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Effect of friction stir welding parameters on the mechanical properties and microstructure of the dissimilar Al5083–copper butt joint

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Y Fotoohi, S Rasaee, H Bisadi and M Zahedi

Abstract

In this paper, butt joining of Al5083 to commercially pure copper by friction stir welding method has been investigated. The effect of welding parameters, rotational speed of the tool and tool offset on joint strength and microstructure have been studied experimentally. By examining different situations, joint strength was optimized in terms of rotational speed and offset. Results show that tool offset to the copper side reduces defects and increases the joint strength. Welded joint that was conducted at the rotation speed of 800 r/min, tool traverse speed of 40 mm min^{-1} and 1 mm offset to the copper side had the highest tensile strength, about 96% of the weak base metal strength. Microstructure in the stir zone had different morphology from that observed in the base metal. The analyses were performed in intermetallic compounds formed in this area. Al_4Cu_9 and Al_2Cu, were the intermetallic compounds detected in stir zone.

Keywords

Friction stir welding, dissimilar, intermetallic compounds, microstructure, tensile strength

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Introduction

Friction stir welding (FSW) is a thermomechanical solid state welding method. It is a perfect method for welding low fusion weldable materials that are hard to be joined by conventional fusion welding methods or brazing. Although this procedure was used initially to connect high strength aluminium alloys, today it is used to connect many alloys such as magnesium, copper and steel. In recent years, many of the applied research works conducted in the fields of power generation, petrochemical, nuclear, aerospace, transportation and electronics industries have been led to joining dissimilar materials. Due to the different chemical, mechanical and thermal properties of the material, welding of dissimilar materials is very difficult and a high quality welded joint was difficult to obtain by means of conventional welding methods. However, the different properties of materials are the problem for dissimilar welding of material but forming intermetallic compounds that are brittle and low melting is more critical. So solid connection methods such as explosive, friction and FSW methods are useful to join dissimilar materials. Most previous research works focus on welding of dissimilar aluminium alloys in a wide range of thickness. Welding of other dissimilar materials have been less investigated.

Metals such as copper and aluminium are widely used in many industries and by development of industries high quality connection of these materials became an important concern. Based on Jiahu et al.'s investigation, copper and aluminium are incompatible metals due to higher affinity at temperatures higher than 120°C and produce brittle intermetallics on the interfaces.[1] Recently, FSW method is used to connect copper to aluminium due to features of this method. Dissimilar FSW copper–aluminium lap-joint has been studied, but fewer investigations have been done on butt joints. Abdollah-Zadeh et al. experimentally studied lap-joints of

Faculty of mechanical engineering, Iran University of Science and Technology, Iran

Corresponding author:
Sajad Rasaee, Faculty of mechanical engineering, Iran University of Science and Technology, Narmak, Tehran 13114-16846, Iran.
Email: srasaee@iust.ac.ir

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copper–aluminium plates that had been welded by FSW method.[2] The microstructure changes during process, tensile strength of the joint and the hardness profile of the welding section of the joint were discussed by Abdollah-Zadeh et al. Vahid Firouzdor and Sindo modified the copper–aluminium lap-joint by changing the position of the plates and improved the tensile strength of it.[3] They studied microstructure and mechanical properties of modified joint and compared to the traditional joints. Bisadi et al. studied lap-joints of pure copper to 5083 aluminium alloy.[4] They experimentally investigated the effects of FSW parameters, rotation speed and welding speed, on the microstructure and mechanical properties of the joint. Jiahu et al. investigated the changes in microstructure during butt FSW of copper–Al6061.[1] They also measured the temperature distribution in the plate and studied the microstructure of joint by optical microscope (OM) and X-ray diffraction (XRD) to identify the intermetallic compounds that formed during the process. Peng et al. studied the mechanical properties and microstructure of the copper–aluminium welded joints by using tensile test, XRD and OM.[5] In their study, the effect of process parameters on the microstructure was not examined and only the mechanical properties were optimized in terms of rotational and welding speed. Mechanical properties and microstructure of copper–Al1060 joint welded by FSW were studied by Xue et al.[6] They focused on the microstructure and defects forming on the weld nugget zone. In another study, Xue et al. studied the interface of the Al1060–copper joint welded by FSW and determined the formation of intermetallic compounds in interface.[7] Galvão et al. studied the effect of the shoulder geometry on forming and distribution of intermetallic compounds in FSW of copper–aluminium butt joint by using two different tools.[8]

Previous research works have shown that many parameters such as tool rotation speed, welding speed and offset of the tool affect the quality of the dissimilar FSW joints. Until now, few studies have been done on dissimilar FSW copper–aluminium butt joint and many aspects of the process are still unknown and further investigations are needed. Thus, studying the effect of FSW parameters on the microstructure and the mechanical properties of dissimilar copper–aluminium joint seems to be worthwhile. In this paper, dissimilar FSW Al5083–copper butt joints has been studied and effects of tool rotation speed and tool pin offset on the quality of the welded joint have been considered. The aim of this study was to clarify the effect of these parameters on the mechanical properties and the microstructure in butt dissimilar Al5083–copper FSW joints.

Experimental procedures

In this study, 5-mm thick, 200 mm in length and 100 mm in width plates of Al5083 and commercially pure copper were butt-welded. The chemical composition and mechanical properties of the used materials are given in Table 1. The edges and surfaces of the plates were cleaned to remove the oxides and pollutions. A vertical mill which had automatic vertical and horizontal movement was used in the process. In the conventional friction stir butt-welding, tool pin moves on weld line equally on both plates. The tool offset, moving of the tool into one side, can be effective in the quality of the joint for dissimilar welding. In dissimilar welding, tool offset into the softer material has good effect on the quality of the joint.[6] Thus, only the effect of the tool offset into copper was investigated and the pin stirred mainly in the copper during the FSW process with offset. Also the location of the aluminium and the copper on advancing or retreating side affect the quality of the joint. In this study, aluminium plate was located on advancing side. The tool moves at a constant speed (40 mm min^{-1}) during the process. Due to lack of required equipments force control during welding was not possible and the tool movement was controlled. Welding process was conducted at the tool traverse speed of 40 mm min^{-1} and rotation rate of 600 and 800 r/min.

Influence of offset on the properties of the joints was not considered in all the previous investigations. In few performed investigations, the change was mainly about a millimetre. The properties of the welded joints changing by offset depend on the thickness of the parts. For thick plates, significant changes are seen in large offsets and vice versa, offsets in the range of tenths of millimetres for welding sheets with a thickness of less than 1 mm are necessary. Both 1 mm offset into copper side and welding without any offset condition were performed. All the FSW conditions of the specimens are shown in Table 2. Each experiment was repeated three times and the results are compared with each other.

The tool was cylindrical, made of tool steel H13 and heat treated to increase strength and hardness. The tool shoulder was concave with 6° concavity and 20 mm in diameter. The pin was simple cylindrical and non-threaded, 5 mm in diameter and the 4.7 mm in length. The tool had 3° tilt angle for the better

Table 1. Chemical and mechanical properties of workpieces.

	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al	Hardness	Tensile strength (MPa)
Al5083	0.4	0.4	0.1	0.5	4.5	0.2	0.2	0.1	Balance	85 (Brinell)	317
Cu	-	-	>99.5	-	-	-	-	-	-	49 (Vickers)	224

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performing the process. To prevent lateral movement and bending of the plates during welding a fixture was designed and built. The fixture and tool geometries are shown in Figure 1(a) and (b).

Table 2. Parameters of performing experiments.

Test number	Rotational speed (r/min)	Welding speed (mm min^{-1})	Offset of the tool pin into copper side
1	600	40	Without offset
2	800	40	Without offset
3	600	40	1 mm
4	800	40	1 mm

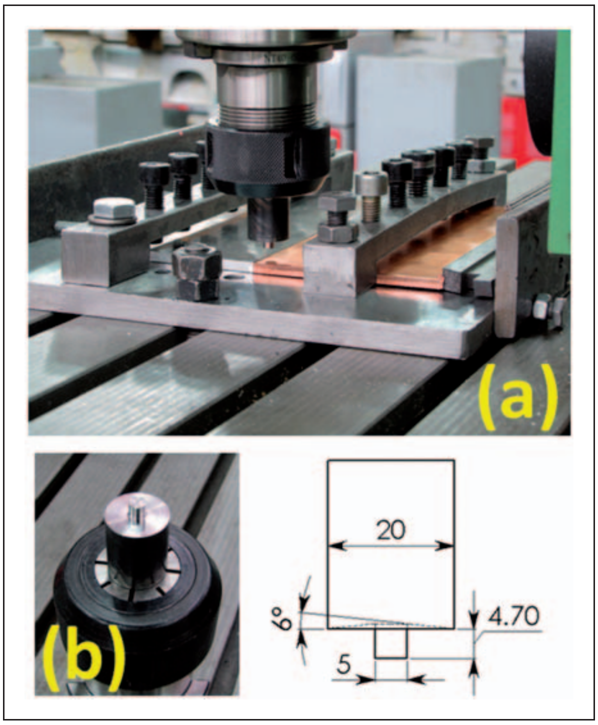

Figure 1. (a) The used fixture; (b) tool and schematic geometry of the tool.

After welding, a cross-section of the weld was prepared using usual preparing microstructural methods include cutting, grinding and polishing for metallographical analysis. The Poulton's reagent solution was used for etching aluminium and another solution (60% H_2O and 40% HNO_3) used for copper. After etching, OM was used to observe the microstructure of the welded joints. Microstructure characterization and analyses were performed by scanning electron microscopy (SEM), complemented by element distribution analysis maps and XRD.

To evaluate the strength of the joint, tensile test was done. Tensile specimens according to ASTM-E8M and by using water jet were cut from welded plate perpendicular to the weld line that the joint was in the middle of the specimens. All tensile tests were performed using a constant pulling speed 2 mm min^{-1} and with SANTAM STM250 machine. For each sample, the maximum tensile load and position of failure were recorded.

Results and discussion

The surfaces of the welded joints are shown in Figure 2. All surfaces of samples somewhat had the acceptable quality, especially joint welded at 800 r/min had a smoother surface with less flash. By increasing the tool's rotation speed, more and homogeneous mixing of copper and aluminium was observed at the surface of the weld. Clearly, the surface of the weld joint showed that offset causes more mixing material and increases the flow of copper into the aluminium side. The offset also reduced the flash created at aluminium side while increased it at copper side.

The cross-sections of the specimens are shown in Figure 3. By offsetting the tool to copper side, flow of copper into the aluminium side is increased especially at the upper section of the joint. At rotation speed of 600 r/min mixing of material in the walled section was almost uniform along the interface, but at 800 r/min mixing at upper side was significant and decreased at the lower section of the joint. It seems that softening of the material at higher temperatures and changing

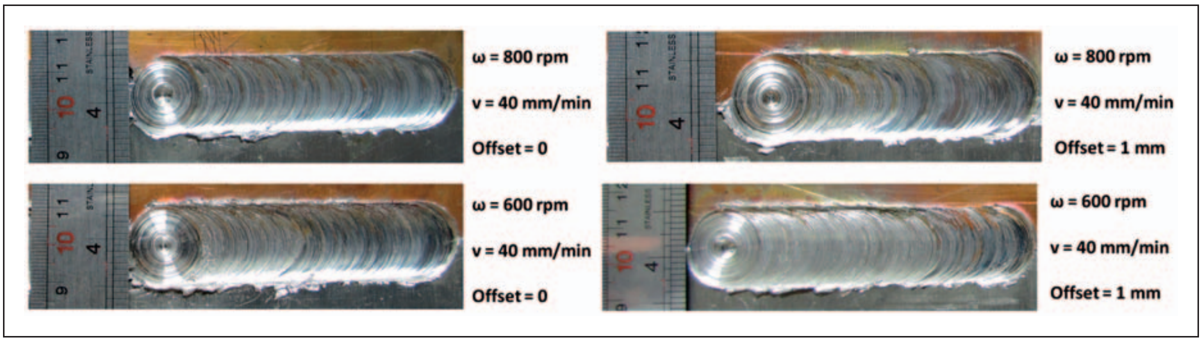

Figure 2. The surface of welded specimens.

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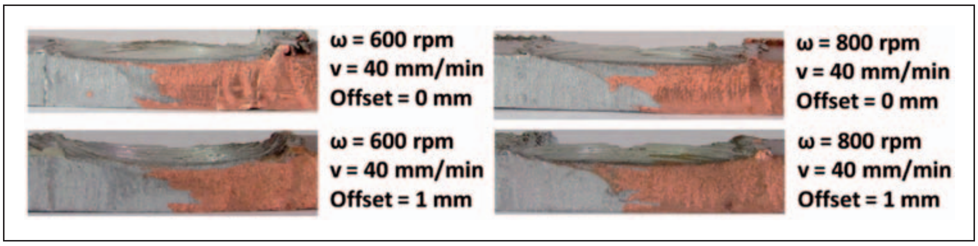

Figure 3. The cross-sections of welded specimens.

the boundary condition from slide to stick were the reasons of more mixing of materials at the upper side. At the beginning of the process, there is a slip at the tool–workpiece interface and heat is produced because of friction. By increasing temperature, the material ductility increases and behaves as a fluid with high viscosity. Thus in this situation, material stick to the surface of the shoulder (as in viscous fluid flow occurs) and slip conditions between tool and workpiece is changed to a stick. At the upper side, transportation of copper to aluminium and proof of the sticking materials to shoulder surface are obvious. The situations also exist at the tool–workpiece contact surfaces. More transportation of materials indicates more mixing of materials during the process. As a result of rising temperature and changing conditions on contact surfaces of the tool–workpiece, more mixing is performed. In the upper and lower section of the joint (which were, respectively, below the shoulder and the pin tool), the flow of copper into the aluminium matrix was similar with smaller scale.

Figure 4 shows the macroscopic appearance of an Al–Cu joint (Figure 4(a) shows OM and Figure 4(b) shows SEM). The dark area can be seen in the middle section of the joint in the stir zone. This area has obvious contrast and different structure and composition from base materials and full of particles that has been formed in the stir zone. Based on the Al–Cu phase diagram, aluminium and copper are incompatible and produce intermetallic components at temperatures higher than 120°C.[1] Thus, due to rising temperature during the process, intermetallic compounds are formed in the stir zone as well as the interface. Thus the dark area and particles inside in the stir zone can be mainly intermetallic compounds that formed during the process.

Figure 5(a) shows an area in the stir zone with some particles that are observed as large bright particles in the dark matrix. Element distribution analysis maps were done for this area and results are shown in Figure 5(b) and (c). Based on map analysis results, large bright particles in the region were mainly composed of Cu and surrounded by a matrix that mainly was Al. Actually, by rotating and moving the tool's pin some piece of Cu is cut off from copper plate and spread in aluminium matrix and formed an area full of particles in the stir zone. Particles are spread

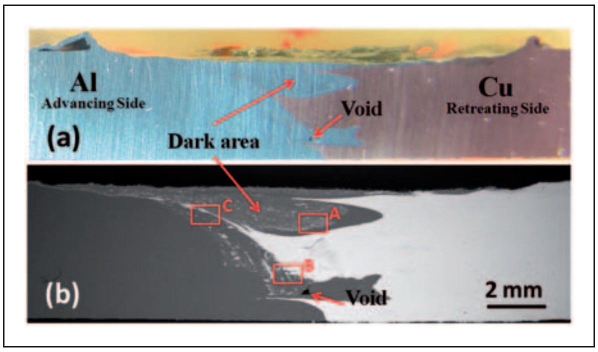

Figure 4. The macrostructure of cross-section of the welded joint by (a) OM (b) SEM, which was conducted at the tool traverse speed of 40 mm min^{-1} and rotation rate of 800 r/min and without offset.

irregular and randomly in aluminium matrix with different sizes and shapes. It can be seen that small particles are on the upside of the joint and particle sizes are increased by moving to the bottom of the joint. Particles are spread over a wide region at the top of the joint, but in the bottom particle distribution is limited in a narrow area. There were copper particles in aluminium matrix, while aluminium particles were not seen in the copper matrix.

Magnified view of an area in stir zone and near the interface is shown in Figure 6(a). In this area, three regions can be distinguished: the bright area that is copper, light grey area that mainly consists of aluminium and copper particles are distributed in it and the dark grey area that is smaller particles, in comparison to copper particles, is seen in it are intermetallics (Figure 6(b)). Figure 6(b) shows a magnified view of the interface. The intermetallic compound layer covered the interface of the aluminium–copper. In the interface layer, there were scattered particles that had different combinations of base metals and were intermetallics. Dispersed copper particles in the structure were covered with a layer of intermetallic compounds as well. Figure 7 shows a magnified view of a particle in stir zone. An area with similar morphology and structure to what was seen in the stir zone surrounded this particle. The intermetallic compound layers could be observed around large particles. Like what was concluded by Peng et al.,[5] smaller particles were transformed into the Al–Cu intermetallic compounds and most of the copper was transformed into intermetallic compounds.

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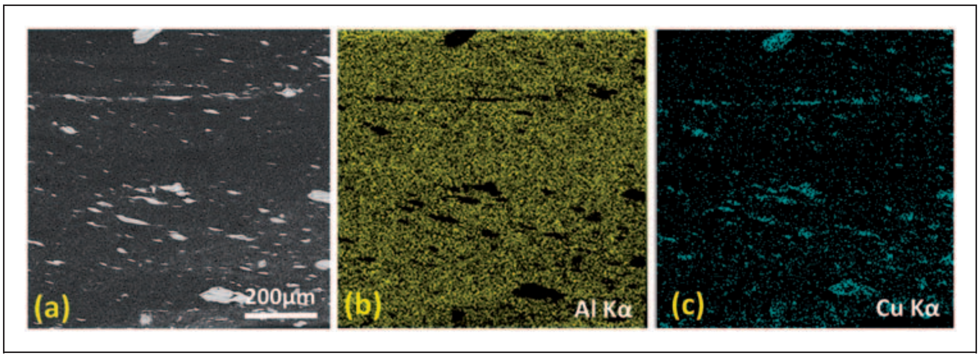

Figure 5. Element distribution maps of the region in stir zone (the place is located in a box A in Figure 4): (a) magnified view of a region in stir zone, (b) Al element and (c) Cu element, conducted at the tool traverse speed of 40 mm min^{-1} and rotation rate of 800 r/min and without offsets.

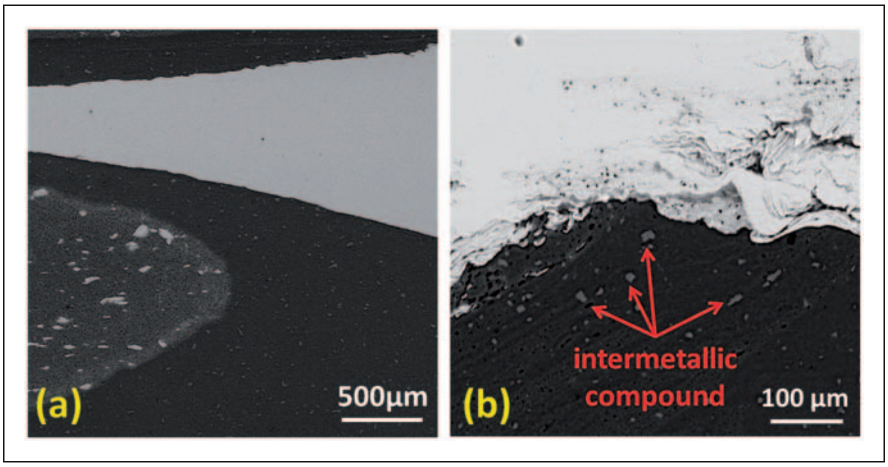

Figure 6. The interface of the joint: (a) different layers of the interface (the place is located in a box A in Figure 4) and (b) intermetallic particles in the interface layer (the place is located in a box B in Figure 4).

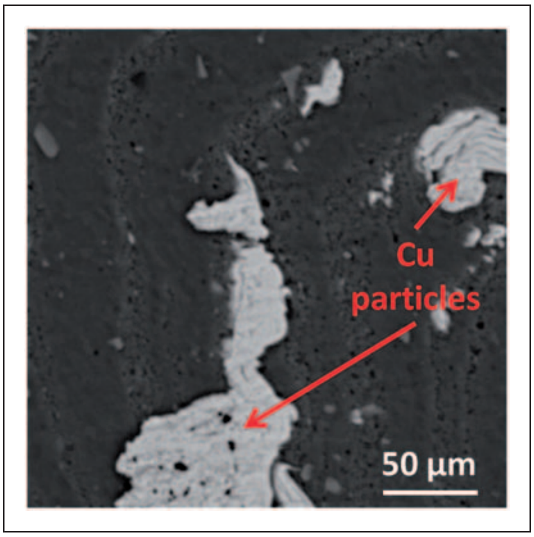

Figure 7. A copper particle in stir zone (located in a box C in Figure 4) covered by intemetallic layer.

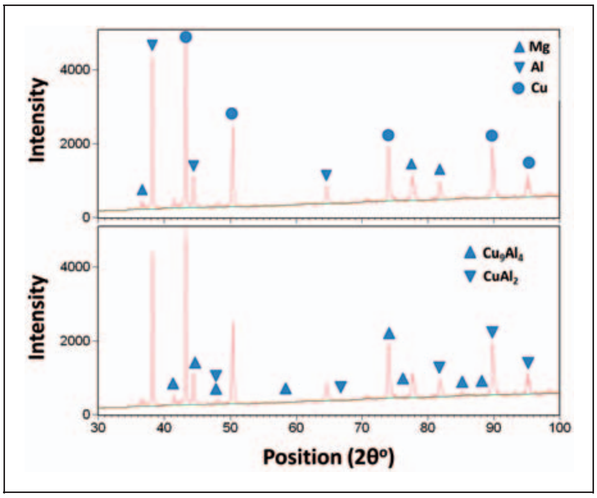

Figure 8. X-ray diffraction patterns of cross-section of Al-Cu joint that was conducted at the tool traverse speed of 40 mm min^{-1}, rotation rate of 800 r/min and without offsets.

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Table 3. Mechanical properties and fracture locations of welded joints.

Rotation speed (r/min)	Welding speed (mm min^{-1})	Tool pin offset to copper side	Tensile strength (MPa)	Maximum deformation (μm)	Fracture location
Al5083 base material	-	-	317	-	-
Copper base material	-	-	224	-	-
600	40	Without offset	182.5	3750	Interface (stir zone)
800	40	Without offset	203.5	2150	Interface (stir zone)
600	40	1 mm	215.6	7350	Interface (stir zone)
800	40	1 mm	164	2450	Interface (stir zone)

XRD results from a cross-section of a joint are shown in Figure 8. Results indicated that in addition to Al, Cu and Mg that obviously have visible peak, intermetallic components Al_4Cu_9 and Al_2Cu were clearly identified. Comparison what was observed in the SEM images with the morphology of Al_4Cu_9 and Al_2Cu confirm the XRD results. So, stir zone and inside particles as interfaces were consisted of Al_4Cu_9 and Al_2Cu that were intermetallic compounds of Al–Cu.

Some defects were seen at the bottom of the joints of specimen number 1 and 2. Defects were formed on the surface of the particles dispersed in the matrix or in the boundary between the area of the intermetallic compounds and matrix. Offsetting the tool's pin to the copper side reduced the formation of the defects by limiting the amount of the intermetallics.

Table 3 shows the tensile properties of base metals and Al–Cu joints welded by FSW. The weld joint conducted at the tool traverse speed of 40 mm min^{-1}, rotation speed of 600 r/min and with 1 mm offset into the copper side had the greatest strength, about 96% of the weaker material. In low rotation speeds, the tool offset has a good consequence on joint strength while has a bad result at high rotation speeds. At high rotation speed, tool offset causes separation of more and especially larger particles, conversely at low rotation speed separation of copper particles is decreased by offsetting. Therefore at high rotational speed, offset decreases the strength and vice versa, offset in low speed increases the strength. At low speed mechanical mixing of material was noticeable and offsetting increased it. The formation of intermetallic compounds was more significant at high rotation speeds and by increasing tool offset it has been increased too. The maximum deformation of specimens is shown in Table 3. Deformation before the fracture is reduced by the increasing the rotation speed of the tool and it is more significant in specimens with offset.

Conclusions

In this study, dissimilar plates of copper and Al5083 in butt condition were connected by using FSW. Effects of the pin position motion in the workpiece (offset of the pin) and the rotational speed of the tool on the process and the quality of the joint were studied and by changing and control of the welding parameters sound joint were achieved. Joint that was conducted at the tool traverse speed of 40 mm min^{-1}, rotation speed of 600 r/min and 1 mm offset was sound defect-free joint, and the tensile test results showed that the maximum value of tensile strength was about 215 MPa, about 96% of copper and all the specimens failed in stir zone.

There were some defects in without offset samples at the lower part of the joint and down part of the pin and it was observed that the tool offset reduced the voids. The microstructure analysis showed a structure which consists of the intermetallic compound that is formed in the stir zone. The extent of this region and distribution of intermetallic particles in aluminium matrix increase by increasing tool rotational speed and the tool offset increases the intermetallic compound formation and the size of the particles that separate from copper plate and distributed in the structure. The XRD analysis indicated that intermetallic compounds mainly formed in the stir zone were Al_4Cu_9 and Al_2Cu.

By reducing the tool rotational speed the area of the intermetallic compounds is reduced. Although the moving of the tool pins to the copper side increases the amount and size of copper particles dispersed in the structure, amount of intermetallic compounds is reduced.

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