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Study On The Effect Of FSW Process Parameters On Joint Quality Of Dissimilar Materials

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Abstract

Friction stir welding (FSW), a solid state joining technique is widely used for joining Aluminum alloys in marine, aerospace, automotive and many other applications of commercial importance. In the present study, dissimilar materials (AA 8011-H18 and 99.65% pure copper) plates were FS welded by varying only tool pin offset and other parameters such as Tool rotational speed, weld speed and tool tilt angle and plunge depth are made to be constant. The mechanical properties (Hardness and Tensile strength) of the Dissimilar Friction Stir welded (DFSW) specimens were tested and compared with the base materials. The observations have been elaborated in detail and it is observed that the weld parameters have a significant effect on mechanical and microstructural properties of the welds. A cylindrical pin profile is adopted as its geometry had been proven to yield better weld strengths.

Keywords: AA 8011 and 99.65% Cu, Friction stir welding (FSW)

1. Introduction

Dissimilar materials joints are widely used in power generation, chemical, petrochemical, nuclear, aerospace, transportation, and electronics industries due to their technical and beneficial advantages [1]. Basically Aluminium (Al) and copper (Cu) are the two common metals in the electrical power industry. Al–Cu transition pieces are widely used to transmit the electricity. Due to different chemical, mechanical and thermal properties of materials, dissimilar materials joining present more challenging problems than similar materials joining by friction stir welding (FSW). However, the dissimilar combination of Al and Cu is generally difficult for fusion welding. Therefore, the solid-state joining methods, such as friction stir welding, roll welding, and explosive welding have received much attention. The relative motion between the tool and the substrate generates frictional heat that creates a plasticized region around the immersed portion of the tool. The tool shoulder prevents the plasticized material from being expelled from the weld. The tool is traversed along the joint line, forcing the plasticized material to coalesce behind the tool to form a solid-phase joint. The micro structural evolutions after the FSW process are characterized by three zones: the Stir Zone (SZ), the Thermo-Mechanically Affected Zone (TMAZ), and the Heat-Affected Zone (HAZ).

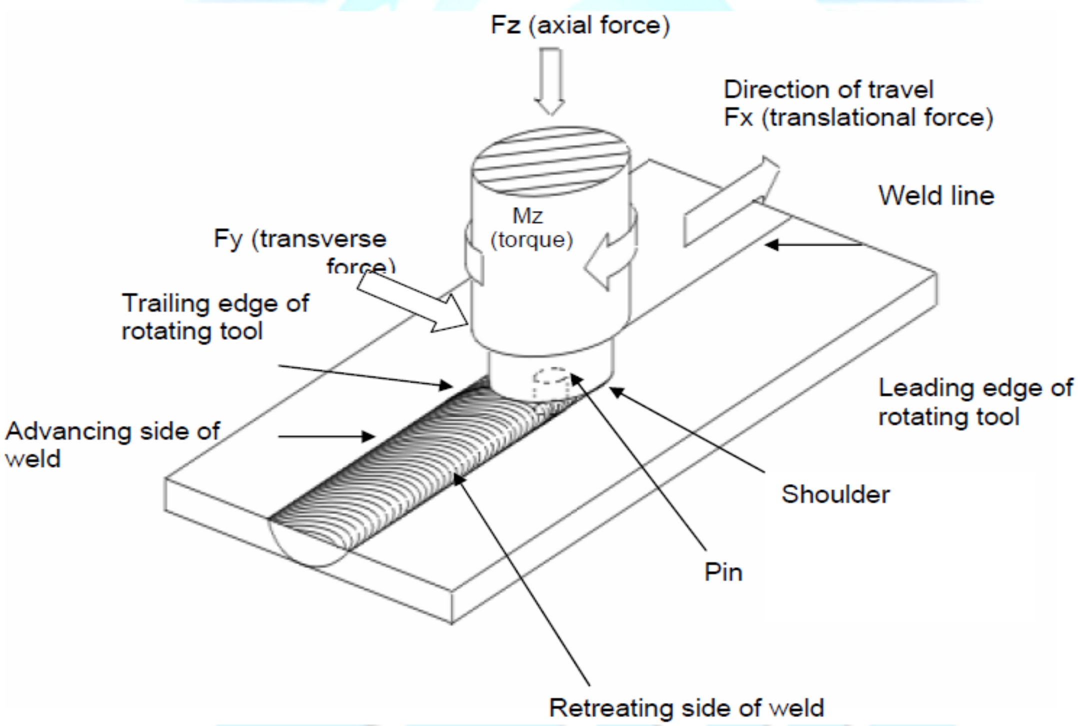


Fig.1. Schematic of Friction Stir Welding

It was reported that sound dissimilar FSW Al–Cu joints were difficult to achieve, and the joints usually failed at the nugget zone or along the interface between the two materials during the mechanical tests. The poor weld formed is due to the ability of the various brittle IMCs formed in the nugget zone [2-4]. The formation of Al_4Cu_9 and Al_2Cu could be formed at the joint interface [5]. A sound FSW Al–Cu joint could be obtained by offsetting the tool to the Al side under a lower heat input condition [6]. It is well documented that many parameters, such as tool offsetting, rotation rate and traverse speed, influenced the weld properties of the dissimilar FSW joints [7-8]. Limited studies have been performed on the FSW dissimilar Al–Cu joints till now, and systematic research on the FSW parameters is still lacking. Therefore, it is worthwhile to study the effect of FSW process parameters on the microstructure and mechanical properties of the dissimilar FSW Al–Cu joints. In this paper, various FSW butt Al–Cu joints were produced under different pin offsets and the microstructure and mechanical properties were studied in detail. The purpose of this study is to find out the feasible combination of FSW process parameters to perform defect free welding of dissimilar materials and to investigate the effect of the tool offset as a strategy to weld dissimilar materials.

2. Experimental procedures

8011Aluminum and commercially pure copper (99.65% purity) plates 3mm in thickness, 180mm in length, and 45mm in width were butt-welded using a heavy-duty vertical milling machine adapted for FSW: Bharat Fritz Werner (BFW) with spindle motor capacity 11KW as shown in the fig. 2. The welding tool used in this study was made of tungsten carbide and had a shoulder 20mm in diameter and a pin 6mm in diameter and 2.65mm in length as shown in the fig. 3. And the chemical composition is given in Table 1.Welds were made with a clock-wisely rotating pin at a rotation rate of 750 rpm and a constant traverse speed of 100 mm/min. Tool tilt angle of 2 degrees was used in the present study. The process parameters of the FSW taken up for the experiment and their levels are given in the (Table 2).

Table 1

Shows the Chemical Composition of the metals

Material	Al	Cu	Mg	Si	Fe	Ni	Mn	Zn	Sn	Pb	Ti	Cr	V
Al 8011	98.50	0.103	0.086	0.231	0.710	0.0120	0.132	0.160	0.004	0.019	0.012	0.021	<0.01
Copper	----	99.65	- - -	- - -	0.001	0.235	----	0.012	0.037	---	----	----	----

Table - 2

Factors and their Levels

Parameters	Levels			units
	Level 1	Level 2	Level 3	
Tool Pin offset	0.5	1.0	1.5	mm
Rotational speed	550	750	950	rpm

During the welding processes, several pin offsets from 0mm to 5mm were used. For convenience, in this study, an offset of 0mm denotes the position where the pin just located at the butt line. Micro structural characterization and analysis were carried out using Optical microscope: *Mitutoyo, Japan*. Tensile tests of 3mm thick specimens having 12mm gauge length were performed according to ASTM E8M standard at room temperature at a crosshead speed of 3mm/min. The tensile test specimens were prepared by Wire EDM and tested on the Tensometer.

Fig. 2. Experimental setup of FSW

Fig. 3. Tool used in present study

To perform Friction stir welding and testing of dissimilar material welded samples, following machines/equipments were required; Shaper machine for dimensioning the work piece, A heavy-duty vertical milling machine adapted for FSW: *Bharat Fritz Werner (BFW),*FSW fixture, Wire EDM for making sample for testing : *Steer Corporation, China,* Tensometer for Tensile testing: *Kudale Instruments Pvt. Ltd., Pune,* Micro-hardness testing machines: *Mitutoyo, Japan,* Metallurgical polishing machine for grinding and polishing, Optical microscopes for microstructure: *Mitutoyo, Japan,* Steriozoom microscope for macrograph: *Mitutoyo, Japan.*

3. Results and discussion

3.1. The effect of fixed location on the weldability of the joints

Whenever the stronger material and the soft material were friction stir welded together, previous studies indicate that the weld quality was clearly influenced by the fixed location [9].For a sound weld to occur the stronger material should be fixed at the advancing side and the softer material should be placed at the retreating side. In this case the Cu plate is the stronger material and so it was placed on the advancing side.

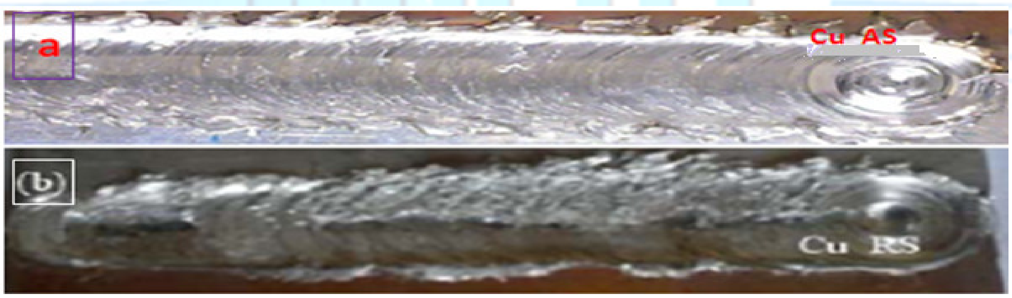


Fig.4. Surface Morphologies of FSW weld joints showing:
(a)Cu at the advancing side ,(b) Cu at the retreating side.

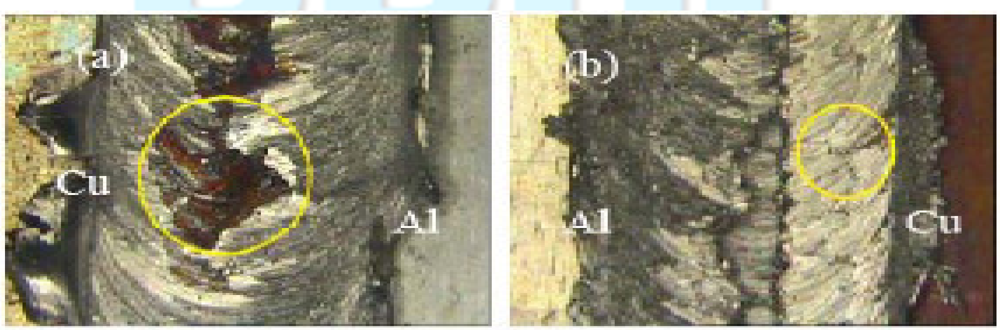


Fig.5. Surface morphologies of FSW weld joints showing (a) Macro Cracks
(b) Micro Cracks [15]

This study shows that even though cracks were observed in both the positions of the Cu plate, a better mixing of the Al-Cu was found when Cu was kept at the advancing side. When the Cu plate was fixed at the retreating side, the hard material not seems to have reacted in the welding process. When the Cu plate was fixed on the retreating side certain macro cracks were observed but when the Cu plate was fixed on the advancing side certain micro cracks have been observed as shown in the fig.5. Surface morphology of the FSW Al–Cu joints for the different fixed locations at a welding parameter of 750 rpm – 100mm/sec is shown in the fig.4. It is clear that when the Cu plate was fixed at the advancing side, sound weld surface was achieved, as shown in Fig.4 (a). However, when the Cu plate was fixed at the retreating side, the weld surface was very poor and certain macro cracks were observed. In a study of FSW Al–Fe joints, Watanabe et al. [9] reported that a long crack line was observed on the weld surface when the pin rotation direction was counter clock-wise, and sound weld surface could be obtained in a reversed rotating direction.

3.2 The effect of pin offset on the weldability of the joints

In FSW of dissimilar materials, the pin offset is an important parameter influencing the weld quality [10, 11, 12, and 13]. The results in this study and most previous studies [10, 14] proved that sound dissimilar welds would be produced under a larger pin offset to the softer material. This should be related to the huge differences in physical, chemical and mechanical properties between the dissimilar materials. When the pin offset was larger towards the softer material, only a few Cu pieces with relatively small size were moved from the Cu bulk. It was easy for the small Cu piece to mix into the Al base and react with the Al base in the nugget zone, and therefore sound metallurgical bonding would be obtained at the Al–Cu interface. On the other hand, many large Cu pieces were stirred into the nugget zone at a smaller pin offset. The Cu pieces were harder than the Al matrix, therefore, the large Cu pieces were hard to deform and flow in the Al matrix, and the mixing between the large Cu pieces and the Al matrix would be very difficult. This led to the poor surface bonding and the formation of many voids has been shown in Fig.6. Moreover, when the pin offset was smaller, more Al–Cu IMCs have been formed because the more Cu pieces were stirred into the nugget zone. Thus, the joining between the Al and Cu became poor due to the brittle nature of the IMCs.

Fig.6. Cross-sectional macrostructure of the joints at rotation rates of (a) 400 rpm. [15]

During the FSW process, the materials were transported from the retreating side to the advancing side behind the pin where the weld was formed [16]. The hardness of the Cu is larger than that of the Al, and the pin stirred mainly in the Al base metal during FSW, so the material flow occurred mainly in the soft Al base metal. If the stronger material was fixed at the retreating side, the hard material was difficult to transfer to the advancing side because the hard material hardly flew. In this case, a large volume defect would form and the excessive soft material would be extruded out from the nugget zone. However, when the softer material was fixed at the retreating side, the soft material was transported to the advancing side easily, and the material flow cycle in the nugget zone was performed normally.

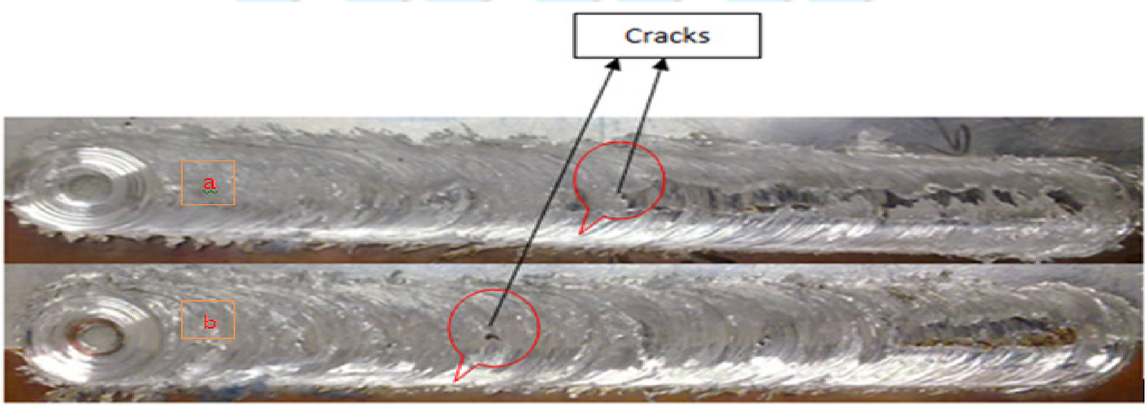


Fig.7. Surface morphologies of the FSW Al–Cu joints under a welding parameter of

750 rpm-100mm/min for pin offsets of (a) 0mm, (b) 0.5mm

In the present research the surface quality became poorer under the smaller pin offsets. Many cracks were observed obviously on the weld surface for a pin offset of 0mm and 0.5mm as shown in Fig. 7. Sound defect-free joints could be obtained at a larger pin offset of 1.0 mm when pin is offsetting towards Al side and the nugget zone consisted of a mixture of the Al matrix and Cu pieces. Therefore, sound defect-free welds could be achieved only at larger offsets, no less than 1mm in this study.

3.3 The effect of rotational speed on the weldability of the joints

Fig.8. shows the surface morphologies of FSW Al-Cu joints under different rotation rates. As shown fewer cracks were seen under a lower rotation rate of 600 rpm but at 950 rpm and 1200 rpm sound weld was not achieved. This might be due to the formation of inter-metallic compounds under the enhanced reaction between Al and Cu. Under the rotation speed of 1200 rpm many macro cracks were observed. When the rotation of the tool pin was high, large pieces of Cu would be detached from the bulk and get distributed in the bottom and the retreating side of the nugget zone. When the rotation speed was fixed to 750 rpm small pieces of Cu would be scratched off from the bulk and thus at a certain portion of the weld zone seem to have mixed properly. The increase in rotational speed from 750 to 1200 rpm resulted in a harsher material flow. In Fig.8 (d) the distribution of particles along the onion rings in composite structure does not exist anymore. Also the majority of particles will increase than that seen at 750 rpm.

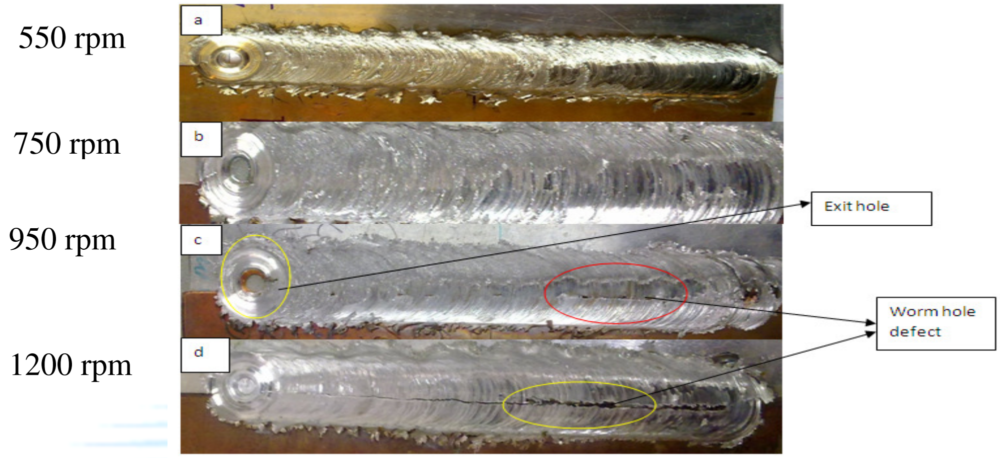


Fig.8. Surface morphologies of the FSW Al–Cu joints under a welding parameter of 100 mm/min and rotational speed of (a) 550 rpm (b) 750 rpm (c) 950 rpm (d) 1200 rpm

3.4 Tensile testing observation

Tensile tests of 3mm thick specimens having 12mm gauge length were performed according to ASTM E8M standard at room temperature at a crosshead speed of 3mm/min in order to determine the mechanical properties (ultimate tensile strength and Elongation) of the welded and base materials. The reduced section length is 66 mm and its width is 10mm. The tensile test specimens were prepared by Wire Electro Discharge Machining and tested on the Tensometer. Properties that are directly measured via tensile test are ultimate tensile strength, maximum elongation and reduction in area. Fig. 9 shows tensile testing specimen. Mechanical properties of the base metal were shown in table 3.

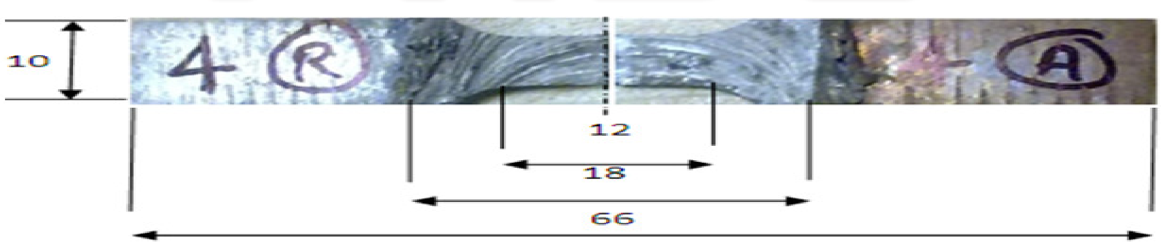


Fig. 9. TensileTesting specimen

Table 3

Mechanical properties of the base metal

Base metal	Tensile strength (MPa)	Elongation (%)
Al 8011	127.3	8.56
Cu pure	350.4	5.67

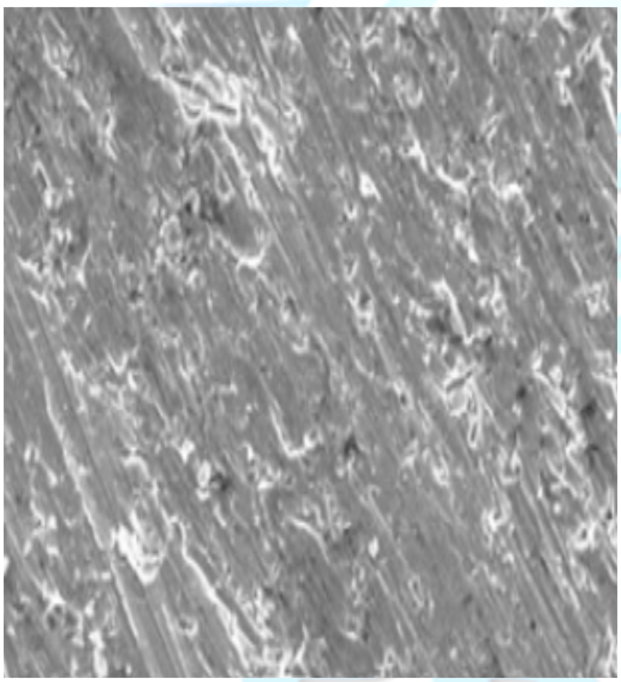


Fig.10. Microstructure of AA8011-H18

Fig.11. Microstructure of pure copper

Microstructure of Al 8011 and copper is shown in the fig.10 & fig.11 respectively.

Table 4

Mechanical properties and fracture locations of the welded joints in transverse direction to the weld center line.

Pin offset (mm)	Tensile properties at room temperature		
	Tensile strength (MPa)	Elongation (%)	Fracture location
Cu side			
1.5	43.6	2.75	TMAZ of Cu
1.0	114.6	3.25	TMAZ of Cu
0.5	136.6	2.50	Nugget
0	105.0	4.16	Nugget
0.5	139.0	6.63	TMAZ of Al8011
1.0	145.0	4.00	TMAZ of Al8011
1.5	134.0	1.50	TMAZ of Cu
Al side			

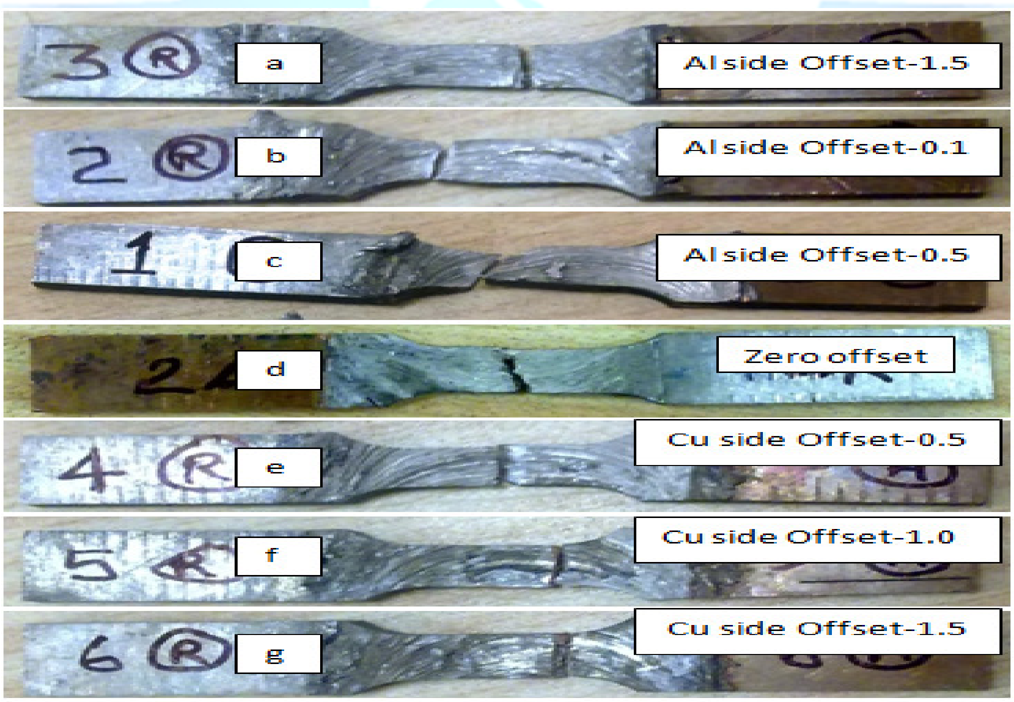


Fig.12. Showing fracture location at various offsets.

Fracture location position in the tensile specimens was shown in the fig. 12.while fig.13 shows the variation of tensile strength with tool pin offset. In the present study, tool pin offset was varied between 0 to1.5 mm. Ultimate tensile was found to be 105MPa at zero offset. Tensile strength of the joint was 139MPa at a pin offset of 0.5mm towards Al side. Maximum strength was obtained at a pin offset of 1mm towards Al side. The strength of the joint was decreased at a pin offset of 1.5mm.when pin is offsetting towards copper side then maximum tensile strength was obtained at a pin offset of 0.5 mm and minimum tensile strength was obtained at a pin offset of 1.5mm.

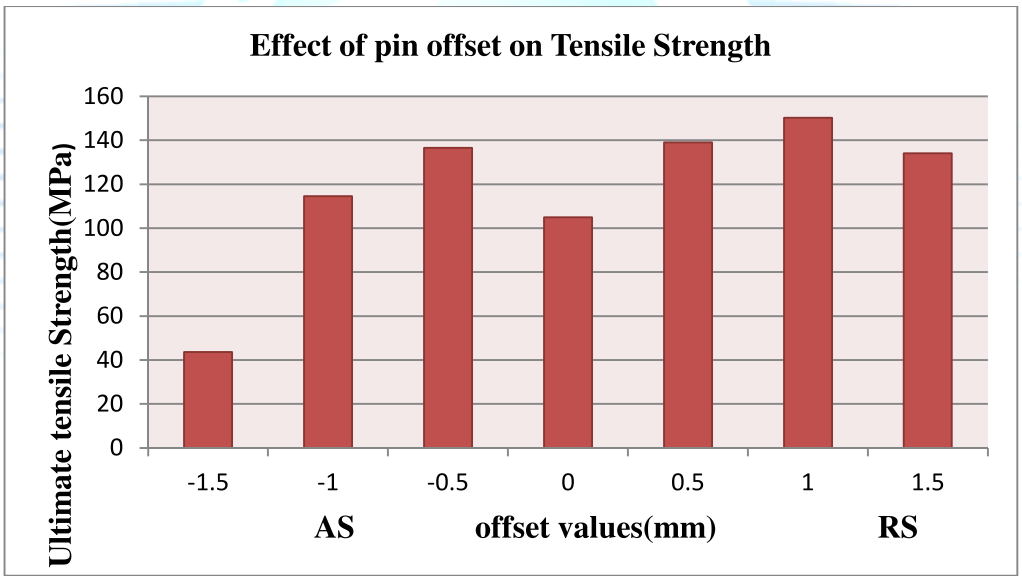
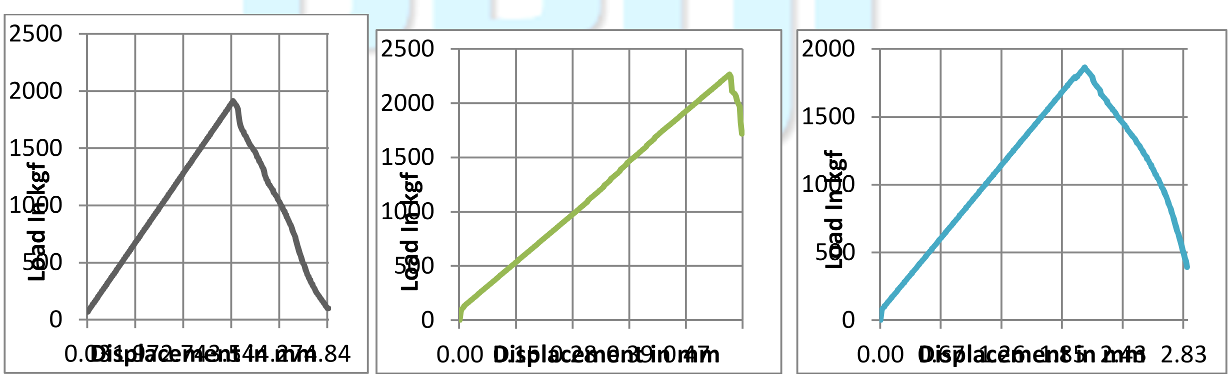


Fig.13. Ultimate tensile strength of welded joint at different offset values**.**



(a) (b) (c)

Fig.14. Stress - strain curves of welded specimens welded with 750rpm and 100 mm/min at (a) 0.5 mm tool pin offset, (b) 1mm tool pin offset (c) 1.5 mm tool offset.

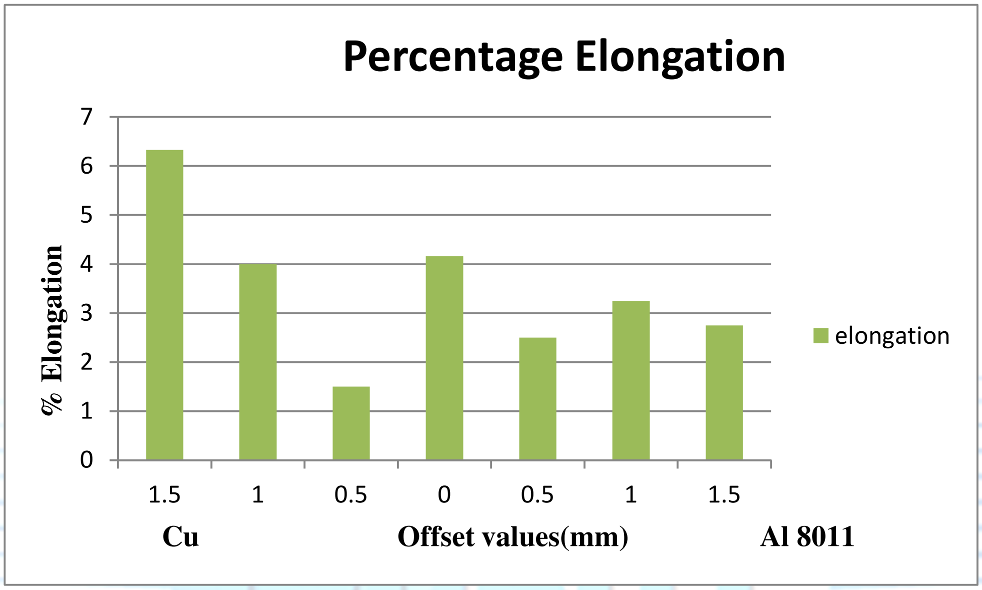


Fig.15. Percentage Elongation of welded joint at different offset values.

3.5 Microstructure analysis

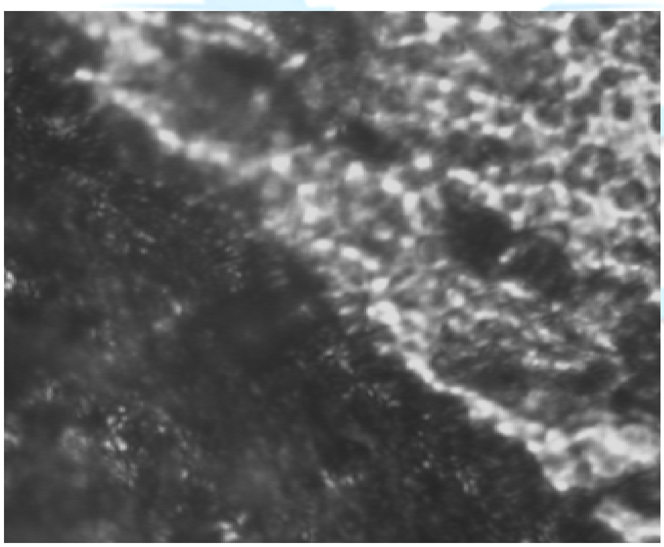


Fig.16. Microstructure of Al-Cu Weld interface at750rpm and 100mm/min at 100x magnification

Fig.16 shows the microstructure of weld joints at 750rpm and 100mm/min at 100x magnification. The sample was polished using emery sheets of different grades and then disc polished using abrasives, suspended in a water solution, on cloth-covered electrically powered wheel distilled water. The etchant for Aluminium 8011 alloy is a modified Keller's reagent made of 95ml distilled water, 1ml Hydrofluoric acid, 1.5 ml HCI, and 2.5 ml Nitric acid. For Copper the etchant composition was made of 90 ml distilled water, 5gm Ferric Chloride, and 10 ml Hydrochloric acid. On observing the weld nugget it was seen that the metal close to copper side in the WNZ showed a lamellar structure. However, in the Al side of WNZ the metal showed a mixed structure characteristic. Friction heat of tool induces the different metal structure on both sides. The metal Al experienced a "continuous" dynamic recrystallization (CDRX) and the grain in this region was refined obviously. The metal Cu in weld nugget zone experienced plastic flow by friction heat, but the Cu would not experience the recrystallization process since the temperature developed during welding was much less than the melting point of Cu. As a result, the weld nugget zone with lamellar alternating and mixed structure was formed by stir action and friction heat of tool. Therefore, the Cu and Al were closely combined in the Al side, and showed a mixed structure. Alternating lamellar structure in weld nugget close to copper side was shown in fig.17.

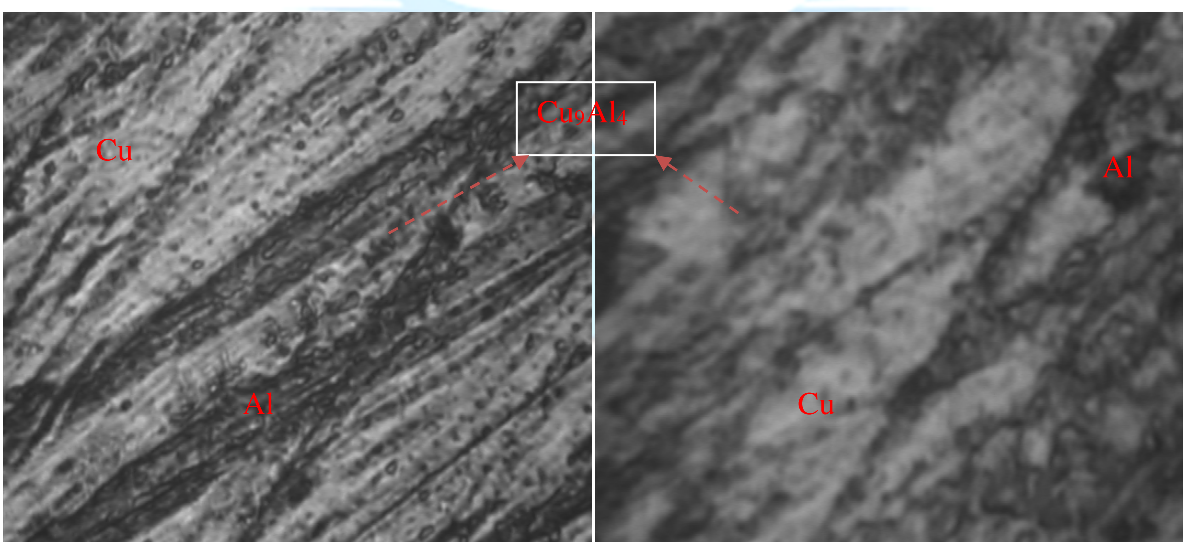


Fig.17. Enlarge view of alternating lamellar structure in weld nugget close to copper side at 100x magnification

Fig. 18 shows the enlarged views of alternative Cu/Cu_9Al_4 lamellae or vortices that appear near the weld nugget. The bright region are unmixed Cu lamellae with a hardness range of 90-195 $HV_{0.2}$,.The lamellar region appear to be saturated solid solution of Al in Cu and Cu_9Al_4.The concentration of copper at the dark Cu- rich regions has a hardness range of 115-180 $HV0_{.2}$ are considered to contain a certain percentage of the **Cu_9Al_4** intermetallic compound. Similar results were also investigated by Ouyang [17] in his study of dissimilar FSW of aluminum to copper. The formation reason for Cu_9Al_4 is generally attributed to mechanical mixing and interaction in the solid state.

4. Conclusions

AA8011H18 and commercially pure copper were friction stir welded at various welding parameters, and the effect of the fixed location, pin offset and rotation rate on the microstructure and mechanical properties was investigated. The following conclusions are reached:

1) Sound defect-free joint could be obtained only when the hard Cu plate was fixed at the advancing side. A large volume defect was observed when the soft Al plate was fixed at the advancing side. This is attributed that the hard Cu bulk material was hard to transport to the advancing side during FSW.

2) Sound defect-free joints were obtained under the pin offsets of 1mm to the Al matrix, and a good metallurgical bonding between the Cu bulk/pieces and Al matrix was achieved. However, defects formed easily at smaller pin offsets due to the hard mixing between the large Cu pieces and Al matrix.

3) The joint surface became poorer as the rotation rate increased. Many defects were formed in the nugget zone at the lower rotation rate of 600 rpm; whereas at higher rotation rates, good metallurgical bonding between the Cu pieces and Al matrix was achieved. However, the thick stacking layered structures developed on the interface at higher rotation rates of 950, 1200 rpm.

4) Poor tensile properties were obtained at the very large pin offsets and/or low rotation rates due to the insufficient reaction between the Cu bulk pieces and Al matrix. Sufficient reaction were

achieved in the FSW Al–Cu joints produced at higher rotation rates and proper pin offset of 1mm towards Al side, resulting in the good tensile properties.

5) The mechanically mixed region in a dissimilar 8011aluminium alloy/copper weld consists mainly of Cu_9Al_4. A mixed layer of Cu_9Al_4 and deformed copper solid solution that showed an intercalated microstruture or vortex flow pattern is formed in copper adjacent to the bottom of the weld by mechanical investigation of Al into copper.

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