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## The impact of submerged friction stir processing on the friction stir welded dissimilar joints

Sipokazi Mabuwa and Velaphi Msomi

Cape Peninsula University of Technology, Mechanical Engineering Department, Bellville, 7535, South Africa

E-mail: [sipokazimabuwa@gmail.com](mailto:sipokazimabuwa@gmail.com)

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### Abstract

The submerged friction stir processing (SFSP) technique was employed on the prior friction stir welded (FSW) AA6082/AA8011 dissimilar aluminum alloy joints. The tap water with room temperature was kept at 40 mm depth throughout the processing. The AA6082 was kept at the advancing side during FSW and SFSP process and this was done to enhance the strength of the joint. The SFSP joints were studied comparatively with the FSW joints. The sampling position was also studied for both the FSW joint and SFSP joint. The employment of the submerged friction stir processing resulted in the microstructural grain size refinement. The tensile strength of the SFSP joint was found to be higher than that of AA8011 base metal but lower than that of AA6082 base metal. The tensile strength of the FSW joint was found to be lower than that of both base metals. There was a clear correlation between the tensile properties and the grain size refinement. The SFSP joint exhibited good microhardness properties compared to the FSW joint.

## 1. Introduction

Friction stir processing (FSP) is a variant of the friction stir welding process. FSP uses the same principle as the friction stir welding but does not join the metals rather modifies the local microstructure in the near-surface layer of metals [1–3]. The material subjected to the FSP technique undergoes extreme plastic deformation at higher temperatures. This then results in a stirred zone consisting of recrystallized fine microstructural grains, mostly referred to as the dynamic recrystallized zone [4–6]. For non-heat-treatable Aluminum alloys, the dynamic recrystallized zone usually consists of the best mechanical properties [7]. FSP has successfully improved the mechanical properties and refined the microstructural grain sizes of the plates [8–10]. Recently FSP has also been proven to enhance the mechanical properties of the joints [11–13]. Alkbakri *et al* [14] reported that managing heat during the FSP is very crucial, for surplus heat could melt the material, especially the soft grade like series 1xxx and 8xxx. The effective cooling was found to be the solution to removing the surplus heat which promotes grain growth. This effective cooling is known as the submerged friction stir processing.

The submerged friction stir processing (SFSP) has the same working principle as friction stir processing except that the whole processing takes place under submerged conditions [14, 15]. The submerged condition could be water [15], a combination of water, methanol, and dry ice [16], copper backing plate [17], nitrogen [18], etc. Liu and Feng [19] employed water-submerged friction stir processing on aluminum alloy (AA) 2219 to study the microstructure and microhardness of the processed surface. It was found that the application of SFSP resulted in the removal of softened regions, a significant increase in microhardness, and grain size refinement. Additionally, the microhardness was found to decrease with an increase in heat input which is dependent on the rotational speed [20]. Shukla *et al* discovered that the tensile strength increases with a decrease in grain size during the SFSP of the AA5083 [21].

The 2A14 aluminum alloy was FSPed underwater and air conditions to compare the differences in the microstructure and mechanical properties of the processed surface [22]. The underwater stir zone

microstructure was reported to show equiaxed, fine, highly misoriented grains with an average range of 1.19–3.1  $\mu\text{m}$ . The underwater conditions were found to be more effective in the significant refinement of grain sizes, high angle boundaries, and second phase particles compared to FSP under air. The tensile strength and the microhardness were found to increase as the cooling rate increased as a result of grain refinement and second phase particle uniform distribution. Chai *et al* [23] also discovered that the application of SFSP yields better ductility compared to the FSP on air. The microstructural grains were significantly refined which increased the tensile strength of the SFSP joint. Darras and Kishta [24] used three different processing conditions, room temperature water, hot water, and air. The results revealed that the SFSP at room temperature water had finer grain structure compared to the other conditions. The same reaction was also noted on the tensile properties. Additionally, FSP at room temperature was found to take less time (4 s), while the hot water processing took 7 s and the FSP on-air took 16.5 s.

It has also been observed that the SFSP technique can be employed in producing surface composites with improved mechanical properties compared to the NFSP. Yang *et al* [25] have used the SFSP technique to fabricate surface composites (also called AMCs) that were reinforced with high entropy alloys (HEA) particles. The microstructural analysis revealed the formation of the dual interface which was composed of a face-centered-cubic (FCC) phase with nanotwins-like structures. The tensile strength of composites reinforced with HEA particles was found to be higher compared to composites without reinforcement. The wear resistance of the composites with reinforcement was found to be higher compared to composites without reinforcement. Yang *et al* [26] also utilized the SFSP technique to incorporate AlCoCrFeNi HEA particles into the AA5083 matrix. The investigation was performed between the as-received material and the HEA reinforced composite. The microstructural observations revealed a homogeneous distribution of HEA particles in the matrix coupled with grain refinement. The microstructural observations further revealed the good metallurgical bonding between the interfaces of HEA and matrix. The microhardness of the HEA reinforced composites was significantly higher compared to the as-received aluminum. The wear resistance of HEA reinforced composites was way higher compared to the as-received aluminum.

Huang *et al* [27] have employed the SFSP technique to fabricate nitinol shape memory alloy particulates (NiTi) based AMCs. The microstructural observations revealed a good dispersion of NiTi in the AMCs with refined grain structures. The good bonding between NiTi and aluminum interfaces was also observed. The incorporation of NiTi to the aluminum matrix resulted in the composites to exhibit the shape memory effect. It was further observed that the incorporation of NiTi to the AMCs resulted in the improved tensile strength without compromising the ductility. The AA5083 surface composites reinforced with titanium (Ti) particles were fabricated by Huang *et al* [28] through the multi-pass SFSP technique. The multi-pass SFSP technique contributed to the significant grain refinement which resulted in an improved ductility and ultimate tensile strength. It was further observed that the grain refinement was caused by the continuous type of recrystallization process which was accompanied by rapid cooling from the surrounding water.

The recent development has reported on the application of the SFSP on the friction stir welded dissimilar joint [29]. The submerged friction stir processed dissimilar joint was investigated comparatively with the normal friction stir processed (NFSP) dissimilar joint. An extensive analysis was performed such that the impact of material positioning was also considered during the analysis. The joints processed using SFSP had higher ultimate tensile strength compared to those processed using NSFP. The grains of the joints processed using SFSP were finer compared to the joint grains processed using the NFSP technique. It was also observed that the mechanical properties of the specimens sampled from the beginning of the joint were less than the properties of the specimens sampled from other locations of the joint. This variation of properties was attributed to the adequacy and inadequacy of the heat input.

SFSP technology has been used extensively in enhancing and producing surface composites and has recently been employed on the friction stir welded joints. However, there are limited works that deal with the employment of SFSP technology to the welded similar or dissimilar joints. This then suggests that more investigation is required to bring more knowledge and understanding in this area. In this paper, the mechanical properties of the friction stir welded AA8011/AA6082 dissimilar joint are studied comparatively with the submerged friction stir processed AA8011/AA6082 dissimilar joint. In simple terms, the properties of the friction stir welded dissimilar joint are studied comparatively with the properties of the SFSP dissimilar joint. The sampling aspect is also considered during the investigation.

## 2. Materials and methods

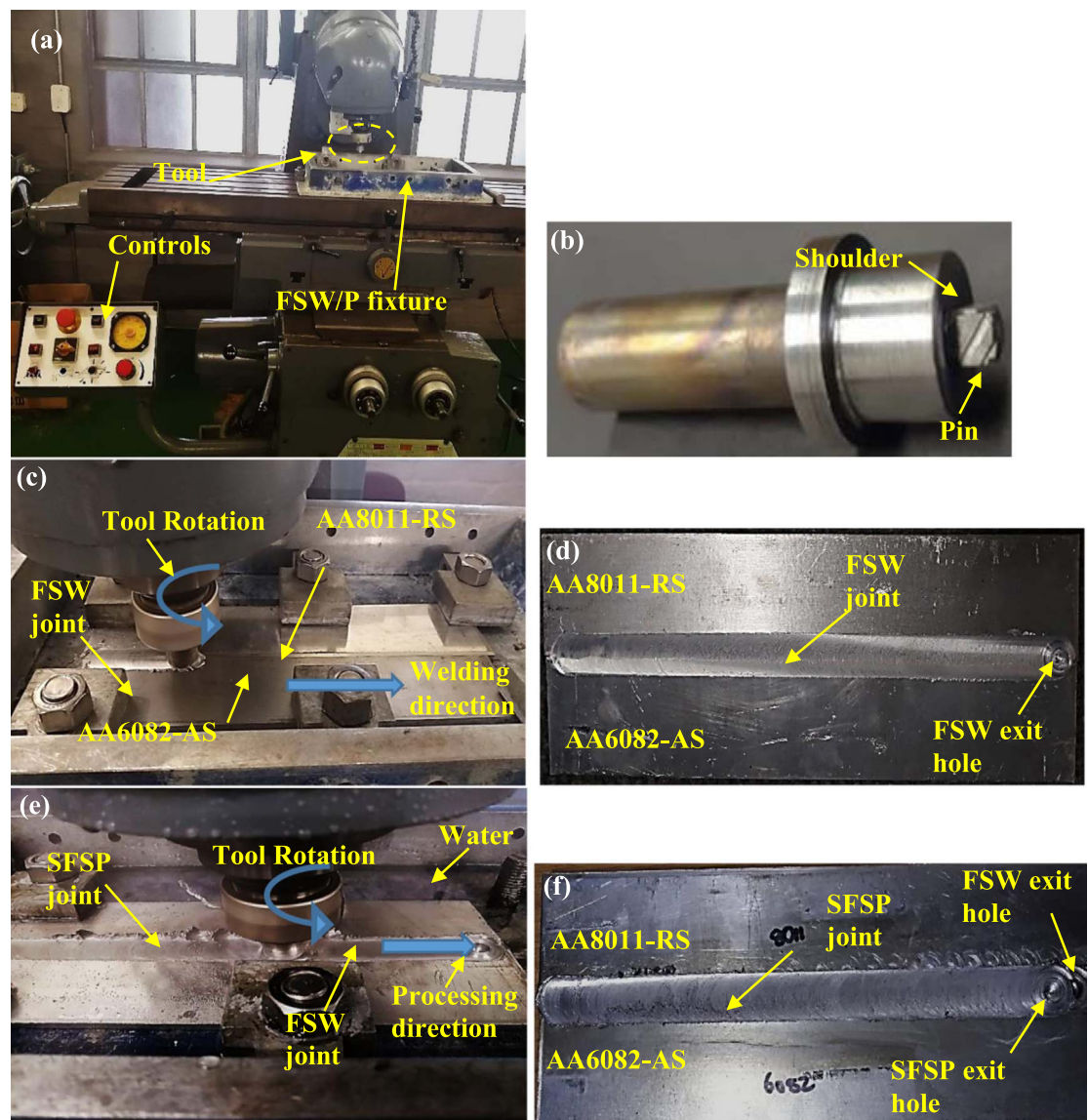
Aluminum alloy 6082-T651 (AA6082) and aluminum alloy 8011-H14 (AA8011) plates with 6 mm thickness were used in this study. The chemical composition and mechanical properties of the materials are shown in table 1 and table 2, respectively. Two sets of AA6082 and AA8011 plates with dimensions of 260 × 52 mm were

**Table 1.** Chemical composition of the base materials (wt%) [29, 30].

| Material | Mg   | Zn    | Ti    | Cr    | Si   | Mn   | Fe   | Cu   | Al  |
|----------|------|-------|-------|-------|------|------|------|------|-----|
| AA8011   | 0.28 | 0.084 | 0.016 | 0.028 | 0.52 | 0.46 | 0.74 | 0.13 | Bal |
| AA6082   | 1.1  | 0.2   | —     | 0.25  | 0.9  | 0.7  | 0.5  | 0.1  | Bal |

**Table 2.** Mechanical properties of the base materials [31].

| Material | Tensile Strength (MPa) | Elongation (%) | Hardness |
|----------|------------------------|----------------|----------|
| AA8011   | 94.1                   | 40.17          | 33.5 HV  |
| AA6082   | 308                    | 25.42          | 89.6 HV  |

**Figure 1.** (a) FSW machine, (b) FSW/FSP tool, (c) FSW application, (d) FSWed plate, (e) Submerged FSP application and (f) Submerged FSPed plate.

friction stir welded (FSWed) using the semi-automated milling machine shown in figure 1(a). The process parameters used include a rotational speed of 1100 rpm, tool feed of 60 mm min<sup>-1</sup>, tool shoulder of 20 mm, tool probe diameter of 7 mm, tool pin length of 5.9 mm, dwell time of 10 s, and a tool tilt angle of 2°. The material used for the FSW/P tool shown in figure 1(b) was the high-speed steel (HSS) AISI 4140. A single-pass FSW



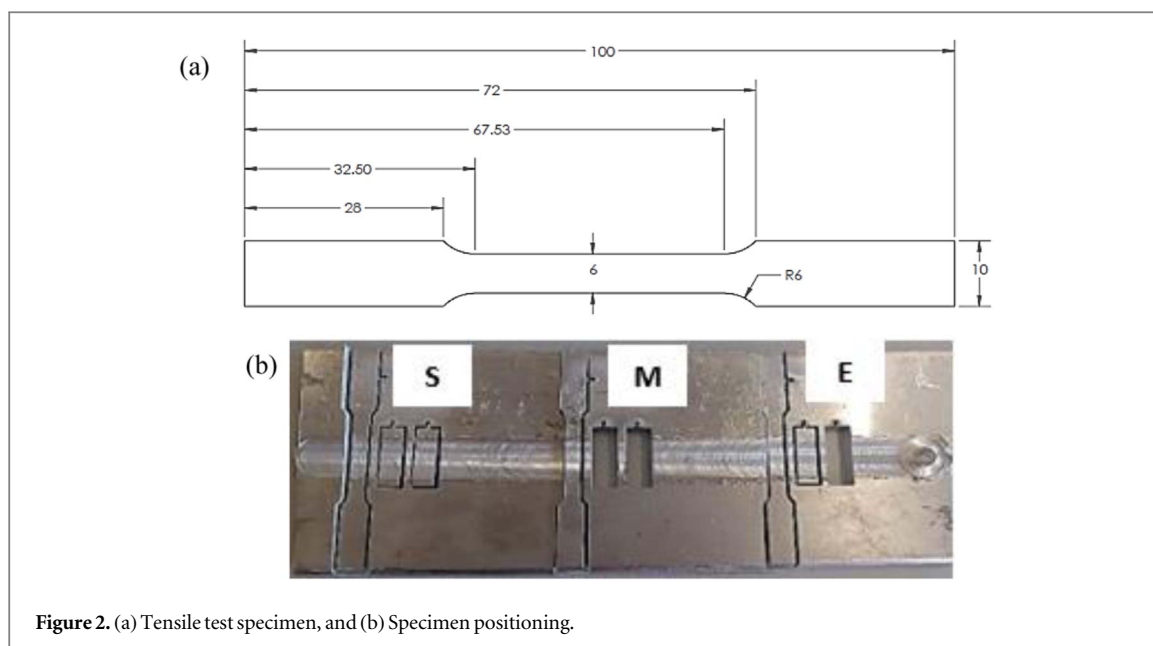


Figure 2. (a) Tensile test specimen, and (b) Specimen positioning.

technique was used to join the two dissimilar plates at room temperature. Figure 1(c) shows the FSW setup and performance on the AA6082-AA8011 plates. Figure 1(d) shows the FSWed plate which was produced under room temperature. The FSWed plate was then friction stir processed under cold water condition. The friction stir processing was applied to start at the same starting point of the FSW joint following the same direction as that followed during FSW (see figure 1(e)). Figure 1(f) shows a plate with the joint processed using the submerged FSP technique. The water level during SFSP was kept at 40 mm throughout the process. The process parameters used for submerged friction stir processing were the same as the one used for FSW. The parameters were pre-determined using Taguchi L18 method, separately. The specimens for various tests were prepared plates using the waterjet technology method. It should be noted that AA6082 was kept on the advancing side while AA8011 on the retreating side for both FSW and SFSP.

### 2.1. Mechanical testing

The tensile tests were performed using the Instron 8801 with a maximum 100 kN load cell. The ASTM-E8M-04 standard was used for tensile testing and the  $3 \text{ mm min}^{-1}$  strain rate was employed in all the specimens. Figure 2(a) shows the tensile specimen with dimensions in mm. Data was logged using the Bluehill 3 software. The tensile test specimens were further analyzed for the nature of fracture using a scanning electron microscopy (SEM). The InnovaTest Falcon 500 machine was used for microhardness testing. The ASTM E384-11 standard was used for Vickers microhardness testing. The 190 HV standard was used for setup. The 0.3 kg load, objective 10x, and 20x were used. The 1 mm interval was used from the center to either side of the specimen (advancing to retreating). The specimen location for the test performed was as shown in figure 2(b). The labeling format where 'S' stands for the specimen extracted at the start of the weld joint, 'M' for the specimen at the middle, and 'E' for the specimen extracted at the end weld joint was used.

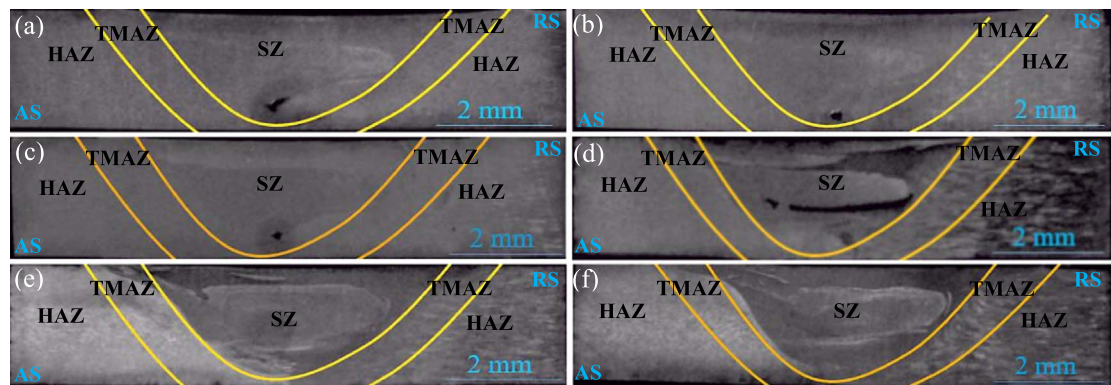
### 2.2. Metallographic analysis

The microstructural analysis of the cross-section of the friction stir welded and friction stir processed specimens was performed using the Motic AE2000 optical microscope. The specimens were mounted, ground, polished, and etched using the modified Keller's and Weck's agents. The modified Keller's reagent chemical composition was the 10 ml nitric acid ( $\text{HNO}_3$ ), 1.5 ml hydrochloric acid (HCL), 1.0 ml hydrofluoric acid (HF) and 87.5 ml distilled water ( $\text{H}_2\text{O}$ ) and the Weck's reagents composition was 1 g sodium hydroxide (NaOH), 4 g potassium permanganate ( $\text{KMnO}_4$ ) and 100 ml distilled water ( $\text{H}_2\text{O}$ ). The grain sizes were measured using the ASTM E112 standard and the linear intercept technique using the ImageJ software was employed.

## 3. Results and discussion

### 3.1. Macrostructural analysis

Figures 3(a) to (c) presents the macrographs of the friction stir welded joint and figures 3(d) to (f) for the submerged friction stir processed joints. In all the macrographs three zones namely heat-affected zone (HAZ),



**Figure 3.** Macrographs, FSWed dissimilar joints: (a) FSW-Start, (b) FSW-Middle, (c) FSW-End, Submerged friction stir processed FSWed dissimilar joint: (d) SFSP-Start, (e) SFSP-Middle, (f) SFSP-End.

thermomechanical affected zone (TMAZ), and stir zone (SZ) also known as nugget zone were identified. The macrographs of the FSWed joint revealed a structure with oval-shaped stir bands, sometimes referred to as onion rings [32, 33]. Similar observations were also observed on the submerged friction stir processed FSWed macrographs. These onion rings were formed due to the maximum deformation of the materials and dynamic recrystallization which resulted in equiaxed grain structure [34–36]. Figures 3(a) to (d) reveals the visibility of defects in the stir zone. This behavior is very common with dissimilar joints and is associated with onion skin partial bonding defects [37–39]. The absence of defects is observed in figures 3(e) to (f) and this indicates the proper mixing at the stir zone.

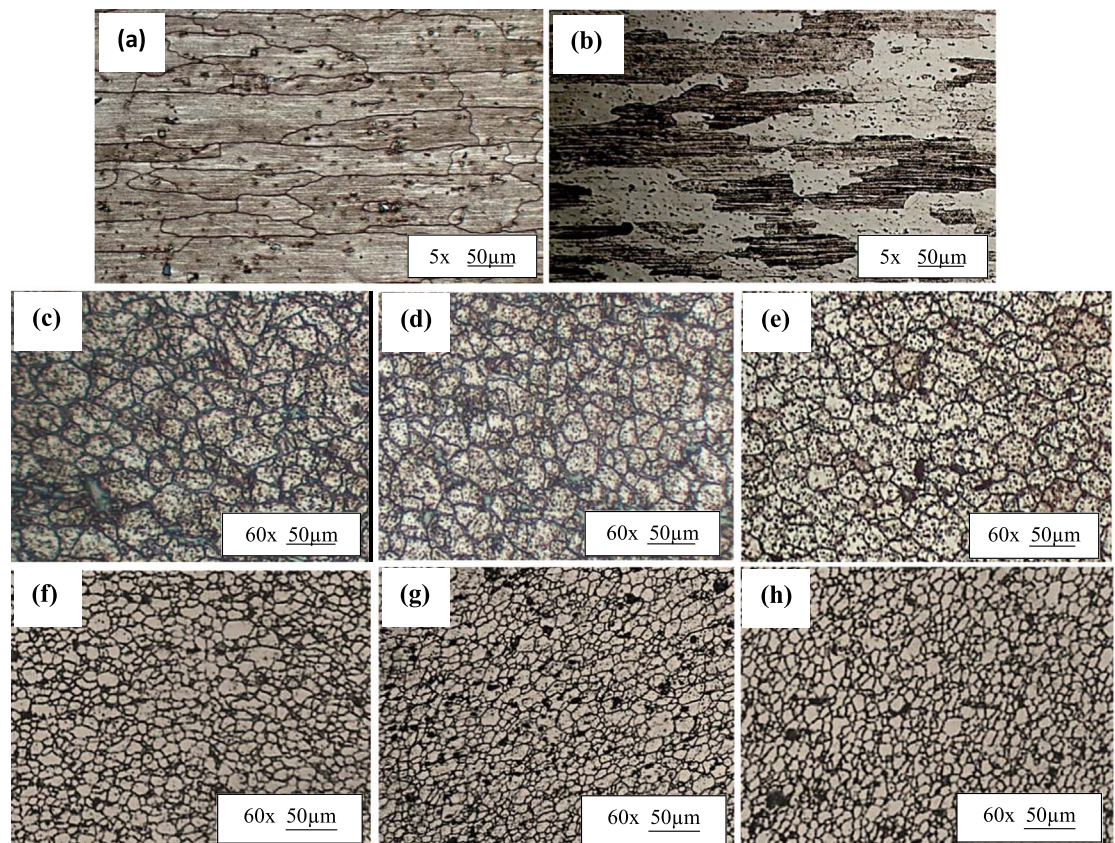
### 3.2. Microstructural analysis

Figure 4 shows the microstructure of the base materials, stir zone micrographs for the friction stir welded and submerged friction stir processed dissimilar aluminum alloy joints. Figure 4(a) shows the AA6082 base material micrographs with the mean grain size of  $64.04\ \mu\text{m}$ . Figure 4(b) depicts microstructural grains of AA8011 with the mean grain size of  $51.57\ \mu\text{m}$ . Figures 4(c)–(e) depicts the microstructural arrangement of grains for FSW specimens sampled from the beginning until the end of the joint. There is a uniform distribution of grains across the FSW joint and these grains are partly homogeneous with almost the same size. A similar trend was also observed on the SFSP joint but with refined grains. The summary of the grain size distribution is presented in table 3. The mean grain size for the FSW joint ranges between  $17.75\ \mu\text{m}$  to  $20.81\ \mu\text{m}$  with the maximum mean grain size measured from the start of the joint and the least measured from the end of the joint. A similar grain size distribution was also observed on SFSP joints, however, the SFSP range was measured to be less than that of the FSW joints. The reduction of grains is as a result of dynamic recrystallization in which the thermal softening and the plastic deformation occurs in the stir zone of the dissimilar joint [40, 41]. The refined grains on SFSP joints is due to the fact that the joint is experiencing second dynamic recrystallization and the rapid cooling rate due to the presence of water [15, 20, 22, 24, 42, 43]. It was also noted that there was a decrease in standard deviation for the SFSP joint which is an indication of the closeness of the measured grain sizes. Figure 5 depicts the grain distribution histograms.

### 3.3. Tensile test

The post tensile test specimens are shown in figure 6 revealing positions of fracture. Both friction stir welded and submerged friction stir processed FSWed specimens failed in similar positions. The specimens extracted at the start of the weld/processing failed at the weld zone, meaning the tensile strength of the joint was lower compared to both base materials [44, 45]. The specimens cut at the middle and towards the end of the joint failed at the heat-affected zone towards the AA8011 side. This, therefore, means that the tensile strength of the welded joint was stronger compared to the HAZ region of AA8011 base material. The heat-affected region has been reported to be the weakest region for crack initiation within the specimen, depending on materials selected and process parameters employed [46, 47]. Moreover, the heat-affected region is also known for having the minimum hardness compared to the stir zone [48, 49].

Figure 7 presents the engineering stress and strain curves for the FSWed and the submerged friction stir processed dissimilar joints with table 4 showing the summarized tensile properties. The FSWed dissimilar joints had a maximum tensile strength of 92 MPa, while the submerged friction stir processed dissimilar joints had a maximum tensile strength of 103.37 MPa. This slight increase in tensile strength is linked to the grain size refinement which was observed from the SFSP joints [50–53]. It was noted that both maximum tensile strengths



**Figure 4.** Microstructure; (a) AA6082 base material, (b) AA8011 base material, (c) FSW-Start, (d) FSW-Middle, (e) FSW-End, (f) SFSP-Start, (g) SFSP-Middle, (h) SFSP-End.

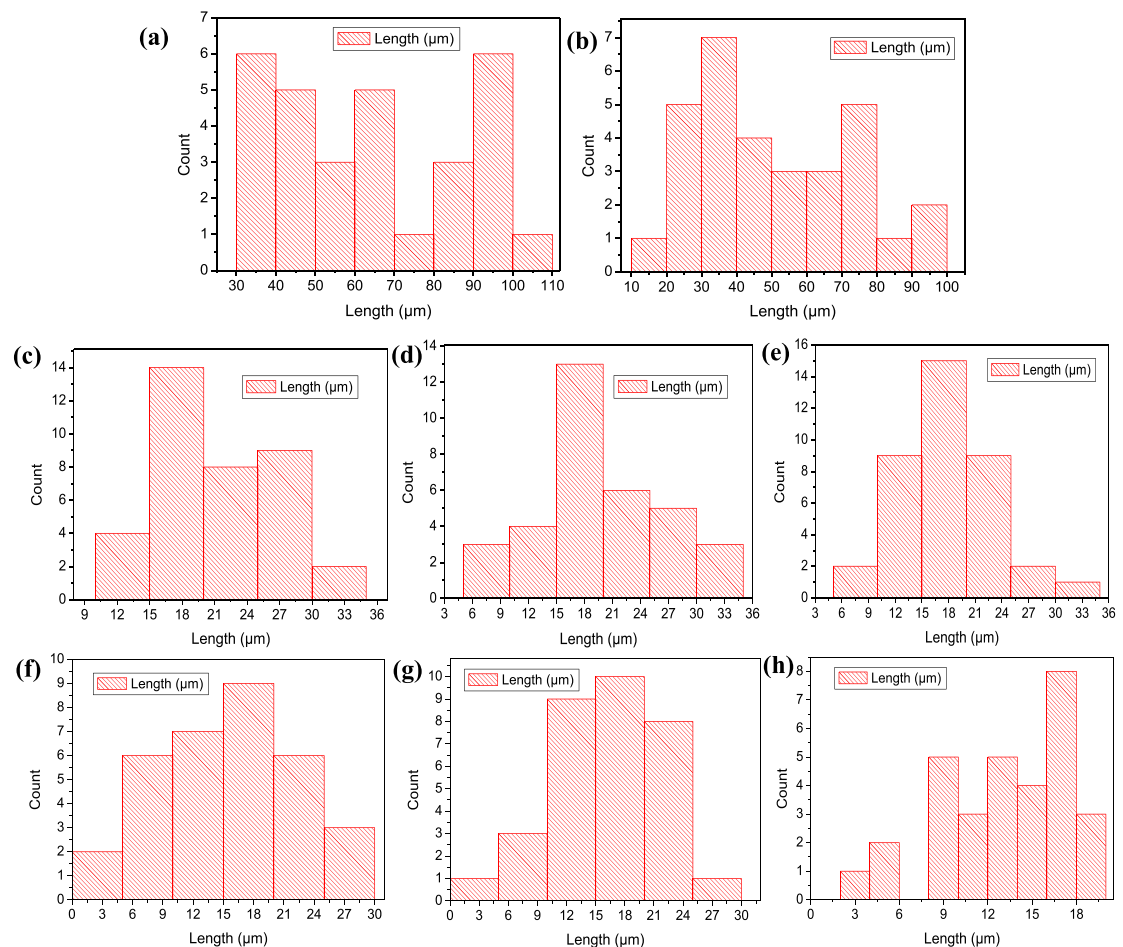
**Table 3.** Grain size and standard deviation.

| Joint       | Mean grain size ( $\mu\text{m}$ ) | Minimum grain size ( $\mu\text{m}$ ) | Maximum grain size ( $\mu\text{m}$ ) | Standard Deviation ( $\mu\text{m}$ ) |
|-------------|-----------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| AA6082      | 65.04                             | 33.75                                | 104.15                               | 24.24                                |
| AA8011      | 51.57                             | 19.01                                | 99.94                                | 23.67                                |
| FSW-Start   | 20.81                             | 10.08                                | 31.94                                | 5.43                                 |
| FSW-Middle  | 19.48                             | 8.84                                 | 32.49                                | 6.71                                 |
| FSW-End     | 17.75                             | 8.36                                 | 31.248                               | 5.22                                 |
| SFSP-Start  | 15.69                             | 3.63                                 | 25.79                                | 6.37                                 |
| SFSP-Middle | 16.51                             | 3.74                                 | 26.68                                | 5.47                                 |
| SFSP-End    | 13.17                             | 3.29                                 | 19.69                                | 4.37                                 |

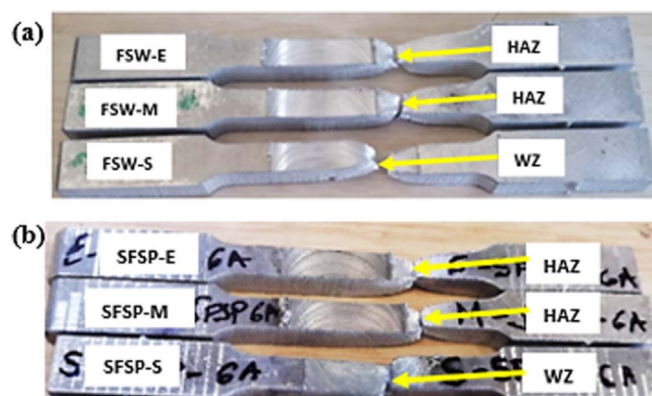
were obtained on the specimens sampled from the end of the joint. In both cases, the specimens sampled from the beginning of the joint had the least tensile strength and this is generally caused by instability in heat input [54]. This behavior is in agreement with the positions of failure depicted in figure 6. The percentage elongation of the submerged friction stir processed joint was significantly improved compared to that of the friction stir welded joint (23.7% - FSW, 28% - SFSP). This improvement in the tensile strength of the submerged friction stir processed joints was related to the Hall-Petch relationship [55].

Figure 8 presents the fractured surface SEM images for the FSWed and submerged friction stir processed tensile specimens. Figure 8(a) shows the fractured surface of FSWed specimen sampled at the start of the joint. This surface is dominated by the large dimples and voids which are indication of low ductility of the material and this coincide with the lowest percentage elongation associated with this specimen [39, 56]. Figures 8(b)–(c) show the mixture of fine and large dimples with the presence of trans-granular cleavage facets. The existence of finer dimples indicates the improvement of material ductility before failure. Figure 8(d) shows the fractured surface of the submerged friction stir processed specimen sampled at the start of the joint. This surface is





**Figure 5.** Grain distribution; (a) AA6082 base material, (b) AA8011 base material, (c) FSW-Start, (d) FSW-Middle, (e) FSW-End, (f) SFSP-Start, (g) SFSP-Middle, (h) SFSP-End.



**Figure 6.** Post tensile specimens, (a) FSWed AA6082-AA8011 joints and (b) Submerged friction stir processed FSWed AA6082-AA8011.

dominated with uniform fine dimples which are the indication of a very ductile behavior of the specimen before failure. This morphology is in agreement with the highest percentage elongation possessed by this specimen [56–59]. The mixed sized dimples are observed in figures 8(e)–(f) and this indicates the moderate ductility behavior of the material before failure. The mixed sized dimples and the presence of trans-granular cleavage facets compromised the percentage elongation of the specimens associated with these surfaces [20, 57].



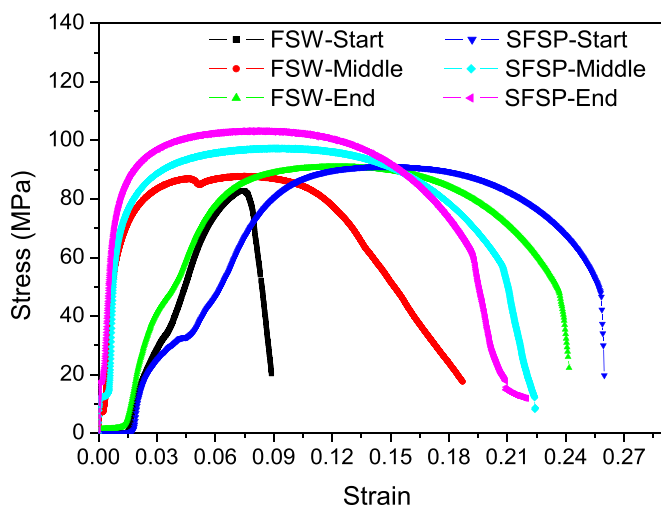


Figure 7. Engineering stress-strain curves for the FSWed and submerged friction stir processed FSWed joint.

Table 4. Tensile properties.

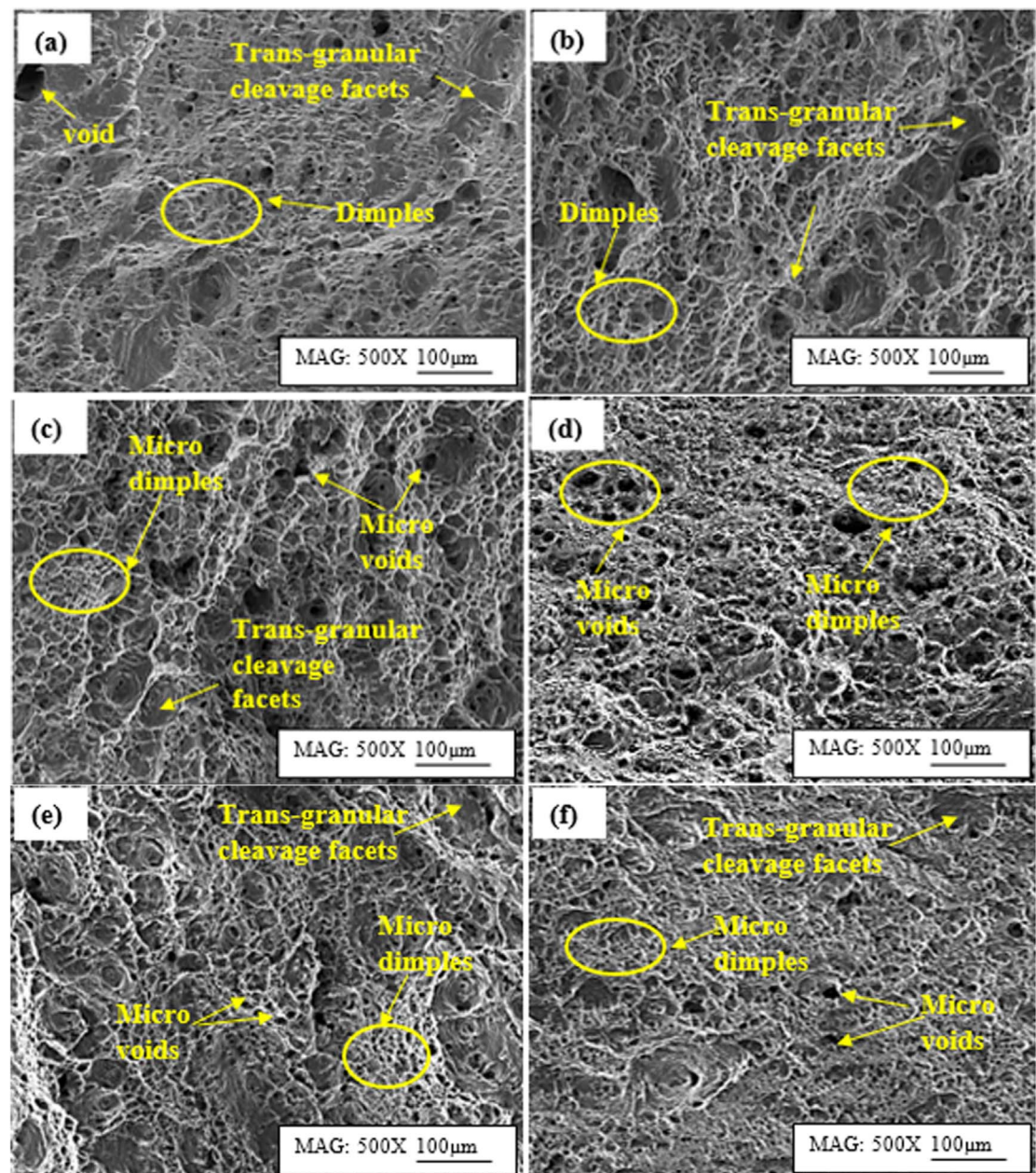
| Joint       | Maximum tensile stress (MPa) | Percentage elongation (%) |
|-------------|------------------------------|---------------------------|
| FSW-Start   | 82.9                         | 8.84                      |
| FSW-Middle  | 88                           | 21.4                      |
| FSW-End     | 92                           | 23.7                      |
| SFSP-Start  | 90                           | 28                        |
| SFSP-Middle | 97.33                        | 24.2                      |
| SFSP-End    | 103.37                       | 21.9                      |

### 3.4. Microhardness

The microhardness profiles for the FSWed and submerged friction stir processed dissimilar joints are presented in figures 9(a) and (b), respectively. The microhardness of the FSWed joints at the center of the stir zone was found to be in the range of 26–37 HV, with the specimen cut in the beginning and middle having the least microhardness. The SFSPed joints had a center microhardness range of 37–66 HV with the specimens cut at the beginning of the AA6082-AA8011 joint having the least value. The SFSP microhardness was found to be lower compared to the AA6082 base material but higher compared to the AA8011 one and to that of FSW stir zone one. The microhardness was found to be in correlation with the tensile strength of the two joints and this behavior is similar to that reported in the literature [19, 22, 60]. The submerged FSP experiences controlled heat input which prevents the coarsening of the microstructural grains hence an improved microhardness values [55, 61]. Both figures 9(a) and (b) show the declining trend from the advancing side towards the stir zone and further decline is observed from the stir zone towards the retreating side. However, the magnitude of decline differs in both joints (FSW and SFSP joints). The microhardness of the TMAZ region was found to be higher compared to that of the HAZ region and this behavior is similar on both the advancing side and the retreating side of FSW and SFSP specimens. However, the microhardness range between TMAZ and HAZ of the retreating side was found to be lower compared to that of the advancing side. However, the range of SFSP specimens was higher compared to that of the FSW specimens and this is caused by the fact that the submerged conditions prevented the material softening [62–65]. It was further observed that the microhardness measured from the stir zone were all less than that of the parent materials. The low in microhardness value suggests the coarsening of grains in that specific region hence the failure shift towards the region dominated by the coarsened grains [62–65]. The other factor that contributed to low microhardness is the deterioration of strengthening precipitates due to the stirring action of the pin which results in temperature exceeding 200 °C [44, 56, 66, 67].

### 3.5. Conclusions

The microstructure and mechanical behavior of the friction stir processed and submerged friction stir processed AA6082/AA8011 joints were studied comparatively. The following conclusions were drawn:



**Figure 8.** Fractographs, FSWed AA6082-AA8011 joints, (a) Start, (b) Middle, (c) End; Submerged friction stir processed AA6082-AA8011 joints, (d) Start, (e) Middle and (f) End.

- The microstructure and the mechanical properties were found to be commonly varying with the sampling location for both FSW and SFSP dissimilar joints.
- The FSW and SFSP specimens failed outside the stir zone except the specimens sampled from the beginning of both joints. All the specimens failed on the HAZ of the retreating side (AA8011 side) and this indicates that this region was dominated by the coarser grains. In as much as the tensile behavior for both specimens is similar, however, the SFSP specimens showed improved tensile strength and percentage elongation compared to the FSW specimens. The improved tensile properties were attributed to the grain size refinement associated with SFSP specimens.
- It was further observed that the tensile strength of the FSW specimens was all lower than both parent material. However, the tensile strength for SFSP specimens was found to be higher than that of AA8011 but less than the AA6082 parent material. This phenomenon is attributed to the controlled heat input due to the processing medium.

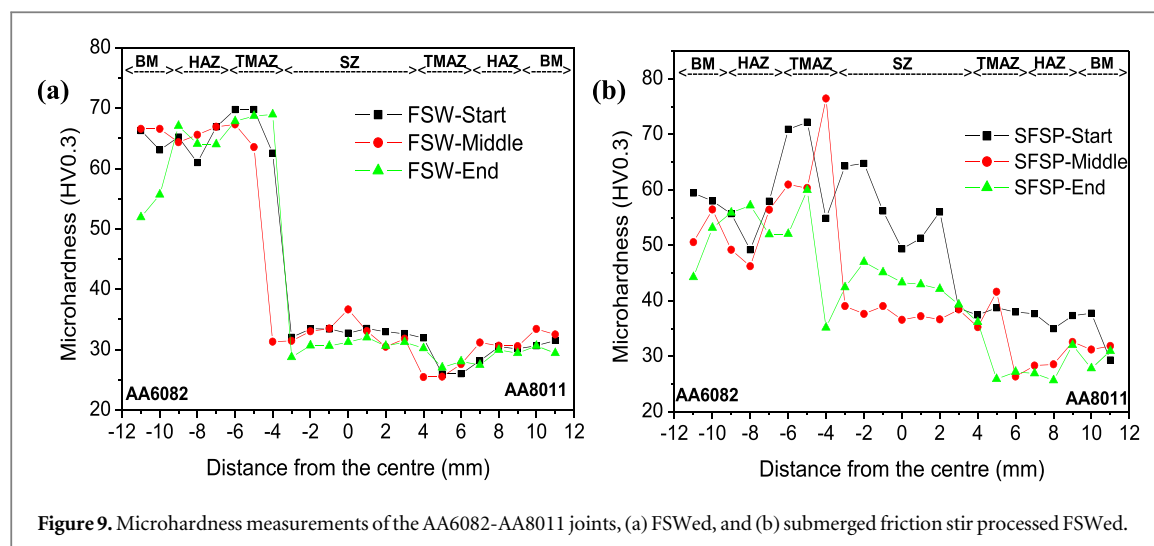


Figure 9. Microhardness measurements of the AA6082-AA8011 joints, (a) FSWed, and (b) submerged friction stir processed FSWed.

- Both FSW and SFSP specimens showed dimpled fracture which symbolizes the ductile behavior. However, the SFSP specimens showed more fine and uniform dimples which played a significant role in the ductility improvement.
- The microhardness of the SFSP joint was found to be higher compared to that of the FSW joint and this is caused by the Hall-Petch relationship and the Orowan mechanism.
- The performance of friction stir processing under cold water assist with the facilitation of heat input. The controlled heat input plays a significant role in grain size refinement which is influential in the mechanical properties of a material.

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## Data Availability

The authors would like to confirm that the data generated during the study is available and can be accessed on request.

## Conflicts of Interest

The authors declare that no conflict of interest may arise from this work.

## ORCID iDs

Sipokazi Mabuwa <https://orcid.org/0000-0002-3775-7731>

Velaphi Msomi <https://orcid.org/0000-0002-5752-8848>

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