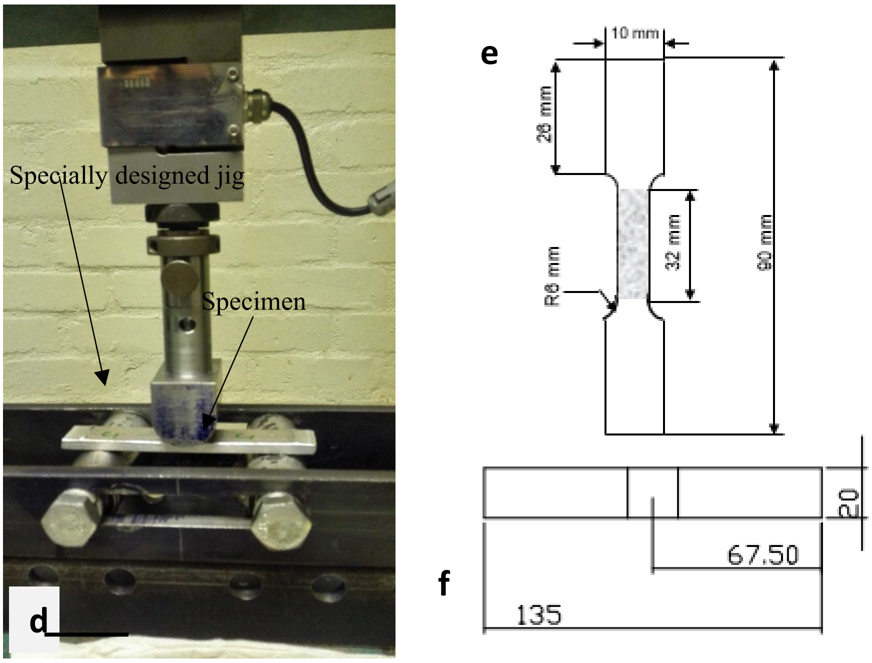


Figure 1: (a) FSW pin profile; (b) Sample of the TIG-welded plates; (c) friction stir welding of the plates



(d) Three-point bending setup, (e) Schematic diagram of tensile specimen, (f) schematic diagram of bending specimen (dimensions in mm).

The two sets of welded plates were prepared for different tests, including macrostructural analysis, microstructural analysis, tensile test, bending test, and microhardness test. The Motic AE2000Met inverted metallurgical microscopy was used to conduct microstructural measurement and the etchants used are the same as those reported in the literature [17]. Before running microhardness analysis, the macrostructure profiles were captured using InnovaTest Falcon 500 machine. The microhardness analysis was conducted based on ASTM E384-11 standard, and the load of 0.5 kg with the10s dwelling time were used in all tests. The tensile and bending tests were conducted using Hounsfield tensile testing machine with the guidance of ASTM E8-04 and ASTM E290-14 standards. The strain rate of 3mm/min was used in conducting the tensile tests. The bending setup is shown in figure 1(d), and the dimensions of the tensile test and the bending test specimens (shown in Fig. 1 (e) & (f)) were adopted from the literature [15,17]. The tensile and bending tests were performed on the specimens until they failed.

Results and Discussions

Macrostructural analysis

Fig. 2 (a) and (b) depict the macrostructural profile for TIG-welded and friction stir-welded joints. The H-like profile was observed in Fig. 2(a), and this is the trace of the filler used in TIG welding and the H-like shape of the joint is due to the V-groove used during the welding preparation. There was a crack detected on the joint, which was caused by uncontrolled cooling of the joint post welding. The onion rings without a trace of cracks were observed in Fig. 2(b), and this is always the macrostructure of friction stir welded joint [15-18]. The absence of defects suggests the proper bonding of the joint. The stacked like feature observed from the FSW joint is the tooth trace of the pin.

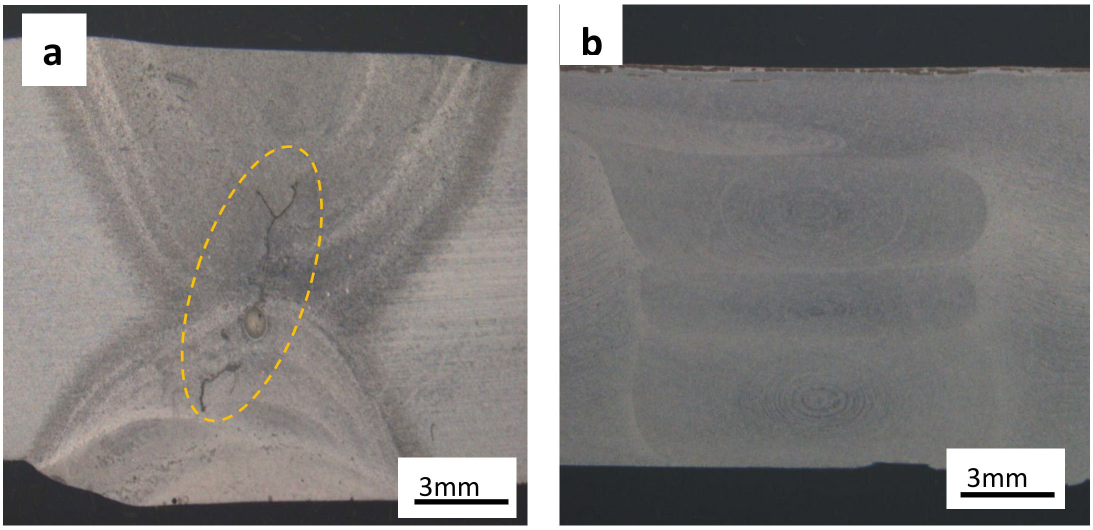


Figure 2: (a) Macrograph of TIG-welded joint; (b) Macrograph of friction stir welded joint

Microstructural analysis

The microstructure of the FSW and TIG welded joints is depicted in Fig. 3 (a) and (b), respectively. The grain sizes of each joint were measured using ImageJ software through the Linear Intercept technique [17,18]. The joint produced using the FSW technique shows a nearly uniform grain size, while grain size variation could be easily seen on the TIG welded joint. The measured average grain size of the TIG welded joint was 27.811 µm, while the average grain size of the friction stir welded joint was 11.258 µm. The refined grains in the FSW joint are as a result of high temperature and high deformation rate from the pin stirring action [19,20].

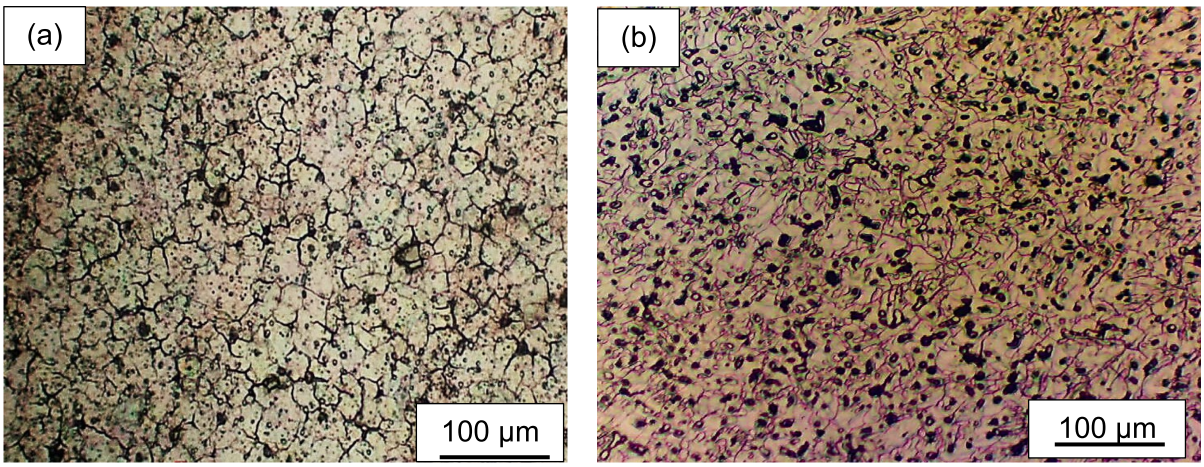


Figure 3: Micrographs, (a) FSW SZ and (b) TIG SZ.

Mechanical properties

The tensile test results for FSW and TIG welded joints are shown in figure 4 (a), while the bending test results of the same joints are depicted in Fig. 4 (b). It should be noted that the mechanical tests were repeated twice and only the best results were included in this paper. The ultimate tensile strength (UTS) for the friction stir welded joint was approximately 379 MPa, while that of the TIG welded joint was about 260 MPa. The high UTS observed from the FSW joint is credited to the grain arrangement and the Mg-based precipitates that are always associated with this grade of aluminium [21]. However, the tensile elongation for the TIG welded joint (18.4%) was higher than that of the friction stir welded joint (6%). The bending results show two curves per joint, and this is because the bending was conducted on the face and the root of each joint [15]. The friction stir welded joint exhibited higher bending strength (~600 MPa) than the TIG welded joint (~300 MPa). This difference in bending properties is credited to grain refinement [22]. It was also observed that the bending strength on the face was higher than at the root in each joint, and this phenomenon was reported elsewhere [23]. It is evident from the bending graph that FSW joints can withstand the load that is almost twice the load that the TIG welded joint can withstand.

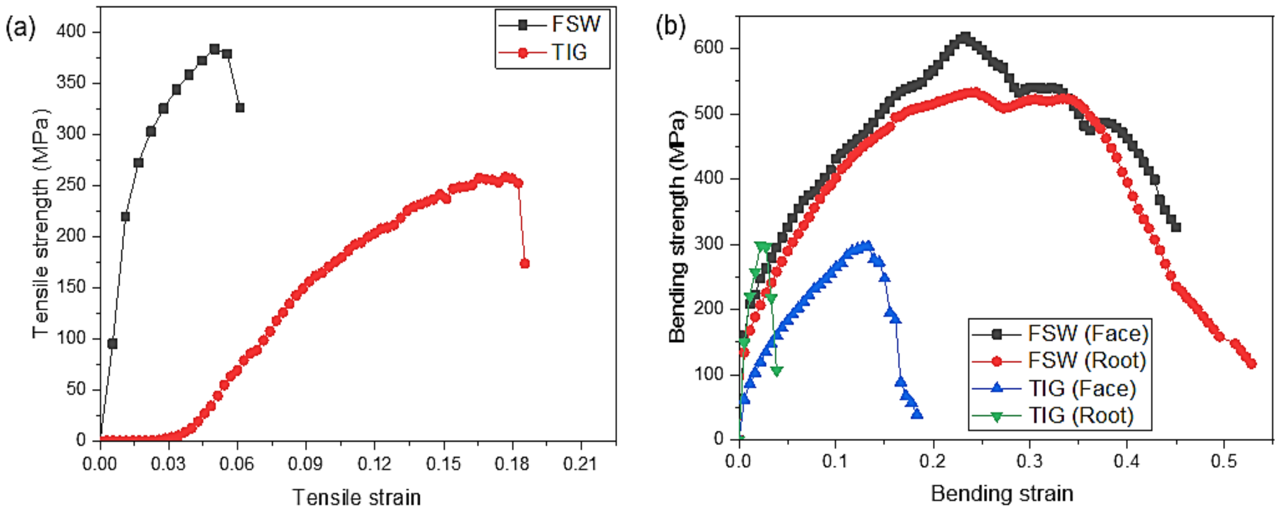


Figure 4: (a) Tensile properties of FSW and TIG welded joints; (b) Bending results for FSW and TIG welded joints

Conclusions

The correlation between the microstructure and the mechanical properties of friction stir welded and TIG welded joints was studied successfully. The following conclusion was drawn from this study:

- The friction stir welded joint was composed of refined grains (~11 μm) while the coarse grains dominated TIG-welded joint (~27 μm). The refined grains resulted from dynamic recrystallisation due to the pin stirring action.
- The UTS of the TIG-welded joint was lower (260 MPa) than that of the friction stir welded joints (379 MPa). The difference in UTS was attributed to the microstructural arrangement of the joints. The tensile elongation of the TIG-welded joint was higher (18.4%) than that of the friction stir welded joints (6%) and this phenomenon is normal.
- The bending strength of the friction stir welded joint was almost twice (~600 MPa) that of the TIG- welded joint (~300 MPa). This behaviour was also attributed to the microstructural arrangement of the joints.

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