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Effect of material positioning on fatigue life of the friction stir processed dissimilar joints

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Abstract

The investigation on the fatigue behavior of the friction stir processed (FSPed) dissimilar joint is reported in this work. The main focus was to analyze the influence of material positioning on the fatigue life of the joint. The 1pass friction stir processing technique was applied on the friction stir welded AA8011/AA6082 and AA6082/AA8011 dissimilar joints (AA8011/AA6082 means AA8011 on the advancing side, AA6082/AA8011 means AA6082 on the advancing side). The friction stir processing was conducted under normal conditions (room temperature). The samples were prepared for different analyses using waterjet cutter technology. The tests conducted include tensile, microstructural analysis, microhardness, fatigue, and fracture surface morphology. The microstructural analysis revealed a correlation between material positioning and grain sizes. There was a notable decrease in grain size when AA6082 was positioned on the advancing side during processing. The tensile properties of the FSPed AA6082/AA8011 joint were found to be higher compared to the AA8011/AA6082 joint. The AA6082/AA8011 joint was found to be more ductile compared to the AA8011/AA6082 joint. The stir zone microhardness values for the AA8011/AA6082 and AA6082/AA8011 joints were found to be approximately 68HV and 73HV, respectively. The fatigue strength of AA6082/AA8011 was found to be higher compared to that of AA8011/AA6082.

Introduction

The friction stir welding technique is regarded as the most suitable method of joining aluminum alloys and other soft metals [1]. This includes both similar and dissimilar metals and alloys. Numerous investigations are being in progress that is looking into the compatibility of FSW on the dissimilar aluminum alloys [1–4]. However, it has been noted that there are many factors that compromise the quality and strength of the dissimilar joint. Some of the factors include welding parameters, material positioning, and welding surrounding conditions [5, 6]. Additionally, the joining of dissimilar materials was found to result in the formation of intermetallic compounds, which is also a major contributing factor towards the weakening of the joint strength [6, 7]. This, therefore, opened a gap for a post welding technique to strengthen the joint strength. The friction stir processing technique was found to be a suitable method in modifying the joint/surface properties. The friction stir processing (FSP) works the same way as the friction stir welding, but it does not join material together but modifies the microstructure of the material [8, 9]. FSP has been used successfully to modify both single surfaces and welded joints [10–13].

The FSP technique still has many areas that still need to be investigated. Some of those areas include the impact of FSP on the fatigue life of the processed joint. There is very limited literature available in this area. However, it has been shown by various authors that the occurrence of most structural failures originates from fatigue [14, 15]. This then makes it a need that special attention is given to this area as there is a high possibility of utilizing dissimilar aluminum alloys in the aerospace and automotive industries. These industries require very

Table 1. Chemical compositions [25, 26, 23].

	Mg	Zn	Ti	Cr	Si	Mn	Fe	Cu	Al
AA8011-H14	0.28	0.084	0.016	0.028	0.52	0.46	0.74	0.13	Bal
AA6082-T651	1.1	0.2	—	0.25	0.9	0.7	0.5	0.1	Bal

Table 2. Mechanical properties of the base materials.

Material	Ultimate tensile strength (MPa)	Elongation (%)	Microhardness (HV)
AA8011-H14	94.1	40.17	33.5
AA6082-T651	308	25.42	89.6

Table 3. FSW/P conditions.

Shoulder diameter	Pin diameter	Tilt angle	Pin length	Rotational speed	Traverse speed
20 mm	7 mm	2°	5.6 mm	1100 rpm	60 mm min ⁻¹

high safety, which makes fatigue resistance of joints very pivotal for ensuring the integrity of such structures [16, 17].

Hussein and Shammari [18] comparatively studied the FSWed and FSPed AA5083-H111 joint to determine the respective fatigue and fracture behavior of the joints. The fatigue test was performed under constant stress amplitude cantilever. The analysis of the fatigue properties revealed that the FSPed samples yielded better fatigue limits compared to the FSWed samples. Uematsu and Tokaji [19] employed FSP on the cast aluminum alloy A356-T6 to study its fatigue strength. The fatigue strength of the FSPed A356-T6 was found to be lower than that of the base material, nonetheless, the fatigue limit was significantly improved by FSP. The increase in fatigue limit was said to be due to the elimination of the casting defects during FSP, while the decrease in fatigue strength was due to matrix softening by the dissolution of precipitates caused by heat input during FSP leading to a faster crack growth rate in the FSPed region.

Park *et al* [20] discovered that the application of FSP increased the fatigue life of the processed joint by 42% compared to that of the welded one. Additionally, the fatigue strength was found to increase with a decrease in the microstructural grain size. Similar results were consistent with those reported in the literature [21]. FSP was employed on the TIG welded AA6061 joint intending to increase the fatigue life of the joint [22]. The constant amplitude loading and a stress ratio of zero were used. The application of FSP resulted in the tensile strength being improved by 5%–13% while the hardness was increased by 5%–10%. Subsequently, the fatigue strength improvement of about 30%–60% was observed and these improvements were due to the microstructural grain refinement in the stir zone as well as the modification in the geometry that occurred at the weld toe.

There is a very limited work available that involves the processing of the friction stir welded dissimilar joint. This work is focusing on analyzing the impact of the FSP on the friction stir welded AA8011/AA6082 dissimilar joint. The analysis was being performed correlatively with material positioning during FSP.

Materials and methods

The 6 mm thick AA8011-H14 (AA8011) and AA6082-T651 (AA6082) were used in the formation of the joint through the friction stir welding (FSW) technique. Table 1 present the chemical compositions of both AA8011-H14 and AA6082-T6. The mechanical properties of the materials of the same materials are presented in table 2. The plates were cut into rectangles of 260 mm × 52 mm. The dimensioned plates were friction stir using LAGUN FA.1-LA semi-automated milling machine. The welding was performed under room temperature using the parameters presented in table 3. The material on the advancing side was positioned interchangeably i.e. the first FSW was performed with AA8011-H14 on the advancing side followed by the second with AA6082 on the advancing side (see figure 1). The friction stir welded plates were allowed to cool down for a day before they are subjected to friction stir processing. The friction stir welded plates were then subjected to the single-pass friction stir processing (FSP) after they have cooled down. The friction stir processing was performed on the same machine used in performing FSW. The parameters used in the FSP procedure are the same as those that were used in the FSW procedure. The parameters were kept uniform for both procedures (FSW and FSP) to

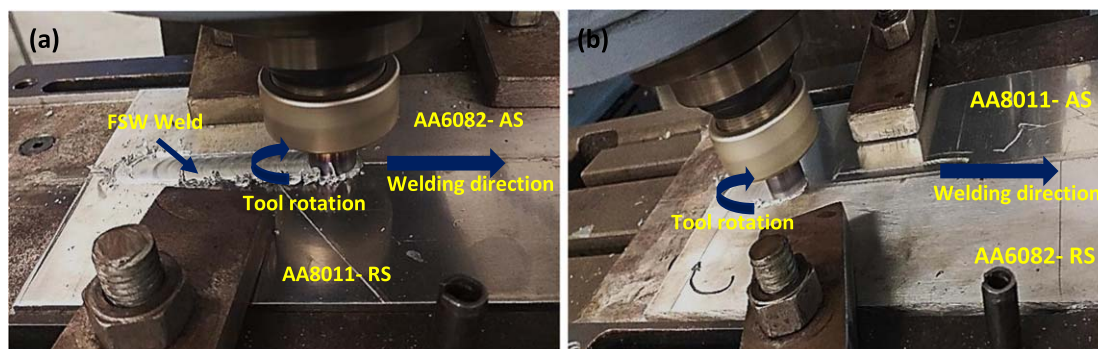


Figure 1. FSW setup, AS-advancing side, RS-retreating side, (a) AA6082-AS and (b) AA8011-AS.

reduce variation that can influence the results and this practice has also been adopted previously [4, 23, 24]. The FSW/FSP tool used was made of high-speed steel (HSS) AISI 4140 [23].

The waterjet technology was used to prepare the specimens for various tests. It should be noted that all the specimens were cut perpendicular to the FSP direction. The tests conducted include microstructural analysis, tensile tests, microhardness, and fatigue tests. The microstructural analysis was performed using Motic AE2000 optical microscopy. The linear intercept method was used in measuring grains through ImageJ software. The specimens were ground, polished, and chemically etched before the microstructural analysis. The chemical etchants used were the modified Keller's reagent (10 ml HNO₃, 1.5 ml HCL, 1.0 ml HF and 87.5 ml distilled H₂O) and Weck's reagents (1g of NaOH, 4g of KMnO₄, and 100 ml of distilled H₂O). The Keller's etchant was used to corrode AA8011 while Weck's etchant was used to corrode AA6082. The microhardness test was performed using the InnovaTest Falcon 500 machine through the guidance of the ASTM E384-11 standard. The load of 300 g with 10 s dwell time was used in conducting microhardness analysis. The Hounsfield H25K tensile testing machine with Horizon operating software was used to perform the tensile tests. The ASTM-E8M-04 standard was used in designing the tensile specimen and also the performance of the tensile tests [23]. The fatigue tests were conducted using the Instron 8801 (100kN) with Bluehill-3 operating software. The fatigue was performed based on the ASTM: E466-07 standard. The flat dog-bone shaped specimens were prepared for the fatigue tests. The length of the fatigue specimen was 90 mm with a 44 mm gauge length. The thickness was uniform across the specimens besides the stir zone. The pull-push fatigue tests were conducted at a frequency of 20 Hz with the minimum and the maximum amplitudes of 30% and 80% of the ultimate tensile strength (UTS). Three fatigue tests were performed per stress level and the average values were used to produce the fatigue graph. It should be noted that there was no special treatment that was performed on the surface of the specimens before testing. The notation of AA8011/AA6082 means that AA8011 was placed on the advancing side while AA6082 was on the retreating side and the visa versa. This notation is being followed for the rest of the paper.

Results and discussion

Microstructural analysis

Figure 2 shows the optical micrographs of the base materials and friction stir processed dissimilar joints. The AA6082 base material showed an elongated coarse grain structure with mean grain diameters of 52.08 μm leaning towards the rolling direction (see figure 4(a)). The AA8011 base material microstructure also showed coarse pan-cake like grains with a mean grain size of 67.36 μm (see figure 4(b)). The microstructure of the FSPed AA6082/AA8011 and AA8011/AA6082 joints consisted of three zones namely the thermo-mechanically affected zone (TMAZ), the heat-affected zone (HAZ), and the stir zone (SZ) also called nugget zone (NZ) (see figures 4(c)–(d)). The grain morphology at the stir zone of each processed joint is shown in figures 2(e) and (f) and the grain size measurements were conducted in this region because it is the region that experiences pin disruption. The equiaxed fine grains were observed at the stir for both AA6082/AA8011 and AA8011/AA6082 FSPed joints (see figures 2(e) and (f)). The grain refinement at the SZ was due to the high temperature experienced by this zone and the dynamic re-recrystallization which occurred during the processing [11, 23, 27]. The AA6082/AA8011 friction stir processed dissimilar joint had a mean grain size of 11.98 μm while the AA8011/AA6082 was 15.87 μm . The difference in grain size is attributed to the dynamic re-recrystallization which occurred under different heat input caused by different material positioning.

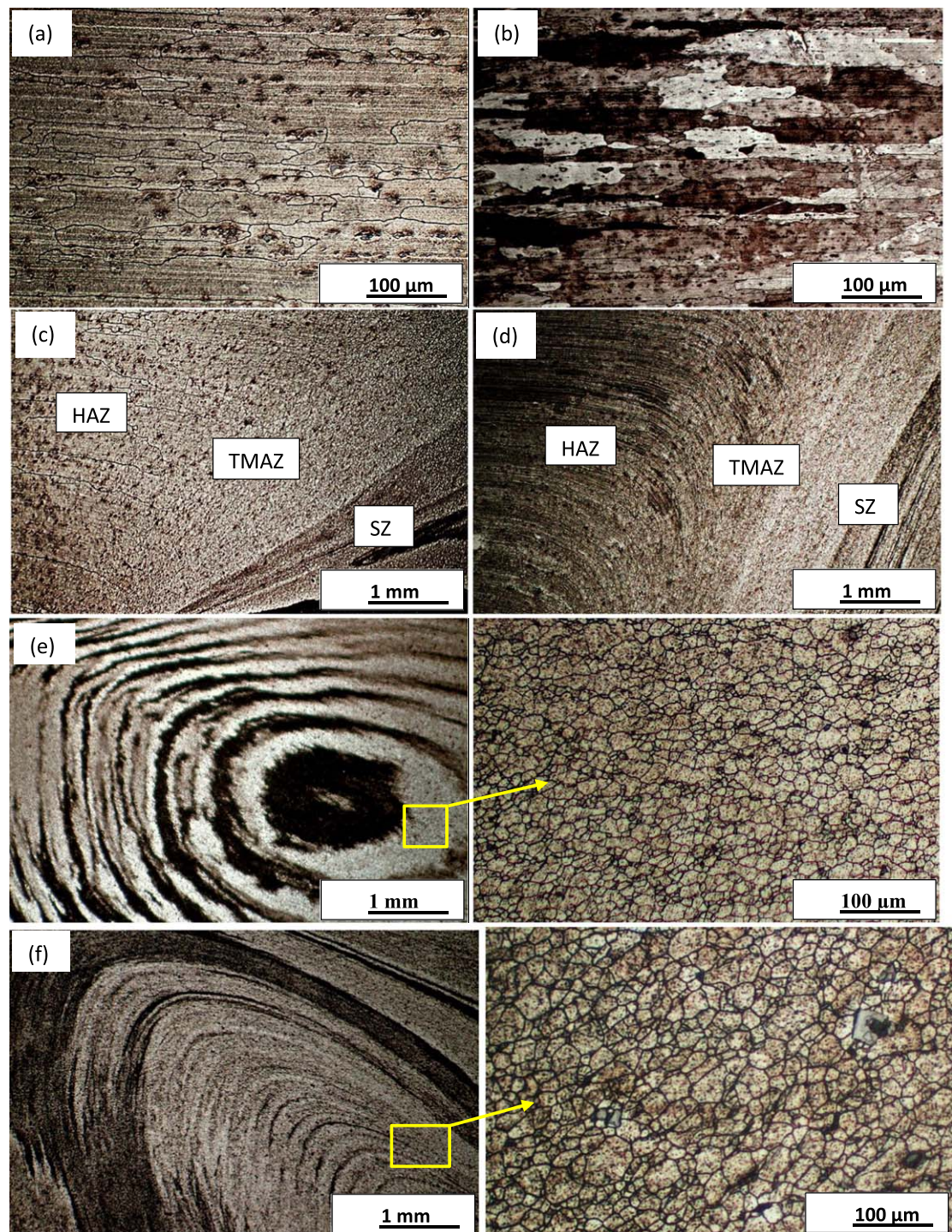


Figure 2. Optical micrographs, (a) AA6082 base material, (b) AA8011 base material, (c) Friction stir processed AA6082/AA8011 joint advancing side, (d) Friction stir processed AA8011/AA6082 joint advancing side, (e) Stir zone (AA6082/AA8011) and (f) Stir zone (AA8011/AA6082).

Tensile strength

Figure 3 shows the tensile properties of the base materials and the friction stir processed dissimilar joints. It should be noted that the values used in generating figure 3 are average values that were obtained from three repetitions hence the error bars are included. It should also be noted that all the tensile specimens fractured outside the stir zone towards the AA8011 side (see figure 3). The ultimate tensile strength (UTS) of AA6082 and AA8011 was found to be 308 MPa and 94.1 MPa, respectively. The percentage elongation for AA6082 was found to be 25.42% while the percentage for AA8011 was found to be 40.17%. The AA6082/AA8011 joint recorded the maximum UTS of 91.45 MPa with 22.28% of percentage elongation whereas the AA8011/AA6082 joint recorded a maximum UTS of 85.1 MPa with a percentage elongation of 20.22%. This, therefore, means that

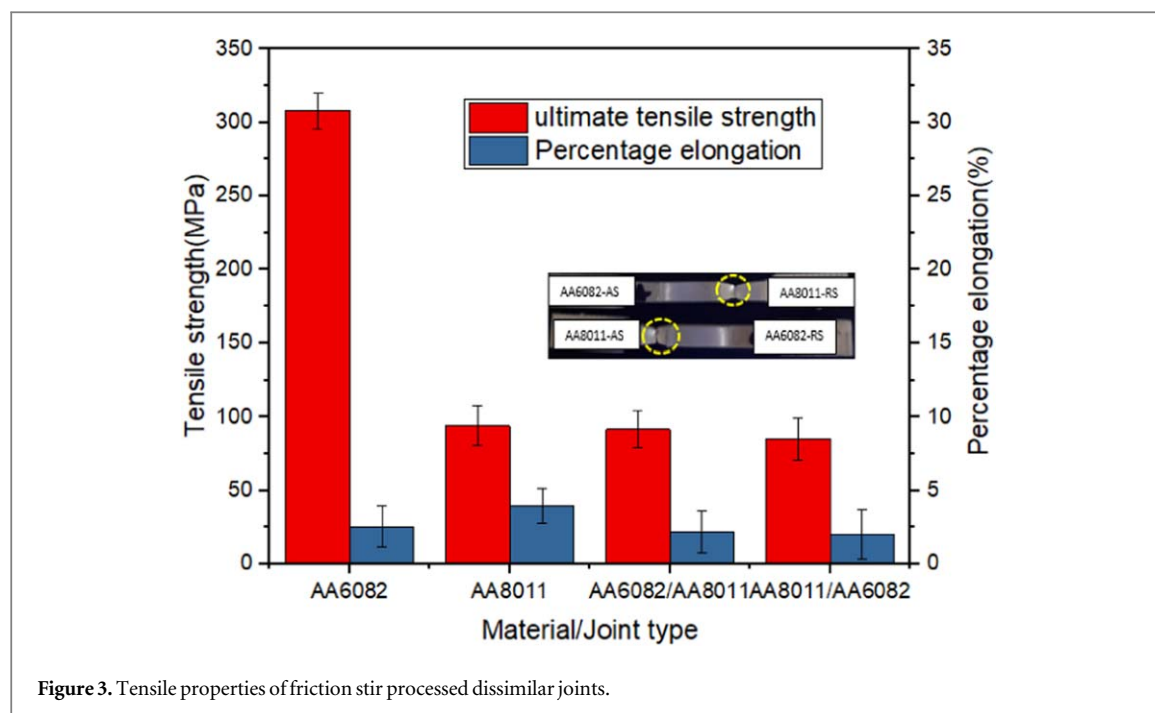


Figure 3. Tensile properties of friction stir processed dissimilar joints.

positioning of AA6082 on the advancing side resulted in better tensile properties in comparison to AA8011 on the advancing side. This difference in tensile properties is attributed to the grain refinement that was observed during microstructural analysis. Generally, the morphology and alignment of grains play an important role in the tensile properties of a material [25, 26, 23]. It was observed that the tensile properties of the joints were found to be lower compared to the parent materials (see figure 3) although the grains at the SZ were finer compared to both base materials. This is caused by the non-uniformity of grains found in different regions of the FSPed joint and the fact that fracture occurred outside the FSPed joint where material softening is normally found [28–31]. Generally, HAZ is known to be the weakest region amongst the regions found in the FSP/W joint because of grain coarsening that is always associated with this region [32–34]. The failure would generally occur in this region if the SZ is defect-free. Moreover, the tensile properties obtained in this study are higher compared to those found from the friction stir welded joint [35].

Figure 4 presents the fractured surface morphology of the tensile specimens. The tensile specimens failed at the HAZ of the AA8011 hence both joints showed similar fractographs. The ductile failure mode characterized by quasi-state cleavage, dimples, matrix cracks, microvoids, and tear ridges were observed from both fractured surfaces [31, 36].

Microhardness

The microhardness profiles of the FSPed dissimilar joint are presented in figure 5. The tests were performed in three layers across the thickness of the stir zone of each specimen i.e. 1 mm interval from the top to the bottom surface of each specimen. The average values from the three layers were used to generate the profile shown in figure 5. The microhardness profile of the AA6082/AA8011 joint showed a decreasing path from the advancing side towards the TMAZ and a sharp increase is observed at the stir zone. However, the declining trend is observed from the stir zone towards the retreating side of the FSPed dissimilar joint. This behavior is generally caused by the grain size variation that is found from each region of the joint. The microhardness profile of the AA8011/AA6082 joint behaves contrary to that of the AA6082/AA8011 joint. There is an increasing trend that is observed from the advancing side towards the SZ and the decline from the SZ towards the retreating side of the AA8011/AA6082 joint. The microhardness value recorded at the center of the SZ was approximately 73 HV for the AA6082/AA8011 joint while 68 HV was recorded for the AA8011/AA6082 joint. The difference in microhardness for both joints is caused by the difference in grain size at the SZ. Generally, the microhardness depends on the size and orientation of grains of material and this relationship is defined by the Hall-Petch relationship [32, 33]. It was observed that microhardness values of both FSPed joints were lower compared to the base materials and this behavior is normally associated with dissimilar aluminum alloy joints [36–38]. There was generally an increase in microhardness at the SZ and this indicates good material mixing at this region hence fracture occurred outside this region [39–41].

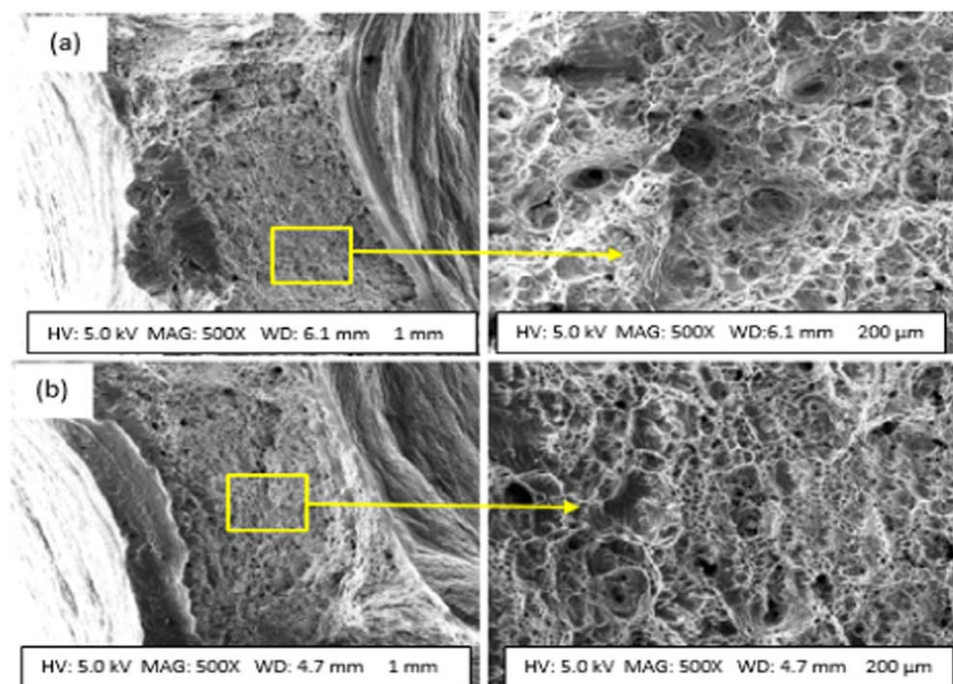


Figure 4. Fractographs for the friction stir processed joints, (a) AA6082/AA8011, (b) AA8011/AA6082.

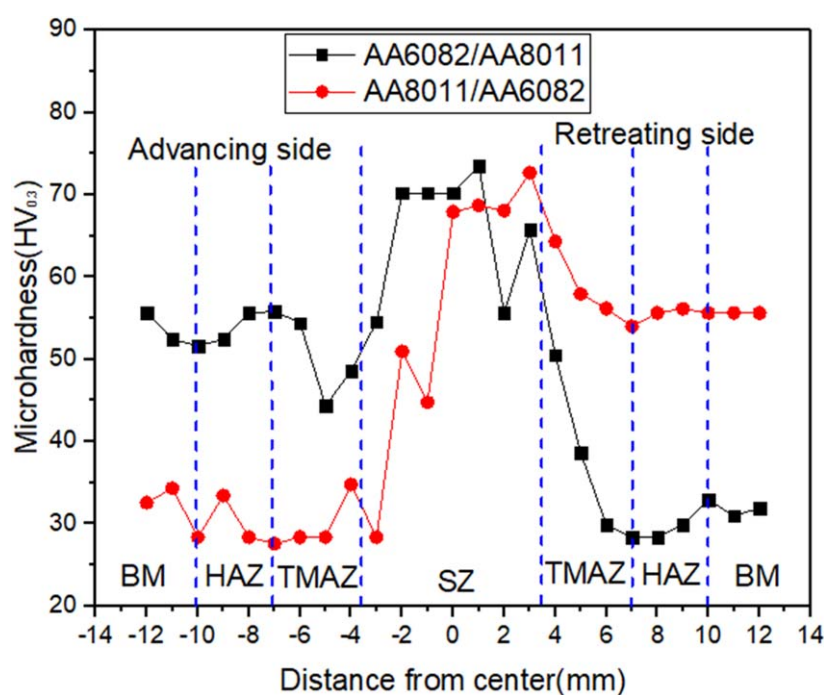


Figure 5. Friction stir processed microhardness profiles.

Fatigue analysis

Figure 6 shows the stress—number of cycles to failure curves for the AA6082/AA8011 and AA8011/AA6082 friction stir processed dissimilar joints. This analysis was performed to understand the behavior of the processed dissimilar joint when it is exposed to the environment with vibration. The fatigue response of both joints shows dependency on the stress amplitude. The AA8011/AA6082 joint had the highest fatigue cycle of 4.89×10^5 while 2.51×10^6 maximum fatigue cycle was achieved from AA6082/AA8011 dissimilar joint. All the fatigue specimens failed consistently on the HAZ region of the AA8011 side. The AA6082/AA8011 had a longer fatigue life cycle compared to the AA8011/AA6082 joint and similar behavior is also reported in the literature [42–44].

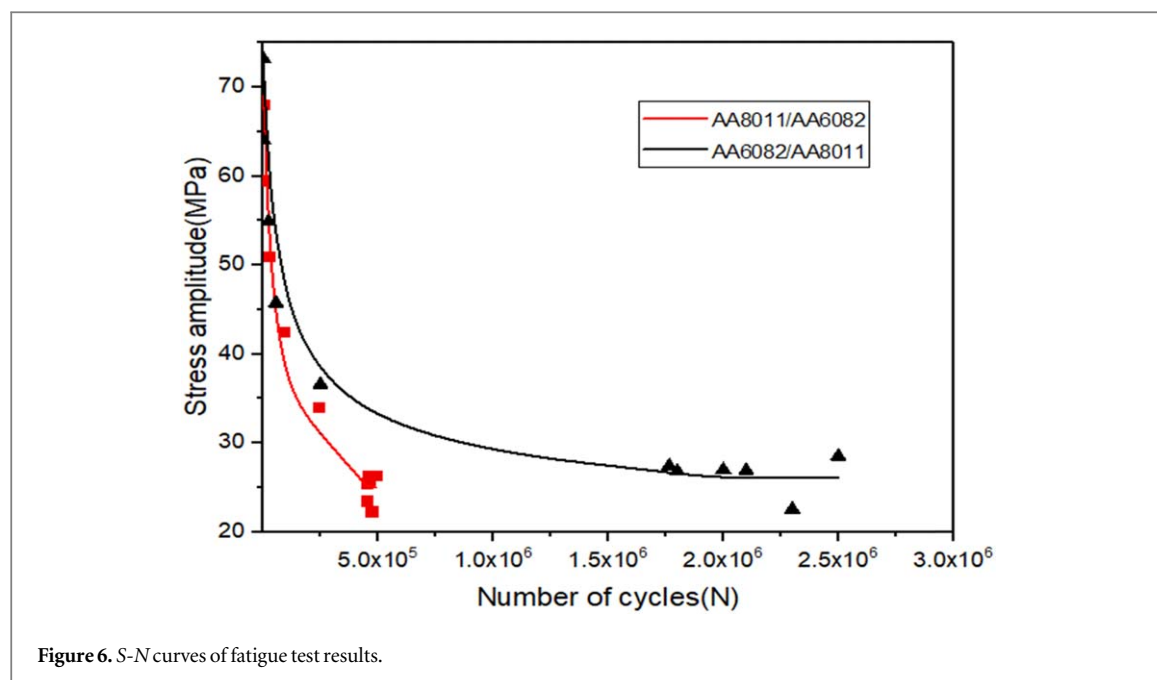


Figure 6. S-N curves of fatigue test results.

The fatigue life behavior was found to agree with the findings by Park *et al* [20], where the relationship between the microstructure and the fatigue life is linked to grain refinement.

The fractured surfaces from fatigue tests were further examined using scanning electron microscopy (SEM) to establish the failure mechanism associated with each stress amplitude. All the examination was performed at the tip of each specimen. Figure 7 shows the fractured surface of the friction stir processed AA6082/AA8011 dissimilar joint post fatigue test. The crack growth created a band of markings known as striations on the fractured surface at the highest stress intensity and these striations are very useful in determining crack growth direction [45, 46]. The various shapes of striations are evident on surfaces associated with the stress amplitude range between 0.3UTS to 0.8UTS (see figures 7(a) to (f)). The teared-cluster-like and normal dimples were observed from the surfaces of figures 7(a)–(c) and these types of dimples are the characterization of ductile fatigue fracture [47, 48]. The rocky-like morphology was also observed from figures 7(d)–(f) and this type of morphology was consistently observed on the specimens fail at higher stress amplitude range. Moreover, there were particle inclusions (circled in yellow) that were also observed on the surfaces in figures 7(a), (e) and (f). Figures 8(a) to (e) show the fractographs for the FSPed AA8011/AA6082 joints failed under fatigue loading. The morphological surfaces of the friction stir process AA8011/AA6082 dissimilar joint are presented in figures 8(a) to (e). Figures 8(a)–(c) shows the rocky-like fracture with some hollow features which are an indication of brittle failure mode [4, 12, 23]. This kind of fracture mechanism was consistent in all the specimens that failed at a higher stress amplitude range. The wave-like fracture with some circular structures was observed at the tip of the surfaces that failed at a low stress amplitude range. It was further observed that there were no indications of striations on all the surfaces of the processed AA8011/AA6082 dissimilar joint. The striations that were visible from some surfaces could not be linked with the direction of the crack growth.

Conclusions

The influence of material positioning on the fatigue strength of the friction stir processed dissimilar AA6082/AA8011 and AA8011/AA6082 was successfully investigated. Based on the results obtained the following concluding remarks were made:

- The positioning of AA6082 on the advancing side influenced the grain size refinement at the stir zone. This influenced the tensile properties of the joint processed when AA6082 is positioned at the advancing side i.e. AA6082/AA8011 dissimilar joint. The positioning of AA8011 at the advancing side was found to have a negative impact on the tensile properties of the joint i.e. AA8011/AA6082.
- The stir zone microhardness of AA8011/AA6082 was found to be lower than that of AA6082/AA8011 dissimilar joints.

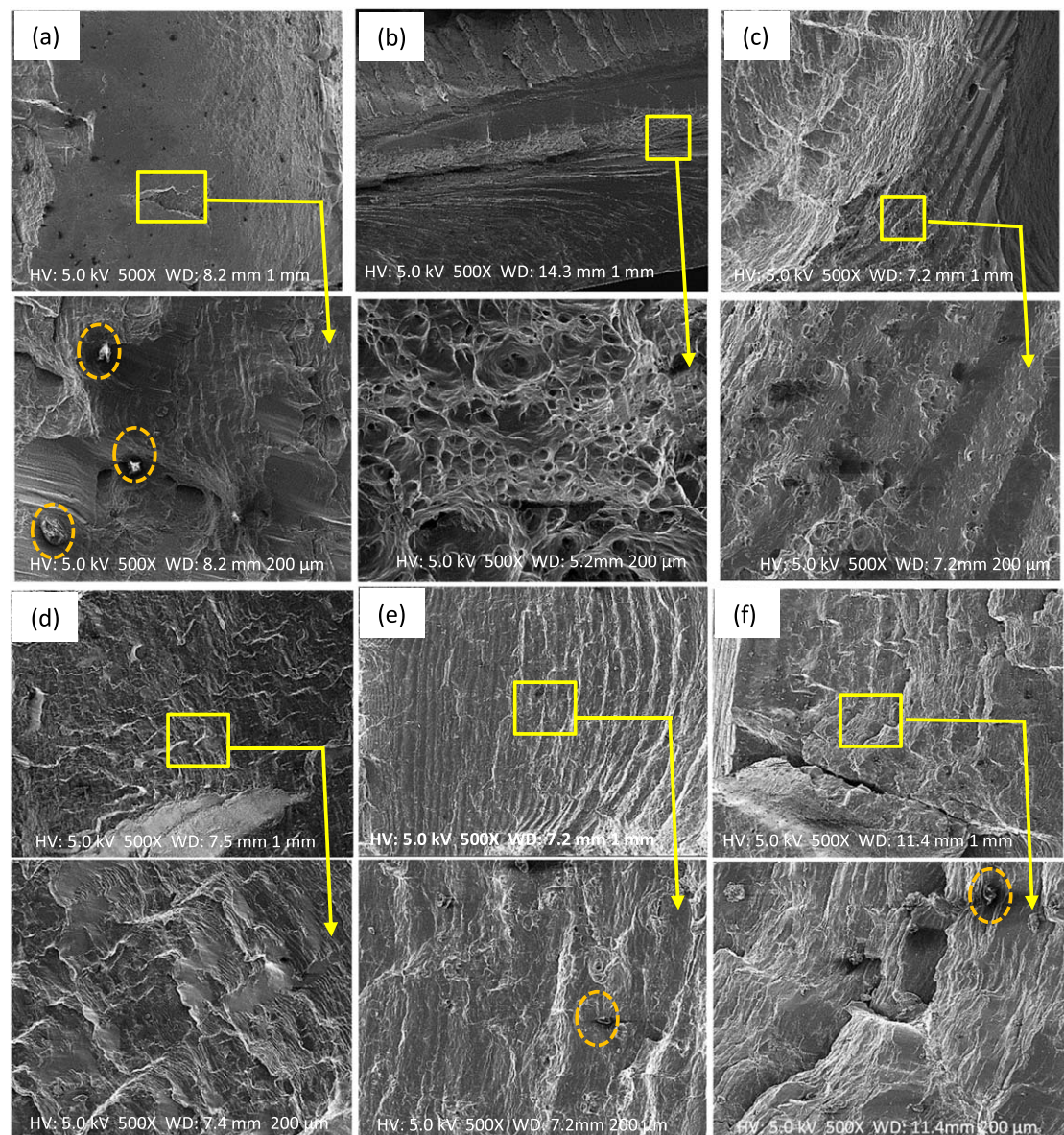


Figure 7. SEM fractographs for friction stir processed dissimilar AA6082/AA8011 joints fatigue tests, (a) 0.8UTS, (b) 0.7UTS, (c) 0.6UTS, (d) 0.5UTS, (e) 0.4UTS, (f) 0.3UTS.

- The fatigue strength of AA6082/AA8011 dissimilar joint was found to be higher compared to that of the AA8011/AA6082 dissimilar joint. There was a notable variation in fracture morphology with different stress amplitudes. The ductile fracture morphology with some striations was observed on the fractured surface of AA6082/AA8011. It was observed that the visible striations could not be used to track the crack growth direction.

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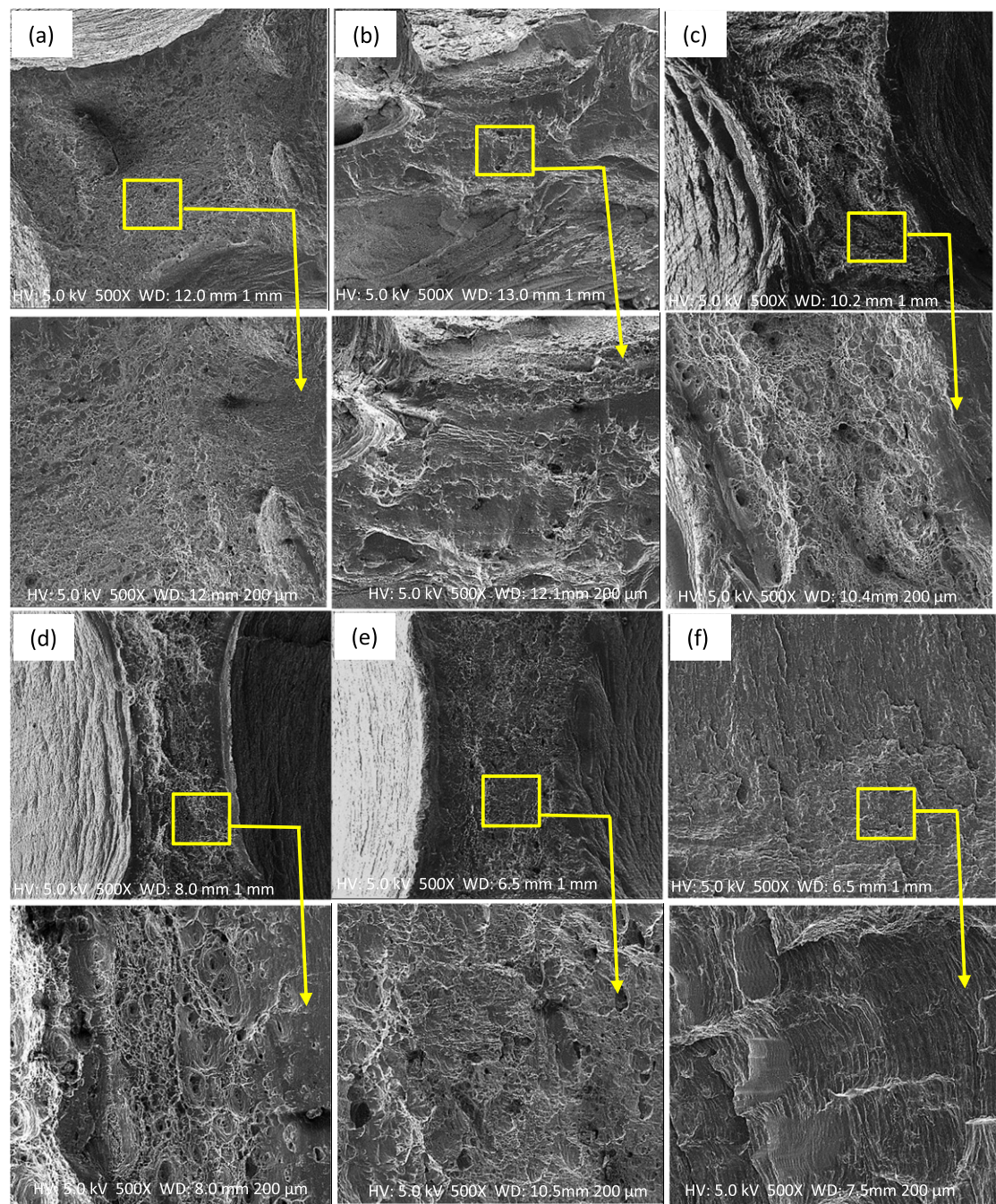


Figure 8. SEM fractographs for friction stir processed AA8011/AA6082 dissimilar joints fatigue tests, (a) 0.3UTS, (b) 0.4UTS, (c) 0.5UTS, (d) 0.6UTS, (e) 0.7UTS, (f) 0.8UTS.

Data availability

The data used in this work can be obtained from the corresponding author upon request.

Conflict of interest

Authors declares that there is no conflict of interest anticipated from this work.

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