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Published in:
Measurement: Journal of the International Measurement Confederation

DOI:
[10.1016/j.measurement.2019.07.019](https://doi.org/10.1016/j.measurement.2019.07.019)

Published: 08/07/2019

Document Version
Peer reviewed version

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Please cite the original version:
Shankar, S., Vilaça, P., Dash, P., Chattopadhyaya, S., & Hloch, S. (2019). Joint strength evaluation of friction stir welded Al-Cu dissimilar alloys. *Measurement: Journal of the International Measurement Confederation*, 146, 892-902. <https://doi.org/10.1016/j.measurement.2019.07.019>

Accepted Manuscript

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PII: S0263-2241(19)30646-3
DOI: <https://doi.org/10.1016/j.measurement.2019.07.019>
Reference: MEASUR 6791

To appear in: *Measurement*

Received Date: 5 May 2019
Revised Date: 28 June 2019
Accepted Date: 5 July 2019

Please cite this article as: S. Shankar, P. Vilaça, P. Dash, S. Chattopadhyaya, S. Hloch, Joint strength evaluation of friction stir welded Al-Cu dissimilar alloys, *Measurement* (2019), doi: <https://doi.org/10.1016/j.measurement.2019.07.019>

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Joint strength evaluation of friction stir welded Al-Cu dissimilar alloys

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Abstract

Friction stir welding has been successfully employed to fabricate dissimilar thickness AA1050 and oxygen free copper (Cu-OF). The highest value of the joint tensile strength obtained was 91% of the AA1050 alloy strength with the tensile fracture path on the aluminum side. At the Al-Cu interfacial microstructure, a layer of Al₄Cu₉ and Al₂Cu intermetallic compounds (IMCs) with thickness of 2.2 μ m to 0.26 μ m was developed at different welding speeds. The voluminous IMCs have an adverse impact on the tensile characteristics of the joint. The IMCs (0.26 μ m - 0.77 μ m) at welding speeds of 160 mm/min and 213 mm/min with 1 mm tool offset, has trivial effect on the tensile property. The mechanical property of the joint was significantly affected by the tool offset and welding speed. Image processing techniques such as Gaussian blur, histogram normalization and binarisation were utilized to understand the distribution of copper in the weld stir zone.

Keyword: Aluminum, Oxygen free copper, intermetallic compounds, weld interfaces, microstructure, mechanical properties

Abbreviations:

Cu-OF - oxygen free copper
IMC - intermetallic compound

1. Introduction

Rising concerns related to weight reduction and cost effectiveness call for the demand of lightweight bus-bars in switchboards. The typical characteristics of aluminum are high ratio of strength stiffness to weight, decent formability, acceptable resistance to corrosion, and recyclable nature. These properties make it the ideal metal to replace heavier materials in any industry. Aluminum has 61% electrical conductivity as compared to oxygen free copper (Cu- OF) but has

only 30% of the weight of Cu-OF copper which makes aluminum a potential material for bus-bars. High thermal expansion of aluminum alloys shows sensitiveness towards the heat affected zones. It would be better to replace aluminum with Cu-OF in the heat affected zones. In spite of complications in getting an electrically durable bolted joint between aluminum and copper, a lot of work has been carried out earlier to weld these two metals. Since the electrical conductivity of Cu-OF is higher than the aluminum alloy so there remains no motivation in replacing and joining the same thickness of copper with the aluminum alloy in electrical applications. Ends of bus bar is an electrical hot spot and thus results in increased temperature when the system is in use. The ends are under high forces from the bolt and due to the thermal cycle, some deformation is registered at the ends. This results in the loosening of the bolted ends and thus encounters higher resistance and elevated temperature. Copper has better thermal and electrical conductivity so it will help in the fast removal of heat from the bolted ends. Copper has also 30% less thermal expansion than aluminum so it will definitely improve the maintenance cycle of the bus bar. Thus, a bimetallic hybrid configuration is typically favored for the accomplishment of the preferred product performance, necessitating the development of stable dissimilar techniques of joining material

Vilaça et al. successfully joined the two dissimilar thickness material by fusion welding and FSW methods in which FSW was the most reliable and productive method[1]. However, joining of aluminum with copper in industries may encounter some initial hassles. Fabrication of aluminum and copper is usually problematic due to alterations in their physical and chemical properties. Xue et al. described that the surface macrostructure, mechanical property and interfacial microstructure were greatly influenced by the welding parameters in case of Al-Cu joint welded by FSW method. A decent bending angle of 180° was obtained at a 600 RPM speed of rotation and tool offset along the aluminum side. Cracks were initiated at stacking layers at relatively higher rotational speed. Joining of materials with decent joints is crucial for many industries[2]. Wang et al. used friction stir welding for joining fuel tanks materials for aerospace industry[3]. Miller et al. applied friction stir welding for joining the aluminum alloys in automobile industry as it helps in weight reduction, which further augments the fuel efficiency[4]. Karvinen et al. used friction stir channeling an advanced version of friction stir welding for producing cooling channels in electronic industry[5]. Almost every traditional welding technique is unable to generate decent dissimilar joints due to distinct mechanical, thermal and chemical characteristics of the participating material in the region of welding. It has been established that the FSW is suitable to produce acceptable quality joints with dissimilar materials. Kar et al. tried to weld the aluminum to titanium by sandwiching the niobium interlayer in-between. The main purpose of the niobium layer was to prevent the reaction between the aluminum and titanium. The lack of intermetallic zone in the nugget region results in improved mechanical properties. The defects around the niobium flakes in the weld region lead to the reduction of ultimate tensile strength[6].

Friction stir welding (FSW), invented by the Welding Institute (TWI) is widely engaged in industries for fabricating dissimilar materials. FSW has resolved the issues related to overheating by joining the metals below their melting temperatures. Recently, a lot of study has been done to examine the friction stir welded Aluminum-Copper joints. Pan et al. performed the interfacial joint characterization to check the joint stability of friction welded Al-Cu rod of 21 mm diameter. The

maximum tensile strength was 88 MPa and fracture occurs in the heat affected zone of aluminum side while the thickness was less than 1 μm [7]. Xavier and Jayabalan investigated the influence of speed of welding on the joint strength by considering various macrostructural and microstructural parameters. The joint tensile strength depends on the distribution of the particles in the nugget zone and thickness of the intermetallics[8]. Bisadi et al. described the combined effect of speed of welding and speed of rotation on the lap welded samples of commercially pure copper and AA5083 by friction stir welding. Intermetallic phases and their influence on the mechanical characteristics were also examined[9]. Beygi et al. used different tool pin profiles to obtain Al-Cu bimetal joint and found that the threaded taper tool provides the best results. It is difficult to get the high value of joint efficiency due to the presence of micro voids[10]. Galvão et al. carried out dissimilar Al-Cu welding by considering the impact of tool rotational speed and plate position in the material flow. The welds performed by keeping the aluminum along advancing side results irregular morphology and flash formation[11]. However, Wei et al. explained that the metallurgical immiscibility of Al in Copper significantly obscures the joint characteristics due to the formation of different IMCs, comprising AlCu, Al₄Cu₉, and Al₂Cu. These intermetallic compounds affect the mechanical, chemical and electrical characteristics of the Al-Cu joint welded by friction stir welding[12].

Moreover, the tool offset plays a dominant part at the time of dissimilar friction stir welding if one of the material is harder. The tool pin center was marginally shifted towards the softer material alloy sheet fixed to the retreating side of joint, by the pin radius. Maximum part of the tool along the harder metal results in tool wear. Zero tool offset means that the tool pin is positioned exactly at the weld center line (Fig. 2).

Table 1

Friction stir welding parameters adopted to fabricate specimens

Specimen	Welding speed (mm/min)	Rotational speed (RPM)	Force (kN)	Pin plunging depth (mm)	Welding tilt angle	Offset (mm)
No. 1	128	640	18	2.9	1.45	0
No. 2	160					0
No. 3	213					0
No. 4	128					1
No. 5	160					1
No. 6	213					1

The greater impact of the tool offset is on the distribution of optimal amount of heat input for both the materials. Insufficient tool offset results in thicker intermetallic region at the interface and in turn reduces the joint strength. Loureiro et al. reported that the offsetting the tool from the interface to the softer material restricted the formation of intermetallic compounds during welding which have a great influence in the welding morphology and mechanical properties[13]. Genevois et al. used an exclusive pin offset along the aluminum side. No mixing of either of the materials was observed in the welding zone. They concluded that the bonding due to interfacial interdiffusion between both the metals results in the formation of a very thick intermetallic compound at the

interface[14]. Xue et al. reported that a moderate value of tool offset along the aluminum side results in improved microstructural and mechanical properties[2].

The process parameters of FSW are the deciding factors that help in determining the heat input compulsory for the material movement and the formation of a stir zone free of defects. Welding speed is one of the controlling parameters. Progression of unlike flow stresses during dissimilar FSW of Al-Cu is a noticeable issue for weld defects. Aghajani and Elyasi reported that the welding speed has a considerable influence on the harder material fragments size in the weld region. Amount of heat generation due to friction during welding has greater impact on the tensile strength and the width of the intermetallic compound in the weld region[15]. Sedmak et al. claimed the insufficient heat input reduces the softening of material and thus affects the mixing of material in the stir zone[16].

Very few studies have been conducted on friction stir butt welding of different thickness as well as dissimilar metals. The impact of welding speed on the development of intermetallic compounds at the Al-Cu interfacial microstructure and mixing of material in the weld nugget is discussed in detail. In the present study, the Cu-OF copper and aluminum alloy 1050, which are extensively used in electrical industries as a bus bar, are welded with FSW in modified butt joint configuration as represented in Fig.1. The effects of the main welding parameters including welding speed and pin offset of the tool, on the material flow, distribution of copper in the aluminum and intermetallic compound are examined. The effect of these factors on the tensile characteristics of the joints are critically inspected as the joint tensile strength of the welded specimen is a demanding criterion in bus bars.

2. Joint configuration

For joining Al and Cu alloys of dissimilar thickness using FSW technique, the elementary butt joint layout should be again reorganized to achieve the good weld quality, formability and ease of welding. It has been revealed that an improved dissimilar FSW joint was achieved by plunging the tool along the softer material.

All the welds were produced in butt joint configuration, which provides a flat surface for the easy movement of shoulder and further leads to seamless shoulder movement area according to the application (Fig. 1).

Fig. 1. Simplified illustration of the Al to Cu modified butt joint layout

3. Governing equation

The governing equation helps to understand the reason for joining the dissimilar thickness aluminum- copper alloy. From the Joule's law of electrical heating:

By considering the identical current, for the same length and width of both the aluminum and copper alloy.

For same amount of heat generation due to electrical resistance in both the alloy

$$I^2 \cdot R_{Al} = I^2 \cdot R_{Cu} \quad (1)$$

where I = Current flow (constant), R_{Al} = Electrical resistance of aluminum, R_{Cu} = Electrical resistance of copper.

Now, from equation (1)

$$R_{Al} = R_{Cu} \quad (2)$$

$$\frac{\rho_{Al} \times L_{Al}}{A_{Al}} = \frac{\rho_{Cu} \times L_{Cu}}{A_{Cu}} \quad (3)$$

where ρ = Resistivity of the materials, L = length of the metals.

For the same length of both the material, from equation (3)

$$\frac{\rho_{Al}}{A_{Al}} = \frac{\rho_{Cu}}{A_{Cu}} \quad (4)$$

where A = area of cross-section of the material.

Area = width (w) x thickness (t), from equation (4)

$$\frac{\rho_{Al}}{\rho_{Cu}} = \frac{A_{Al}}{A_{Cu}} \quad (5)$$

For the same width, from equation (5)

$$t_{Cu} = \frac{\rho_{Cu}}{\rho_{Al}} \times t_{Al} = \frac{\sigma_{Al}}{\sigma_{Cu}} \times t_{Al} \quad (6)$$

where σ = Conductivity of materials, σ_{Cu} = 100% of IACS, σ_{Al} = 61% of IACS.

The above equation helps in calculating the required thickness of copper as compared to the 6 mm thick aluminum alloy.

4. Materials and methods

3 mm thick rolled sheet of oxygen free copper and 6 mm thick rolled sheet of aluminum alloy 1050 were selected as weld materials. 200 mm x 100 mm plates of both the materials were used for the experiments.

Table 2

Chemical composition of base materials

Material	Al	Zn	Mg	Cu	Fe	Si
AA1050	Balance	0.07 wt. %	0.05 wt. %	0.05 wt. %	0.4 wt. %	0.25 wt. %
Cu-OF	O ₂ max 10 ppm			99.99 %		

Since the copper was half the thickness of aluminum alloy therefore attaining a good quality of weld and for ease of welding same dimension of metallic sheet was used underneath to provide the support and protect it from distortion at the time of welding (Fig. 1). The Cu-OF were placed at the advancing side for butt FSW procedure. FSW experiments were performed using ESAB made water cooled professional FSW machine and weld tool of tempered H13 tool steel. A flat with two negative scrolls and 24 mm diameter shoulder with a threaded taper probe tool was used for all the experiments. The diameter of the probe in root area was 5 mm and at the top was 4.2 mm. The pin length was 2.9 mm, marginally less than the thickness of Cu-OF alloy to get a smooth surface specimen after welding from both sides.

Fig. 2. Schematic representation of FSW at different offsets

The major process control parameters of FSW comprised the speed of tool rotation (RPM), speed of welding (mm/min) and tool offset. In order to examine the properties of as welded Al to Cu-OF butt interfacial microstructure under different conditions, the value of welding speed and tool offset were changed however the rotational speed, tool tilt angle and welding force were kept constant during the process. The value of tool tilt angle and vertical force was 1.45° and 18 kN respectively for each experiments. During FSW process the water was continuously flowing through the shoulder of the machine to remove the excessive heat during the welding as the major part of the heat is generated by the tool shoulder.

Samples for the metallographic examination were cut and polished adhering to the standard procedure used for microstructural analysis. Separate etchants were used for both the materials to reveal the interface images. The etchant used for aluminum side was modified Keller's reagent composed of 190 ml of distilled water, 5 ml of Nitric Acid (HNO_3), 3 ml of Hydrochloric Acid

(HCl) and 3 ml of Hydrofluoric Acid (HF). A solution made of 5 g FeCl_3 , 50 ml HCl and 100 ml H_2O was used to etch the copper side. The thickness, size of the intermetallic compound, distribution of one material over the other and fracture surface of tensile tested specimen were analyzed using the Supra 55 (Carl Zeiss, Germany) FE-SEM machine. EDS analysis were performed to reveal the chemical composition at various places (mostly at the interface). Ametek made electron probe micro-analyzer (EPMA) was used for map scanning of the samples nearby the interface zone. Empyrean, Malvern Panalytical X-ray diffraction (XRD) machine was applied to discover the phase constitutions of interface surface. The transverse tensile test specimens were taken out from the weld joint and tests were conducted in the universal testing machine according to the ASTM: E8/E8M-11 guidelines as represented in Fig. 3.

Fig. 3. Symbolic dimensions of the tensile testing specimen of the modified joint [17]

5. Results and discussion

5.1 Microstructural analysis

5.1.1 Analysis of weld zone area using optical microscope

The appearance and images of the weld zone, top weld surface and processed image to identify the distribution of copper in the weld zone prepared at tool offset of 0 mm, 1 mm and welding speed of 128, 160 and 213 mm/min are shown in Table 3 and Table 4 respectively. Almost every samples has a similar structure at the copper-aluminum interface, but varying towards the weld zone. Different sizes of copper fragments were noticed in the weld zone, and are distributed throughout the region. The superiority of the joint is arbitrated by the appearance of the weld and the presence of internal or external defects. Shifting of the aluminum layer is observed towards the copper side of the top surface. Tunnel defect is also observed at the center and retreating part of the weld zone. Insufficient heat input or improper stirring is the cause of these defects[18]. Galvão et al. suggested

that the material transports from retreating side to advancing side in shoulder affected region and from the side of advancing to the side of retreating in the pin affected region[19]. Fragmented copper is observed along the retreating aluminum side. Most part of the weld zone is occupied by the aluminum as shown in Table 3 and Table 4. Transport of material from aluminum to copper side and copper to aluminum side is detected in the weld zone at all speeds. Xavier and Jayabalan claimed that the excessive heat input in the weld stir zone at the 50 mm/min welding speed results in high amount of plasticization at the same time the lack of viscosity in the weld stir zone results in high turbulence in stir zone and finally leads to different type of defects. Tunnel defects are the most common defects as a result of high heat input in the stir zone. Softening of copper at the interface neighborhood leads to clustered copper particles[8]. Loureiro et al. observed that the sharp corner around these copper fragments so it is very difficult for the plasticized aluminum to fill the area around these sharp corners which results in the cracks around these corners[13]. These cracks are also propagated to the surface of the weld. These unfilled gaps and cracks result in the efflux of some additional aluminum which can be easily observed in the shoulder movement area of the weld zone.

Some of the basic image processing techniques implemented using MATLAB were used as a part of the data analysis. First, a rectangular region of interest was selected and then it was converted to grayscale, followed by a Gaussian blur operation, Histogram normalization and finally, binarisation to yield a processed image representing the abundance of copper and aluminum in various regions of the joint as given in Fig. 4 and Fig. 5. In the nugget region, two different regions are identified with different color contrast. The light region consists of the aluminum alloy 1050 and the yellow region is the distribution of copper in the aluminum matrix.

At tool offset of 0 mm

Cracks are observed in the weld zone and top surface of each sample prepared with tool offset of 0 mm. Tunnel defect is also noticed at 213 mm/min welding speed. The copper in the weld zone remains unmixed and is found as a clustered particle. Processed images of the samples prepared at zero offset reveal that the distribution of copper particle in stir zone of each sample which is almost negligible in the mixed zone, as shown in Fig. 5.

At tool offset of 1 mm

Cracks are almost disappeared from the weld zone and shoulder affected zone while experiments were shifted from 0 mm offset to 1 mm offset, keeping other parameters constant. Uniformly distributed copper particles were observed in the stir zone which vary with the change in welding speed. A defect free shoulder affected surfaces were observed at welding speed of 128, 160 and 213 mm/min welding speeds. The processed image indicates a uniform mixing of aluminum and copper in the stir zone as shown in the Fig. 4.

Table 3

Friction stir welded samples prepared at a tool offset of 0 mm

Weld speed	Weld bead	Top surface
128 mm/min	<p>Crack</p> <p>20 μm</p>	<p>Crack</p> <p>20 μm</p>
160 mm/min	<p>Clustered particle</p> <p>20 μm</p>	<p>Crack</p> <p>20 μm</p>
213 mm/min	<p>20 μm</p>	<p>Aluminum efflux</p> <p>20 μm</p>

Table 4

Friction stir welded samples prepared at a tool offset of 1 mm along the aluminum side

Weld speed	Weld bead	Top surface
128 mm/min
160 mm/min
213 mm/min

Fig. 4. Distribution of copper and aluminum in the weld stir zone at different welding speeds and 1 mm tool offset

5.1.2. Effect of welding speed and tool offset on material mixing and distribution of the material

Esmaeili et al. found that the stir zone of the weld resides primarily in aluminum part which is a mixture of harder material particles spread in an aluminum matrix[20]. At tool offset of 1 mm relatively limited copper particles were disintegrated from the copper plate. Due to size of the copper particle it would be easier to mix it with aluminum in the weld stir zone. Therefore, a strong metallurgical bonding would be achieved at the stir zone. The size and the no of particles of harder material are affected by the tool offset. Mirzaei and Hayati claimed that 2 mm offset to copper increases the number of hefty particles in the stir zone[21]. Esmaeili et al. showed that the lamellar composite structure increases the tensile strength and the disappearance of this composite structure results in the reduction in tensile strength[20]. Composite like structure, and

Fig. 5. Distribution of aluminum and copper in the weld stir zone at different welding speeds and tool offset of 0 mm

distribution of copper in the aluminum is shown in Fig. 6a, Fig. 6b and Fig. 6c. At 128 mm/min welding speed, partial distribution of copper particles is observed in the stir zone. The mechanism of joining is mechanical mixing between two materials that produces a composite microstructure into the weld region. However, after marginal increment in the welding speed to 160 mm/min a non-uniformly distributed copper fragments is obtained as shown in Fig. 6b. An appreciable quality of stirring action occurred in the weld stir zone which definitely increases the tensile strength of the joint to 101.34 MPa due to the distributed copper particles in the weld nugget zone. At higher welding speed of 213 mm/min, uniformly distributed copper fragments are manifested (Fig. 6c). This uniform distribution of copper in the stir zone forms composite structure which further increases the tensile strength to 102.34 MPa.

Fig. 6. Samples prepared at 1 mm offset and at a welding speed of a) 128 mm/min b) 160 mm/min c) 213 mm/min

At tool offset of 0 mm, there is a relatively additional fraction of copper fragments in the weld stir zone compared to the samples prepared at 1 mm offset. At 128 mm/min welding speed, completely conglomerated copper particles are detected in the weld stir zone (Fig. 7d). This results in a lower tensile strength of 59 MPa compared to the uniformly distributed copper samples. At 160 mm/min welding speed the distribution of copper particles in distinct regions of stir zone was observed which resulted in higher tensile strength of 65.40 MPa (Fig. 7e). Table 5 presents the distribution of the copper and aluminum particles separately near the Al- Cu weld interface in the Al metal matrix composite.

Fig. 7. Samples prepared at 0 mm offset and welding speed of d) 128 mm/min e) 160 mm/min

5.1.3. Interface microstructure

The interactions of two unlike materials in solid state welding bring a remarkable compositional gradient at the weld interface capable of facilitating elemental diffusion at the time of welding. Interfacial diffusion, which depends upon the temperature rise can occur during friction stir welding. Intermetallic compounds are formed by the interfacial diffusion. Li et al. found that the voluminous intermetallic compounds of (IMC) interlayer at the welded interface had an adverse influence on the tensile properties of the Al-Ti joint. For 10 μm intermetallic thickness sample had a tensile strength of 179 MPa whereas for 2 μm intermetallic thickness sample had a tensile strength of 292 MPa[17]. Ouyang et al. showed that the interface of the Al/Cu welded joint is prone to the formation and progression of intermetallic compound at temperature beyond 120 $^{\circ}\text{C}$ [22]. Esmaeili et al. claimed that the number of copper particles were separated from the copper plate and these particles mixed and react with the aluminum matrix, resulting in the formation of layered structures[20]. These separated Cu pieces are hard to flow and occurred near the interface. Therefore, the thick layered structures developed without difficulty in this case (Fig. 8a and Fig. 9d).

Table 5

Elemental mapping result of joints root part at 1 mm tool offset and different welding speeds

Fig. 8. Samples prepared at 0 mm tool offset and welding speed of a)128 mm/min b)160 mm/min and c) 213 mm/min

Saeid and Sazgari studied the initiation and propagation of the cracks at this interface. The joint tensile strength is affected by two factors: the amount of hard and brittle intermetallic compound and the cold weld condition[23]. It was explained that thin intermetallic layers can increase mechanical characteristics. In order to investigate the metallurgical bonding between the materials along the advancing side, Field Emission Scanning Electron Microscope was utilized for better magnified view. Fig. 8 and Fig. 9 shows the Al-Cu interface at several welding speeds while keeping the 640 RPM rotational speed and offsets of 0 mm and 1 mm respectively. A recognizable interface layer with different color and of different thickness were observed at the interface.

Fig. 9. Samples prepared at 1 mm tool offset and welding speed of d) 128 mm/min e) 160 mm/min and f) 213 mm/min

Fig. 10. Variation between welding speed and intermetallic thickness at the interface

The weld joints prepared at 160 mm/min welding speed result in moderate intermix thickness (0.93 and 0.77 μm). The interface is almost half the thickness of intermix observed in 128 mm/min (2.2 and 1.44 μm) of welding speed. Fracture occurs in this case at the intermix layer and result in the acceptable tensile strength (Fig. 13). EDS result near the interface displaying the composition close to Al_4Cu_9 and away from the interface is close to copper and aluminum solid solution marked as point 1, 2 and 3 (Fig. 11a) while the EDS result in the mix zone representing the composition close to Al_2Cu and AlCu marked as point 4 and 5 (Fig. 11b). Test of the interface mix layer using XRD shows the presence of Al_4Cu_9 (Fig. 12). The diffraction pattern shows the phases formed after the friction stir welding of the samples.

Fig. 11. EDS image of the a) interface and b) mixed zone

Table 6

Chemical composition of the points as indicated in Fig. 8a and Fig. 8b in (at %)

Point	Al	Cu	Possible phase
1	29.4	70.6	Al ₄ Cu ₉
2	14.7	85.3	Cu
3	81.6	18.4	Al
4	67.2	32.8	Al ₂ Cu
5	48.5	51.5	AlCu

When the welding speed was 213 mm/min, all the joints failed at weld nugget (WN) and weld nugget-aluminum (WN-Al) interface. A thin mix reaction layer (0.79 μm and 0.29 μm) was observed at the interface. It signifies a sound joint at the interface and verifies that the joint at the interface was stable than the weld nugget, thus it failed at WN, WN-AL interface zone. Relation between the welding speed and intermetallic thickness is shown in Fig. 10.

Fig. 12. XRD analysis of the interface

5.2. Tensile strength

The tensile testing of dissimilar welded joints was conducted at different welding speeds from 128 mm/min to 213 mm/min, a pin offset of 0 mm or 1 mm along aluminum side and at a constant rotational speed of 640 RPM is shown in the Table 1. It is found that keeping the rotational speed constant, the joints welded with an offset of 1 mm showed (38%-58%) increase in tensile strength compared to the ones welded at 0 mm offset, at various welding speeds. From the result, the fracture force of the joint gradually increases from a welding speed of 128 mm/min to 160 mm/min and approximately remains constant at 213 mm/min with respect to 160 mm/min. Thus, not only the rotational speed and welding speed but also the tool offset was found to have a detrimental effect on the tensile strength of the joint.

Fig. 13. Tensile strength at different offsets and welding speeds

Fig. 14. Percentage increase in tensile strength at 1 mm offset as compared to 0 mm offset

Bakhtiari et al. established that the joint efficiency of the weld produced by friction stir welding is always lesser than the aluminum base metal 5754-H114[24]. Azhiri et al. proposed that the FSW of acrylonitrile butadiene styrene (48 MPa tensile strength) thermoplastic polymer in addition with nanosilica results in joint efficiency upto 98 percent[25]. Mixing and material movement in the stir zone, thickness of the intermetallic compound and the distribution of copper may be the most important factors affecting the tensile characteristics of the dissimilar joint. Tensile strength of the joints prepared at 128, 160, and 213 mm/min welding speed with a tool offset of 1 mm were 83.39 MPa, 101.45 MPa and 102.34 MPa respectively, were found to be 73.75%, 89.68% and 91.56% of that of the AA1050 aluminum alloy strength respectively. While tensile strength of the samples prepared at 128, 160 and 213 mm/min welding speed and 0 mm tool offset were 59 MPa, 65.4

MPa and 65.25 MPa respectively which stand at 52.22%, 57.88% and 57.74% of AA1050 alloy respectively (Fig. 13). The tensile test indicated that most of the crack initiated at the interface between weld zone and copper (Fig. 15), which marks this zone as the weakest area. The tensile strength of the samples prepared at travel speeds of 128 mm/min, 160 mm/min and 213 mm/min with 1 mm offset registered 41%, 56.44% and 60% increase in tensile strength compared to the tensile strength of samples prepared at the same welding speeds and 0 mm tool offset (Fig. 14)

Fig. 15. Fracture location of the welded joints

Every joints welded at a welding speed of 128 and 160 mm/min fractured at the Weld nugget (WN) – copper interface while the samples prepared at the welding speed of 213 mm/min fractured at the middle of the weld nugget and weld nugget–Aluminum interface results in tensile strength of 104 MPa and 65 MPa respectively for the offsets of 1 mm and 0 mm respectively. The joints fractured at WN and WN- Al interface shows plastic rupture while the joints failed at WN-copper interface show brittle fracture.

5.3 Fractography

The surface morphologies were studied using FESEM images to Figure out the nature of failures at various parameters. Fracture surface is considered for the detailed explanation of failure types in each joint. Figures representing the size and spacing between dimples produced at the top surface of welded region. Fig.16a manifests the fracture surface image of samples prepared at 128 mm/min travel speed and 1 mm tool offset with the failure in nugget zone. The fracture surface combines both unevenly sized dimples (8 μ m- 49 μ m) and a little amount of flat surfaces. The elongation of the dimples in the loading direction represents the ductile failure whereas the flat fracture surface reflects the brittle fracture. Equiaxed micro voids and pulling indicative of shear fracture of the weld zone (Fig. 16b). Similar observations were noticed by the Garg and Bhattacharya [26]. Number of equiaxed dimples in the image are indicative of the facts that there is a strong metallic bonding between aluminum and copper (Fig. 16c). Void growth in the sample resulted in deep dimples implying participation of greater energy before the fracture which was also observed by Khan et al. [27] . The failure during tensile testing of Fig. 16c is purely ductile in nature.

Fig. 16. Fracture surface of samples prepared at tool offset of 1 mm and welding speed of a) 128 mm/min b) 160 mm/min c) 213 mm/min

Shallow dimples indicates the insignificant mixing of aluminum and copper. This type of morphology represents that the fracture behavior is more brittle than the ductile (Fig. 17d). Combined shallow dimples and flat surfaces with secondary cracks are due to the difference in thermal expansion (Fig. 17e). Same type of observations were also observed by Hosseini et al. [27]. Fig. 17f displays the fracture surface consists of small dimples. There is also some cleavage, illustrative of the completely brittle fracture.

Fig. 17. Fracture surface of samples prepared at tool offset of 0 mm and welding speed of d) 128 mm/min e) 160 mm/min f) 213 mm/min

6. Conclusion

The effect of tool travel speed and tool offset on the microstructure, intermetallic development and consequent tensile properties of the dissimilar joint with different thickness of Aluminum-Copper fabricated by Friction Stir Welding has been critically investigated and summarized below:

1. FSW of Al/Cu with dissimilar thicknesses by offsetting 1 mm of probe into the aluminum side can result in sound and smooth joints under welding condition of 160 mm/min and 213 mm/min. Thus, the FSW can be used to weld the dissimilar thickness aluminum-oxygen free copper to get a bus-bar with improved life and reduced maintenance cost.
2. The probe offset has an abundant influence on the weld nugget microstructure. Insufficient tool offset of 0 mm results in cracks and holes in the stir zone which further results in reduced tensile strength, whereas tool offset of 1 mm results in aluminum metal matrix composite in the stir zone and improved tensile strength. The offset along the aluminum

side results in small fraction of copper (which is relatively harder than the aluminum) in the weld zone leading to the proper stirring of the harder material.

3. Defect free stir zone results in excellent tensile property of 102.34 MPa and 101.45 MPa. Formation of aluminum metal matrix composite in the weld stir zone results in the strengthening of the joint.
4. The thickness of the intermetallic layer at the interface affects the tensile property of Al/Cu joints. Due to high heat input at 128 mm/min welding speed results in enhance diffusion at Al/Cu interface. Intermetallic thickness at interface decreases with increasing the travel speed from 128 mm/min to 213 mm/min. Relatively thin intermetallic layer is noticed at 160 mm/min (0.93 μm and 0.77 μm) and 213 mm/min (0.79 μm and 0.26 μm) welding speed, compared to 128 mm/min (2.2 μm and 1.44 μm). Thin intermetallic compounds of Al_2Cu and Al_4Cu_9 give rise to decent tensile strength.

Friction stir welding which joins materials below their melting point is suitable for the joining of two dissimilar materials having different chemical and physical properties. This method can be used to fabricate the dissimilar thickness aluminum and oxygen free copper alloys to get a hybrid bus-bar configuration which results in improved life cycle. The future work includes the joining of these two metals at different offsets and conducting some electrical tests for its utilization in bus bar application.

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Highlights

- Al-Cu joint of dissimilar thickness is successfully obtained using FSW method.

- Joint tensile strength of dissimilar metals is examined at different tool offsets.
- The joint quality is improved by 1 mm of tool offset along aluminum side.
- Joint properties are influenced by the varying intermetallic thickness.