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RESEARCH ARTICLE

The Impact of Material Positioning Towards the Friction Stir Welded Dissimilar Aluminium Alloy Joints

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Abstract: ***Background***: Friction stir welding is an advanced process that could be used to join dissimilar materials and alloys. However, there are some areas that require some further analysis. This involves the impact of the material positioning on various dissimilar joints.

Objective: The purpose of this paper is to investigate the influence of material positioning on the microstructure and the mechanical properties of AA8011/AA6082 and AA6082/AA8011 dissimilar joints.

Methods: The materials used in this study were the 6mm thick AA8011 and AA6082-T6 plates. The welding conditions include a tool rotational speed of 1100 rpm, and a traverse speed of 60 mm/min. Microstructural analysis, Vickers hardness and tensile tests were conducted in order to be able to draw a comparison between the respective joints.

Results: The joints (AA8011/AA6082 and AA6082/AA8011) both experienced dynamic recrystallization. The positioning of the stronger strength alloy on the advancing side resulted in finer microstructural grains compared to when the lower strength alloy was positioned on the advancing side. The maximum stir zone hardness of 75 HV was obtained on the AA8011/AA6082 dissimilar joint, while the AA6082/AA8011 had a minimum hardness of 68 HV. Both hardness values were lower than the AA6082 hardness but greater than that of the AA8011. The positioning of AA6082 on the advancing side resulted in higher ultimate tensile strength than when AA8011 was on the advancing side. The AA6082/AA8011 joint was found to be more ductile in comparison to the AA8011/AA6082 joint. The fracture surface morphology of the post tensile specimens also revealed a ductile failure morphology.

Conclusion: Placing the stronger strength alloy on the advancing side resulted in valid overall results of the tests conducted.

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1. INTRODUCTION

The Friction Stir Welding (FSW) technique was developed and patented in 1991 in the United Kingdom at The Welding Institute [1]. During FSW, a non-consumable rotating tool, consisting of a shoulder and a pin towards the end, gets plunged into the base material and progresses in the welding direction [2]. FSW technique is considered to be a fumeless welding technique that is best suitable to join soft materials that are difficult to join by traditional welding methods like aluminum, copper, nickel, titanium, etc. [3]. FSW is also known to have the capability of mitigating the residual stresses that are normally associated with the long-existing welding technique. The development of FSW has spiked interest in most researchers, hence numerous works have been published from various aspects. This includes the welding of similar and dissimilar aluminum alloys.

Material positioning during FSW of dissimilar aluminium alloys was found to influence the material flow, which affects the mixing and material stirring [4]. The material positioning also plays a vital role in the joint microstructure due to the differences in the mechanical properties of the selected base materials [5, 6]. Niu [7] investigated the microstructure of the friction stir welded AA2024-AA7075 joint and discovered that the top section if the stir zone was composed of the base material placed on the retreating side, while the middle and bottom sections were composted of the base material placed on the advancing side. Retaining the high strength alloy on the advancing side resulted in defects

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Table 1. Chemical Compositions.

-	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-T6	0.6-1.2	0.0-0.2	0.0-0.10	0.0-0.20	0.7-1.3	0.0-1.0	0.0-0.5	0.0-0.1	Bal

Table 2. Mechanical Properties of the Base Materials.

-	Ultimate Tensile Strength (MPa)	Elongation (%)	Microhardness (HV)
AA8011	94.1	40.17	33.5
AA6082	308	25.42	89.6

and excessive agglomerations caused by inadequate material flow [8].

Guo *et al*., [9] investigated the effect of welding parameters on the quality of AA6061/AA7075 dissimilar joint. This investigation revealed that the material positioning influenced the material mixing. The effective material mixing was observed when AA6061 was placed on the advancing side during welding. There was a grain size refinement that was observed when AA6061 was located on the advancing side.

Guo *et al*., [10] performed the fatigue analysis on the dissimilar joints formed using AA5083 and 6061 plates. The loading conditions used in conducting various tests were based on the structural applications. The kissing bond defect was found to have a direct impact on the reduction of fatigue life of the joint. Moradi *et al*., [11] performed the microstructural and textural investigation on the friction stir welded AA2024 and AA6061 dissimilar joint. The stir zone was found to have grain refinement due to continuous and discontinuous recrystallization. It was also observed that the texture intensity was weaker on the advancing side compared to the starting materials. The microhardness of the advancing side was found to be identical throughout, while three distinct zones were observed from the profile of the retreating side.

Various studies have been performed to develop an understanding of the impact of the tool position during the FSW on various properties of the joint. Amongst other properties that are affected by the positioning of the tool, grain size refinement has been consistently significant in the results. The grain refinement is associated with the heat input during welding [12-16]. It has been demonstrated from various works that the FSW technique could be employed on materials with far different mechanical properties with success. This includes the welding of AA1050 and 6061, AA2024 and AA7075, AA2024 and AA7075, AA2219 and AA7475, AA5010 and AA6061, AA5086 and AA6061, AA5052 and AA6061 [17-22]. There is very limited literature which reports on the performance of friction stir welded dissimilar aluminum alloy joint where AA8011 is involved. There are few works that involve the optimization of the welding parameters of the dissimilar joint. This requires assessing the influence of tool profile on the mechanical properties of the AA8011/AA6061 dissimilar joints [23, 24]. There is no work based on the influence of material positioning towards the behavior of the AA8011/6082 dissimilar joint. This paper reports the influence of the material positioning towards the mechanical properties of AA8011/AA6082 dissimilar joint.

2. MATERIALS AND METHODS

Base materials AA8011 and AA6082-T6 with a thickness of 6 mm were used as received in the performance of FSW. The nominal chemical composition of the two base materials is shown in Table **1** [25, 26]. The mechanical properties of the base materials are shown in Table **2**. The FSW was carried out using the conventional milling machine. The welding parameters used in producing the welds are shown in Table **3**. The H13 tool profile is also portrayed in Table **3**. The joints were produced when the two materials were placed on the advancing side interchangeably. The welding conditions were fixed to those shown in Table **3** to critically analyze the impact of the material positioning. Figure **1** presents the view of the dissimilar welded joints AA8011/AA6082 and AA6082/AA8011 with AS for the advancing side and RS for the retreating side. From the figure, an exit hole at the end of the joint indicates the position where the tool pin stopped before it was pulled up after FSW. Comparing the two weld surfaces of the said joints, they looked similar to the AA6082/AA8011 showing notable flash.

Table 3. FSW Parameters.

Parameter	Condition
Tool shoulder diameter	20mm
Tool probe diameter	7mm
Tool pin length	5.9mm
Rotating speed	1100rpm
Traverse speed	60mm/min

The welded plates were cut for the preparation of various tests and the waterjet technology was used. The tests con-

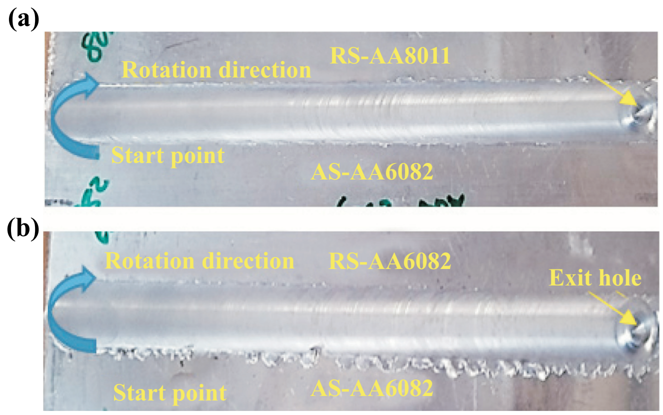

Fig. (1). FSW welded joints-top view, (**a**) AA8011/AA6082 and (**b**) AA6082/AA6082. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

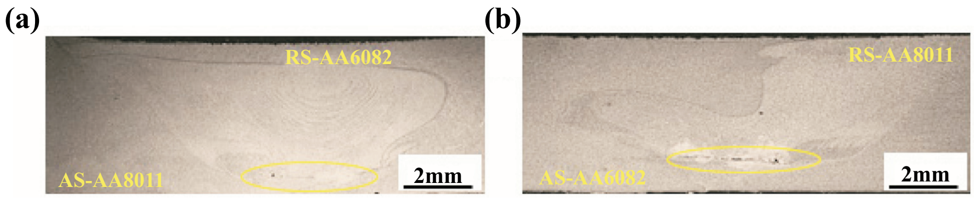

Fig. (2). Macrographs, (**a**) FSWed joint AA8011/AA6082, (**b**) FSWed joint AA6082/AA8011. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

ducted were the tensile test, microhardness and metallographic analysis. The tensile test specimens were further analysed for the nature of fracture using a Scanning Electron Microscopy (SEM). The tensile tests were performed using the Instron 8801 with a maximum 100kN load cell. The ASTM-E8M-04 standard was used for the tensile specimen geometry and operating parameters. Data was logged using the Bluehill 3 software. The InnovaTest Falcon 500 machine was used for microhardness testing. The ASTM E384-11 standard was used for Vickers microhardness testing. The 190HV standard was used for experimental setup. 0.3kg load, and objective 10x and 20x were used. The 2mm interval was used from the edge to edge (advancing to retreating). The metallographic analysis was performed using the Motic AE2000 microscope. The cross-section surfaces of the welds were etched using the modified Keller's reagent (10ml HNO_3, 1.5ml HCL, 1.0ml HF and 87.5ml distilled H_2O) and Weck's reagents (1g NaOH, 4g $KMnO_4$ and 100ml distilled H_2O). The grain sizes were measured using the ASTM E112 standard and the linear intercept technique using the imageJ software.

3. RESULTS AND DISCUSSION

The macrostructures of the FSWed joints are shown in Fig. (**2**). Figures **2a** and **2b** show FSWed AA8011/AA6082 and AA6082/AA8011 dissimilar welds respectively. The AA8011/AA6082 FSWed joint showed circular banded structure known as onion rings, while the AA6082/AA8011 one showed a J-like shaped structure. Small cracks (defects) were noted at the bottom of the onion rings circled in yellow on the FSWed joints, which are very common with FSW of dissimilar alloys [24, 27, 28]. Figure **3** shows base materials and the micrographs of the dissimilar joints. The micrographs consisted of three distinctive regions, the Heat-Affected Zone (HAZ), Thermo-Mechanically Affected Zone (TMAZ) and the stir zone. The zones were a result of the mechanical and thermal deformation induced by the tool during the process [29-31]. The HAZ region consisted of an underformed grain structure and grain coarsening due to the heat influence. The TMAZ consisted of elongated grains, while the stir zone underwent extensive microstructural grain refinement [32-34].

The AA8011 base material consisted of elongated mean grain sizes of 51.84µm, while the AA6082 had a mean grain size of 65.92µm. The microstructural grain size range of 9.57 to 20.81µm was obtained for the AA8011/AA6082/AA8011 welded joint and 7.65 to 17.75µm for the AA6082/AA8011 one. During both material positioning, the stir zones revealed a dynamically recrystallized microstructure with fine equiaxed grains. This is caused by the thermal softening and large plastic deformation that occurred during the FSW [34, 35]. The positioning of the AA6082, which is the aluminum alloy with a higher tensile strength on the advancing side, resulted in finer mean grain size. Similar observations were reported in the literature [36]. Bahemmat *et al*., [37] related this behavior to the plastic deformation that each material experiences during FSW, which results in diverse recrystallization hence different grain sizes. Additionally, the temperature differences experienced by stir zones also play a pivotal role [38]. The Mg_2Si particles were noted in both stir zone micrographs. Similar observations were reported in the literature [39-41].

The Vickers hardness profiles of the dissimilar joints are depicted in Fig. (**4**). The Hall-Petch states that the hardness

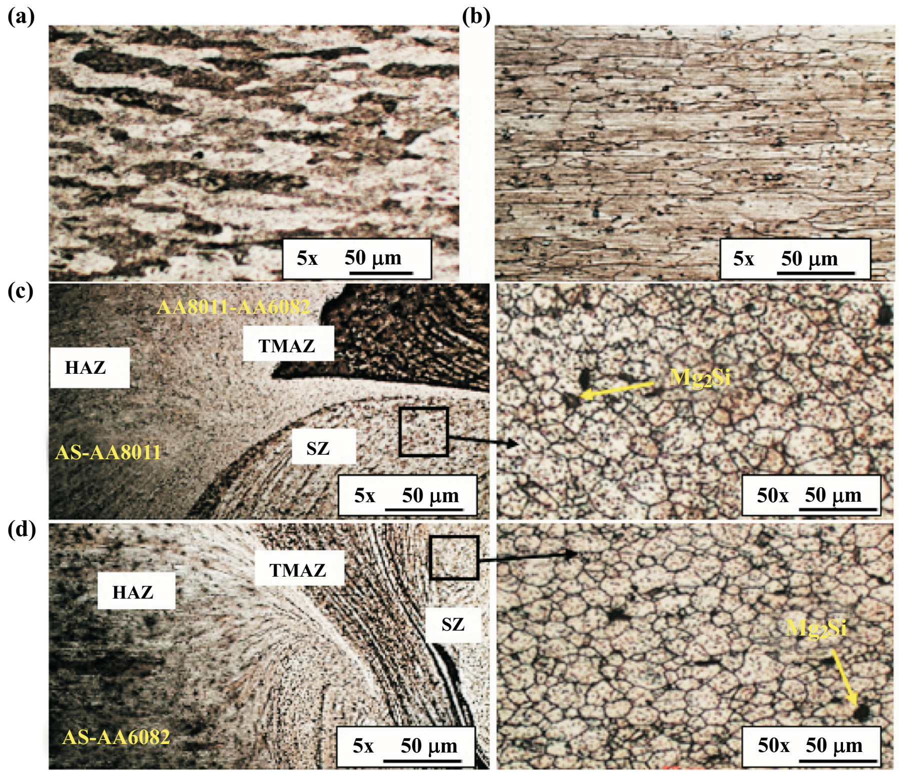

Fig. (3). Micrographs, (**a**) AA8011 base material, (**b**) AA6082 base material, (**c**) FSWed joint AA8011/AA6082, (**d**) FSWed joint AA6082/AA8011. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

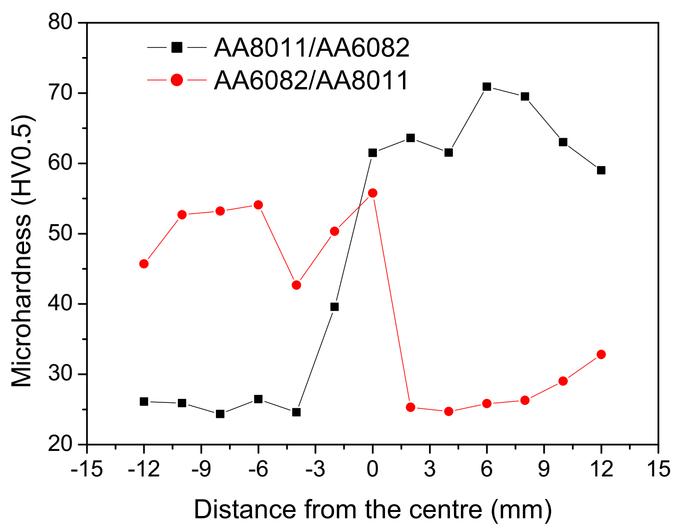

Fig. (4). Hardness profiles of the FSWed dissimilar joints. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

increases with a decrease in the grain size [42]. Examining the figure, the stir zones were found to have maximum hardness compared to other regions, especially on the AA6082/AA8011 joint. Similarly, a few studies concurred with the results obtained where the refinement of the microstructural grains regions showing improved hardness in the stir zone [43-45]. The hardness of the base material AA8011 was 33.5 HV and for AA6082, it was 86.9HV. The shapes of the hardness profiles were found to be somehow inversely proportional to each other. The stir zone hardness of the AA8011/AA6082 welded joint was 75HV and 68HV for the AA6082/AA8011 one. The stir zone hardness was noted to be higher on the AA8011/AA6082 joint. This behavior concurs with the study by Cavaliere and Panella [12]. The AA6082/AA8011 joint had a lower hardness which was as a result of the refinement in the grain size compared to the AA8011/AA6082 joint. These results confirm the theory that the hardness decreases with a reduction in the grain size [46-49].

The stir zone hardness of both joints was noted to be lower compared to that of the AA6082 base material. This

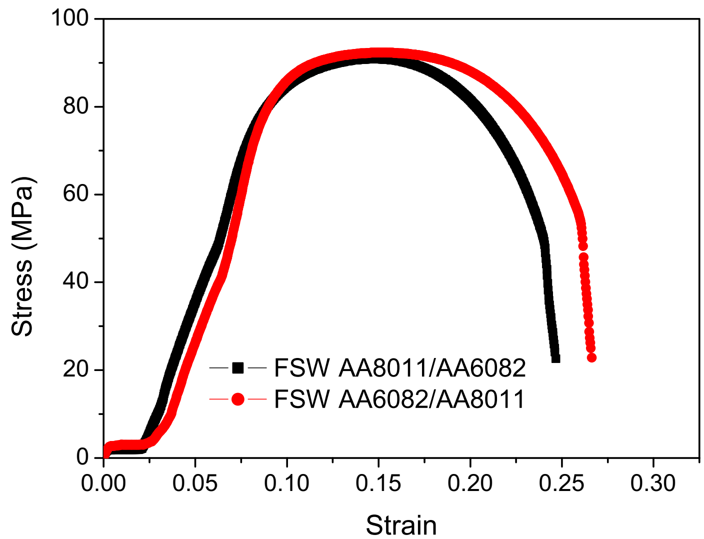

Fig. (5). Stress-Strain curves of the FSWed dissimilar joints. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

Table 4. Tensile Properties of the FSWed Dissimilar Joint.

-	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Percentage Elongation (%)	Position of Fracture
AA8011/AA6082	79	90.9	24.07	HAZ
AA6082/AA8011	82	92.3	26.04	HAZ

decrease associated with the thermal cycles caused by the dissolution and coarsening experienced by strengthening, precipitates during the friction stir welding process [50-52]. Additionally, the HAZ was found to have lower hardness due to grain coarsening [53-55]. This then makes the HAZ the most likely region of failure under tensile loading [32, 56].

Figure **5** presents the stress and strain curves of the dissimilar joints with tensile properties tabulated in Table **4**. Both specimens fractured in the HAZ of the AA8011 (lower strength) alloy; this is due to this position having a minimum hardness than all other regions [20, 38, 57, 58]. Higher ultimate tensile strength of 92.3 MPa was noted on the joint with AA6082 on the advancing side. The placing of the lower strength alloy AA8011 resulted in tensile strength of 90.9 MPa. In literature, similar behavior has been reported with FSW of dissimilar alumnium alloys where the placing of the high strength alloy resulted in a better tensile strength [38, 59, 60]. Moreover, Priya *et al.*, [61] were certain that the material placed on the advancing side dominated the stir zone more than the one placed on the retreating side. The similar justification was reported in the literature [62-64]. This then concurs with the AA6082/AA8011 dissimilar joint having a higher ultimate tensile strength due to the AA6082 being a higher strength alloy.

The ultimate tensile strengths of both dissimilar joints were lower in comparison to the base material ones. Similar observations were reported in the literature [12, 38]. Kolraji *et al.*, [65] showed that this behaviour was due to the cold work loss in the HAZ, which was a result of annealing. It was noted that the yield strength of the said dissimilar joints also followed the same trend as that of the ultimate tensile strength.

The percentage elongation obtained was 26.04 and 24.07% for the AA6082/AA8011 and AA8011/AA6082 joints respectively. The AA6082/AA8011 joint was found to be ductile than the AA8011/AA6082 one and the AA6082 base material, but less ductile in comparison to the AA8011 base material. This confirms that friction stir welding does enhance the ductility of the dissimilar joint as reported in the literature [66-71].

The fracture surface morphologies of the tensile specimens are presented in Fig. (**6**). It is evident that all the specimens failed in a ductile mode, due to the presence of same dimples [12, 72-74]. The other features noted were the cleavage faces and micro-voids [75]. The AA8011/AA6082 dimples were found to be more uniform than the AA6082/AA8011 which showed more micro-voids and irregular dimples.

CONCLUSION

The impact of material positioning towards the friction stir welded AA6082/AA8011 dissimilar joint has been successfully determined. Based on the results obtained, the following conclusions were made: The joints (AA8011/AA6082 and AA6082/AA8011) both experienced dynamic recrystallization. The positioning of the stronger

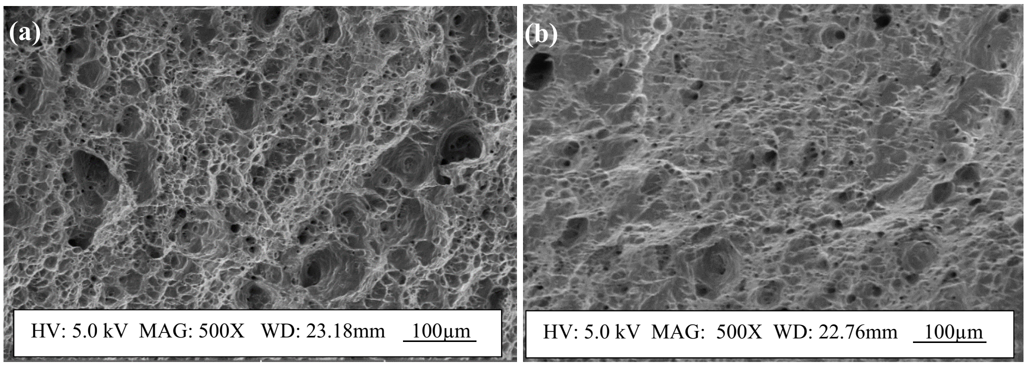

Fig. (6). Fractographs, (**a**) FSWed joint AA8011/AA6082, (**b**) FSWed joint AA6082/AA8011. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

strength alloy on the advancing side resulted in finer microstructural grains compared to when the lower strength alloy was positioned on the advancing side. The maximum stir zone hardness of 75HV was obtained on the AA8011/AA6082 dissimilar joint, while the AA6082/AA8011 had a minimum hardness of 68HV. Both hardness values were lower than the AA6082 hardness (40HV) but greater than that of the AA8011 (33.5HV). This therefore means that the materials were properly mixed during FSW. The positioning of AA6082 on the advancing side resulted in higher UTS than when AA8011 was on the advancing side. The AA6082/AA8011 joint was found to be more ductile in comparison to the AA8011/AA6082 joint. The fracture surface morphology of the post tensile specimens also revealed a ductile failure morphology. Placing the stronger strength alloy on the advancing side resulted in sound overall results of the tests conducted.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data supporting the findings of the article will be made available upon request from the corresponding author (Prof. Sipokazi Mabuwa).

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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