The effect of FSP conditions towards microstructure and mechanical properties of the AA6082/AA8011 TIG-welded joint

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Abstract

The friction stir processing (FSP) technique was employed on the AA6082-AA8011 TIG-welded joints to investigate the contribution of the processing conditions on the microstructure and mechanical properties of the processed joints. The TIG-welded joints were subjected to the FSP technique under normal and submerged conditions. The tests conducted included microstructural analysis, tensile, Vickers hardness and fracture surface analysis. The microstructural analysis of the normal FSP joints showed the minimum average grain size of 7.83 μm and maximum average of 9.25 μm, while the submerged FSP joints had a range of 6.33 μm to 4.86 μm. All the FSPed joints showed a great grain size refinement compared to the TIG-welded joints which had an average grain size range of 25.71 μm to 21.99 μm. The ultimate tensile strength (UTS) of the joints processed under normal conditions ranged between 87.14 MPa and 88.33 MPa while that of the submerged conditions ranged between 88.79 MPa and 91.56 MPa. The elongation range of the normal FSP joints was 22.71% to 24.28% while 24.08% to 28.81% was obtained from the submerged FSP joints. The TIG-welded joints had a UTS range of 80.27 MPa to 85.36 MPa with an elongation of 21.82% to 23.58% respectively. FSP improved both the tensile strength and ductility of the joints with the submerged conditions giving best improved results. The fracture surface morphology revealed a ductile failure mode for all the specimens. The TIG-welded joints had a maximum hardness range of 56 HV to 60 HV, while that of the normal and submerged FSP joints ranged between 54 HV and 57 HV, and between 60 HV and 65 HV, respectively. The application of Normal FSP on the TIG welded joints slightly compromised the hardness of the joints under normal conditions but improved under SFSP due to rapid cooling.

1. Introduction

The joining of dissimilar aluminium alloys has become the new norm and gained much attention in many industries due to the favourable advantages involved [1, 2]. The fabrication of the dissimilar aluminium alloy joints can be produced using various techniques including tungsten inert gas (TIG) welding and friction stir welding techniques (FSW). The friction stir welding technique was patented in 1991 by The Welding Institute (TWI) in the United Kingdom [3, 4]. The friction stir welding later variated to the friction stir processing (FSP) technique adapting the same principle of FSW [4]. The friction stir processing technique is known as a microstructural modification technique, where a rotating tool is inserted in a single work-piece for the modification of the microstructural grain structure to improve a specific property [4, 5]. The FSP application continues to expand since it is now being used to enhance the properties of the fusion-welded similar and dissimilar material joints. This is due to fusion-welded joints having many drawbacks like porosities, solidification cracking, and thermal residual stresses, and excessive heat experienced by the joint which weakens joint properties especially in soft materials [5, 6]. There are recent works that have employed the FSP technique on welded joints and this includes works that are presented below.
Mehdi and Mishra [7] evaluated the microstructure and mechanical properties of the friction stir processed TIG-welded AA6061/AA7075 dissimilar aluminium alloy joints. The results revealed that the tensile strength of the friction stir-processed TIG-welded joints was higher than that of the TIG-welded joints. The microstructural grain size was found to be finer compared to the TIG-welded ones. The maximum percentage elongation was obtained on the friction stir processed joints. The hardness of the friction stir processed joints was also improved from 70 HV to 105 HV. The influence of friction stir processing on the TIG-welded AA2024 was successfully investigated by Devireddy et al [8]. They discovered that the defects and porosities created by the TIG welding technique were reduced after friction stir processing. The application of FSP also destroyed the coarse dendritic grain structure which resulted in the precipitates of the second particles found along the grain boundaries being dissolved. Furthermore, the microstructural grains and mechanical properties were significantly improved. FSP was successfully used to improve the hardness and tensile properties of the TIG-welded AA6061 joint by Thakral et al [9]. The microstructure of the FSP joint was refined and equiaxed. FSP was employed to improve the properties of the AA5083 TIG-welded joints. The results showed a great improvement in the yield and tensile strength, post-FSP in comparison to the welded. The fracture mode of the joints was transformed from brittle to ductile fracture mode [10]. Similar works where FSP was successfully used to improve the joint properties of the fusion-welded joints were reported elsewhere [11–13].

The continuous improvement being made in FSP technology has resulted in the discovery of the new variation of FSP known as submerged friction stir processing (SFSP). SFSP is an alternate method that has been praised for producing attractive results. The SFSP is known for creating fine-grained microstructure [14]. This method uses the same principle as FSP but the entire procedure is conducted under immersed conditions [14–16]. Since SFSP is conducted underwater, the temperature experienced by the tool in SFSP is lower than in normal FSP (NFSP) [17]. Sabari et al [18] and Feng et al [19] added that adding a cooling medium during FSP lowers the peak temperature and weakens the annealing effect of the thermal cycle in the joint. Liu and Feng [20] employed SFSP on the AA2219-T6 to evaluate microstructure characterization of the stir zone of the AA2219-T6 alloy. It was found that the average grain size of the stir zone was significantly reduced compared to the base material one. The hardness of the stir zone was reported to be lower than that of the precipitation strengthened base. Mabuwa and Msomi [21] conducted a comparative analysis between the normal and submerged friction stir processed friction stir welded dissimilar friction stir welded joints. The results showed that the SFSP conditions showed finer grain sizes in comparison to normal FSP ones and friction stir welded ones. The SFSP dissimilar joints were reported to be more ductile than the normal FSPEd ones. The tensile strength of the SFSP specimens was more improved compared to the normal FSP ones. These improvements were substantiated to be caused by the water rapid cooling system. The specimen sampling was also found to have an impact on the microstructure and mechanical properties of both friction stir welded and friction stir processed conditions, where the specimens extracted towards the end of the joints yielded better results.

Based on the provided literature it is evident that FSP has been successfully applied to improve the welded joints including TIG-welded similar and dissimilar NFSP joints. However, there is no searchable literature where SFSP was applied on the TIG-welded joints and compared to other fusion welded joints, hence this study was undertaken. This study is reporting on the effect that both normal and submerged friction stir processing have on the microstructure and mechanical properties of the dissimilar TIG-welded AA6082/A8011 dissimilar joints.

### 2. Materials and methods

The materials used in this study were the 6 mm thick aluminium alloy plates AA6082-T651 and AA8011-H14. AA6082-T651 is an Al-Mg-Si alloy consisting of sufficient plasticity for extrusions and contains very high relative strength [22, 23]. AA8011-H14 is an Al-Fe grade consisting of moderate strength with excellent corrosion resistance, high ductility, and a reflective appearance [23].

The two mentioned aluminium alloys are mostly used in aerospace engineering. Table 1 shows the chemical compositions of the materials. Three pairs of the dissimilar plates were dimensioned to 250 mm × 55 mm. The cut plates were TIG-welded using the parameters presented in table 2. It should be noted that the ER4043 wire

| Table 1. Chemical compositions (wt.%). |
|---------------------------------------|
| Mg | Zn | Ti | Cr | Si | Mn | Fe | Cu | Al                          |
|----------------|----|----|----|----|----|----|----|-----------------------------|
| AA6082-T651    | 1.052 | 0.544 | 0.013 | 0.000 | 1.211 | 0.355 | 0.679 | 0.028 | Bal           |
| AA8011-H14     | 0.549 | 0.084 | 0.016 | 0.028 | 0.275 | 0.758 | 1.332 | 0.051 | Bal           |
filler used during TIG welding chemical composition included 0.05% of magnesium, 0.10% of zinc, 5.3% silicon, 0.8% of iron, 0.025% of copper and 93.705% of aluminium [11]. The TIG-welded plate is shown in figure 1. One pair was friction stir processed underwater at room temperature and one pair was friction stir processed at room temperature (normal) using a converted semi-automated milling machine. During FSP, the AA6082-T651 was positioned on the advancing side of the tool with AA8011-H14 on the retreating side. The process parameters for both FSP conditions included a traverse speed of 55 mm min\(^{-1}\), a tool rotational speed of 1200 rpm, a tool tilt angle of 2\(^\circ\), and a dwell time of 20 s. The tool used was made of high-speed steel and its pin profile was triangular with flutes. The tool shoulder of 20 mm, tool pin length of 5.8 mm, and a tool pin diameter of 7 mm. A single-pass FSP was performed for both normal and submerged conditions. The normal friction stir processed TIG-welded (NFSP-TIG) and the submerged friction stir processed TIG-welded (SFSP-TIG) plates are shown in figures 1(e) and 1(f) respectively.

Figure 2(a) shows the tensile specimen designed and dimensioned according to the ASTM E8 standard. The tensile test was conducted on Hounsfield 50 K tensile testing machine at a 3 mm min\(^{-1}\) rate. The Vickers micro-hardness tests were conducted using the InnovaTest Falcon 500 hardness testing machine. Figure 2(b) depicts the specimen used for hardness testing. The ASTM E384-11 standard was used for hardness testing. A 500 g load, objective 10 \(\times\), and 20 \(\times\) were used for specimen focusing. The same specimen used for hardness testing was used to form microstructural analysis. The specimen was ground, polished, and etched in preparation for the analysis. The Weck’s reagent was used as a pre-etch followed by the modified Keller’s reagent. The Mira 3 Tescan SEM
microscope was used for microstructural analysis and fracture surface morphology testing. The linear intercept
technique based on the ASTM E112-12 standard was used for grain measurement through the use of ImageJ
software. A total of three specimens were used for each test with specimens sampled from the start, middle, and
end of the welded and processed joints.

3. Results and discussion

3.1. Macrostructural and microstructural analysis
The macrographs for the TIG-welded and FSP-TIG joints are presented in figure 3. The TIG-welded
macrographs in figures 3(a)–(c) showed welds with no visible defects. Both NFSP-TIG and SFSP-TIG
macrographs showed tunnel defects in figures 3(d), (e), (g), and (h). The defects are shown using the yellow
circles. The defects are generally caused by insufficient heat input and material flow during the FSP procedure
[24, 25]. During the FSP of the dissimilar materials, the AA8011 being a weaker material picks heat quickly and
softens earlier than the stronger material. This creates rapid heat dissipation from the immediate deformation
zone and produces cold hard welds which then become a very high possible point of fracture during tensile
testing [26, 27].
Figure 4 shows the SEM micrographs of the TIG-welded, NFSP-TIG, and SFSP-TIG joints. The microstructural average grain sizes of the TIG-welded joint ranged between 21.99 μm and 25.71 μm, the NFSP-TIG joint ranged between 7.83 μm and 9.25 μm, and the range of SFSP-TIG joint was between 4.89 μm and 6.33 μm. This, therefore, shows that the microstructural average grain sizes were greatly improved after both NFSP and SFSP procedures. This improvement was due to the occurrence of dynamic recrystallization caused by the frictional heat and the plastic deformation experienced by the friction stir processed zone [28–30]. Comparing the SFSP to the NFSP method average grain sizes, the SFSP-TIG ones were decreased significantly to 4.89 μm, while the NFSP-TIG average grain size was 7.83 μm. This intriguing grain refinement is a result of the water cooling method which results in reduced duration of high temperature eliminating the grain growth [14, 31–35]. A notable reduced standard deviation of 1.09 was found when measuring grain size on the SFSP-TIG joints and a 1.77 for the NFSP-TIG-welded joints. This was performed to analyze the variability of data points. The specimens extracted towards the end of the joints were found to have finer grains compared to those extracted from the start and the middle of the joints. This behaviour was assumed to be caused by insufficient heat input experienced by the joint at the start of the joint which later accumulates as the tool traverses along with the joint [36, 37].

3.2. Mechanical properties
Figure 6 shows the post tensile specimens. The TIG-welded specimens in figure 6(a) all failed on the thermo-mechanical affected zone (TMAZ) on the AA8011 side. This, therefore means that the joint strength of the nugget zone was stronger than that of the base material AA8011 [38, 39]. Figure 6(b) shows the NFSP-TIG
specimens, all the specimens failed on the stirred zone (SZ). The SFSP-TIG specimens are depicted in figure 6(c) where the specimens extracted from the start and middle of the joint failed on the stir zone due to tunnel defect observed at the joints. The defect could be a result of insufficient heat experienced by the joint at the respective
positions [37, 40, 41]. The specimen extracted from the end of the joint failed on the TMAZ of the AA8011 side and this zone is always associated with coarse grains [40, 41]. Figure 7 shows the stress-strain curves for TIG-welded, NFSP-TIG, and SFSP-TIG specimens. Table 3 tabulates the tensile properties of the tensile curves shown in figure 7.
The TIG-welded joints exhibited the ultimate tensile strength (UTS) range of 80.27 MPa to 85.36 MPa, while NFSP and SFSP-TIG welded joint exhibited UTS range of 87.14 MPa to 88.33 MPa, and 88.79 MPa to 91.56 MPa, respectively. The maximum percentage elongation obtained for the TIG-welded joints was 23.79%, 24.28% was found on NFSP-TIG joints, and 28.81% was found from the SFSP-TIG joints. The tensile properties are summarized in Table 3. These results are in correlation with the microstructural grain results obtained at the respective joints and specimen sampling position. It was observed that the specimens that were produced through the SFSP technique did not compromise the percentage elongation due to the increase in UTS as it is used to be the case according to the Hall-Petch relationship \[42\]. Similar behaviour was reported in the literature \[22, 36\]. Comparing the NFSP-TIG with the SFSP-TIG tensile results, the SFSP-TIG resulted in more improved UTS and percentage elongation and this correlates with what has been reported previously \[20, 43, 44\]. The phenomenon behind such improvement is the rapid cooling brought by the water and the dynamic recrystallization experienced by the joints during the FSP procedure \[14, 21\].

Figure 8 shows the fractographic morphology of the TIG-welded, NFSP-TIG, and SFSP-TIG joints. All the joints showed a predominant ductile failure mechanism. This behaviour was denoted by the presence of dimples, microvoids, teared ridges, and cleavage facets \[45, 46\]. However, figures 8(f), and (g)-(i) showed teared dimples and ridges dispersed distribution and a second phase particle was noted in figure 8(h), denoted by an arrow. The fracture surface results correlated with the tensile results.

Figure 9 shows the TIG-welded, NFSP-TIG, and SFSP-TIG stir zone hardness profiles. The TIG-welded joints had a maximum NZ/SZ hardness range of 56 HV to 60 HV, while the SZ hardness range for NFSP-TIG and SFSP-TIG welded joints ranged between 54 HV and 57 HV, and between 60 HV and 65 HV, respectively. The application of NFSP on the TIG welded joints slightly compromised the hardness of the joints and this is suggested to be caused by high processing temperature due to AA6082 being on the advancing side. The AA6082-T651 alloy is a precipitate hardened alloy. The strengthening precipitate of this alloy is the Mg5Si6 also referred to as \(\beta\) phase which is very sensitive to temperatures above 200 °C \[47\]. Once the temperature goes beyond 200 °C, the \(\beta\) precipitates get dissolved thus decreasing the hardness \[34, 48, 49\]. The employment of the SFSP procedure resulted in an increase in the hardness of the stir zone due to the reduced peak temperature which prevented the dissolution of precipitates and grain growth \[50\]. The hardness of the joints on the AA6082 side showed the declining trend from the base metal to the heat-affected zone (HAZ), TMAZ, and the stir zone. This was due to the microstructural grain size variation and their exposure to heat at the respective zones. The HAZ is known to coarse grains resulting in lower hardness \[51, 52\]. This then makes this zone a weaker spot for failure during tensile loading \[21, 53–55\]. Whereas the TMAZ is a region that consists of high deformation, grain coarsening, and temperature variation \[36\]. This, therefore, resulted in both the TMAZ and the HAZ referred to as the lowest hardness distribution regions (LHDR) \[57–59\]. A similar trend was observed when looking at microhardness variation from AA8011 base material to the center of the stir zone. It was observed that the hardness results correlated to those of the tensile strength.

### 4. Conclusions

The impact of FSP methods on the microstructure and the mechanical properties of the TIG-welded joints was successfully carried out. The NFSP-TIG joints were compared to SFSP-TIG ones. Based on the results obtained the following conclusions were drawn:
The microstructural analysis of the NFSP joints showed the minimum average grain size of 7.83 μm and maximum average of 9.25 μm, while the NFSP joints had an average grain size range of 6.33 μm to 4.86 μm. Both friction stir processed joints showed a great grain size refinement compared to the TIG-welded joints which had an average grain size range of 25.71 μm to 21.99 μm. Great grain size refinement was noted on the SFSP joints.

The UTS of the NFSP joints ranged between 87.14 MPa and 88.33 MPa while the UTS of the SFSP joints ranged between 88.79 MPa and 91.56 MPa. The tensile elongation range of the NFSP joints was found to be 22.71% to 24.28% while the maximum tensile elongation of 24.08% to 28.81% was found on the SFSP joints. The TIG-welded joints were found to have a UTS range of 80.27 MPa to 85.36 MPa with a tensile elongation of 21.82% to 23.58% respectively. It was found that FSP not only improved the tensile strength but also improved the ductility of the joints with the submerged conditions giving best improved results. The tensile properties correlated to the grain sizes obtained. The fracture surface morphology revealed a ductile failure mode for all the specimens, with the SFSP-TIG specimens showing more refined dimples.

The TIG-welded joints had a maximum hardness range of 56 HV to 60 HV, while the hardness range for NFSP-TIG and SFSP-TIG welded joints had a hardness range between 54 HV and 57 HV, and between 60 HV
and 65 HV, respectively. The application of NFSP on the TIG welded joints slightly compromised the hardness of the NFSP due to high processing temperature and the AA6082 alloy being a precipitate strengthened alloy that is sensitive to heat. However, the hardness of the SFSP joints was improved due to rapid cooling.

![Hardness profiles](image)

**Figure 9.** Hardness profiles: (a) TIG-welded joints, (b) NFSP-TIG and (c) SFSP-TIG.
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest

The authors declare no conflict of interest.

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