

## Effect of Rolling on Strength of Friction Stir Welded Joint of Aluminium Alloys

(Kesan Gelekan terhadap Kekuatan Sambungan Kimpalan Kacau Geseran Alooi Aluminium)

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### ABSTRACT

*Friction stir welding (FSW) technique is one of the best options especially for joining dissimilar aluminium alloys. However, there is a limitation to weld thin plate using this method since it produces due to less amount of materials mixing in the stir zone hence result in bad aesthetics of the welding surface. In this study, two different types of aluminium alloys, namely AA6061 and AA1100, were butt-joined by using FSW method. The rotational and transverse speeds of the tool were 1,000 rpm and 100 mm/min, respectively. The friction stir welded samples were subsequently cold rolled to a different thickness reduction percentages of 10, 20, and 40%. From the microscopic observation of the sample's cross-section, no internal defect was detected at the welding area for both the as-welded joints and the rolled specimens. The tensile strength of FSWed sample was 93 MPa. This was only 80% of welding efficiency as compared to the tensile strength of AA6061 at 116 MPa. The results showed that the tensile strength of the dissimilar joint increased with the increase of the rolling percentage. The welding efficiency of samples after 10, 20, and 40% rolling were 86, 94 and 110%, respectively. However, the total elongation of the sample decreased from 29 to 56% with an increase in the rolling percentage. It is worth to acknowledge that there was no crack or defect observed at the FSW joint after the rolling of 40% thickness reduction. Furthermore, the fracture location of the rolled FSW joints was near the thermo-mechanically affected zone/heat affected zone (TMAZ/HAZ) and indicated ductile fracture behaviour with evidence of dimples on the fracture surface. In conclusion, reducing the thickness of dissimilar FSW joint aluminium alloys plate by the rolling process is possible without any defect nucleation.*

**Keywords:** Friction stir welding; rolling; aluminium alloys; dissimilar joint; tensile strength

### ABSTRAK

*Kaedah kimpalan kacau geseran (FSW) adalah pilihan terbaik bagi penyambungan terutamanya untuk dua alooi aluminium tak serupa. Namun begitu, kimpalan geser kacau sukar dilakukan ke atas kepingan logam nipis kerana jumlah bahan yang sedikit di dalam zon kacau lantas menghasilkan estetik permukaan kimpalan yang kurang memuaskan. Dalam kajian ini, dua jenis alooi aluminium gred AA6061 dan AA1100 dikimpal temu menggunakan kaedah FSW dengan parameter 1000 rpm bagi laju putar dan 100 mm/min bagi laju melintang. Sambungan terkimpal kemudiannya digelek sejuk pada peratusan pengurangan ketebalan yang berbeza iaitu 10%, 20% dan 40%. Pemerhatian daripada keratan rentas mendapati tiada kecacatan dalaman yang terjadi pada sambungan terkimpal mahupun yang digelek. Kekuatan tegangan sampel terkimpal FSW adalah 93 MPa. Nilai ini hanyalah 80% kecekapan sambungan berbanding nilai kekuatan tegangan bahan AA6061 iaitu 116 MPa. Keputusan menunjukkan kekuatan tegangan sambungan tak serupa meningkat dengan peningkatan kadar gelekan. Kecekapan sambungan sampel selepas gelekan 10, 20 dan 40% masing-masing adalah 86, 94 dan 110%. Walau bagaimanapun, jumlah pemanjangan sampel menurun sebanyak 29 hingga 56% dengan peningkatan kadar gelekan. Adalah merupakan suatu pencapaian baik apabila tiada retak atau kecacatan yang terhasil di kawasan sambungan FSW selepas gelekan 40% pengurangan ketebalan dilakukan. Tambahan pula, lokasi patah sampel sambungan FSW tergelek adalah berhampiran zon terkesan termo-mekanikal/zon terkesan haba (TMAZ/HAZ) and memperlihatkan sifat kepatahan mulur dengan kehadiran lompong pada permukaan patah. Sebagai kesimpulan, pengurangan ketebalan kepingan sambungan FSW alooi aluminium tak serupa melalui proses gelekan adalah mungkin tanpa penghasilan sebarang cacat.*

**Kata kunci:** FSW; gelekan; alooi aluminium; sambungan tak serupa; kekuatan tegangan

## INTRODUCTION

Aluminium alloys are well-known as lightweight materials with good mechanical properties (Amir et al. 2017). Over the decades, aluminium alloys have been used as the materials in various industries such as automotive, constructions and aerospace (Amini & Asadi 2014). There are several types of aluminium grades depend on the major alloying elements. AA1100 and AA6061 are typical aluminium alloy grades that are commercially available and commonly used in many manufacturing industries. AA1100 is almost pure aluminium alloy, whereas AA6061 consists mainly of Mg and Si as the alloying elements. AA6061 can be strengthened by heat treatment process. These aluminium alloys are widely used due to high corrosion resistance, lightweight, and high formability (Cobden & Banbury 1994).

However, welding of aluminium alloys is difficult to be conducted using conventional welding processes. A conventional welding process involves melting of metal, which releases hydrogen gas from aluminium alloy and affects the occurrence of voids and cracks (Mishra & Ma 2005). Furthermore, joining two different materials using the conventional process is very challenging. This is because different compositions and material flow affect the materials by weakening the joints (Luijendijk 2000; Mishra 2014). Therefore, the development of friction stir welding (FSW) in 1991 creates a new pathway for welding technology, especially for aluminium alloys. The innovation of FSW has been used to join aluminium alloys, but later on, this method has been applied to other metals such as steel and composite (Thomas et al. 2003).

FSW is different from a conventional welding method because the joining is conducted in solid-state condition. The essential principle of this method involves the use of a welding tool. Figure 1 shows the schematic diagram of FSW and the use of the welding pin in FSW. During welding, the tool is plugged in between two metal plates. The rotational and transverse motion of the tool will generate heat due to the frictional force between the pin and the materials. The shoulder functions by avoiding materials emitting from the welding area. The heat generated from frictional force will soften the materials under the shoulder. In addition, the movement of the pin in the welding direction stirs and mixes the softened material and consequently encourages the joining to occur.

The tilt angle of the pin also influences force and material movement during welding. Usually, the pin length is shorter than the thickness of the material to avoid heat transfer from reaching the back of welding plates. Welding parameters such as travelling speed, rotational speed, pin geometry, and tilt angle determine the quality of welding. Welding parameters are important to ensure sufficient heat input is induced during welding. Appropriate heat input can be considered as a main critical issue for smooth material flow and mixing in the joining process (Dehghani et al. 2013).

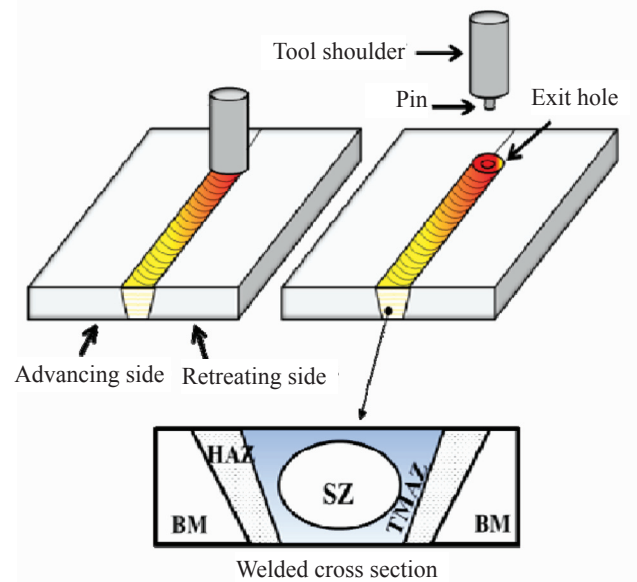


FIGURE 1. Schematic diagram of FSW and welded cross-section of the joint

The metal located parallel to the welding direction is known as the advancing side, whereas the other side is known as the retreating side. For dissimilar joint, the determination of metal at the advancing or retreating side is important for increasing material flow efficiency. Due to this reason, the materials with high strength are preferred to be placed at the advancing side (Vinayak & Bhatwadekar 2015). A welding cross-section consists of several zones, such as heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ), and nugget zone (NZ). These zones are different in terms of heat and mechanical experience from pin rotation. Therefore, the microstructure of different zones has dissimilar shape and grain size.

Usually, the increasing size of HAZ that is affected by the heat transfer will lower the hardness and strength of the joint (Sifullah et al. 2017). Therefore, several methods have been developed to enhance FSW joint, such as by introducing heat treatment (Krishnan 2013). For dissimilar welding joint, the intermetallic layer formed in the welding zone can be reduced using the rolling process. The intermetallic layer needs to be reduced to increase the mechanical strength of the joint. This method has been investigated for a dissimilar metal joint of aluminium and copper (Deng et al. 2016; Kahl & Osikowicz 2013).

Hence, the rolling process is a good solution for a post-weld treatment in order to reduce the thickness of FSW plates because FSW has limitations for joining very thin plates. The surface of the thin metal can be affected by excessive heat and forging effect from the tool shoulder. In addition, the material flow to stir and mix is limited to make a joint, where excessive heat from the pin rotation will reduce welding quality (Rodrigues et al. 2015). In this research, dissimilar FSW joints were subsequently rolled for different thickness reduction percentages. From the result, the effect of rolling on the FSW joints in terms of microstructural, mechanical properties and welding efficiency was discussed.

# METHODOLOGY

In this research, two types of aluminium alloy grades i.e. AA1100 and AA6061 were used as base metals. All aluminium plates were annealed prior to FSW in order to eliminate production history. The ultimate tensile strength (UTS) of the AA1100 and AA6061 base metals was 122 and 116 MPa, respectively. The aluminium alloys were butt joined using FSW method. In order to get good welding flow, AA6061 was placed on the advancing side and AA1100 was positioned on the retreating side. Table 1 shows the compositions of alloying elements in the base metals. The FSW process was conducted at Sharif University of Technology, Iran. Prior to welding, aluminium alloy plates with 5 mm of thickness were prepared with the dimensions of 150 mm × 50 mm. Then, all plates were cleaned using a steel brush and ethanol to remove the oxidation layer on the surface of the plates. Removal of oxidation layer is important to avoid internal defects in the joining area such as kissing bond formed from the oxidation layer of the plate surface.

Prior to welding, both base metals were fixed tightly onto the table of the FSW machine. The fixer was used to prevent any movement of the metal plates during welding as presented in Figure 2. The base metals need to be held tightly to ensure there is no gap between the two plates in order to prevent the formation of voids. Welding parameters, the rotational and transverse speeds, were fixed at 1000 rpm and 100 mm/min, respectively. These optimum parameters were chosen based on the results of the preliminary study. The tilt angle was set to 3° for all samples.

The welding tool was made from H13 steel with a shoulder diameter of 20 mm. The hardness of the tool is much higher than aluminium alloys to make sure it can resist the heat generated during the FSW process. The pin geometry is a simple thread with the length and diameter of 4.7 mm and 5.0 mm, respectively.

After welding, 0.5 mm thickness was removed for both top and bottom sides of all the welded plates using a milling machine. This is to eliminate welding flash from the welded plates, which indirectly reduces stress prior to the rolling process. The thickness of the welded plate before the rolling process is 4 mm. The welded plates were rolled vertically using a pair of rollers as shown in Figure 3. The post-weld cold rolling was done at 10, 20 and 40% thickness reduction.

To simplify, in this paper, the term FSWed refers to the as-welded joint. The cold rolling process was carried out parallel to the welding direction. Several passes of rolling were applied on the welded plates until the desired thickness reduction percentage is achieved. A small thickness reduction during the rolling process can avoid bending and cracking of welded joints.

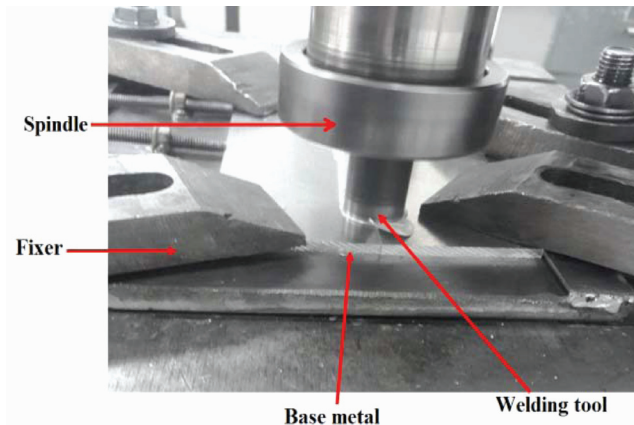


FIGURE 2. Two different base metals are placed on the FSW machines with pin insert between the metals

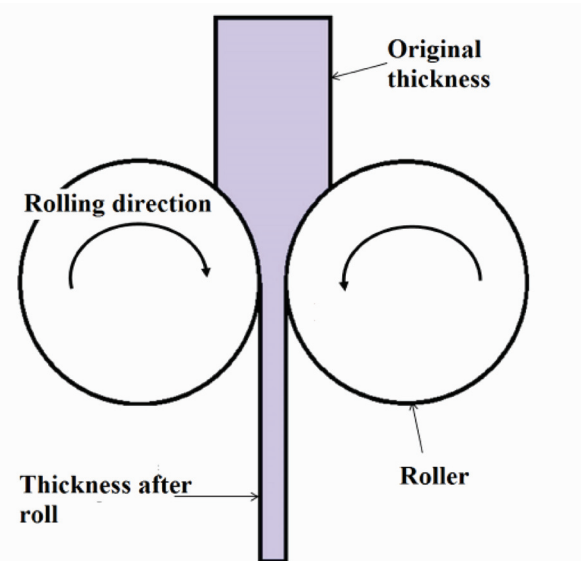


FIGURE 3. Illustration of the rolling process applied to the welded plates

TABLE 1. Composition of alloying elements in the base metals

Aluminium alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
AA1100	-	0.05	-	-	0.12	-	-	0.06	Bal.
AA6061	0.52	0.70	0.39	0.15	0.88	0.24	0.16	0.14	Bal.



The tensile specimens were cut using Electrical Discharge Machining (EDM) from the rolled welded. The length and width of the specimens for gage length were 40 mm and 6 mm, respectively. The specimens were cut parallel to the welding direction with the welding area located in the middle of the gage length. The tensile test was performed in accordance with ASTM E8 using a 100 kN Zwick/Roell universal testing machine (UTM).

The micrographs of the welded cross-section of the plates were observed using an optical microscope. The samples were cut by EDM perpendicular to the welding direction for the preparation of metallography specimens. After that, the materials were hot mounted prior to grinding using different grades of emery paper (#600, #800, and #1200). The specimens were polished using diamond suspension up to 0.1  $\mu\text{m}$  until the specimens became mirror surface. Keller's reagent with the compositions of 190 ml of  $\text{H}_2\text{O}$ , 5 ml of  $\text{HNO}_3$ , 3 ml of  $\text{HCl}$ , and 2 ml of  $\text{HF}$  was used in the etching process. The etching procedure was conducted prior to observation under an optical microscope. For fracture surface characterization, the tensile specimen surface was observed using a field emission scanning electron microscope (FESEM) (Supra 55, Germany). This procedure managed to obtain the fracture behaviour during the tensile test of welded joints.

## RESULTS AND DISCUSSION

Figure 4 presents the image of welded cross-section FSW joints subjected to the rolling process. As AA6061 has high strength mechanical properties, it should be located on the advancing side. The location of metal types is important to determine the quality of welding joints, especially for dissimilar materials. This is because the force from the advancing side will encourage materials to flow to the retreating side. The material flow will stir and mix to form the welding joint (Jamshidi et al. 2011). On the other hand, the image obviously shows different colour between the advancing and retreating sides due to the effect of materials reacting to the etchant. Therefore, the advancing side was darker from the retreating side.

Furthermore, the material flow during the stir and mixing in the NZ formed a lobe pattern. From the mixing pattern, the material from the advancing side (AA6061) was located at the top of joints compared to the retreating side (AA1100) that was mixed in the advancing side. This pattern occurs due to different material strength and material flow between the advancing and retreating sides. The low mechanical property at the retreating side (AA1100) was easily softened by the heat and easily influenced to mix with materials at the advancing side.

The image in Figure 4 shows the area under the tool shoulder, with the lines indicating the different zones. The HAZ and TMAZ were obtained at both welding sides. The grain size at TMAZ was elongated and bent towards the NZ, while the HAZ had similar or larger grain size than base

metals. Meanwhile, the heat and severe deformation in the NZ produced recrystallized grains.

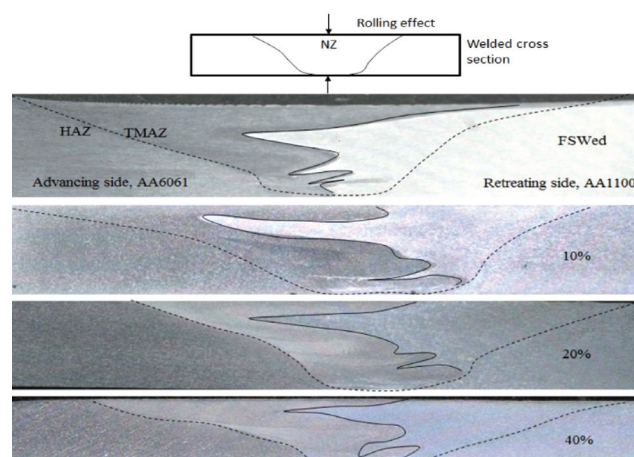


FIGURE 4. Cross section of welded joints for FSW Wed followed by cold rolled under the different percentage

The visual observation indicated no internal and external defects on the welded plates even after the rolling process was employed to 40%. The success of the rolling process on the welded plates is contributed from the good mechanical joint. In fact, appropriate welding parameters such as rotational and transverse speed play important roles for good joining. In addition, rotational and transverse speed determines sufficient heat input as well as the quality of welded joint (Sharma et al. 2012). Adequate heat input generates good material flow during the joining process and prevents the formation of cracks or voids.

Post-weld cold rolling (PWCR) process compressed the welded plates and increased the width of the welding area. The deformation of cold work slightly changed the pattern of material flow in the NZ. The cold rolling process enforced severe plastic deformation on the welded joints, therefore reduced the microstructure of materials. The grain size in the NZ and base metals were also elongated from the rolling process. The deformation of grain size could change the mechanical properties of welding joints.

By PWCR the tensile strength of welded joints has been increased dramatically, without any defect occur internally or externally at the joints. This finding almost similar to Gabrielli et al. (2017) that mentioned cold rolling can be implemented for reducing the welded sheet thickness. Rolling process is useful for dissimilar welded joints as it can be reduced the thickness of the materials at the same time maintain or increase the tensile strength. This is because the FSW process is limited to weld the thin sheet and it can deteriorate the welding surface due to forging effect from the pin shoulder.

Figure 5 shows the stress curves of FSW joints under different rolling percentages. From the curve, it was shown that FSWed samples had the highest elongation and the lowest UTS. PWCR increased the yield strength and UTS but decreased the elongation. The UTS increased the FSWed samples (93 MPa) by PWCR of 10, 20, and 40% to 100, 109,

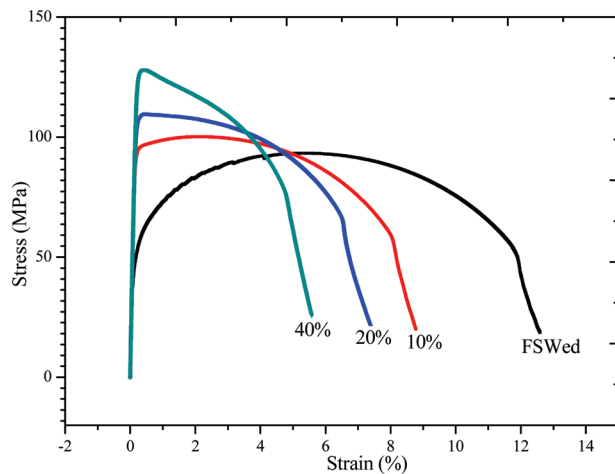


FIGURE 5. Stress-strain curves of FS Wed and welded joints with a different rolling percentage

and 128 MPa, respectively. Therefore, the UTS increased to 7.5, 17, and 37.6% by increasing the rolling percentages. Meanwhile, the elongation decreased to 29, 41, and 56% by increasing the rolling percentages. However, the annealing process after rolling up to 66% of AA1100 can improve the elongation of materials (Mhedhbi et al. 2017).

The improvement of tensile strength is related to the decrease of grain size during the rolling process. The decrease of grain size leads to high dislocation density in the structure, in which high dislocation density makes slip difficult to occur. Moreover, small grains means there are a lot of grain boundaries. Therefore, the increase of grain boundaries makes grain movement difficult and as a consequence, limits elongation. Hence, the increase in rolling percentages performed on the welded samples led to high dislocation density and increased mechanical properties such as strength and hardness of joints (Callister 2007). The rolling process affects to the dislocation density of grains as nature mechanism involved during the formations (Sivasankaran et al. 2018).

Figure 6 shows the welding efficiency of welded joints under different rolling percentages.

Welding efficiency of welded joints could be obtained by comparing the UTS of current joints and the base metals. The calculation was based on AA6061, since the comparison should be made with the base metal with the lowest UTS (Ilangovan et al. 2015). The joint efficiency of welded joints was calculated using Eq. (1). It was noted that the joint efficiency tended to improve by increasing the rolling percentage. The FSWed had the lowest joint efficiency as much as 80%. By increasing the rolling percentages to 10, 20, and 40% of the joint efficiency increased to 86, 94, and 110%, respectively.

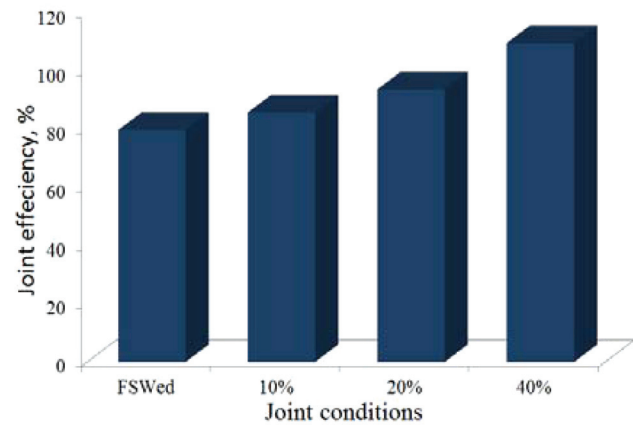
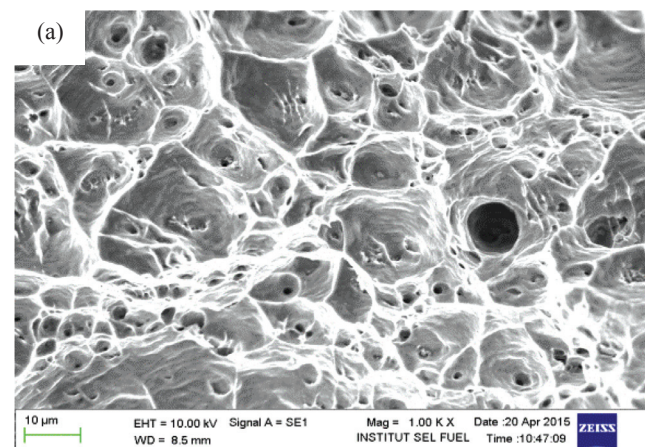


FIGURE 6. The welding efficiency of welded joints as compared to the base metal AA6061

$$\text{Joint efficiency, \%} = \frac{UTS_{\text{welded}}}{UTS_{\text{base metal}}} \times 100\% \quad (1)$$

After the tensile test, FSWed specimens had fracture near TMAZ/HAZ at the retreating side. By applying the rolling process, it did not change the location of the fracture. The fracture at the HAZ indicated that it was the weakest point of the welding area. This is because the grains in the HAZ experienced annealing-like process by heat transfer from the NZ during welding. Hence, the grain size increased, whereas the mechanical properties and hardness decreased.

Figure 7 depicts the fractography of fracture surface for FSWed and PWCR samples. The dimple shape on the surface highlights the ductile behaviour of the samples (Abdul et al. 2014). It was proven by the necking process before the samples were broken. Furthermore, the size of dimples in FSWed samples was deeper and wider, which indicates the highest elongation. Meanwhile, after the rolling process, the size of the dimples was elongated due to the compression force from the rolling process.





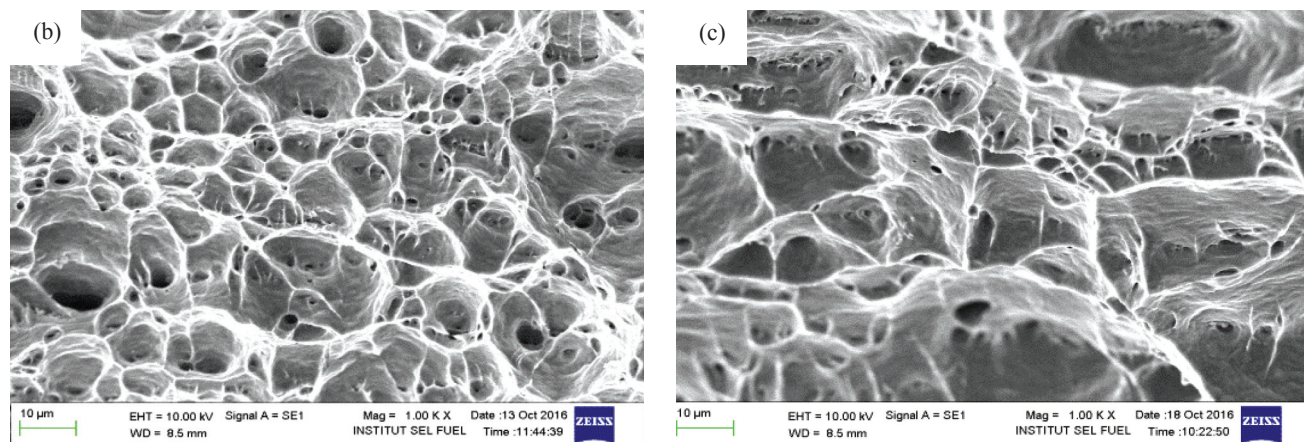


FIGURE 7. Fractograph of fracture surface on the tensile samples (a) FSWed (b) 10% (c) 40%

### CONCLUSIONS

The butt joints of dissimilar aluminium alloys, AA6061 and AA1100, have been successfully welded using FSW at the rotational and transverse speed of 1,000 rpm and 100 mm/min, respectively. The rolling process performed on the welded joints up to 40% improved the tensile strength without forming any cracks in the welding area. Furthermore, the increase in rolling percentage by 10, 20, and 40% improved the welding efficiency to 86, 94, and 110%, respectively. On the other hand, the fracture surface of tensile specimens showed the ductile behaviour for all joints. Generally, the rolling process increases the tensile properties without decreasing the quality of welding joints.

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