

Fatigue behaviour of the multi-pass friction stir processed AA8011-H14 and AA6082-T651 dissimilar joints



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ABSTRACT

The AA8011-H14 and AA6082-T651 were used to produce dissimilar joint through the use of friction stir welding (FSW) technique. The produced dissimilar joint was processed using multi-pass friction stir processing (FSP). The microstructural analysis revealed that the grain sizes reduced with an increase in the number of FSP passes irrespective of material positioning. However, the multi-pass AA6082-AA8011 joints had finer grain structure compared to the multi-pass AA8011-AA6082 one. The ultimate tensile strength of the multi-pass FSP had an increase of 11.6% compared to that of the single-pass one, but only for the AA8011-AA6082 joints, while the AA6082-AA8011 had an increase of 9% on the two-pass FSP. The number of FSP passes was found to have a marginal effect on the microhardness of the joints. The two-pass FSP joints were found to be more ductile compared to the other passes. The fatigue results revealed that the AA6082-AA8011 joints had longer fatigue life compared to that of the AA8011-AA6082 joints. The increase in the number of FSP passes increased the fatigue life of the AA8011-AA6082 joints, while AA6082-AA8011 joints experienced extended fatigue life cycle on the single-pass FSP.

1. Introduction

Friction stir processing is a surface modification technique that uses frictional heat and stirring action [1]. Friction stir processing was derived from friction stir welding developed by the TWI Ltd, Cambridge, UK in 1991 [2,3]. The grain refinement associated with friction stir processing results tends to improve mechanical properties [4,5] and fatigue strength [6,7]. The application of FSP benefits includes a notable microstructural refinement, homogeneity of the processed zone, homogenization of precipitates in various aluminium alloys, magnesium and composite materials [8,9].

Aluminium alloys, in general, are used in different industries including food packaging, aerospace, marine and automotive industries [10]. Aluminium alloy 8011 and 6082-T651 are mostly used in aerospace applications. These two alloys are mostly used in the environment which involves reflection and corrosion. Amongst the properties possessed by these aluminium alloys is that they are both good corrosion-resistant [11,12]. Generally, most failures experienced by manufactured parts occur due to cyclic loading [13,14]. The literature reveals that the fatigue life of the friction stir welded-processed joint is influenced by the number of factors like parameters used during welding or processing, the tool profile and the material used for tool manufacturing [15–17]. These factors have a direct impact on the microstructural arrangement of the grains which then affect the hardness behaviour of the material [18–22]. The correct setting of these parameters determines the occurrence of weld defects (flash, tunnel defects, surface defects and voids) [23–25]. The literature also reveals that the fatigue life of the joint is influenced by stress ratio (R) which is the minimum stress experienced to that of the maximum stress experienced during a cycle [26–29].

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Table 1
Chemical compositions [11–12].

	Mg	Ti	Zn	Cr	Si	Mn	Fe	Cu	Al
AA8011-H14	0.28	0.016	0.084	0.028	0.52	0.46	0.74	0.13	Bal
AA6082-T651	0.6–1.2	–	0.0–0.1	0.0–0.25	0.7–1.3	0.4–1.0	0.0–0.5	0.0–0.1	Bal

Table 2
Mechanical properties of the base materials [38].

	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Microhardness (HV)
AA8011-H14	94.1	76	40.17	33.8
AA6082-T651	308	270	25.42	89.5

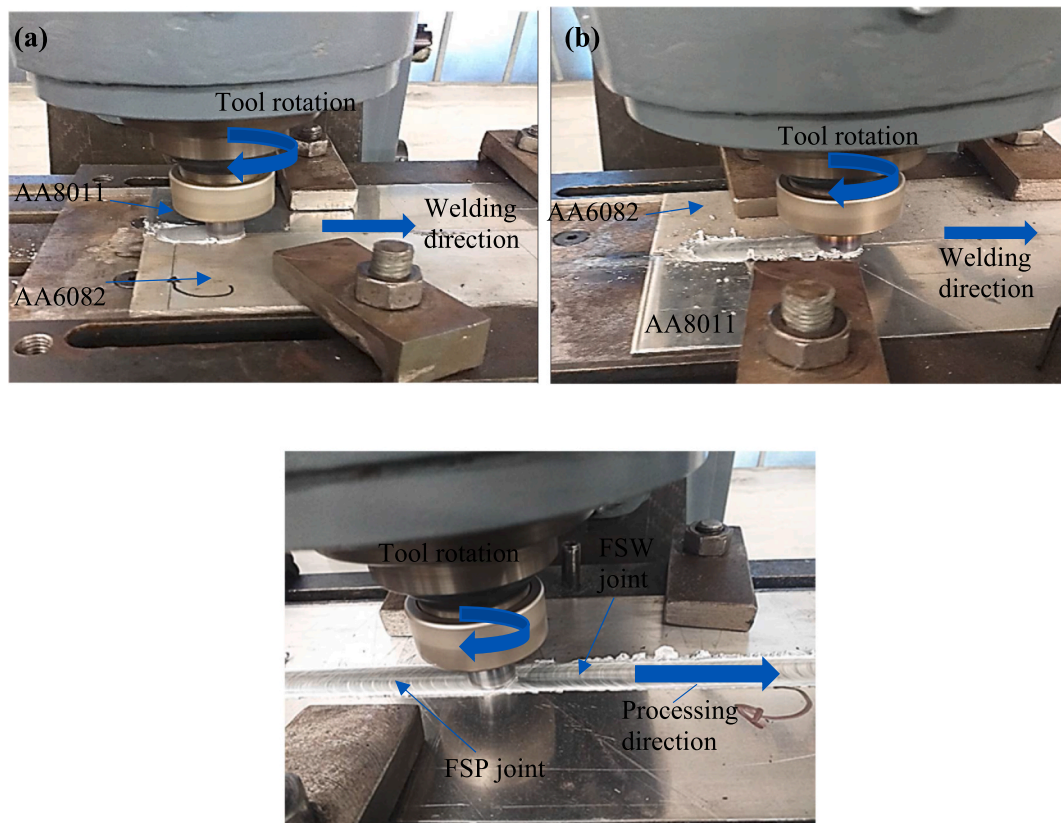


Fig. 1. (a) Friction stir welding with AA6082 on advancing side, (b) AA8011 on advancing side and (c) Friction stir processing.

Table 3
Mechanical properties of the base materials.

FSP joints	Material positioning	
	AA8011-H14 on advancing side	AA6082-T651 on advancing side
1 Pass	AA8011-AA6082	AA6082-AA8011
2 Pass	AA8011-AA6082	AA6082-AA8011
3 Pass	AA8011-AA6082	AA6082-AA8011
4 Pass	AA8011-AA6082	AA6082-AA8011

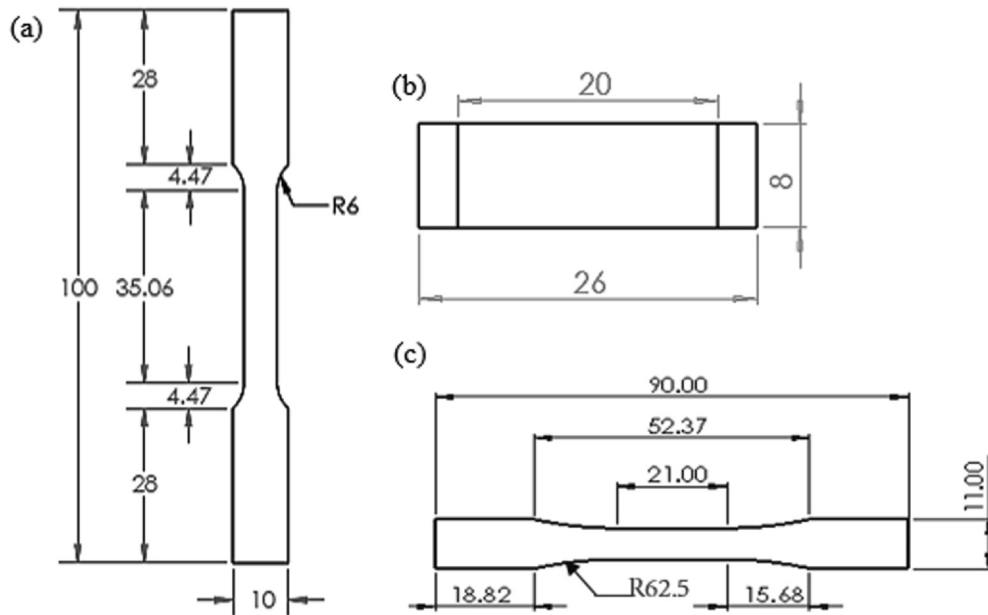


Fig. 2. (a) Tensile test specimen, (b) Microhardness specimen and (c) Fatigue high cycle specimen, (all the dimensions are in mm).

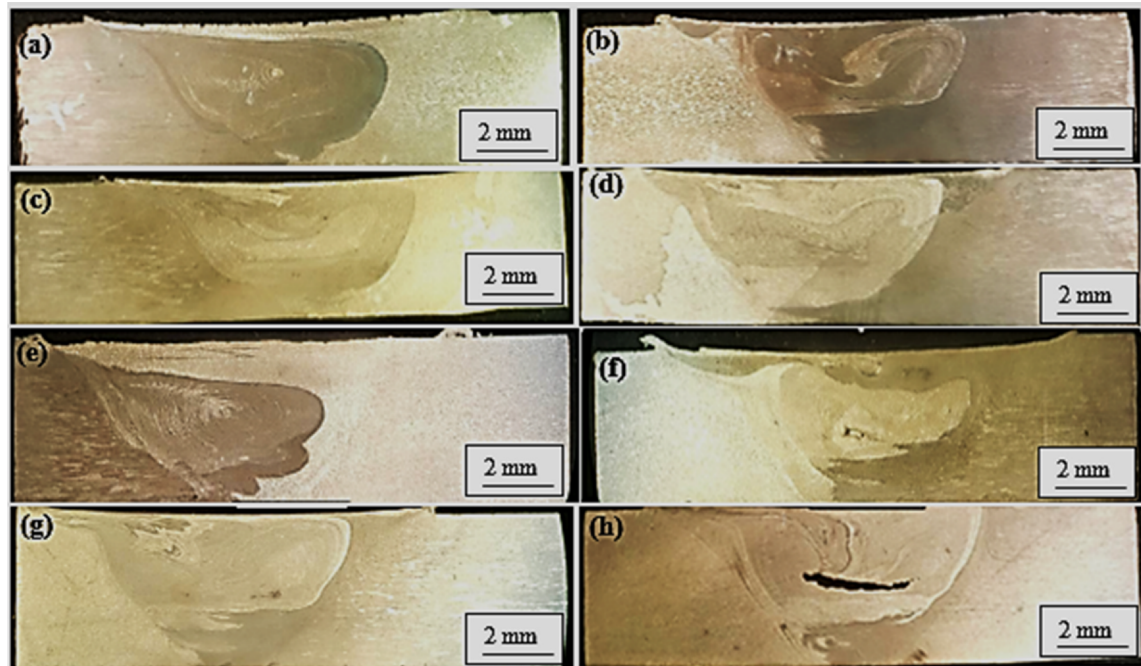


Fig. 3. Macrographs of friction stir processed FSWed joints (a) 1 pass FSP AA8011-AA6082, (b) 1 pass AA6082-AA8011, (c) 2 pass FSP AA8011-AA6082, (d) 2 pass FSP AA6082-AA8011, (e) 3 pass FSP AA8011-AA6082, (f) 3 pass FSP AA6082-AA8011, (g) 4 pass FSP AA8011-AA6082, (h) 4 pass FSP AA6082-AA8011.

It has been noticed that the majority of the literature reports about fatigue behaviour of the friction stir processed single plate [30–32] rather than the friction stir processed joint. However, looking at the two aluminium alloys considered in this study there was no literature on the effect of FSP on fatigue life-strength of the AA8011 plate or joint and one entry was found on the AA6082 one. Silva et al. [20] applied the FSP technique on the AA6082-T6 metal inert gas welded joints to improve the fatigue strength of the joint. The constant amplitude loading test method was used. The results revealed that after FSP there were no substantial changes in hardness and mechanical strength. However, as a result of the modification in the weld toe geometry and grain refinement, the fatigue strength increased significantly.

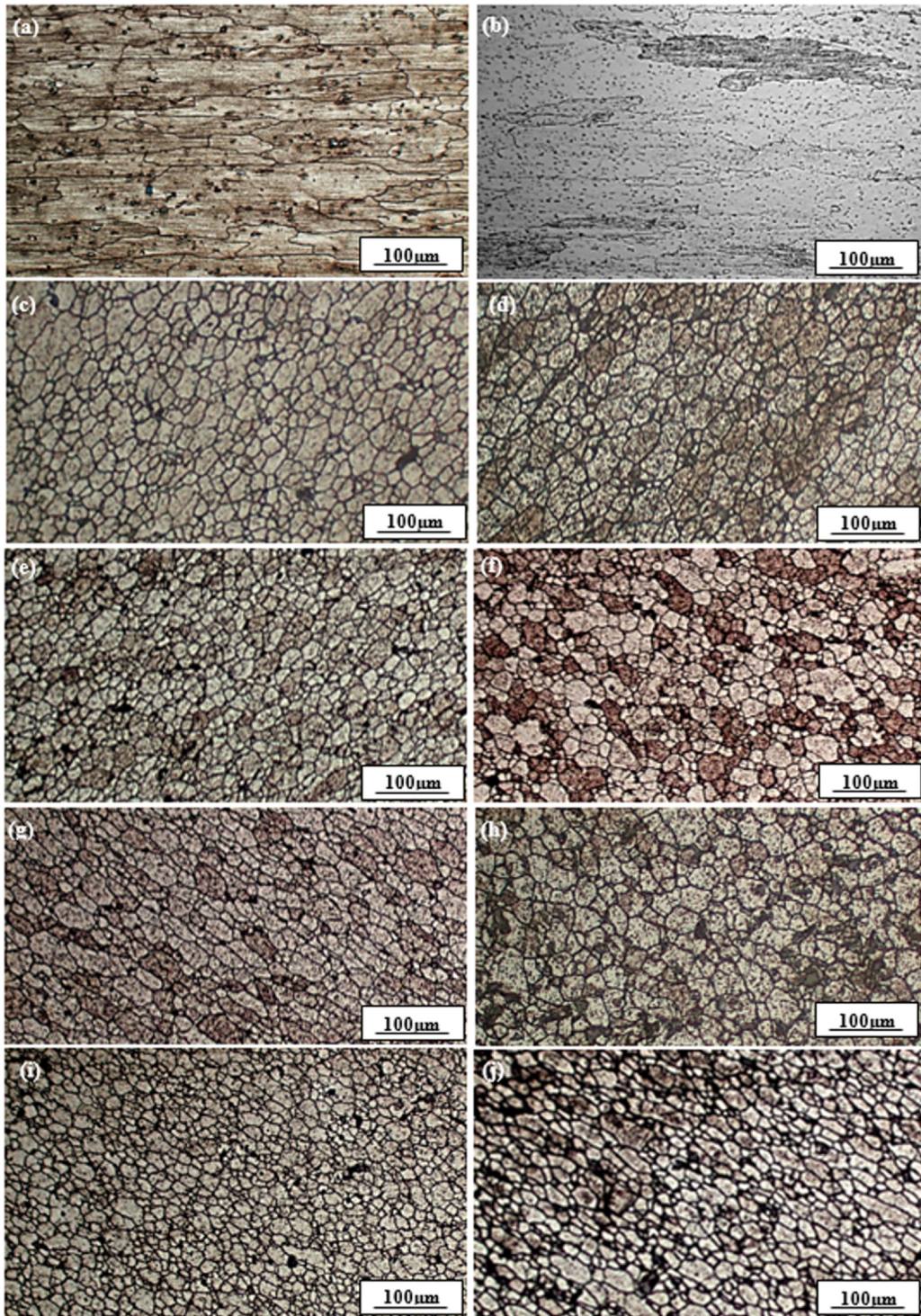


Fig. 4. Base material micrographs at objective 10x (a) AA6082, (b) AA8011; Stir zone micrographs of friction stir processed FSWed joints at objective 50x (c) 1 pass AA8011-AA6082, (d) 1 pass AA6082-AA8011, (e) 2 passes AA8011-AA6082, (f) 2 passes AA6082-AA8011, (g) 3 passes AA8011-AA6082, (h) 3 passes AA6082-AA8011, (i) 4 passes AA8011-AA6082 and (j) 4 passes AA6082-AA8011.

The most investigated properties of the multi-pass friction stir processed plate include mechanical properties, microstructure, hardness and corrosion [33]. El-Rayes and El-Danaf [34] found that the multi-pass FSP on the AA6082 surface resulted in equiaxed grains comprising of high angle grain boundaries due to dynamic recrystallization that occurred in the stir zone. An increase in the grain size and fragmentation of second phase particles was noted to be as a result of the heat accumulated during the multi-pass FSP.

Table 4
Grain sizes and standard deviation.

FSP Joint	Mean Values (μm)
1P AA8011-AA6082	6.83
1P AA6082-AA8011	6.07
2P AA8011-AA6082	6.2
2P AA6082-AA8011	6.1
3P AA8011-AA6082	5.8
3P AA6082-AA8011	5.0
4P AA8011-AA6082	4.18
4P AA6082-AA8011	3.3

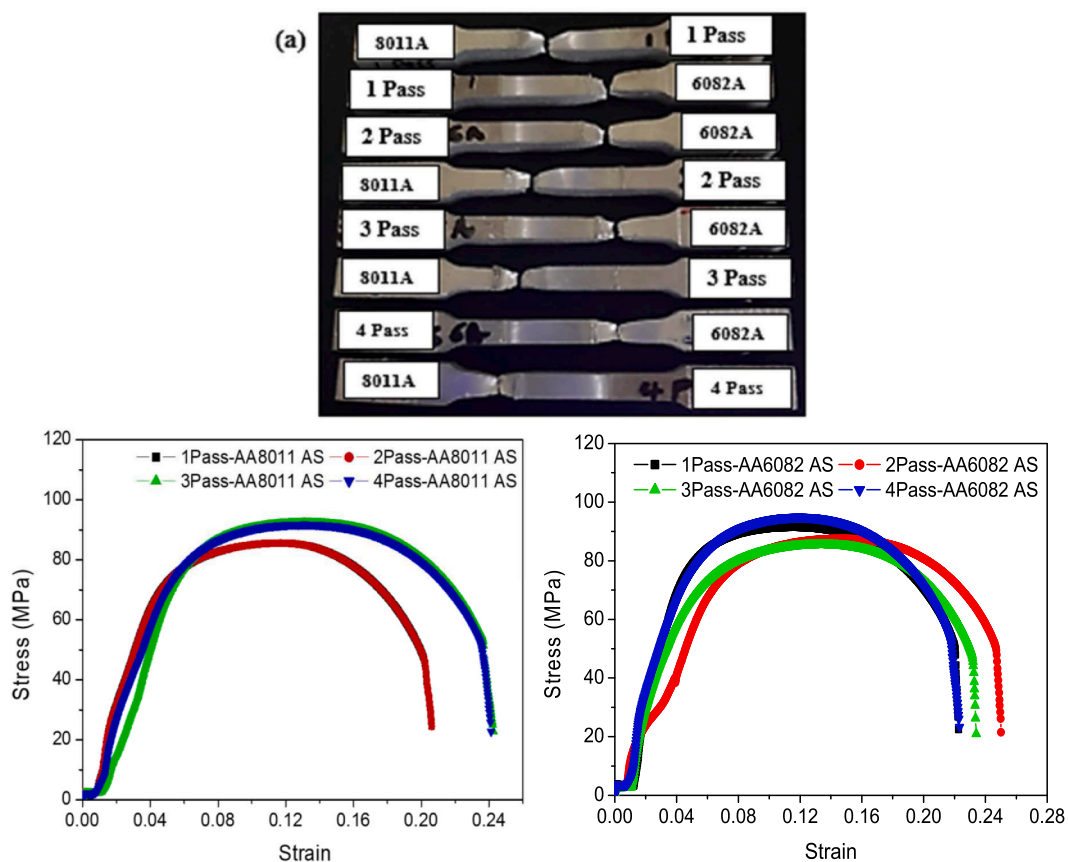


Fig. 5. (a) Post tensile specimens; Stress-Strain curves for the FSP passes (b) AA8011 on the advancing side and (c) with AA6082 on the advancing side.

Table 5
Tensile properties.

FSP passes	Ultimate tensile strength (MPa)	Percentage elongation (%)	Fracture position
1 Pass AA8011-AA6082	85.063	20.22	WZ
1 Pass AA6082-AA8011	91.471	22.28	HAZ
2 Pass AA8011-AA6082	87.444	25.32	WZ
2 Pass AA6082-AA8011	92.302	24.27	HAZ
3 Pass AA8011-AA6082	85.500	24.12	WZ
3 Pass AA6082-AA8011	91.911	23.41	HAZ
4 Pass AA8011-AA6082	94.944	22.32	HAZ
4 Pass AA6082-AA8011	91.083	23.76	HAZ

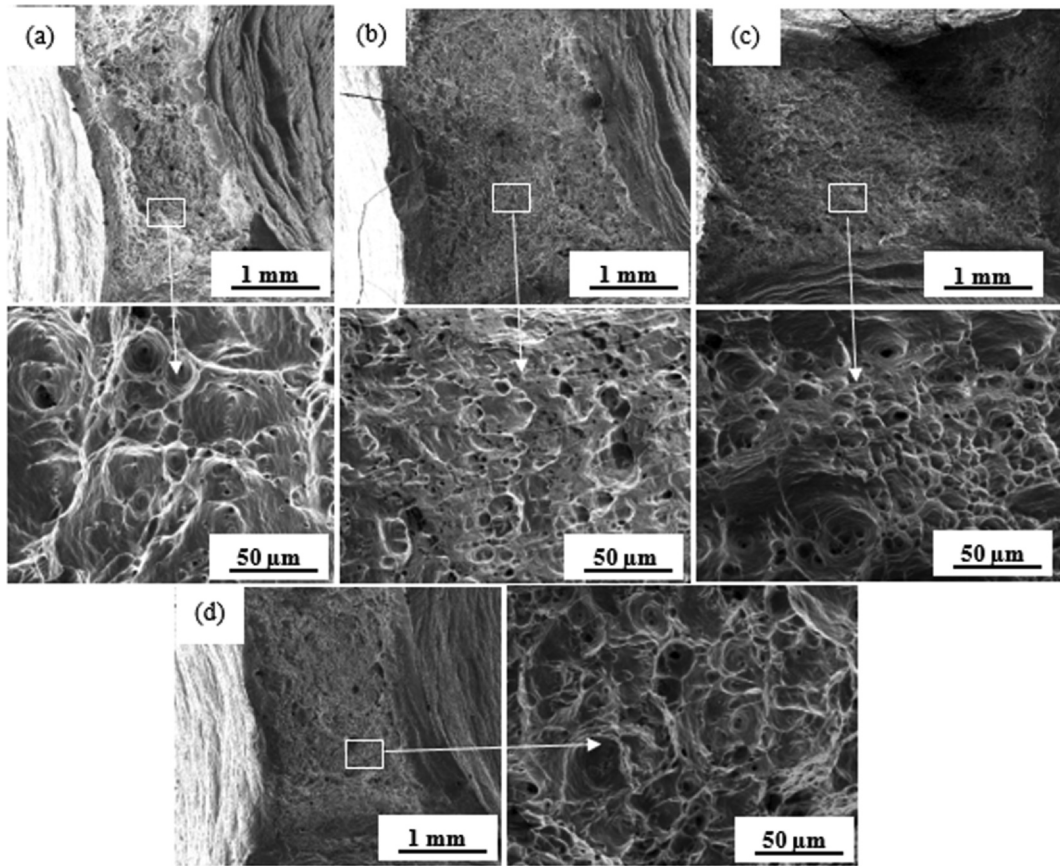


Fig. 6.1. SEM tensile; (a) 1 pass AA8011-AA6082, (b) 2 pass AA8011-AA6082, (c) 3 pass AA8011-AA6082 and (d) 4 pass AA8011-AA6082.

Additionally, the tensile strength decreased with an increase in the number FSP passes. The hardness also decreased due to the softening of the material as the number of passes increased. Senthilkumar et al. [35] conducted a study using varying process parameters, like the number of FSP passes and tool rotational speed on the microstructure and mechanical properties of the AA6082. The increase in rotational speed was found to increase heat generation. The tunnel voids decreased as the number of FSP passes increased. The increase in the number of FSP passes resulted in a reduction in UTS at the stir zone due to the dissolution hardening caused by the heat experienced by the processed surface. The increase in tool rotational speed increased the UTS of the stir zone but reduced the ductility of the joint. The microhardness was not affected by the increase in tool rotational speed. Furthermore, the multi-pass FSP resulted in the exceedingly fine microstructure, but minimal improvement in the microhardness of the stir zone.

There are very few studies that have reported about the impact of FSP on the mechanical properties of the joint. Palani et al. [36] have investigated the impact of FSP on the tensile properties of AA8011-AA6061 dissimilar joint. The FSP technique was performed on the joints with the incorporation of nanoparticles. It was discovered that the processed AA6061 similar joint had 98.58% tensile strength upon the addition of nanoparticles whereas AA8011-AA6061 exhibited 90.08% tensile strength without the addition of nanoparticles. Palani et al. [37] have also investigated the impact of FSP parameters on the mechanical properties of AA8011-AA5083 dissimilar and similar joints. The processing was performed by incorporating Al_2O_3 and SiC nanoparticles. It was discovered the inclusion of the nanoparticles improved the hardness and joint strength of the processed AA8011-AA5083 dissimilar joint.

As it has been mentioned previously that AA8011-H14 and AA6082-T651 are mostly used in the aerospace industry. This then suggests that these materials are exposed to the environment with a lot of vibrations of different intensities. It is paramount important that the fatigue behaviour of the joint formed from these two materials be studied. This paper reports on the influence of the multi-pass FSP technique towards the fatigue behaviour of AA8011-H14 and AA6082-T651 dissimilar joint formed from the FSW technique. The fatigue behaviour of all the passes are comparatively studied.

2. Materials and methodology

In this study, the 6 mm thick AA8011-H14 and AA6082-T651 dissimilar plates were used. Tables 1 and 2 shows the chemical compositions and mechanical properties of the two aluminium alloys, respectively. The dissimilar plates were cut into the dimensions of 460×55 mm. Initially, four plates were friction stir welded with the AA6082-T651 on the advancing side and AA8011-H14 on the retreating side as depicted in Fig. 1(a). All these four plates friction stir welded joints were then subjected to friction stir processing,

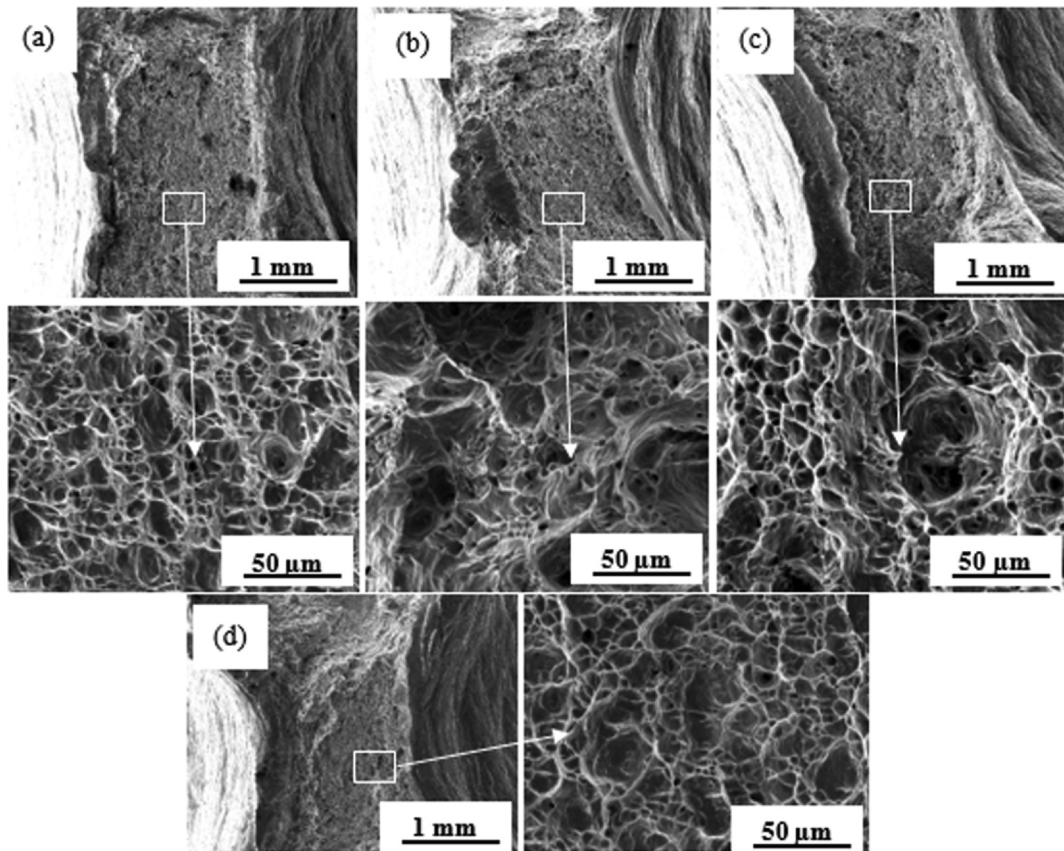


Fig. 6.2. SEM tensile (a) 1 pass AA6082-AA8011, (b) 2 pass AA6082-AA8011, (c) 3 pass AA6082-AA8011 and (d) 4 pass AA6082-AA8011.

the first plate with a one-pass, second one with a two-pass, third one with a three-pass and the fourth one with a four-pass FSP. Secondly, additional four plates were friction stir welded with the AA8011-H14 on the advancing side and AA6082-T651 on the retreating side. Fig. 1(b) shows the friction stir welding setup with AA8011-H14 on the advancing side. Likewise, all these friction stir welded joints were friction stir processed. Fig. 1(c) shows FSP setup, highlighting that the FSP was applied on the FSW joint. A maximum of four passes of FSP that were performed in this study. This yielded a total of eight processed plates. Table 3 shows the joints produced by FSP. The processing parameters used were a tool rotational speed of 1100 rpm, tool traverse speed of 45 mm/min, tool tilt angle of 2° , tool plunge depth of 5.8 mm and a dwell time of 10 s. The processing parameters were obtained using the trial and error method. The same parameters used for friction stir welding were also used for friction stir processing. Similar cases where the same parameters used for FSW were reported in the literature [2,16]. A rectangular threaded tool made of high-speed steel (HSS) AISI 4140. The shoulder diameter was 20 mm, the tool probe diameter was 7 mm and the pin length of 5.8 mm [38]. This tool was used for both friction stir welding and multi-pass friction stir processing.

The friction stir processed plates (FSPed) were cut for different tests using the waterjet cutting technology. The tests conducted were the tensile test, microhardness, microstructural analysis and fatigue test. The post 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 maximum 100 kN load cell. The ASTM-E8M-04 standard was used for the tensile specimen geometry and operating parameters. Fig. 2(a) shows the schematic diagram of the tensile specimen used for this study. The microhardness was performed using Shimadzu machine following ASTM E384-11 standard. The schematic diagram for the specimen used for microhardness is shown in Fig. 2(b).

The microstructural analysis was performed using the AE2000 Motic metallurgical microscope. The etchants used for microstructural analysis were the modified Keller's and Weck's agents. The modified Keller's is used for the AA8011 and the Weck's agent is used for the AA6082. However, the joints in this paper are dissimilar. After preliminary attempts to use either of the two, the sound results were obtained when the modified Keller's was used as a pre-etch, then the Weck's was applied on the same after the pre-etch. Using both combination resulted in clear grain structure for the whole stir zone with no over etched parts. The ASTM E112-12 standard was used to determine average grain size. The force controlled constant amplitude axial fatigue tests were performed using the Instron 8801 machine. The ASTM E466-07 standard was used for specimen geometry shown in Fig. 2(c). A sinusoidal cyclic loading was applied. The fatigue tests were conducted at a frequency of 20 Hz with an amplitude range from 30% to 80% of the ultimate tensile strength (UTS). A total of 6 specimens per FSP pass were used.

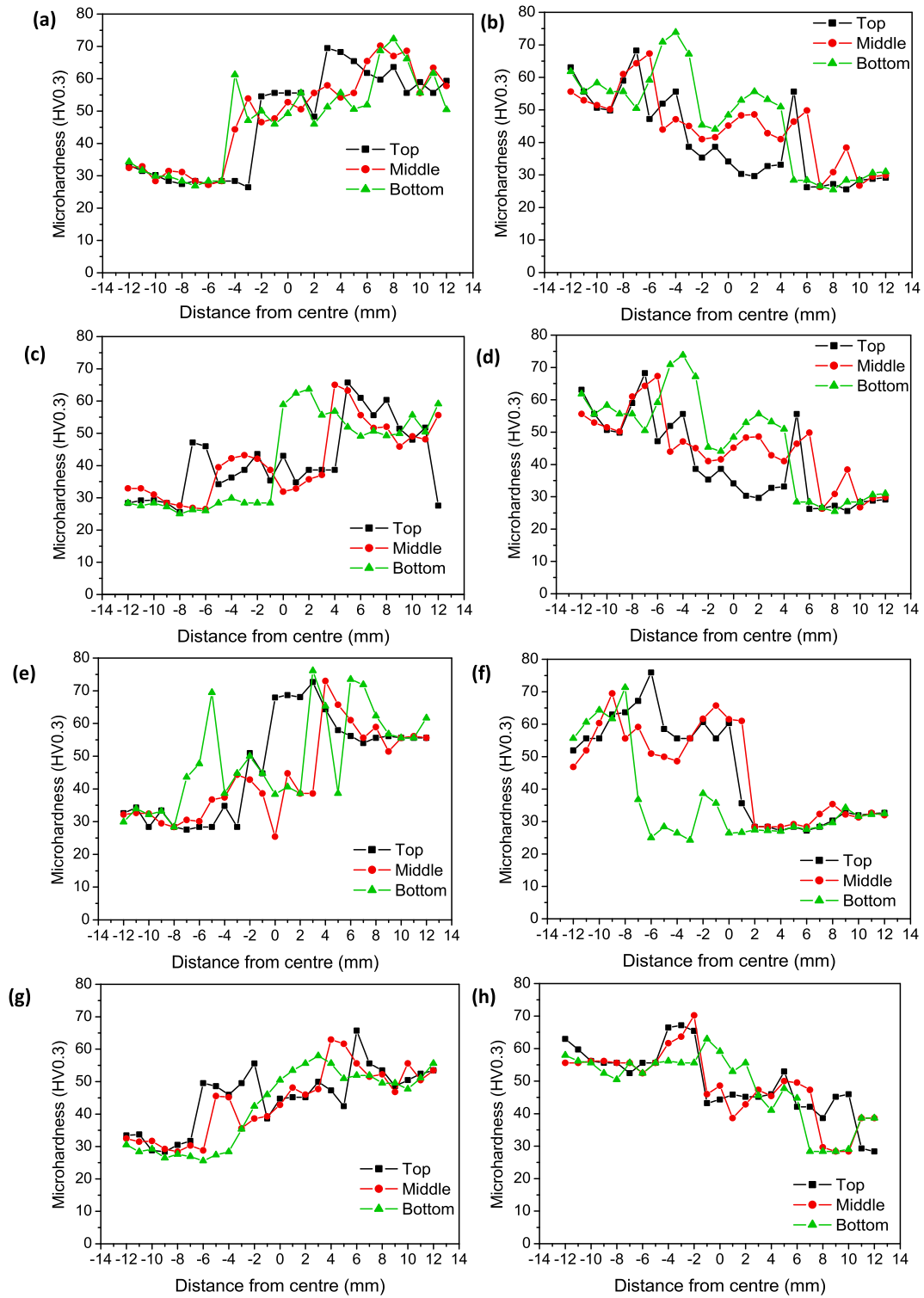


Fig. 7. (a) 1 pass AA8011-AA6082, (b) 1 pass AA6082-AA8011, (c) 2 pass AA8011-AA6082, (d) 2 pass AA6082-AA8011, (e) 3 pass AA8011-AA6082, (f) 3 pass AA6082-AA8011, (g) 4 pass AA8011-AA6082 and (h) 4 pass AA6082-AA8011.

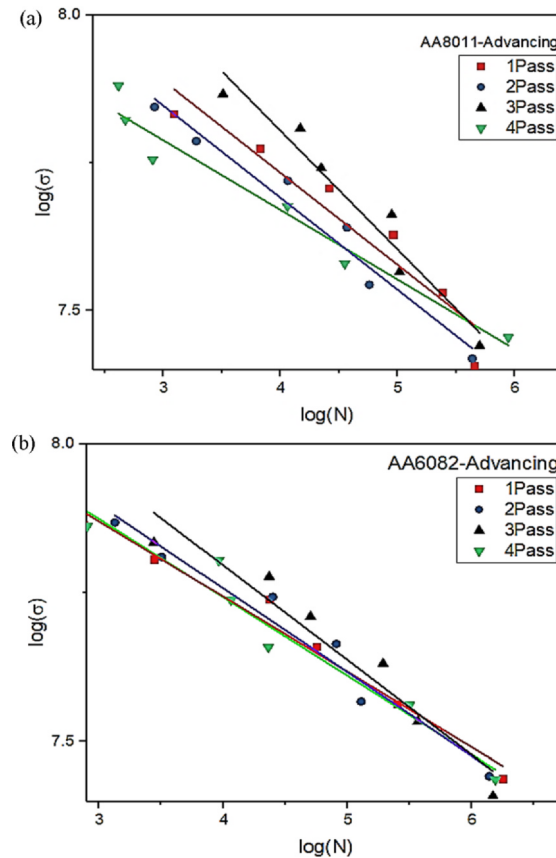


Fig. 8. Nominal stress –number of cycles to failure, (a) AA8011-AA6082 joints and (b) AA6082-AA8011 joints.

3. Results and discussions

3.1. Metallographic morphology

The macrographs of the friction stir processed FSWed joints AA8011-AA6082 (AA8011-H14 on the advancing side) and AA6082-AA8011 (AA6082 on the advancing side) from the first until the fourth pass are shown in Fig. 3(a)-(h), respectively. Fig. 3(a), (c), (e) and (g) shows the macrograph of the nuggets from the one until the four pass FSP when AA8011-H14 was on the advancing side. The macrograph of the nuggets when AA6082-T651 was on the advancing side is depicted in Fig. 3(b), (d), (f) and (h). All the nuggets are displaying serration like morphology [39]. There were no defects detected besides in most passes except the three and the four pass when AA6082-T651 was placed on the advancing side. It is not quite clear the origin of these defects but are suspected to be caused by the heat input resulting from placing stronger material on the advancing side [13,19,40].

Fig. 4(a) to (b) shows the microstructural morphology of the base materials and Fig. 4(c) to (j) shows micrographs of the nugget zones for all the FSP passes. Table 4 presents the grain sizes of the surfaces depicted in Fig. 4 with their respective standard deviations. The AA6082 base material had a mean elongated diameter of 36.21 μm and 25.88 μm for the AA8011. It was noted that in both scenarios when AA8011 is positioned on the advancing side, AA6082 on the retreating side and vice versa the grain sizes decrease with an increase in FSP passes. The grain size refinement is as a result of the recrystallization and re-recrystallization occurring with the increase in the number of FSP passes [3,33,41]. Additionally, the severe heat produced during processing tends to play a major role towards the equiaxed grain sizes and homogeneity [10,34,42].

3.2. Tensile properties

Fig. 5(a) shows the post tensile test specimens, Fig. 5(b) and (c) shows stress-strain curves for multi-pass friction stir processed joints. The tensile properties in relation to Fig. 5 are presented in Table 5. When AA8011 was positioned on the advancing side the ultimate tensile strength increased as the number of passes increased. The one, two and three pass FSP specimens failed on the stir zone while the four passes failed at the heat-affected zone towards the AA8011 side. This suggests that the strength of the weld joint for the four passes was higher than that of the weakest alloy (AA8011) [4,39,43]. When AA6082 was placed on the advancing side, the specimens all failed on the heat-affected zone of AA8011 side. It was noticed that UTS for AA8011-AA6082 was fluctuating

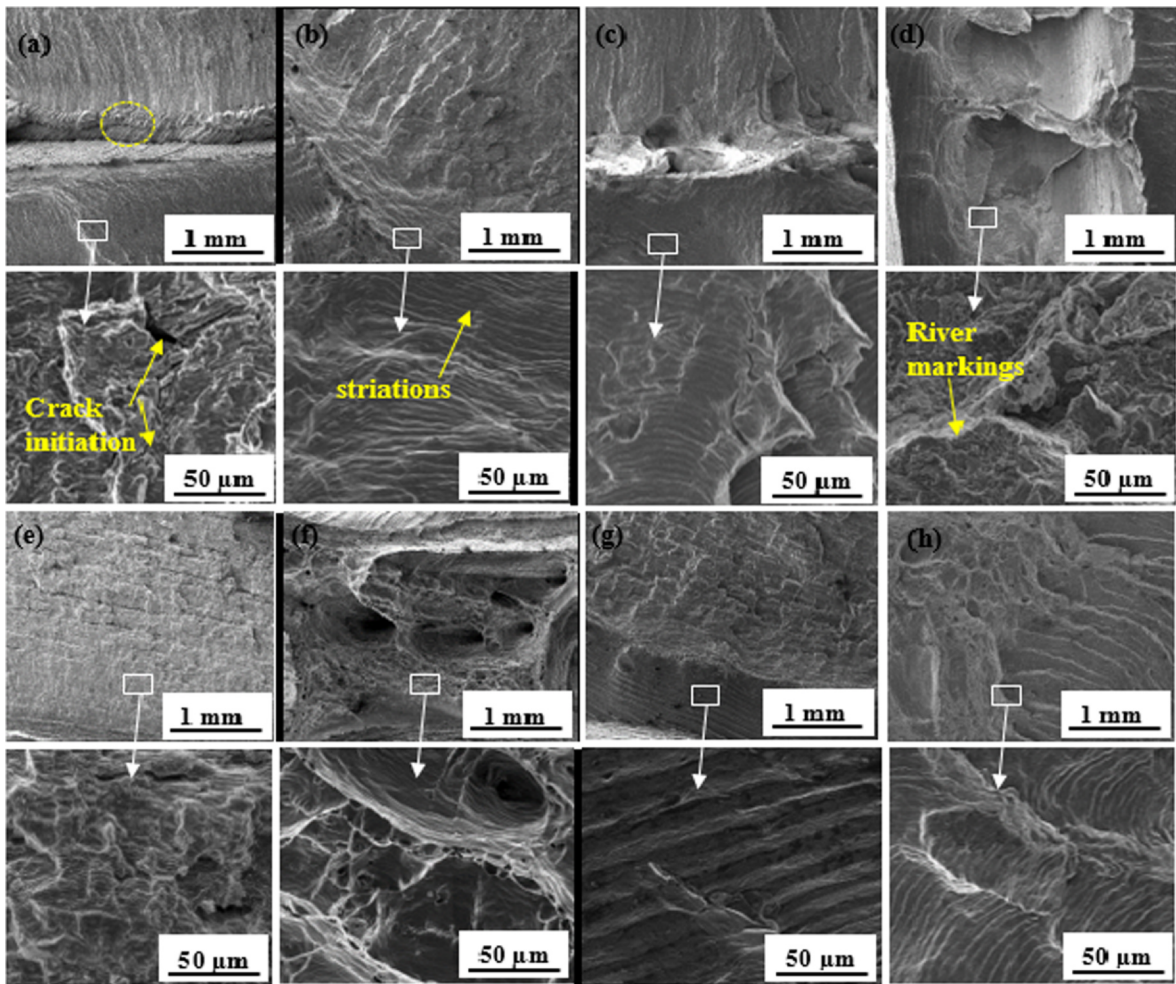


Fig. 9.1. SEM fractographs at 30% UTS; AA8011-AA6082 joints (a) 1pass FSP, (b) 2 pass FSP, (c) 3 pass FSP and (d) 4 pass FSP; AA6082-AA8011 joints, (e) 1pass FSP, (f) 2 pass FSP, (g) 3 pass FSP and (h) 4 pass FSP.

between 85.1 and 94.9 MPa while the UTS fluctuation of AA6082-AA8011 was between 91.1 and 92.3 MPa. There was a notable jump in UTS on the three passes for AA8011-AA6082 joint and this was the highest UTS for all the passes. The percentage elongation for all the joints varies nonlinearly with the increase in the number of passes. The highest percentage of elongation was achieved when AA8011 was placed on the advancing side for the two passes. It was noticed that the joint strength was increasing nonlinearly with the increase in the number of passes when the AA8011 was placed on the advancing side. A similar trend was reported in the literature [37,43–45]. It was noted that all the results are in the range of 80 MPa to 100 MPa of maximum tensile strength to AA8011 and much below AA6082. This is a result of the specimens failing at the heat-affected zone of the AA8011, where the material is weaker. This, therefore, means that the FSPed joint strength was stronger compared to that of the AA8011 base material. Similar behaviour was noted in the literature [46–48].

3.2.1. Tensile surface morphology

The fractographs of the fractured tensile specimens is shown in Figs. 6.1 and 6.2. Fig. 6.1(a)–(d) shows the morphology of the fractured surface for all the passes when AA8011 is placed on the advancing side. The surface morphology of the fractured surface when AA6082 is placed on the advancing side is shown in Fig. 6.2(a)–(d). In all the joints the ductile *trans*-granular failure features were noticeably [49]. All the figures contained dimples of different sizes, micro-voids, and cleavage facets [50–53]. Fig. 6.1(b) and (c) revealed teared facets which represent aluminium matrix at the interface [54].

3.3. Microhardness

Fig. 7 illustrates the Vickers microhardness results for the FSPed joints. The analysis was focused on the stir zone microhardness. Fig. 6(a), (c), (e) and (g) are the microhardness results for AA8011-AA6082. The microhardness for AA8011-AA6082 joint fluctuated between 68 and 77 HV with an increase towards the AA6082 side. This behaviour was noted in all the four FSP passes. The maximum

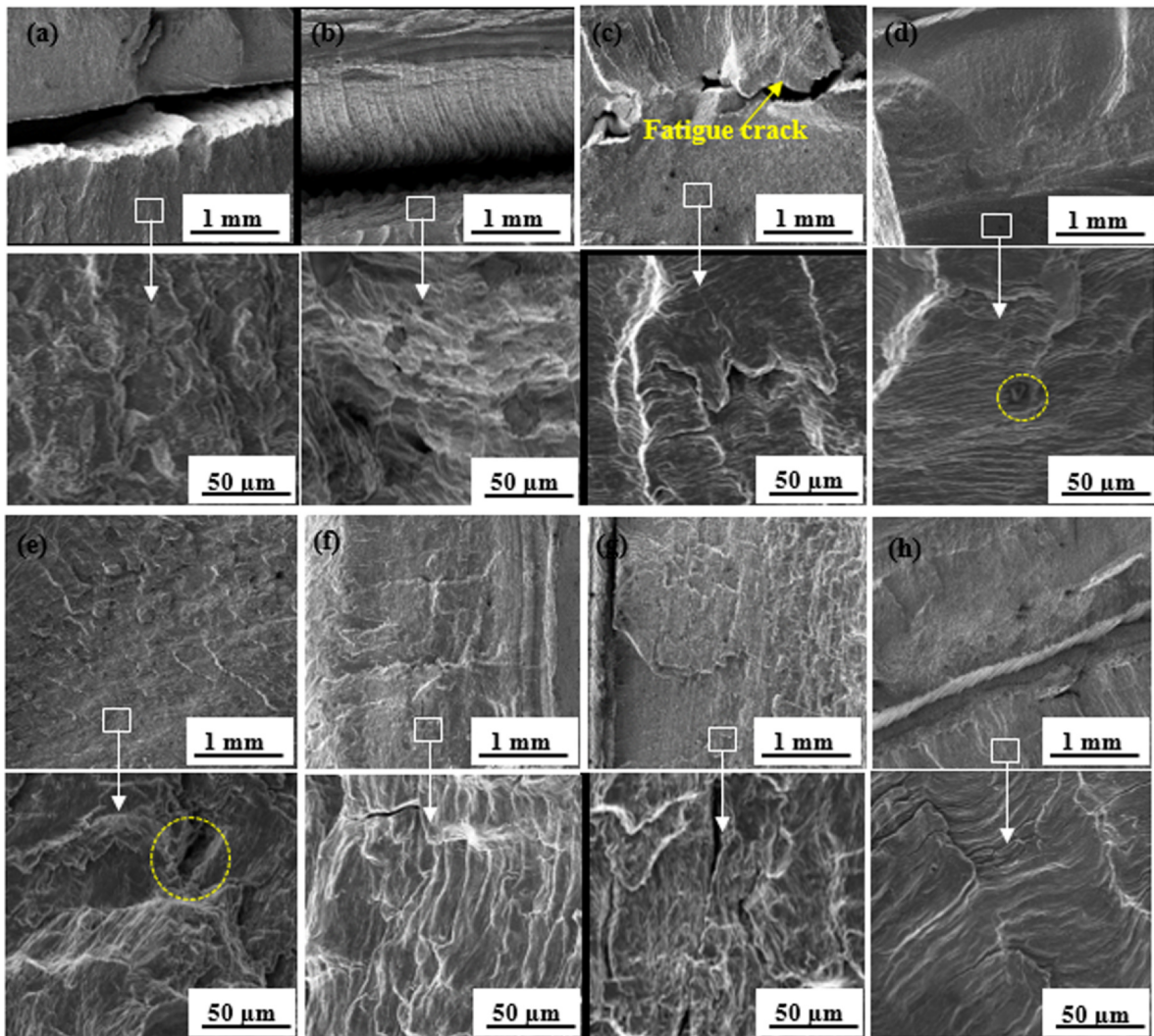


Fig. 9.2. SEM fractographs at 40% UTS; AA8011-AA6082 joints (a) 1pass FSP, (b) 2 pass FSP, (c) 3 pass FSP and (d) 4 pass FSP; AA6082-AA8011 joints, (e) 1pass FSP, (f) 2 pass FSP, (g) 3 pass FSP and (h) 4 pass FSP.

Microhardness of 77 HV was noted on the three-pass FSP for the AA8011-AA6082 joint, while the lower value (68 HV) was noted on the four-pass FSP. The microhardness results of AA6082-AA8011 joint are shown in Fig. 6(b), (d), (f) and (h). The microhardness for AA6082-AA8011 fluctuated between 65 and 73 HV with a notable decrease towards the AA8011 side. The minimum microhardness (65 HV) of the AA 6082-AA8011 joint was noted on the third pass of FSP, while a maximum of 73 HV noted in all the other FSP passes. The decrease in hardness is usually caused by a thermal cycle whereby the strengthening precipitates undergoes dissolution and coarsening [55]. The microhardness of the joint when AA8011 was placed on the advancing side is higher compared to the scenario where AA6082 is placed on the advancing side [35]. It was also noted that all the processed joints possessed microhardness value that was lower than the AA6082 base metal but all higher than those of the AA8011 [33,34]. This behaviour suggests that there was a grain refinement occurred in the weld zone [4,55,56]. The microhardness of the specimens where AA8011 was positioned on the advancing side showed an increase to the AA6082 side, while the ones with AA6082 showed a decrease to the AA8011 side.

3.4. Fatigue strength

Fig. 8(a) shows the nominal stress versus the number of cycles to failure curves when AA8011 is placed on the advancing side while Fig. 8(b) depicts the fatigue behaviour when AA6082 is placed on the advancing side. The fatigue life for all the specimens (irrespective of material positioning) increases linearly with the increase in the number of passes. However, the fatigue life of the AA6082-AA8011 joints was longer compared to that of the AA8011-AA6084 ones [26,57]. In both cases, it was noticed that the specimens at the lower amplitude (30% of the UTS) for each pass took longer to fracture compared to higher amplitude (80%) regardless of material positioning [58].

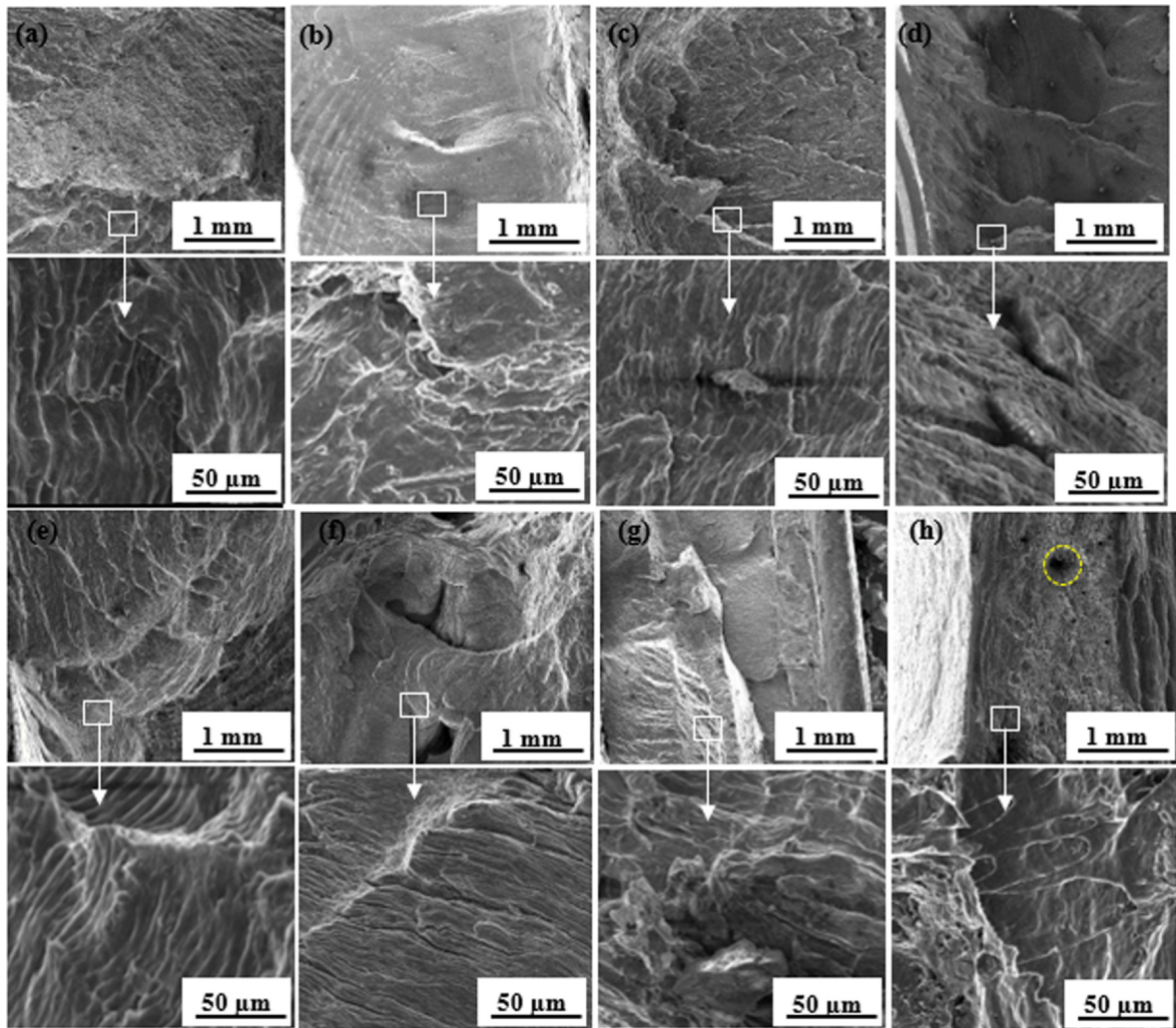


Fig. 9.3. SEM fractographs at 50% UTS; AA8011-AA6082 joints (a) 1 pass FSP, (b) 2 pass FSP, (c) 3 pass FSP and (d) 4 pass FSP; AA6082-AA8011 joints, (e) 1 pass FSP, (f) 2 pass FSP, (g) 3 pass FSP and (h) 4 pass FSP.

3.5. Fractured surface morphology

Fig. 9.1 presents fatigue fractographic images at 30% of the UTS, for AA8011-AA6082 and AA6082-AA8011 FSPed joints. In all the images the 1 mm scale was used for the fracture surface images and 50 μm scale for the crack and striation site. **Fig. 9.1(a)–(d)** show the AA8011-AA6082 joint surface morphology from the one pass until the fourth pass. The first and the four pass FSP show a river-like without a uniform arrangement whereas the two and the three passes show the fine fatigue striations [59,60]. The AA6082-AA8011 surface morphology is shown in **Fig. 9.1(e)–(h)**. Each pass for this joint reveals unique morphology. The surface morphology for the one pass of AA6082-AA8011 resembles a river-like structure while the two-pass surface shows the dimpled surface [61]. The three-pass for this joint shows ribs-like fatigue striations whereas the fourth pass depicts fine fatigue striations.

Fig. 9.2 shows fatigue fractographic images at 40% of the UTS, for AA8011-AA6082 and AA6082-AA8011 FSPed joints. **Fig. 9.2(a)–(d)** show the AA8011-AA6082 joint surface structure from the one pass until the four-pass FSP. The macrograph for all the AA8011-AA6082 surfaces shows some defects which were resulted from fatigue fracture, not from processing. There are no traces of such defects on AA6082-AA8011 surfaces. The micrograph for all the passes, irrespective of material positioning, show a river-like morphology [61].

Fig. 9.3 presents fatigue fractographic images at 50% of the UTS, for AA8011-AA6082 and AA6082-AA8011 FSPed joints. **Fig. 9.3(a)–(d)** show the AA8011-AA6082 joint surface morphology from the one pass until the four pass. There are visible defects on the fractured surfaces for the AA8011-AA6082 joint. The river-like morphology with different orientation is notable in all the surfaces of different passes. The macrographic view for AA6082-AA8011 joint presented in **Fig. 9.3(e)–(h)** shows, differs with pass increase. **Fig. 9.3(e)** shows the defect-free morphology while **Fig. 9.3(f)–(h)** show some defects with different orientations. There are clear fatigue striations on the surface of 1 pass AA6082-AA8011 joint while the other passes show the river-like morphology with different

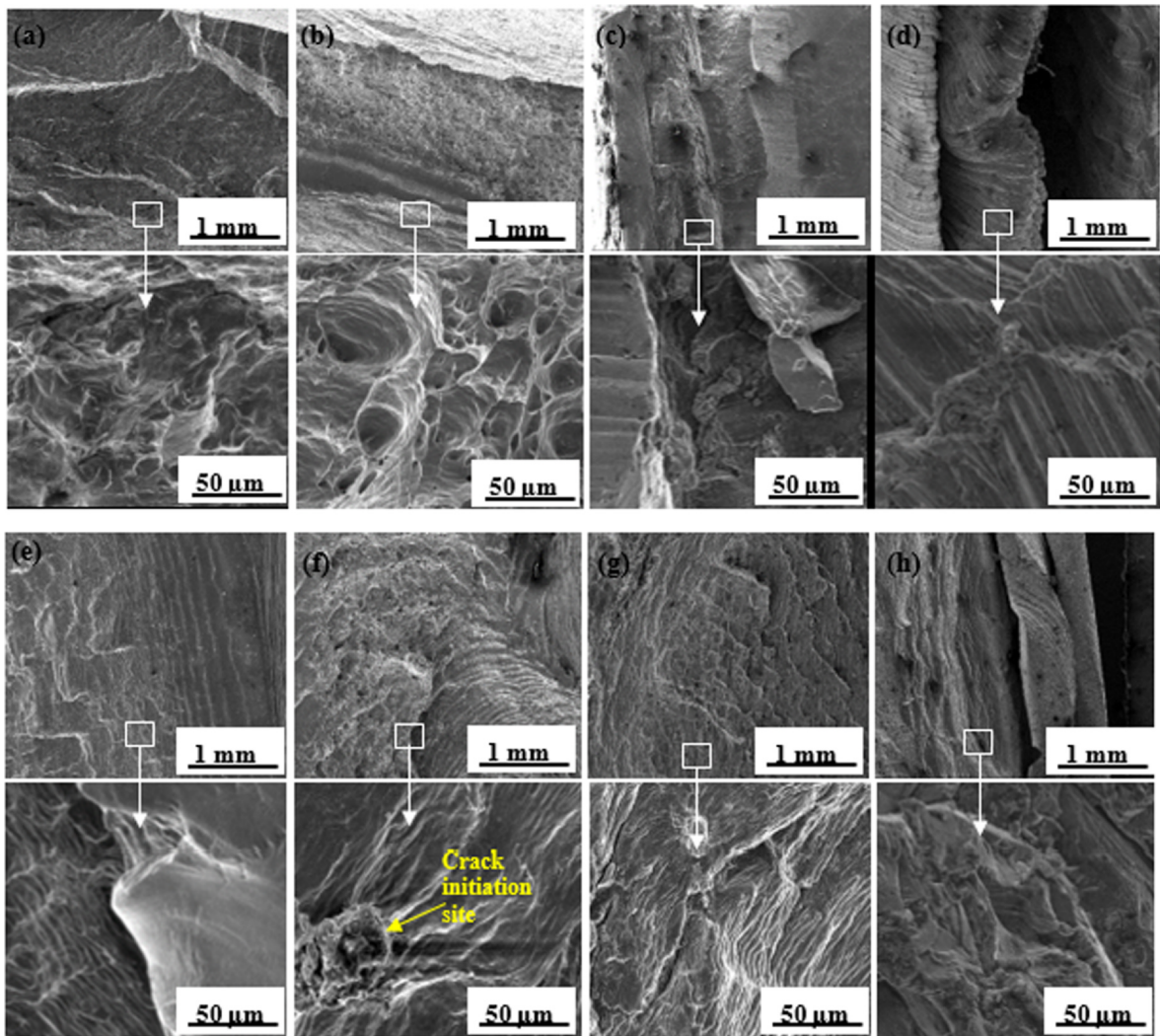


Fig. 9.4. SEM fractographs at 60% UTS; AA8011-AA6082 joints (a) 1 pass FSP, (b) 2 pass FSP, (c) 3 pass FSP and (d) 4 pass FSP; AA6082-AA8011 joints, (e) 1 pass FSP, (f) 2 pass FSP, (g) 3 pass FSP and (h) 4 pass FSP.

orientations.

Fig. 9.4 presents fractographs at 60% UTS amplitude for the FSPed joints where Fig. 9.4(a)-(d) show the results for AA8011-AA6082 joint surfaces while the surfaces for AA6082-AA8011 are shown in Fig. 9.4(e)-(h). There is no trace of defects visible on the macrograph of Fig. 9.4(a)-(c). The fatigue crack with a rope-like structure is visible in Fig. 9.4(d). The micrographic view for Fig. 9.4(a) and (b) show some elongated dimples which symbolize ductile fatigue fracture [62]. Fig. 9.4(c)-(d) show new different morphologies. Fig. 9.4(e)-(g) show macrograph without visible fatigue defects while macrographic view in Fig. 9.4(h) reveals some fatigue cracks. The micrograph in Fig. 9.4(e)-(h) show different orientations of fatigue striations. Fig. 9.5 shows the fatigue results at the 70% UTS amplitude for AA8011-AA6082 and AA6082-AA8011 joints. Fig. 9.5(a)-(d) show the surface morphologies of AA8011-AA6082 joint while the surface morphologies for AA6082-AA8011 are shown in Fig. 9.5(e)-(h). The macrographic view of Fig. 9.5(a)-(d) shows no trace of fatigue crack or defects. This is similar to Fig. 9.5(e), (g) and (h). There is a visible defect on the macrograph for Fig. 9.5(f). Fig. 9.5(a), (b), (c) and (e) show an elongated dimpled structure which shows the occurrence of plastic deformation [53]. Fig. 9.5(d), (f), (g) and (h) show river-like structures with different orientations.

Fig. 9.6(a) to (h) shows SEM performed at 80% of the UTS for AA8011-AA6082 and AA6082-AA8011 joints for all the four FSP passes. The different macrographic morphologies are observed for the AA8011-AA6082 joint presented in Fig. 9.6(a)-(d). There are no cracks developed due to fatigue in all the figures except the rope-like structure observed in Fig. 9.6(b). The micrographs for Fig. 9.6(a)-(d) show striations mixed with dimples [55]. This behaviour shows that the fatigue failure mode was ductile. Similar behaviour is also observed for AA6082-AA8011 joint presented in Fig. 9.6(e)-(h). Moreover, Fig. 9.6(h) shows some pores with quasi-cleavage facets like structures [62].

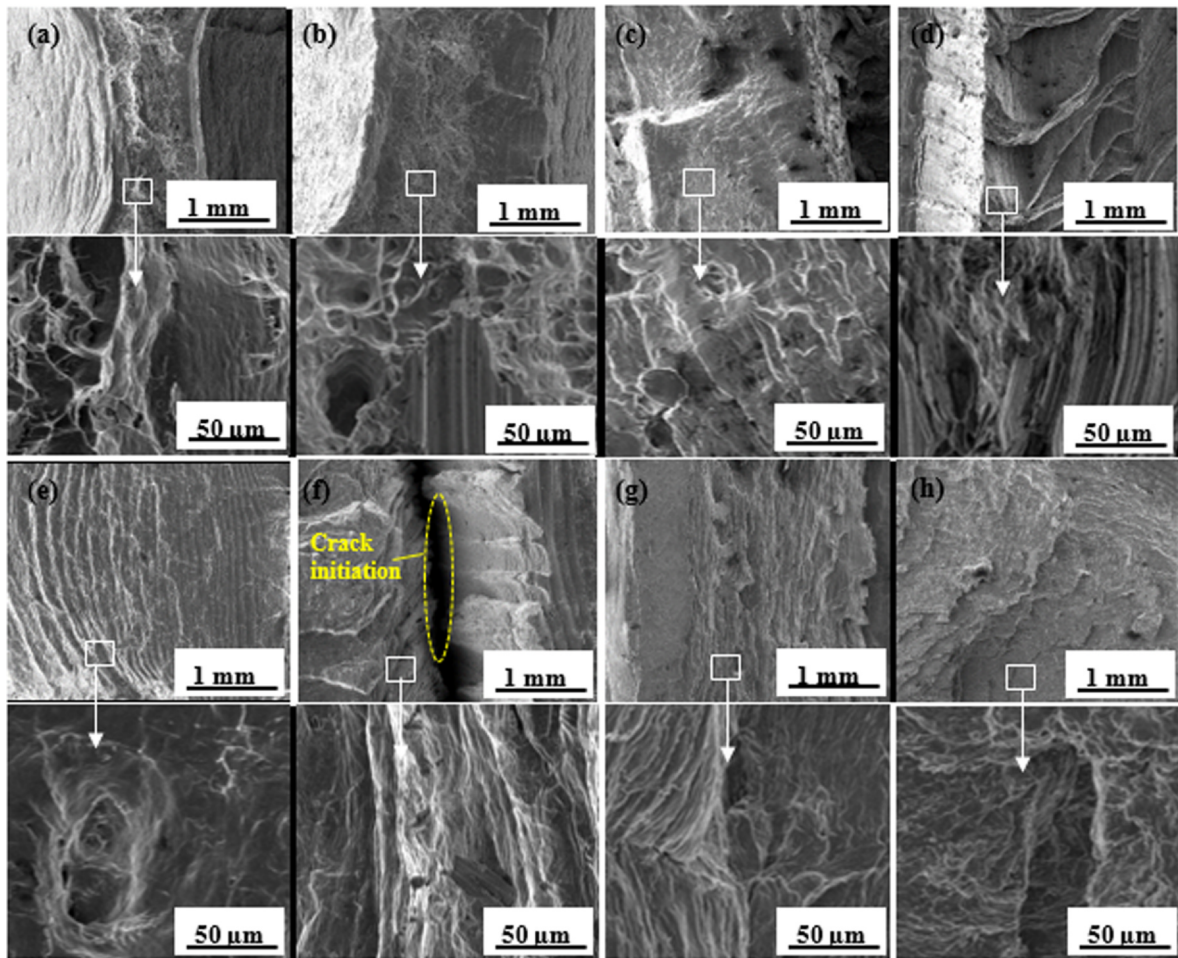


Fig. 9.5. SEM fractographs at 70% UTS; AA8011-AA6082 joints (a) 1 pass FSP, (b) 2 pass FSP, (c) 3 pass FSP and (d) 4 pass FSP; AA6082-AA8011 joints, (e) 1 pass FSP, (f) 2 pass FSP, (g) 3 pass FSP and (h) 4 pass FSP.

4. Conclusions

The fatigue behaviour of the multi-pass friction stir processed friction stir welded dissimilar aluminium alloy joints was successfully conducted. It should be noted that due to the lack of literature on the fatigue of the friction stir processed FSWed similar and dissimilar joints, the results were mostly referenced to the FSW ones from various works of literature. Based on the results obtained the following conclusions can be made:

- The microstructural analysis revealed that the grain sizes reduced with an increase in the number of FSP pass irrespective of material positioning. However, the multi-pass AA6082-AA8011 joints had finer grain structure compared to the multi-pass AA8011-AA6082 ones.
- The ultimate tensile strength increased with an increased in FSP passes, but only for the AA8011-AA6082 joints, while the AA6082-AA8011 fluctuated between 91.1 and 92.3 MPa. The number of FSP passes on the microhardness was found to have a marginal effect. The two passes FSP joints were found to be more ductile compared to the other passes giving maximum percentage elongation of 25.32% for the AA8011-AA6082 joints and 24.12% for the AA6082-AA8011 joints.
- The fatigue life of the AA6082-AA8011 joints had longer fatigue cycle compared to that of the AA8011-AA6082 joints. The fatigue life was longer due to the joint having a finer grain structure compared to the AA8011-AA6082 one. The increase in the number of FSP passes increased the fatigue life of the AA8011-AA6082 joints, while the AA6082-AA8011 joint the longer fatigue life cycle was on the single-pass FSP. The more the passes increased the more the grain refinement occurred. Which therefore means that the fatigue life is grain size dependable. The lower amplitude had longer life cycles regardless of the number of FSP passes. This means that the relationship between the amplitude and the fatigue life cycle was indirect proportional.

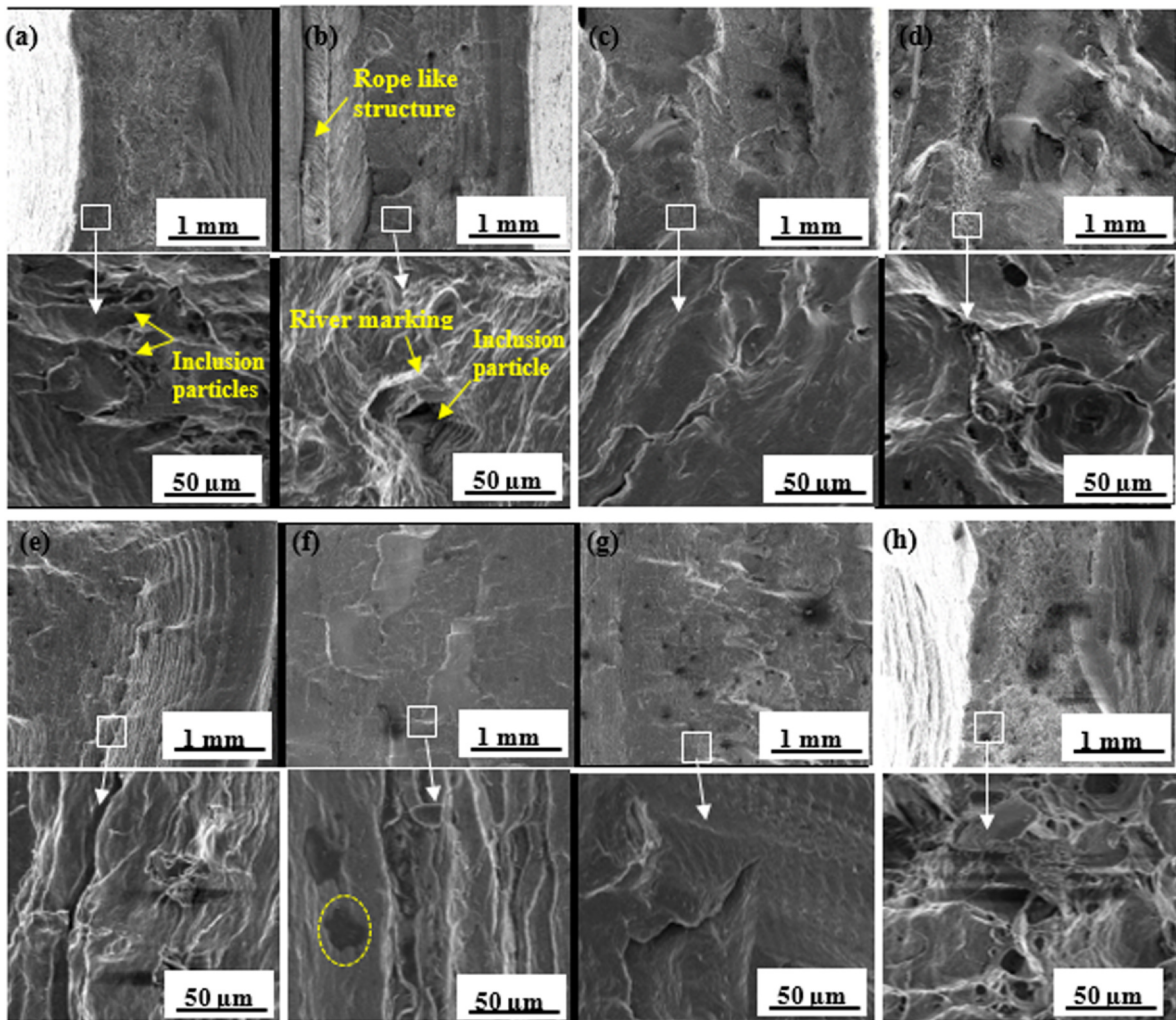


Fig. 9.6. SEM fractographs at 80% UTS; AA8011-AA6082 joints (a) 1 pass FSP, (b) 2 pass FSP, (c) 3 pass FSP and (d) 4 pass FSP; AA6082-AA8011 joints, (e) 1 pass FSP, (f) 2 pass FSP, (g) 3 pass FSP and (h) 4 pass FSP.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Additional data available upon request.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.engfailanal.2020.104876>.

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