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Feasibility Study of Friction Stir Welding of Dissimilar Metals between 6063 Aluminium Alloy and Pure Copper

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Abstract

Butt joints of dissimilar metals between 6063 aluminium alloy (Al6063) and commercial pure copper (Cu) were fabricated by friction stir welding (FSW) using the rotational speed of 1100, 1400 and 1800 rpm and welding speed of 20 and 40 mm/min. The effect of rotational and welding speeds in FSW process on surface morphology, microstructure and mechanical properties of dissimilar FSW Al6063-Cu joints was investigated. The experimental results showed that defect-free dissimilar FSW Al6063-Cu joints could be achieved when rotational and welding speeds in FSW process were used as listed follow: 1100 rpm and 20 mm/min, 1400 rpm and 20 mm/min, 1800 rpm and 20 mm/min. Microstructural analysis revealed that a good mixing of Al6063 and Cu metal with lamellar structure was observed. Furthermore, fine Cu metal and Al6063 particles were also found in stir zone (SZ) of the dissimilar FSW Al6063-Cu joints. EDS and XRD results indicated that intermetallic compounds such as AlCu, Al_2Cu and Al_4Cu_9 were formed in SZ of the dissimilar FSW Al6063-Cu joints. High tensile strength of the dissimilar FSW Al6063-Cu joints would significantly result from a large area of SZ in the joints due to using proper welding pitch.

Keywords: 6063 Aluminium alloy, Copper, Friction stir welding, Microstructure, Mechanical properties.

1. INTRODUCTION

Since the last decade, friction stir welding (FSW) of dissimilar metals joints has been widely applied to industrial applications due to their technical and beneficial advantages [1]. The FSW is used for many joint configurations involving butt joints, lap joints and complex joint-types. During FSW, friction condition between a shoulder and a workpiece is the contribution on the heat input and consequent strongly affects the deformation of metals. Therefore, the deformation of metal under the shoulder can be directly related to flow pattern in weld zone [2]. Generally, deformation and flow of metals in weld zone during FSW is a major issue to determine the microstructure, intermetallic compounds formation and the mechanical properties of the dissimilar FSW joints. However, visualization of flow pattern of metals in weld zone of dissimilar FSW joint is complicated. Recently, the dissimilar FSW joint between aluminium (Al) and copper (Cu) has been desired for the potential application in electronic components and power generation industries. It is due to the combination of the lightweight and low-cost for aluminum alloys as well as the superior electrical and thermal conductivity for copper. However, some researches in dissimilar FSW joint between Al and Cu indicated that defect-free dissimilar FSW joint between Al and Cu was difficultly achieved and few issues still require extensive research [3, 4]. In addition, the appropriate FSW condition for fabrication of the dissimilar FSW joints between 6063 aluminuim alloy (Al6063) and commercially pure copper (Cu) has not been mentioned. From the experiment reported by Xue et al. [3] and Liu et al. [4], the FSW joints between aluminium alloy (Al1060 and Al5052) and copper were fabricated by using low rotational speed (400-1200 rpm) and high welding speed (50-200 rpm). However, using of high rotational speed and low welding speed in the FSW process should be demonstrated. Therefore in present study, dissimilar FSW joints between Al6063 and Cu were conducted under various rotational and welding speeds (1000-1800 rpm and 20-40 mm/min). The surface morphology, macrostructure, microstructure and mechanical properties of the dissimilar FSW joints between Al6063 and Cu were investigated in detail. The intermetallic compounds (IMCs) across weld zone of the joints were characterized by X-ray diffraction (XRD) analyses and energy dispersive X-ray spectroscopy (EDS) elemental point analyses. The relationship between FSW process parameter and microstructure as well as mechanical properties of the dissimilar FSW Al6063-Cu joints was investigated.

2. EXPERIMENTAL PROCEDURE

6063 Aluminium alloy and commercially pure copper plates with a thickness of 6 mm were used in this study. Their chemical compositions are presented in Table 1. The microstructures of as-received the Al6063 and Cu plates are shown in Fig. 1. The specimens with dimensions of 55×25×5 mm were cut and prepared from the as-received Al6063 and Cu plates. In present study, the Al6063 and Cu plates were FSWed using rotational speeds of 1100, 1400 and 1800 rpm with welding speeds of 20 and 40 mm/min. The FSWed were done following The American Bureau Shipping (ABS): Guide for the approval of friction stir welding of aluminium alloy [5]. During FSW process, a 3° tilt angle of tool pin was used and the welding direction was perpendicular to the rolling direction of the as-received plates. The Al6063 and Cu plates were fixed as advancing side and retreating side respectively. The pin tool was a conical right-hand threaded probe of 5 mm length and 0.8 mm pitch and a 20 mm-diameter shoulder made from SKD61 tool steel.

Table 1 Chemical compositions of 6063 aluminium alloy and commercially pure copper in weight%.

Materials	Si	Cu	Zn	Mg	Fe	Al
Al6063	0.45	0.1	0.1	0.63	0.32	Balance
Copper	-	Balance	0.1	-	-	-

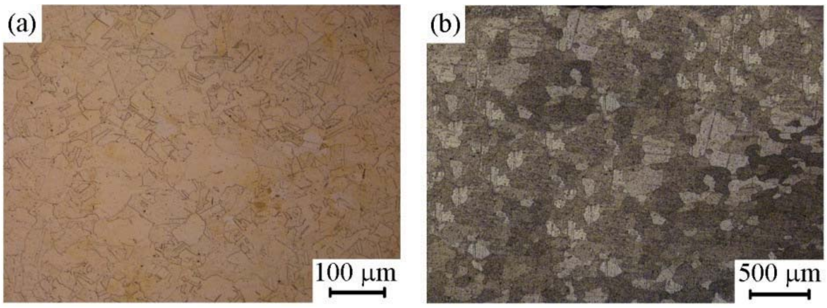


Figure 1 Microstructure of as-received (a) commercially pure copper and (b) 6063 aluminium alloy.

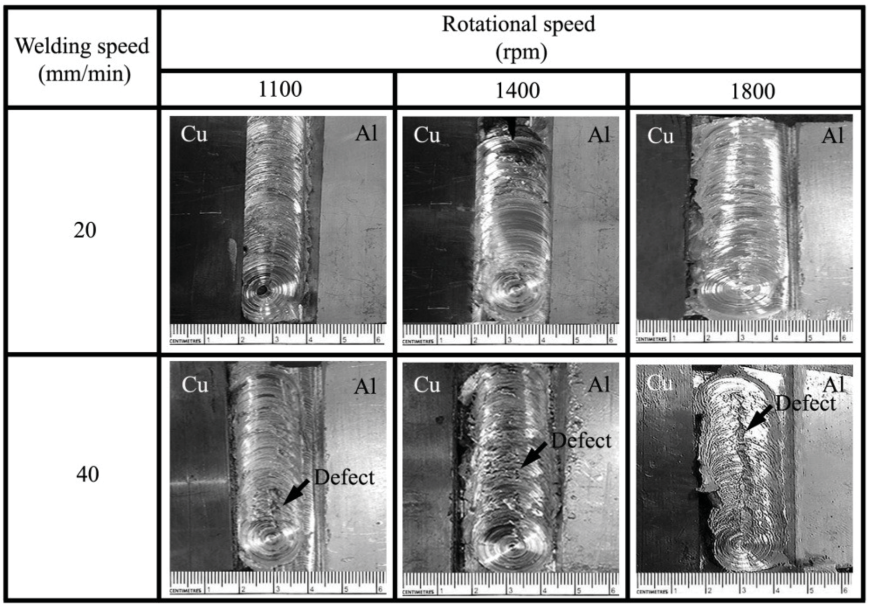


Figure 2 Surface morphology the dissimilar FSW Al6063-Cu joints fabricated under various process parameters.

For macrostructural analysis and microstructural analysis of the dissimilar FSW Al6063-Cu joints, optical microscopy analysis was conducted using a Nikon Eclipse MA200. X-Ray radiographic testing (RT) was carried out for inspection the dissimilar FSW Al6063-Cu joints. The X-ray was generated from the source with 100 KV of voltage, 7.4 mA and the exposure time used for getting the image was 30 s. Scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDS) with an elemental point analysis was also utilized for the microstructural study and phase identification. The X-ray diffraction (XRD) analysis was carried out at slow scan rate of 0.5 (°)/min using a target of CuKα to identify the intermetallic compounds in stir zone of the dissimilar FSW joints. The tensile specimens of the dissimilar FSW Al6063-Cu joints (flat dog bone shape specimens with 20 mm in gage length, 6 mm in gage width and 4 mm in gage thickness) were machined perpendicular to the FSW direction. In this case, the base metal (BM), the heat-affected zone (HAZ), the thermomechanically affected zone (TMAZ) and the stir zone (SZ) of the joints were in the gage section of the tensile specimen. Tensile tests were conducted at room temperature on an Instron 5566 testing machine at an initial strain rate of 1×10^{-3} s^{-1}. Hardness of the dissimilar FSW joints was measured at the middle of the joint (a distance of 2.5 mm from the top of the joints) under a low load of 0.5 kgf and a dwell time of 10 s on a Shimadzu microhardness tester.

3. Results and Discussion

3.1 Surface Morphology and Radiographic testing of Dissimilar FSW Joints

The surface morphologies of dissimilar FSW Al6063-Cu joints fabricated under various rotational and welding speeds are shown in Fig. 2. As seen from the figure, the surface of the dissimilar FSW Al6063-Cu joints was covered by a layer of aluminum alloy. The groove-like defects, which are indicated by arrows in the figure, were observed along the center of bead surface of the dissimilar FSW Al6063-Cu joints fabricated under the rotational and welding speeds as listed follow: 1100 rpm and 40 mm/min, 1400 rpm and 40 mm/min, and 1800 rpm and 40 mm/min. The groove-like defects in dissimilar FSW joints would be caused by insufficient metal flow and improper heat input during FSW process. The results of the radiographic tests conducted on all the dissimilar FSW Al6063-Cu joints are shown in Fig. 3. As seen from the figure, cavity/void defects were not found in all the dissimilar FSW Al6063-Cu joints fabricated in this case study.

3.2 Macrostructure of Dissimilar FSW Joints

Fig. 4 shows the macrostructure of dissimilar FSW Al6063-Cu joints fabricated under various rotational and welding speeds. SZ was also indicated in the figure. From the results of macroscopic examination, cavity/ void defects were not found in subsurface of all the dissimilar FSW Al6063-Cu joints. Normally, the sound dissimilar FSW joint is considered as no any defects on or inside the bead surface. Therefore, according to the results of surface morphology and macrostructural analysis, the sound dissimilar FSW Al6063-Cu joints of this study were achieved when fabricated under the rotational and welding speeds as listed follow: 1100 rpm and 20 mm/min, 1400 rpm and 20 mm/min, and 1800 rpm and 20 mm/min. As compare to the results reported by Xue et al. [3] and Liu et al. [4], it could be concluded that, high rotational speed and low welding speed could be applied for fabricated the dissimilar FSW Al6063-Cu joints. Furthermore, dark area at middle of the dissimilar FSW Al6063-Cu joints was identified as weld nugget or stir zone. Image analysis via the ImageJ was applied for measurement the SZ area of the joints. The SZ area of each the dissimilar FSW Al6063-Cu joint is shown in the Fig. 4. As seen clearly from the figure, the SZ of the dissimilar FSW Al6063-Cu joints fabricated under 1100 rpm and 20 mm/min, 1400 rpm and 20 mm/min and 1800 rpm and 20 mm/min was large compared to others.

3.3 Microstructure of Dissimilar FSW Joints

Generally, microstructure of dissimilar FSW joint consists of different regions which include; the unaffected material or base metal, the heat-affected zone, the thermomechanically affected zone and the stir zone [6]. The stir zone or stir nugget is referred to the region appears of several concentric rings which has been referred to as an "onion-ring" structure occupied by tool pin [7]. Fig. 5 shows the microstructure in various zone of dissimilar FSW Al6063-Cu joint fabricated under rotational and welding speeds of 1400 rpm and 20 mm/min. The microstructure of the dissimilar FSW Al6063-Cu joint consists of different regions as indicated in Fig. 5a. The Al6063 and Cu BMs were unaffected by heat generated during FSW process because they were remote from the weld center. Therefore, the microstructures of the Al6063 and Cu BMs were similar to the microstructure of as-receives materials. Fig. 5b and 5e show microstructures at the HAZ of Cu and Al6063 respectively.

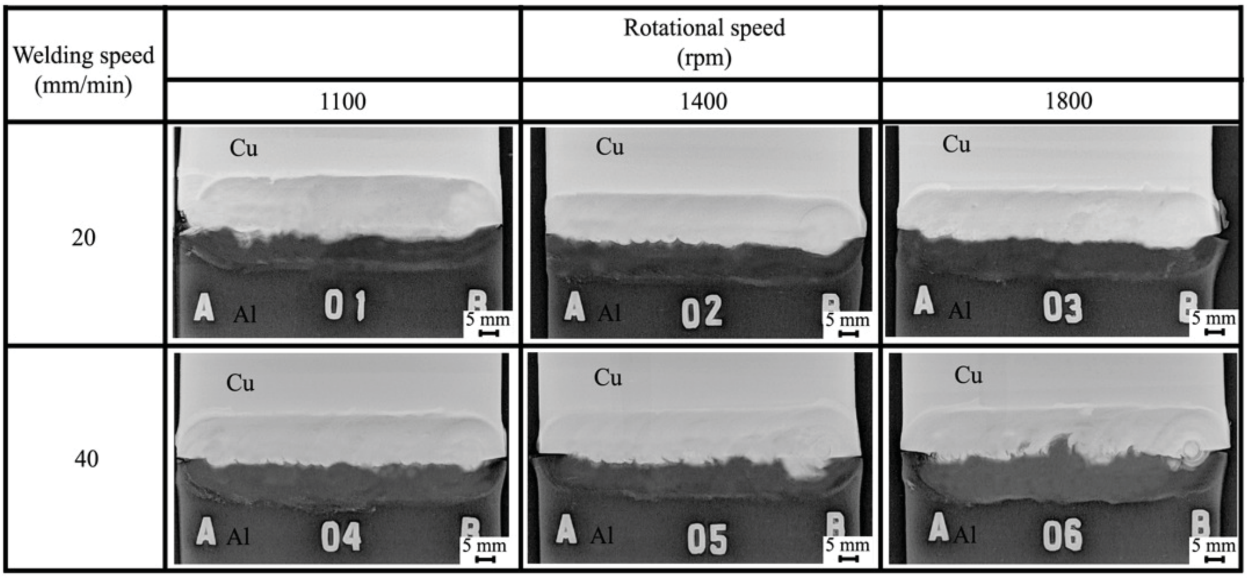


Figure 3 Radiographs of the dissimilar FSW Al6063-Cu joints fabricated under various process parameters

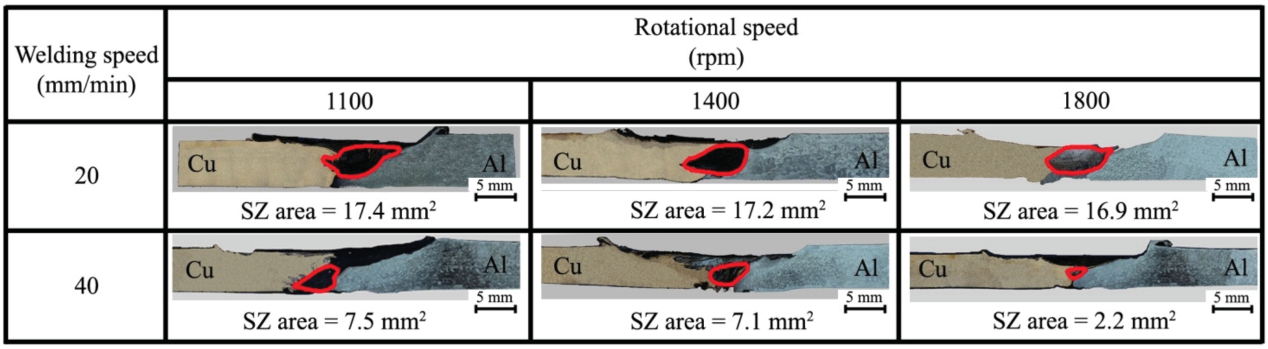


Figure 4 Cross-section macrographs of the dissimilar FSW Al6063-Cu joints fabricated under various process parameters.

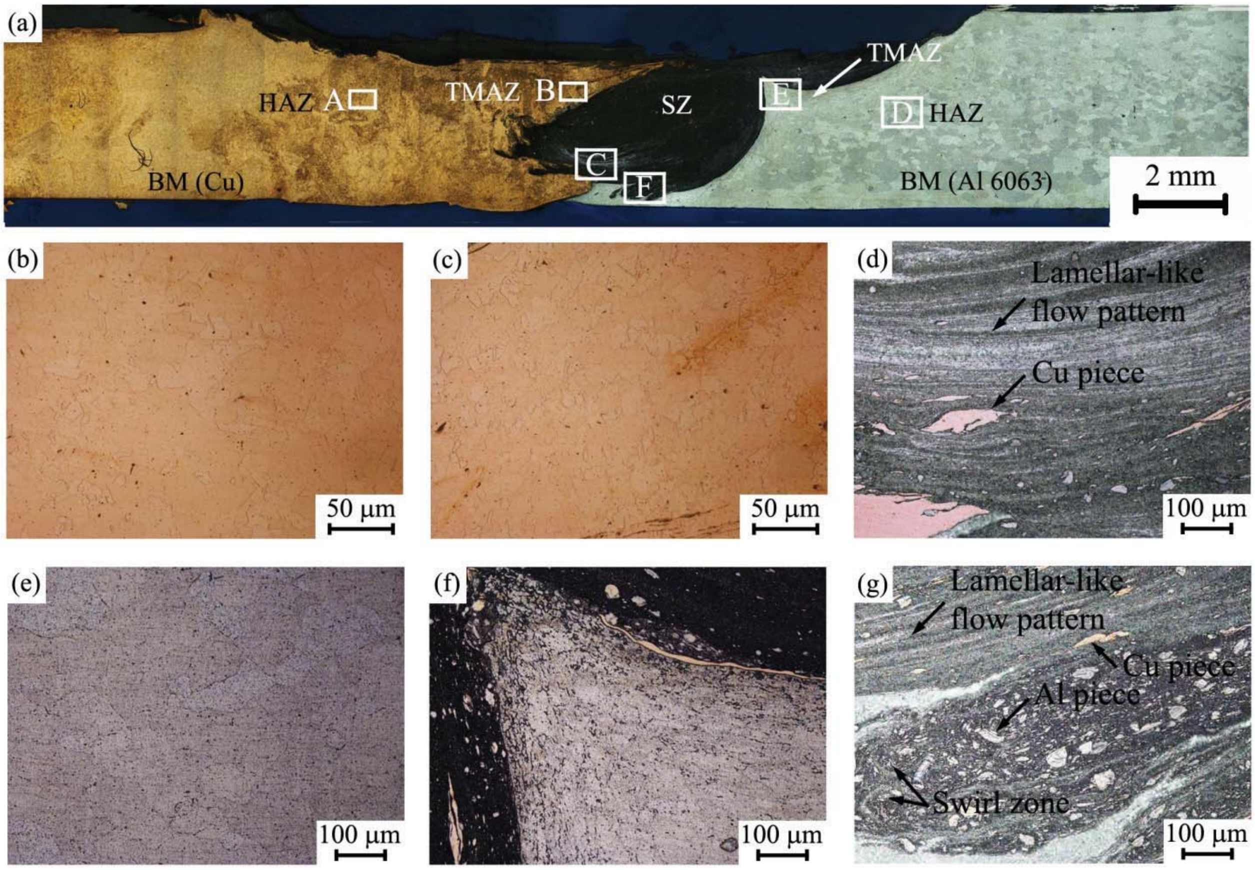
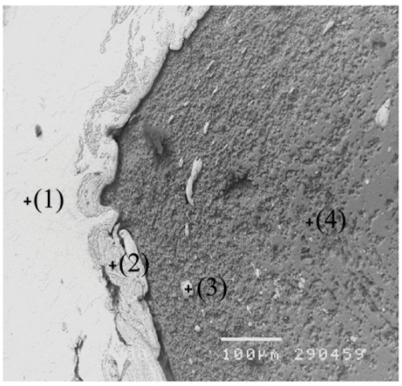


Figure 5 Microstructure of dissimilar FSW Al6063-Cu joints at various zones (processing parameter: 1400 rpm, 20 mm/min), (a) Overall cross-section of the specimen, (b) HAZ of Cu side: region A, (c) TMAZ of Cu side: region B, (d) SZ: region C, (e) HAZ of Al6063 side: region D, (f) TMAZ of Al6063 side: region E, and (g) SZ: region F.



Point	Al	Cu	Composition
1	0.8	98.8	Cu
2	48.7	51.0	AlCu
3	36.0	63.7	Al_4Cu_9
4	98.5	0.7	Al

Figure 6 SEM micrograph and Energy dispersive X-ray result in atomic% of the dissimilar FSW Al6063-Cu joint fabricated under 1400 rpm and 20 mm/min.

The HAZ of Cu and Al6063 was experienced only by heat generated during FSW process. No plastic deformation occurred in the HAZ of Cu and Al6063, so only grain growth was take place. However, it should be noted that the HAZ of Al6063 was larger than that of Cu. Fig. 5c and 5f show the microstructures at the TMAZ of Cu and Al6063 respectively. The TMAZ was experienced by the FSW tool rotation reading to plastically deformed, and the heat from the FSW process was also exerted some influence on the metal. Therefore, the TMAZ of Cu and Al6063 was possible to obtain significant plastic strain with recrystallization. Fig. 5d and 5g show the SZ of the dissimilar FSW Al6063-Cu joint. As seen from the figure, the lamellar-like flow pattern was observed in SZ region. Swirl zone which showed small circular kind of flow with certain Al6063 and Cu metal pieces were also found in the SZ region. It should be mentioned that the lamellar-like flow pattern and the swirl zone were found in all the dissimilar FSW Al6063-Cu joints fabricated in this study. Fig. 6 shows the SEM micrograph of dissimilar FSW Al6063-Cu joint exposed at SZ region. EDX analysis was performed on each point as illustrated in the figure. The chemical compositions of various points were also given in the figure. The EDX result indicated that there were Cu, Al and variation of Al-Cu IMCs in the SZ. However, there was negligible amount of other elements in the SZ. Further, XRD analysis result obtained from the SZ of the dissimilar FSW Al6063- Cu joint as shown in Fig. 7 confirmed that there were Al, Cu, AlCu, Al_2Cu and Al_4Cu_9 in SZ of the dissimilar FSW Al6063-Cu joint.

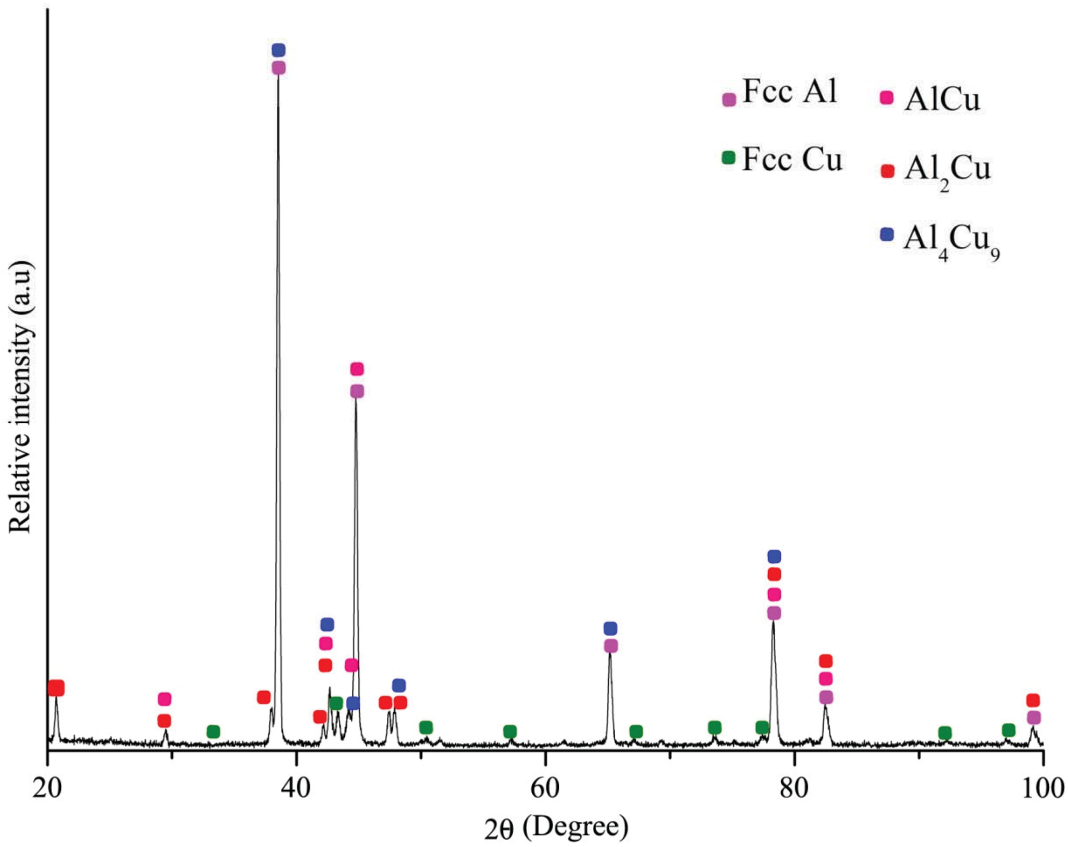


Figure 7 X-ray diffraction pattern at SZ of the dissimilar FSW Al6063-Cu joint fabricated under 1400 rpm and 20 mm/min.

3.4 Mechanical Properties of Dissimilar FSW Joints

Generally, the mechanical properties of the FSW joints mainly depend on the volume of deformed metal created by the stirring action of the tool pin [8]. Strain and stirring in FSW joint strongly affected by welding pitch, which is defined as follows [2, 9]:

$$\lambda = \frac{\upsilon}{\omega} \quad (1)$$

where λ is the welding pitch (mm/revolution), υ is the welding speed and ω is the rotational speed. The welding pitch is also a useful value for estimating the heat input for FSW; a high welding pitch represents a low heat input [10]. Table 2 shows tensile properties of dissimilar FSW Al6063- Cu joints fabricated under various welding conditions. The higher YS of dissimilar FSW Al6063-Cu joints was obtained when using welding conditions as listed follow: 1100 rpm and 20 mm/mm, 1400 rpm and 20 mm/min, and 1800 rpm and 20 mm/min (low welding pitch: 0.011 to 0.018 mm/rev). The lower YS of dissimilar FSW Al6063-Cu joints was obtained when using welding conditions as listed follow: 1100 rpm and 40 mm/mm, 1400 rpm and 40 mm/min, and 1800 rpm and 40 mm/min (high welding pitch: 0.022 to 0.036 mm/rev). Therefore, the superior tensile property of the dissimilar FSW Al6063-Cu joints fabricated at low welding pitch would be attributed to a large area of the SZ affected by using proper welding pitch and/or sufficient heat input. On the other hand, the inferior tensile property of the dissimilar FSW Al6063-Cu joints fabricated at high welding pitch would be attributed to a small area of the SZ affected by using improper welding pitch and/or insufficient heat input. Fig. 8 shows harness profiles of the dissimilar FSW Al6063-Cu joints. It was found that the hardness value was constant initially at the BM of Cu side. However, the hardness value suddenly decreased at HAZ of Cu side. At the SZ, the hardness value suddenly increased and the highest hardness value was achieved. On the other hand at the Al6063 side, the hardness value decreased slowly from the BM of Al6063 side to SZ due to a large area of HAZ in Al6063 side.

4. CONCLUSIONS

The effect of rotational and welding speeds of FSW process on surface morphology, microstructure and mechanical properties of dissimilar FSWAl6063- Cu joints was studied. The main conclusions obtained can be summarized as follows:

(1) Friction stir welding is an appropriate method for butt joining of Al6063 and Cu.

(2) Defect-free dissimilar FSW Al6063-Cu joints were achieved when fabricated under welding conditions as listed follow: 1100 rpm and 20 mm/min, 1400 rpm and 20 mm/ min, and 1800 rpm and 20 mm/ min, (high rotational speed and low welding speed could be applied for fabricated the dissimilar FSW Al6063-Cu joints).

Table 2 Tensile properties of dissimilar FSW Al6063-Cu joints.

FSW conditions			YS (MPa)	UTS (MPa)	Failure strain (%)	Facture location
Rotational speed (rpm)	Welding speed (mm/min)	Welding pitch (mm/rev.)				
1100	20	0.018	106±3	112±5	16±4	SZ
1100	40	0.036	66±2	144±5	22±7	SZ
1400	20	0.014	104±4	128±4	19±3	SZ
1400	40	0.028	34±4	41±3	21±4	SZ
1800	20	0.011	124±3	170±2	22±4	SZ
1800	40	0.022	38±3	41±2	21±5	SZ

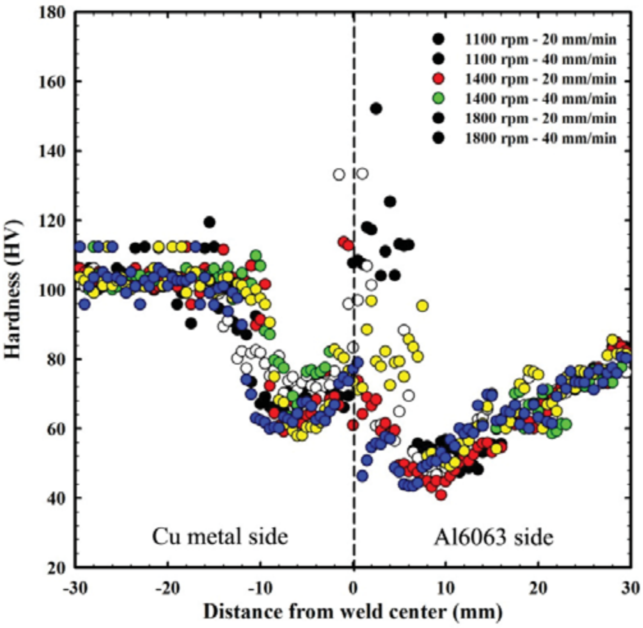


Figure 8 Hardness profiles along middle line of cross-section of the dissimilar FSW Al6063-Cu joints.

(3) The dissimilar FSW Al6063- Cu joints fabricated under welding condition as listed follow: 1100 rpm and 20 mm/min, 1400 rpm and 20 mm/min, and 1800 rpm and 20 mm/min, showed superior tensile property than the others.

(4) There were Cu, Al and variation of Al-Cu IMCs such as AlCu, Al_2Cu and Al_4Cu_9 IMCs in the SZ of the dissimilar FSW Al6063-Cu joint.

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6. BIOGRAPHIES

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