ROLLING EFFECT ON DISSIMILAR FRICTION STIR WELDED AA5083-AA6061 ALUMINIUM ALLOY JOINTS

N.F.M. Selamat[1], A.H. Baghdadi[1], Z. Sajuri[1], S. Junaidi[2] and A.H. Kokabi[3]

[1]Faculty of Engineering & Built Environment,
Universiti Kebangsaan Malaysia, 43600
Bangi, Malaysia.

[2]Department of Mechanical Engineering,
University of Sharjah, 27272 Sharjah,
United Arab Emirates.

[3]Department of Materials Science and Engineering,
Sharif University of Technology,
1365-11155 Tehran, Iran.

Corresponding Author's Email: [1]zsajuri@ukm.edu.my

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ABSTRACT: Friction stir welding (FSW) gives benefits to join un-weldable aluminium alloys, especially for joining dissimilar types of aluminium grade. The limit of FSW is thin materials will get affected due to forging effect from the tool shoulder. In this study, two types of aluminium alloys which are AA5083-AA6061 has been dissimilar welded in butt joint using FSW. The welding parameter used is 1000rpm and 100mm/min for rotation speed and transverse speed, respectively. Then, the post weld cold rolled (PWCR) has implemented to reduce 10%, 20% and 40% from the original thickness of samples. From the microstructure observation, there is defect free at all PWCR samples. The grain size in nugget zone has been reduced from 8μm to 5μm as the rolling is conducted at 10% and 40%, respectively. Further, the higher rolling percentage will improve the tensile strength. Therefore, the ultimate tensile strength is increased to 5%, 26% and 49% for rolling percentage of 10%, 20% and 40%, respectively. However, the elongation has been reduced to 24%, 55% and 68% as the rolling percentage improve. The tensile samples fractures outside the welding zone up to rolled 20%, and the fracture shift inside the welding zone when up to 40% of rolling percentage.

KEYWORDS: *Dissimilar Joint; Aluminium Alloy; Post-Weld Cold Roll; AA508; AA6061*

1.0 INTRODUCTION

Aluminium alloy 5083 and 6061 have been commercialised in various industries especially for automotive, aerospace, manufacturing, and marine. Owing to the high mechanical strength albeit light-weight material, both of AA5083 and AA6061 are advantageous for weight reduction purpose in the manufacturing of structural parts. AA5083 is a non-heat treatable alloy, while AA6061 is a heat-treatable alloy. The difficulties arise for aluminium alloys in conventional fusion welding as they have been categorised as un-weldable alloys. Poor melting and solidification during welding of aluminium alloys tend to form voids and defects, which diminish the mechanical strength of the joints [1]. Therefore, a solid state welding technique was introduced in 1991 by The Welding Institute (TWI) give a bright potential for welding aluminium alloys. FSW process maintaining the mechanical strength of the materials [2] since the welding process occurs in solid state and below the melting temperature. On the other hand, the FSW characteristics make it suitable for joining dissimilar types of alloys [3] especially different aluminium grades [4–6].

The essence principle of FSW is to combine two metal plates by inserting a non-consumable pin tool between two plates. Rotation and transverse motions of the pin will deform and soften the materials at joining area, due to frictional heat generated around the pin. The transverse motion of the pin pushes the deformed materials from front to the back of the pin and completing the joint of two plates [7]. The two plates are distinguished by advancing and retreating sides. The advancing side is the plate located in the same direction of the welding, whereas the retreating side is opposite to the advancing side. In the case of dissimilar joints, the position of particular aluminium alloy plates will indeed affect the joint strength. The previous researcher found that the AA5083 positioned at the advancing side will produce higher yield and strength of the welded joint [7].

Nevertheless, constructing automotive and aerospace parts require different metal thicknesses and shapes. This can be achieved using conventional metal forming techniques such as cold rolling, hot rolling, forging, etc. Therefore, it is desirable if the thickness of welded plates can be reduced using these techniques without compromising the mechanical strength of the weld joints. In fact, the thin materials have limitation for using FSW process, this is due to the excessive heat from the shoulder pin tool give bad aesthetics on welding surface [8]. Further, by previous research result, it was made possible to made PWCR method on the aluminium alloy after the FSW process, purposely, to increase the size of the welded metal sheet [9]. In this research, the attempt is to weld the dissimilar butt joints of the aluminium alloys grade AA5083 and AA6061. The PWCR process of dissimilar joints has reduced the original thickness to 10%, 20%, and 40% of rolling percentage. From the research work conducted, the investigation has been focused on the microstructure and mechanical properties of FSWed and PWCR specimen.

2.0 METHODOLOGY

Aluminium alloys plate (AA5083 and AA6061) with dimension 100mm x 50mm x 5mm aluminium were cleaned using the steel brush and ethanol. Cleaning process before FSW is essential to diminish oxidation layer and prevent a formation of kissing bond inside the welding area. The formation of kissing bond or oxidation in welding are could reduce the mechanical strength of welded joints. Then, two aluminium plates were butt-joined using the FSW. The welding parameters are 1000rpm and 100mm/min for rotation and transverse speed, respectively. All specimens were welded at 3° of the tilt angle. Further, AA5083 was placed on the advancing side, while the retreating side is AA6061 in order to attain the optimal mechanical strength. Table 1 shows the mechanical properties of base metal used in this work(as annealed).

Moreover, the simple threaded geometry pin with 20mm shoulder diameter was used as a pin tool. Else, the pin was made from H13 steel with length and diameter of 4.7mm and 5mm, respectively. Prior to rolling, 0.5mm of samples were removed from the top and bottom of the welded surface. This is due to eliminating welding flash that can induced stress during the rolling process. The welded plates were then cold rolled to 10%, 20%, and 40% from the original thickness. The rolling process has conducted parallel to the welding direction. Several passes of rolling have been conducted to achieve the target thickness. Small deformation during the rolling process can prevent the welded plates from being bend.

The welded plate of AA5083-AA6061 was designated as FSWed. Whereas, to simplify the PWCR samples for 10%, 20%, and 40% reduction were named as CR10%, CR20%, and CR40%, respectively. The microstructure observation has been done on the welded cross-section, as the specimen has ground and polished up to mirror surface. Prior to observe under the optical microscope, the specimens were etched using chemical and electroetching method. The chemical reagent used in this work is Keller reagent (H_2O 100ml, HF 2ml, HCl 3ml, HNO_3 5ml). The electroetching used Barker solution with 20V in 90 to 120 seconds.

The microhardness profile is performed using Vickers hardness along the welded and base metal cross section with 1mm distance between each indentation. The microhardness test has performed with 100g load and 15s of dwell time using Vickers micro-hardness (Zwick, German). Further, tensile specimens were cut perpendicular to the welding direction using EDM. The welded joint area was located in the middle of the gauge length. Whereas the gauge length and width is 40mm and 6mm, respectively. The tensile specimens have ground to eliminate any scratch on the specimen surface. The tensile test was accomplished using Zwick universal testing machine (Zwick, German) with the 100kN capacity load.

Table 1: The mechanical properties of base metal AA5083 and AA6061 (as annealed)

Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness (HV)
AA5083	191	328	22	90
AA6061	68	116	29	46

3.0 RESULTS AND DISCUSSION

3.1 Welding Surface Appearance

Figure 1 displays the welding surface of FSWed joints using welding parameter 1000rpm and 100mm/min, respectively. The image indicates the exit hole appeared at the end of the welded plate as a negative shape of the pin tool. The exit hole is a location where the FSW stop. The rotation direction of the tool is clockwise with respect to the surface side. The beads feature on the welding surface is approximately the size of the tool shoulder diameter, such as 20mm. The smooth welding surface without any external defects and excessive flash indicated that the appropriate welding parameter used during joining process. The smooth welding surface is due to sufficient heat input during the process[10]. Other researchers found that the welding speed of 1000rpm and 100mm/min is the best welding parameters for dissimilar joints AA5xxx and AA6xxx when comparing to other welding parameters [11].

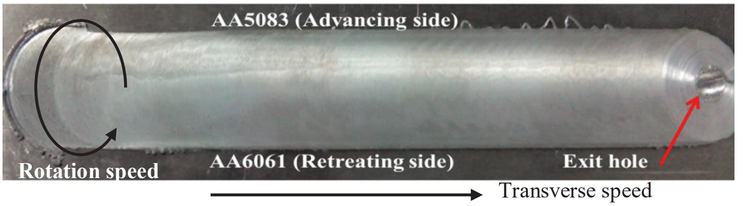

Figure 1: Smooth welding surface on dissimilar joints of FSWed using 1000rpm and 100mm/min of rotational and transverse speed, respectively

3.2 Cross Section and Microstructure of Nugget Zone

Figure 2 shows the transverse cross-section of the welding joint for FSWed, CR10%, CR20%, and CR40%. Contrast colours at the advancing and retreating sides because of the reaction effects from chemical reagents used during the etching process. After the etched process, the advancing side AA5083 looks darker compared to the retreating side AA6061. Cross section of FSWed joints indicated no defects appeared at the welded area. Otherwise, rolling effect on the cross-section of the welded joint is barely significant and the different regions of the welded area still appear normal. The welded area becomes compressed as the rolling percentage increases. Eventhough the rolling percentage is increase, but there is no crack and defect was observed in the welded area. Therefore, it is proved that the FSW joints using the chosen parameter have a high bond and good welding efficiency so that it can not break after rolling.

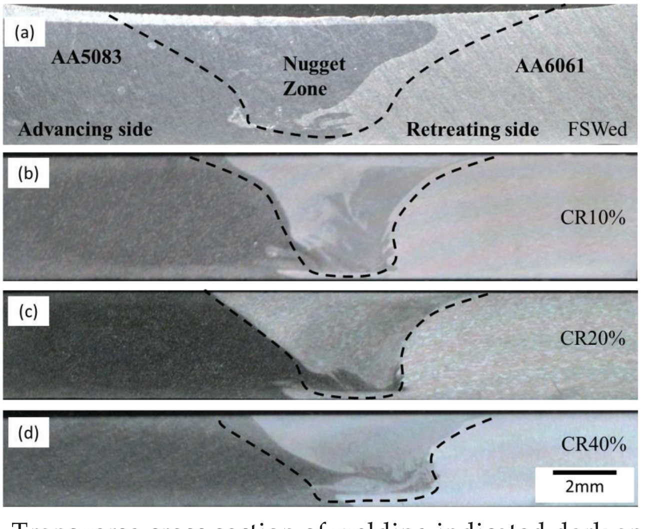

Figure 2: Transverse cross section of welding indicated dark and light color for advancing and retreating side: (a)FSWed, (b) CR10%, (c) CR20% and (d) CR40%

Figure 3 obviously shows the welded joint consists of three different regions, which are the heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and nugget zone (NZ). The unaffected zone is the base metal at the both of advancing and retreating sides. Each zone experiences the different level of deformation due to mechanical stirring effect during the welding process. Furthermore, the HAZ experiences the thermal effect, but not up to cause plastic deformation. The thermal effect of stir process was induced sufficient heat to mechanically deform the microstructures within the TMAZ. The massive deformation of the stirring pin leads to fully recrystallised grains at the NZ [12].

Rotating and stirring effects of the pin movement made the materials up and down in the nugget zone as shown in Figure 3. The microstructures from the advancing and retreating sides are bent towards the nugget zone. Whereas, the TMAZ is located between the nugget zone and heat affected zone. The nugget zone shows distorted and wavy patterns indicating the stirring effect and different material flow during pin rotation. The movement of materials from the retreating to advancing side via pin rotation has created interspersed effects involving torsion and swirl motions [13].

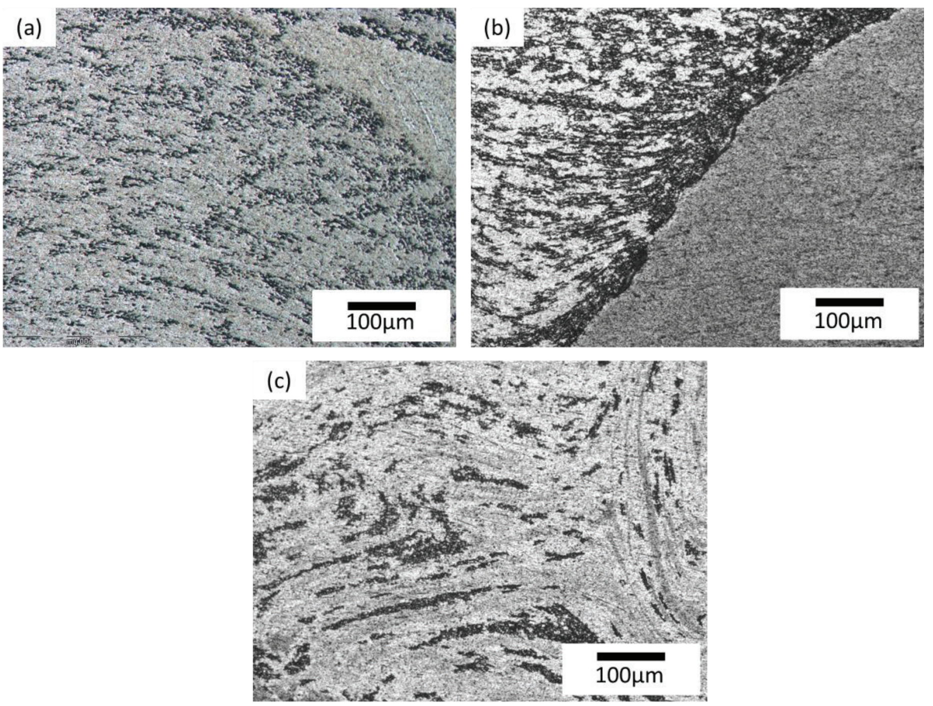

Figure 3: Microstructure of etched material of FSWed by Keller reagent shows the pattern of materials movement in welding joint: (a) advancing side, (b) retreating side and (c) nugget zone

FSW process significantly affected to the grain size at each zone in the welded area. Subsequent rolling process on the welded plates is increased the compressed energy either in base metal or welded area. Figure 4 presents the microstructure of NZ in each specimen after PWCR. The equiaxed grains in NZ of FSWed joints is compressed and elongated after rolled up to 40%. However, the grain size of NZ at 10% barely change due to insufficient energy to compressed the plate. The rolling percentage 40% shows elongated grains in one direction according to the rolling process. The same behaviour obtained at the base metal for both sides, whereas the grain shape is elongated due to the compressing force from the rolling process. The original grain sizes of base metal AA5083 and AA6061 are 12μm and 24μm, respectively. Fundamentally, grain sizes are reduced at NZ due to highly deformation and recrystallization made the grain in NZ as small as 9μm. As the rolling percentages are increased, the grain size within the nugget zone decreases to 8μm, 6μm, and 5μm for CR10%, CR20% and CR40%, respectively. The decreasing of grain size can be related to the rise of mechanical strength.This is because the small grain size will produce high dislocation density, directly made a difficult movement between the grains [14]. Thus, the increasing of dislocation density exhibited the higher mechanical properties of joints.

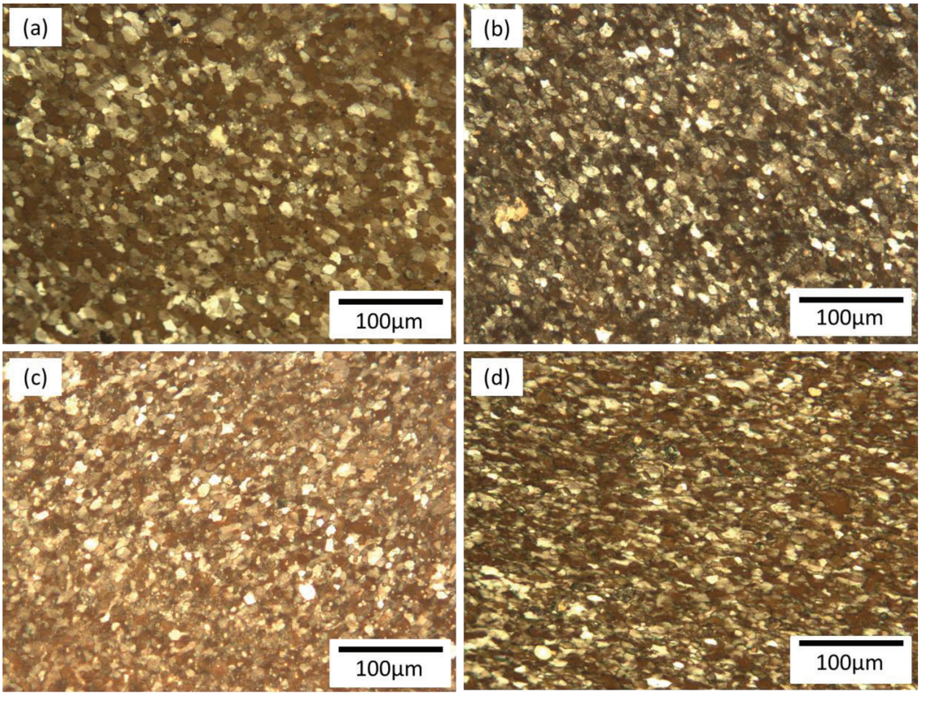

Figure 4: Optical micrograph showing the grain size of nugget zone in (a) FSWed, (b) CR10%, (c) CR20% and (d) CR40%

3.3 Micro-Hardness Profile of Welded Cross Section

As the microstructure size has reduced due to PWCR, it increases the hardness profiles of the welded area at each specimen. Micro-hardness profile from the cross-section of the weld area and base metal at advancing and retreating side is displayed in Figure 5. The hardness of base metal AA5083 and AA6061 is getting higher parallel to the rolling percentage. The highest hardness is achieved at rolling percentage 40% for base metal AA5083. Due to mechanical properties of base metal, higher hardness is located at the advancing side AA5083. When entering the welding area, the hardness starts to drop from HAZ then it is continuously reduced towards the nugget zone. The hardness is nonstop reduced from the nugget zone to the retreating side. The decrease in hardness at welding area is due to the different mechanical properties of AA5083 and AA6061.

Despite, the increasing of rolling percentage improve the hardness of base metal but still the nugget zone will reduce in hardness due to different mechanical properties of the base metal. So, it is indicated that the rolling process has improved the hardness of welding joint due to decreasing of grain size. On the contrary, the effect of rolling prior to welding does not influence the final grain size, as the microstructures continuously experience dynamic recrystallization [15]. Therefore, the hardness values of the base metal AA5083 are 92HV, 105HV, and 109HV for CR10%, CR20% and CR40%, respectively.

Furthermore, the hardness of AA6061 is rather low compared to AA5083, whereby for CR10%, CR20% and CR40% the hardness values recorded are only 48HV, 53HV, and 58HV, respectively.

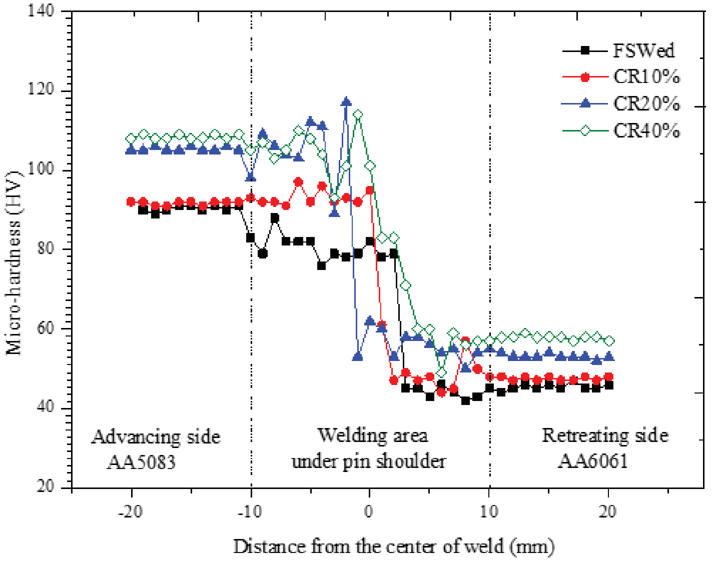

Figure 5: Micro hardness profiles of welding cross section at all specimens by Vickers hardness with 1mm per indentation

3.4 Tensile Properties

Figure 6 shows the engineering stress-strain diagram of FSWed and PWCR joints. The tensile curve displays the base metal AA5083 has higher tensile compared to AA6061. Whereas, the tensile strength of FSWed joint is lower than both of the base metal. Further, increasing the rolling percentage has improved the tensile strength higher than FSWed joint. Increasing percentages of rolling have significantly influenced the mechanical strength as evident in Table 2. As shown in the table, the ultimate tensile strength (UTS), Tensile strength efficiency (TSE), Elongation (EL) and Elongation efficiency (ELE) has been reported for all specimens. The tables revealed that the FSWed joint has a lower strength compared to the base metal.

The elongation of FSWed joint is lower than the both of base metal with decreasing almost 50% from AA6061. The PWCR has increased the value of UTS, and consequently increases the values of TSE to 105%, 125.7%, and 144%, for CR10%, CR20% and CR40% respectively. The increasing of tensile strength can be related to decreasing of grain size as explained through the Hall-Petch strengthening theory [16].

Significantly, the CR40% joint offers the highest tensile properties followed by CR20% and CR10%. The PWCR joints consist of CR10%, CR20% and CR40% indicated increment in terms of yield strength and tensile strength but reduce in terms of elongation. Therefore, the highest rolling percentage 40% shows the highest UTS but recorded the lowest elongation in which only 31.7%. Notably, the rolling process has produced high tensile and yield strength compared to FSWed joint but still below the UTS of AA5083. However, increasing the rolling percentage obviously lowers the percentage of elongation. The failure during tensile test of FSWed joint occurs at the retreating side out of the welding area. As the rolling percentage up to 40%, the fracture location shift to welding area at retreating side. The tensile strength of FSWed is comparing to base metal of AA6061 (on the retreating side) in order to get the joint efficiency in which 97%. Therefore, the joint efficiency of CR10%, CR20% and CR40% are 103%, 122% and 146%, respectively.

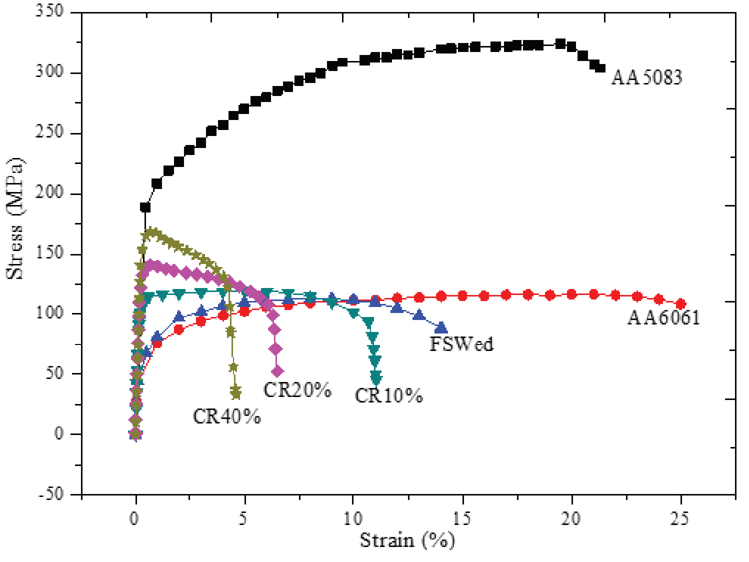

Figure 6: The mechanical strength of base metal and rolling under different percentage

Table 2: Tensile properties of joining samples

Material	UTS (MPa)	EL (%)	TSE (%)	ELE (%)
FSWed	113	14.5	-	-
CR10%	119	11	105	76
CR20%	142	6.5	126	45
CR40%	163	4.6	144	32

3.5 Fracture Analysis

Fracture of tensile specimens occurred at the different location as the minimum hardness region is found to vary within the TMAZ-HAZ and outside the welding, depending on the conditions of the joints. Joints of

FSWed, CR10%, and CR20% were fractured outside the welding region at the retreating side AA6061, but up to CR40% the fracture location move within the TMAZ-HAZ at the retreating side. Figure 7 shows the dimples in varying sizes and deep that were uniformly distributed over the surface as evidence for ductile mode fracture. It can be proved that the necking occurred during the tensile test portraying the largest elongation. But, by increasing the rolling percentage up to 40% forms stress concentrations in the welding joint due to strain hardening that affects to low ductility especially in the welded regions. Consequently, the rolling effect has been influenced to dimple size on the fractures surface of the CR40%. Incomplete and shallow dimples with flat surface indicated the ductile-brittle fracture has occurred at CR40% joint as approved by lower elongation in stress-strain curve [17].

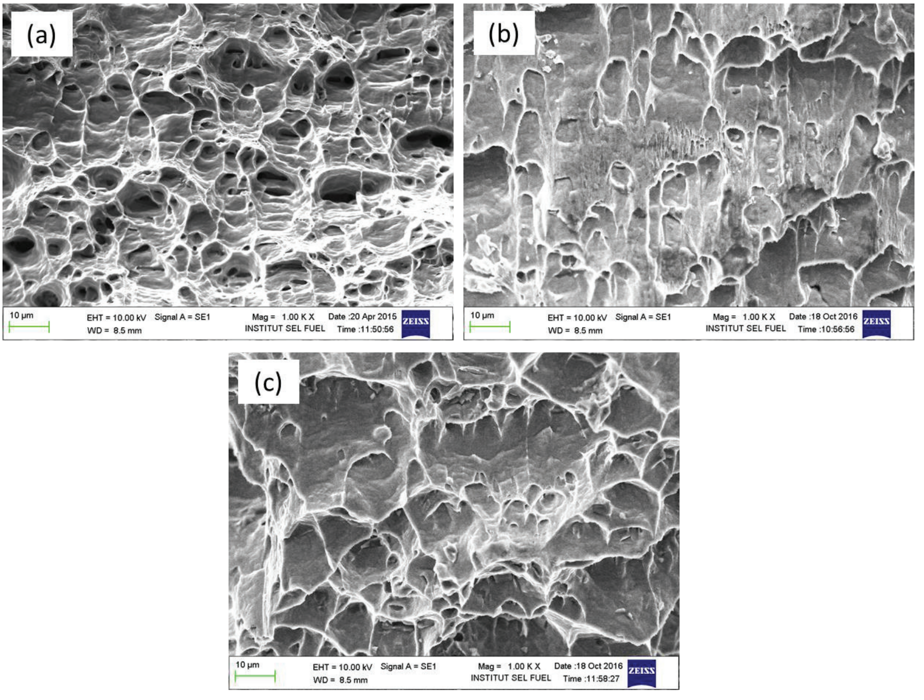

Figure 7: Fracture morphology of (a) FSWed, (b) CR10% and (c) CR40%

4.0 CONCLUSION

This research has successfully investigated on friction stir welding of dissimilar aluminium alloys AA5083-AA6061 with a welding efficiency of 97% from the base metal 6061. The grain size has been reducing from 8μm to 5μm as the rolling percentages are increased from 10% to 40%. Refined grain sizes have also changed the properties of hardness. Pertaining to tensile properties, rolling percentages of 10%, 20%, and 40% have indeed improved the tensile strength efficiency to 105%, 125.7%, and 144%, respectively, However, it leads to reduce of elongation percentage from 77%, 44.8%, to 37%, accordingly. Furthermore, the rolling percentage is increasing the joints efficiency to 103%, 122% and 146% as the rolling percentage increase. Moreover, the fracture location outside the welding area has shifted to TMAZ-HAZ at the retreating side after rolled up to 40%, indicated the ductile-brittle surface.

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