Friction Stir Welding of Dissimilar Materials between Aluminium Alloys and Copper - An Overview

Mukuna P. Mubiayi. *Member, IAENG* and Esther T. Akinlabi, *Member*, IAENG

***Abstract*—Friction Stir Welding (FSW) is a solid state welding process used for welding similar and dissimilar materials. The process is widely used because it produces sound welds and does not have common problems such as solidification and liquefaction cracking associated with the fusion welding techniques. The FSW of Aluminium and its alloys has been commercialised; and recent interest is focused on joining dissimilar materials. However, in order to commercialise the process, research studies are required to characterise and establish process windows. In particular, FSW has inspired researchers to attempt joining dissimilar materials such as aluminium to copper which differ in properties and sound welds with none or limited intermetallic compounds has been produced. In this paper, we review the current research state of FSW between aluminium and copper with a focus on the resulting weld microstructure, mechanical testing and the tools employed to produce the welds and also an insight into future research in this field of study.**

Keywords: Aluminium, copper, dissimilar materials, intermetallic compounds, microstructure.

I. INTRODUCTION

Nowadays, researchers have been focusing on developing fast and eco-friendly processes in manufacturing and this include Friction Stir Welding (FSW) and Processing (FSP). Friction Stir Welding (FSW) is a solid–state joining technique invented and patented by The Welding Institute (TWI) in 1991 for butt and lap welding of ferrous and non–ferrous metals and plastics. FSW is a continuous process that involves plunging a portion of a specially shaped rotating tool between the butting faces of the joint. The relative motion between the tool and the substrate generates frictional heat that creates a plasticized region around the immersed portion of the tool [1].

Friction stir welding process uses a non-consumable rotating tool consisting of a pin extending below a shoulder that is forced into the adjacent mating edges of the work pieces as illustrated in Fig. 1. The heat input, the forging action and the stirring action of the tool induces a plastic flow in the material, forming a solid state weld.

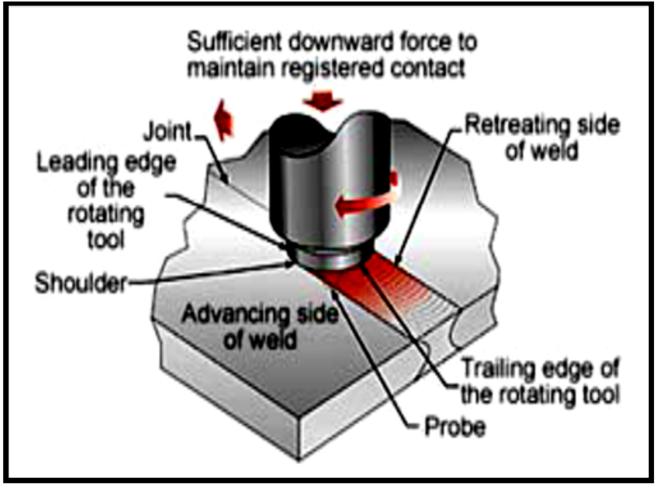

Fig.1. Schematic diagram of the Friction Stir Welding process [2]

It was realised in the development of the FSW process that the tool design is critical in producing sound welds [3]. A basic and conventional design for a FSW tool is shown in Fig. 2 which consists of a threaded pin and a concave shoulder. FSW tools follow the same basic trends in terms of their shapes and geometries. They are generally comprised of three generic features including a shoulder, a probe also known as a pin and external features on the probe.

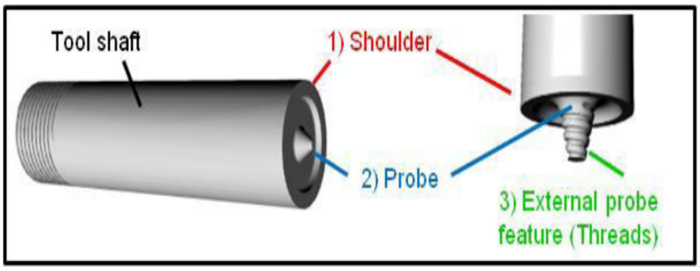

Fig.2. A Schematic View of FSW Tool (Timothy) [4]

FSW joints usually consist of different regions as illustrated in Fig. 3 following the terminologies used by Threadgill [5] which include; the unaffected material or parent metal, the Heat-Affected Zone (HAZ), the Thermomechanically Affected Zone (TMAZ) and the weld nugget.

Mr. M.P. Mubiayi is a doctorate candidate in the Department of Mechanical Engineering Science, University of Johannesburg, South Africa, 2006. (Phone: +2711-559-2931 and +2773 – 808 - 8595; e-mail: patrickmubiayi@gmail.com).

Dr E. T. Akinlabi is a Senior lecturer in the Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park Kingsway Campus, Johannesburg, South Africa, 2006. (Phone: +2711-559-2137; e-mail: etakinlabi@uj.ac.za).

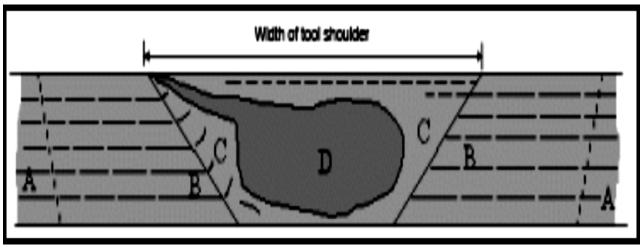

Fig.3. Illustration of different microstructural regions in the transverse cross section of a friction stir welded material. A, parent metal or unaffected material; B, heat-affected zone; C, thermomechanically affected zone; D, weld nugget [5].

The Unaffected material or parent material is the material remote from the weld that has not been deformed. The Heat Affected Zone (HAZ) is the region, which lies closer to the weld-centre; the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties. However, no plastic deformation occurs in this area. The Thermo Mechanically Affected Zone (TMAZ) is the region in which the FSW tool has plastically deformed the material, and the heat from the process has also exerted some influence on the material. In the case of aluminium, it is possible to obtain significant plastic strain without recrystallization in this region; and there is generally a distinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ; and the Weld nugget is the fully recrystallized area, sometimes called the Stir Zone (SZ) or Stir Nugget (SN), it refers to the zone previously occupied by the tool pin [5].

Prior to the development of FSW, conventional fusion welding processes were used to join similar and dissimilar materials. Friction stir welding of dissimilar materials remains not fully researched. Friction stir welding of dissimilar materials such as aluminium to copper in particular need to be fully understood due to their different melting temperatures. The high chemical affinity of both base materials promotes the formation of brittle intermetallic Al/Cu phases, which still require extensive research [6][7]. Furthermore, aluminium and copper are difficult to weld with conventional welding processes due to their high reflectivity and thermal conductivity. Brittle intermetallic phases develop in the joint zone since copper and aluminium are not very soluble in one another in the solid state. These intermetallic phases lower the toughness of the weld and lead to cracks during and after the welding [8].

Moreover, aluminium to copper welding is increasingly used in some practical applications such as heat transfer equipments, wiring, electrical and electronics industries, and aesthetical applications. Furthermore, aluminium alloys are widely used to produce aerospace components with high specific strength. However, Di Paola *et al* [9] published that when traditional welding processes are applied to these aluminium alloys, they often entail disadvantages that have sometimes discourage the use of welded components.

Many researchers have published reviews on friction stir welding and processing focusing on the tools employed [10], Friction stir processing [11], dissimilar alloys [12] and on aluminium alloys [2]. To the best of our knowledge, no review focusing on friction stir welding of aluminium to copper has been published. Therefore, this paper critically reviewed the existing published literature by focusing on the recent work done on friction stir welding of aluminium copper alloys. The rest of the paper is focused on the resulting microstructural evolution, the mechanical properties characterization and the tools employed to produce the welds between aluminium and copper.

II. RELATED STUDIES ON FRICTION STIR WELDING BETWEEN ALUMINIUM AND COPPER ALLOYS

A. MICROSTRUCTURAL EVOLUTION AND X-RAY DIFFRACTION ANALYSES

The development of laboratory work on the friction stir welding of dissimilar materials will provide a good insight on their possible industrial application and therefore enhance industrial development. Liu *et al* [13] observed while welding copper (T2) to AA 5A06 that the distribution between the Copper (Cu) and Aluminium (Al) has an evident boundary and the material in the stir zone shows obvious plastic combination of both materials. Furthermore, they observed clearly an onion ring structure in the stir zone indicating good material flow. Additionally, they indicated that the metal Cu and Al close to the copper side in the Weld Nugget (WN) zone showed a lamellar alternating structure characteristic [13]. However, a mixed structure characteristic of Cu and Al existed in the aluminium side of the weld nugget (WN) zone. The stir action of the tool, frictional heat and heat conductivity of Cu and Al could have induced the different structures of both sides in the weld nugget zone. The X-ray diffraction (XRD) analysis showed that there were no new Cu–Al intermetallics in the weld nugget zone. Consequently, the structure of the weld nugget zone was largely plastic diffusion combination of Cu and Al [13]. However, Xue *et al* [14] successfully welded AA1060 and 99.9% pure commercial copper (annealed), they conducted XRD analysis and their results revealed the existence of distinct characteristic diffraction peaks of Al_2Cu and Al_4Cu_9. Hence, they stated that the Al_2Cu and Al_4Cu_9 were generated around the larger Cu particles, and for the smaller Cu particles most of the copper were transformed into these two intermetallics (IMCs). However, the microstructures of the nugget zone consisted of a mixture of the aluminium matrix and Cu particles. The distribution of the Cu particles with irregular shapes and various sizes was inhomogeneous in the nugget zone and a particles-rich zone (PRZ) was formed near the bottom of the weld [14]. Furthermore, they examined the presence of the particles in the aluminium matrix of the nugget zone and attributed that to the stirring action of the tool pin that worn out the Cu pieces from the bulk copper, breaking up and scattering them during the FSW process [14].

AA5083 and commercially pure copper were joined using FSW by Bisadi *et al* [15]. They observed that a very low welding temperature led to some defects like channels that showed up at a region near the sheets interface especially in the Cu sheet. Also, extremely high process temperature leads to some cavities appearance at the interface of the diffused aluminium particles and the copper sheet material. Additionally, they found that increasing the process temperature reportedly leads to higher amounts of copper particles diffusion to the aluminium sheet, increase in the intermetallic compositions and a number of micro cracks were present.

On the other hand, Xue *et al* [16] welded AA 1060 aluminium to commercially pure copper. They identified many defects in the nugget zone at the lower rotation speed of 400 rpm considered; whereas at higher rotation speeds of 800 and 1000 rpm, good metallurgical bonding between the Cu pieces and Al matrix was achieved. Furthermore, a large volume defect was observed when the soft Al plate was placed at the advancing side. They attributed that to the hard copper bulk material which was hard to transport to the advancing side during FS welding [16]. Esmaeili *et al* [17] joined AA 1050 and 70%Cu–30% Zn brass, the results showed that the structure of the sound joint at the nugget zone of aluminium is made up of a composite structure, consisting of intermetallics and brass particles, mainly at the upper region of the weld cross section. Furthermore, a multilayer intermetallic compound was formed at the interface at rotational speeds higher than 450 rpm. This layer is mainly composed of CuZn, $CuAl_2$ and Cu_9Al_4. The distribution, shape and size of the particles are irregular and inhomogeneous in the nugget zone of aluminium [17].

Ouyang *et al* [18] also conducted dissimilar FSwelds using AA 6061(T6) to copper. They demonstrated that the direct FSW of AA 6061 to copper has been difficult due to the brittle nature of the intermetallic compounds formed in the weld nugget. Moreover, the mechanically mixed region in the dissimilar AA 6061 to copper weld consisted mainly of several intermetallic compounds such as $CuAl_2$, CuAl, and Cu_9Al_4 together with small amounts of α-Al and a face-centered cubic solid solution of Al in Cu [18].

Abdollah-Zadeh *et al* [19] friction stir welded AA 1060 to a commercially pure copper. They observed intermetallic compounds of Al_4Cu_9, AlCu and Al_2Cu near the Al/Cu interface, where the crack can be initiated and propagated preferentially during the tensile tests. They also observed that higher rotational speeds increased the amount of intermetallic compounds formed at the aluminium / copper interface while low rotational speed resulted in imperfect joints.

Saeid *et al* [20] stated that the interface in the central region moved considerably into the bottom plate while joining 1060 aluminium alloy to commercially pure copper. The vertical transport of the interface is attributed to the ring-vortex flow of materials created by the tool pin threads [20]. At higher welding speeds, less vertical transport of the interface was observed on the retreating side [20].

Akinlabi *et al* [21] investigated the microstructure of the joint interface of AA 5754 and C11000 copper welds. The mixing of both materials was observed leading to good metallurgical bonding at the joint interface. The aluminium rich region was black/silver while golden yellow showed copper rich regions. Furthermore, Akinlabi, *et al* [22] observed a thickness reduction in the joint interface but good mixing was achieved in the weld produced at a constant rotational speed of 600 rpm and feed rates of 50 and 150 mm/min. They attributed the reduction in thickness at the joint interfacial regions to heavy flash observed during the welding process [22]. In addition, a good material mixing was achieved in welds produced at lower feed rate due to high heat generated while the welds produced at high feed rates resulted in worm hole defect formation [22]. On the other hand, Galvao, *et al* [23] observed that increasing the heat input, by performing welds under higher ω/v ratio, resulted in the formation of mixed material zones with increasing dimension and homogeneity. Furthermore [23], the morphology of the mixing zones and the type and amount of the intermetallic phases, which they found to result from a thermomechanically induced solid state process, are also strongly dependent on the welding parameters.

Galvao *et al* [24] friction stir welded oxygen free copper with high phosphorous content (Cu-DHP, R240) and AA 5083-H111. They observed that the welds performed with the aluminium placed at the advancing side of the tool were morphologically very irregular, being significantly thinner and exhibiting flash formation due to the expulsion of the aluminium from the weld area. Furthermore, the aluminium, which is expelled, gave rise to the flash displayed for the welds performed with aluminium at the advancing side [24]. It was observed that when the aluminium plate is located at the retreating side of the tool, the material was dragged by the shoulder to the advancing side, where the harder copper plate is located [24]. In FSW of dissimilar metals, the pin offset is a very important factor. Agarwal *et al* [25] joined AA 6063 and 99.9% pure commercially copper using FSW. They observed that as the pin offset is increased there is improper mixing of the Al-Cu metals that resulted in the tunnelling defect.

Singh *et al* [26] observed that there were different microstructure features in the different zones. At the weld centre line, mix region of aluminium and copper were found. Small particles of aluminium and copper were distributed in the opposite side by the stirring forces of the tool. The Thermo Mechanically Affected Zone (TMAZ) is clearly obtained in Copper but it was not found in aluminium. Thus, in both the metals, the Heat Affected Zone (HAZ) was not clear [26].

Ratnesh *and* Pravin [27] successfully joined AA 6061 and copper by FSW. They produced sound joints by shifting the centre line of the tool towards the copper plate on the advancing side. A presence of a ‘‘transition zone’’ was observed by Guerra *et al* [28] while friction stir welding thick AA 6061 plates with a thin high purity copper foil. This transition zone was found to be about twice as thick on the retreating side as it is on the advancing side. They believed that the material in this zone rotates, but its velocity decreases from the rotational velocity of the pin at the inner edge of the transition zone to zero at its outer edge [27].

Xue *et al* [29] joined 1060 aluminium alloy and commercially pure copper with success through friction stir lap welds. They found that the nugget zone consisted of pure Al material and a composite structure in the upper and the lower parts respectively. They found that the Al/Cu interface was characterised by a thin, continuous and uniform intermetallic layer, producing a good interface bonding. Furthermore, good metallurgical bonding was achieved between the Al matrix and the Cu particles in the composite structure due to the formation of a small number of intermetallics [29].

Akinlabi *et al* [30] observed that the joint interfaces are characterised by mixed layers of aluminium and copper as evident in the microstructures resulting from the heat input into the welds by the stirring action of the tool during the FSW process. Furthermore, they observed that the percentage decrease in the grain sizes increases towards the stir zones of the welds.

LI *et al* [31] used pure copper and AA 1350 and successfully joined them through FSW with the pin offset technique. They found that both copper and aluminium are greatly refined after FSW compared to the base materials. No intermetallic compound was found according to the XRD results. Esmaeili, *et al* [32] friction stir welded brass to AA 1050 at different rotation speeds. At low rotation speeds and due to low levels of heat inputs, no detectable intermetallic compound was observed. As the rotation speeds increases, the gradual formation of intermetallics is initiated at the interface. Additionally, the increase in the rotational speed resulted in the thickening and development of intermetallic layers.

Akinlabi [33] conducted XRD analysis on AA 5754 and C11000 FSW welds. It revealed the formation of intermetallic compounds at the joint interfaces including Al_2Cu and Al_4Cu_9, though their concentrations in the welds were very low.

Galvao *et al* [34] observed that the aluminium to copper dissimilar welds displayed poor surface quality and thickness reduction mainly on those welds done with the aluminium in the advancing side. The results were compared to FSW of similar materials welds which nevertheless displayed good surface appearance with low flash and thickness reduction [34]. Avettand-Fenoe *et al* [35] observed Al_2Cu and c1-Al_4Cu_9 phases in the dissimilar AA 6082 (T6) to copper friction stir welds. Their formation is essentially governed by both the thermomechanical history and the local mixing of the chemical species.

Recent research effort on the microstructure evolution and XRD analyses has been reviewed. It can be summarized that in FSW of aluminium to copper; placing the copper plate which has a higher melting temperature at the advancing side yielded welds with good integrities. However, we noticed that most of the studies conducted showed the presence of intermetallic compounds while friction stir welding aluminium and copper, further analyses of these newly formed phases have to be conducted in order to fully understand their impact in the weldments. Optimization of the processing parameters to reduce the formation of the intermetallic compounds at the joint interface also needs to be conducted.

B. MECHANICAL CHARACTERIZATION

The knowledge of the mechanical properties of the dissimilar friction stir welds between aluminium and copper is of importance to enhance their use in the industries.

Research have found that the maximum Ultimate Tensile Strength achieved in FSwelds of aluminium and copper was about 296 MPa and it was obtained when the tool rotational speed is 950 rpm, and the travel speed is 150 mm/min [13]. Akinlabi [36] also measured the tensile test using different welding parameters, the results showed that the welds produced had Weld joint efficiencies of between 73 and 86%, and can be acceptable for design purposes.

Galvao *et al* [34] stated that the welding condition, specifically the rotational speeds and the traverse speeds that results in obtaining welds with good surface appearance do not lead to the production of sound dissimilar welds.

Furthermore, Esmaeili *et al* [32] observed that the mechanical behaviour of joints is influenced as the rotational speed increases. They reported that the tensile strength of the weld produced increases due to the formation of a narrow interfacial intermetallic layer and a lamellar composite structure within the stir zone. Then, the tensile strength decreases due to the disappearance of composite structure and formation of defects in the stir zone [32]. The thickness of the interfacial intermetallic compound formation increases with an increase in the rotational speed which results in the reduction of the tensile strength of the welds produced [32].

Li *et al* [31] observed that the micro hardness values measured are higher at the copper side of the nugget zone than that at the aluminium side, this is expected as the UTS of Copper is higher than that of the aluminium. Additionally, they found that the hardness at the bottom of the nugget is generally higher than other regions due to the stirring action of the tool pin leading to recrystallized grains. The UTS and the percentage elongation of the dissimilar joints were 152 MPa and 6.3%, respectively, and the dissimilar joints failed in a ductile-brittle mixed fracture mode [31].

Akinlabi *and* Akinlabi [30] observed that there is an increase in the microhardness values at the joint interfaces of the welds resulting from strain hardening due to the stirring of the tool pin and the shoulder previously occupied by these regions during the welding process while the high peaks are due to the presence of intermetallics compounds resulting at the joints interface.

However, Xue *et al* [29] demonstrated that the FSW lap Al/Cu joints failed in the HAZ of the Al side, and the tensile shear load reached up to 2680 N when the Al plate was fixed on the advancing side. The hardness increased clearly in the layered structure due to the strengthening effect of the Al/Cu intermetallics, which were mainly composed of Al_4Cu_9 phases [29].

The study conducted by Xue *et al* [14] found that the large tensile specimen of the Al–Cu joint fractured at the HAZ of the Al side with a 13% elongation. The Ultimate Tensile Strength (UTS) and the yield strength were ~90% and ~80% of the Al base material respectively, and slightly lower than those of the Al base material due to annealing softening during the FSW process while the mini-specimen fractured at the particles-rich zone (PRZ), and the UTS was about 210 MPa which was much higher than the Al BM [14].

Bisadi *et al* [15] found that maximum hardness values were measured at the copper side of the joint at the weld SZ because of its fine grain size. In addition, although the grain size reductions, the hardness values of the joint aluminium side SZ were considerably lower than the aluminium base material which could be due to the production of micro voids at this area.

Moreover, intermetallic compounds were detected mostly at the brittle fracture areas and all the ultimate tensile stresses decreased by increasing the process temperature [15]. Poor tensile properties were achieved at the very large pin offsets and/or low rotation rates by Xue *et al* [16] which they suggested could be due to the insufficient reaction between the Cu bulk / pieces and the Al matrix. Furthermore, good tensile properties were achieved in the FSW Al–Cu joints produced at higher rotation rates and proper pin offsets of 2 and 2.5 mm due to sufficient reaction [16].

Results from the work of Esmaeili *et al* [17] indicated that the optimum ultimate strength of the sound joint was achieved from a proper material flow and metallurgical bonding through a narrow intermetallic layer at the interface in addition to crack detection by the occurrence of lamellar composite structure (onion rings) in the stir zone [17].

Ouyang *et al* [18] specifically found that different microhardness levels ranging from 136 to 760 $HV_{0.2}$ were produced in the weld nugget corresponding to various microstructures, intermetallics and material flow patterns.

Singh *et al* [26] found that in the horizontal hardness profiles, the values were found to be about 110 HV and 106 HV for copper and for the aluminium base metals respectively. The hardness values were stable for both metals in the HAZ and had tendency to increase in the nugget zone and this can be attributed to the formation of intermetallic compounds. The average tensile properties of the friction stir weld joints of Cu/Al varied from 138.7 MPa to 135.5 MPa [26].

Shukla *and* Shah [27] found that the maximum tensile strength of Al/Cu joint was low (62.2 MPa) mainly due to the presence of intermetallic compounds. The increase in the rotational speed resulted in lower tensile strength mostly due to the increase in the amount of the intermetallic compounds formed at the Al/Cu interface [27]. Furthermore, in the stir zone, the hardness was slightly higher than the base metals also due to the formation of hard and brittle intermetallic compounds of $CuAl_2$, CuAl and Cu_9Al_4 in the stir zone [27].

Saeid *et al* [20] achieved maximum tensile shear strength of lap joint between aluminum and copper through FSW at welding speed of 95 mm/min. Due to the formation of high amount of microcracks in the dark area at welding speeds of 30 and 60 mm/min, the tolerable tensile shear was lower than that of 95 mm/min. While at higher welding speeds of 118 and 190 mm/min, the cavity defects were produced and again tensile shear strength decreased compared to 95 mm/min [20].

In addition to the tensile testing and microhardness, Akinlabi *et al* [20] measured the electrical resistivity of the welds. The results ranged between 0.087 and 0.1 μΩ. It was observed that the welds with the highest electrical resistivity of 0,101 μΩ were measured in those welds produced with high heat inputs.

In most of the above reviewed research outputs, friction stir welding could be in the future the most used joining technique of dissimilar materials, however more research needs to be done to improve the mechanical properties of the welds.

C. FSW TOOLS USED FOR ALUMINIUM AND COPPER

In most of the research work conducted on FSW between aluminium and copper, the tool geometry and design is generally not fully disclosed which may be due to proprietary reasons. Although tool geometry is a very important factor for producing sound welds. Rai *et al* [11] conducted a review on FSW tools but did not provide much information on FSW tools used for the joining of aluminium and copper in particular. Nevertheless, few researchers disclosed the tools used in their studies to friction stir weld aluminium to copper. Akinlabi *et al* [33] successfully welded 5754 aluminium alloy and C11000 copper by employing the threaded pin and concave shoulder tool machined from H13 tool steel and hardened to 52 HRC.

Abdollah-Zadeh *et al* [19] joined Aluminium alloy 1060 rolled plate to commercially pure copper with thicknesses of 4 and 3 mm using a SPK quenched and tempered tool steel and had a shoulder diameter of 15 mm with a threaded pin of 5 mm diameter and 6.5 mm long. Galvão *et al* [24] used conical and scrolled shoulder tools to weld oxygen-free copper with high phosphorous content (Cu-DHP, R 240) and AA 5083-H111. Whereas, Esmaeili *et al* [17] used a hot working alloy steel which was hardened to 45 HRC to weld AA 1050 to brass ($CuZn_30$). The cited tool used was composed of a 15 mm diameter shoulder and a tapered slotted pin [17]. Saeid *et al* [20] produced weld between rolled plates of 1060 aluminum alloy and commercially pure copper by using a quenched and tempered tool steel. The tool had a 15 mm diameter shoulder and a left-hand threaded pin (φ5mm×6.5 mm).

Furthermore, Li et *al* [31] used a tool with a concaved shoulder and a cone-threaded pin of 16 mm in diameter and 5.2 mm in diameter respectively. The tool pin was 2.75 mm in length to weld pure copper and AA 1350.

Agarwal *et al* [25] used a tool made of AISI H13 tool steel and High Speed Steel (HSS) and had a shoulder 18 mm and 15 mm in diameter and the tool pin 7 mm in diameter and 3.7 mm pin length [25]. The above cited tool was used to weld AA 6063 to commercially pure copper plates. Guerra *et al* [28] successfully joined AA 6061 with a thin high purity copper one-piece pin and shoulder from D2 tool steel heat treated to HRC62. The nib was 6.3 mm diameter and 5.8 mm long with standard 0.25/20 right-hand threads and 19 mm diameter shoulder. FSW tools are of importance in successfully joining similar and dissimilar materials because tools produce the thermomechanical deformation and workpiece frictional heating necessary for friction stirring. Therefore, it is necessary to further improve the FSW tool geometry especially for dissimilar materials to produce high quality welds.

III. CONCLUSIONS AND FUTURE RESEARCH

FSW process is an eco-friendly solid state joining technique compared to the conventional welding techniques. The joining of aluminium to copper using FSW has been reviewed to open a research window to researchers in order to expand the technique to other aluminium and copper alloys with the aim of achieving optimised parameters thereby leading to the commercialization of joints between these materials. Research on friction stir welding between aluminium and copper has not yet been thoroughly researched; much of the work has been focused on welds characterizations and study of the material flow. There is however, a strong need in developing the industrial applications of FSW between aluminium and copper in the manufacturing sector for the enhancement of the industries. Thus, the use of the FSW technique to join aluminium and copper alloys and material shapes is of importance in the development of their industrial applications.

In summary, the review of the friction stir welding of dissimilar materials focusing on aluminium and copper has been successfully conducted. This will provide a comprehensive insight for the current and also provide the current state of research on FSW between aluminium and copper in order to fill the gaps with new research approaches and ideas. Furthermore, new studies on FSW between aluminium and copper with respect to the process optimization and selection of cost effective FSW tools to produce sound welds still needs to be developed.

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