Micro-Friction Stir Lap Welding of Aluminum and Copper: A Short Review

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ABSTRACT

This review article examines the recent progress in Micro-Friction Stir Lap Welding (μFSLW) of Al-Cu thin sheets, comparing the differences in tool geometry and processing parameters of macro-scale and micro-scale Friction Stir Lap Welding (FSLW) of Al-Cu plates. The effect of microstructural evolution, intermetallic formation, hardness distribution, mechanical joint strength, and electrical conductivity is discussed in detail. The most common defects in μFSLW, such as voids, tunnel defects, and hook formations, along with their impact on heat input and tool movement, are examined. Additionally, strategies to improve joint quality, including the addition of engineering interlayers (e.g. zinc foil) and nanoparticles (e.g. graphene), are explored as they mitigate brittle IMCs, improve grain structure, and

enhance both mechanical and electrical properties. Important research gaps, regarding the effects of tool tilt angles and complex tool profiles on the mechanical and electrical joint properties, are highlighted as the potential benefits of assistive technologies, such as ultrasonic vibration, assistive heating and cooling, and assistive magnetic field. Future work is essential to enhance the μFSLW of Al-Cu, investigating complex tool geometries, and improving process parameters.

Keywords-aluminium and copper; dissimilar materials; lap joint; micro-friction stir welding; thin sheets

I. INTRODUCTION

Friction Stir Welding (FSW) is a versatile, energy-efficient, and eco-friendly solid-state joining process that enables the welding of dissimilar materials, such as aluminum (Al) and copper (Cu) alloys [1]. Several studies have investigated the FSW of Al-Cu alloys [2-10], examining the impact of crucial parameters, including tool geometry, plunge depth, rotation speed, and material positioning, on weld quality in both butt and lap joint configurations, along with the microstructure, Intermetallic Compound (IMC) formation, weld surface roughness, and joint resistivity. However, some studies do not distinguish between plates that are few millimeters thick and thin sheets of 1 mm thick or less. Additionally, discussions often do not separately address butt welding and lap welding. As the push for responsible consumption and production becomes one of the Sustainable Development Goals (SDGs), reducing and lightweighting electronic devices by downscaling the component sizes have become extremely important. Hence, there is a demand for joining not only macro-scale aluminum and copper plates but also micro-scale aluminum and copper thin sheets. One example is the welding of aluminum battery tabs to copper busbars in a lithium-ion battery pack for electric vehicles [5, 11], making it possible to have copper cladding over a small area [12]. While defect-free FSW joints have been reported for Al-Cu plates in both butt and lap configurations, and for thin sheets in butt configurations, there is a gap in lap configuration research of μFSLW of Al-Cu sheets. This article provides a comprehensive review of aluminum-copper friction stir lap welding, highlights the existing challenges, and identifies research gaps that could lead to producing microstructurally defect-free joints.

A. *Overview of Friction Stir Welding and the Challenges of Downsizing*

FSW joins materials without melting, requiring less energy, no existence of shielding gas, and is therefore more eco-friendly. Since no melting occurs, solidification induced defects are eliminated, improving the overall weld joint quality. Other advantages of FSW over conventional fusion welding include the absence of volatile alloying element losses, reduced residual stress, and enhanced fatigue strength due to the absence of fusion material [13]. Additionally, avoiding high-temperature processing often means less potential of porosity existence, hot-cracking, and a reduced amount of IMC. During FSW, a non-consumable tool forms frictional contact with the workpiece, generating heat that softens the materials. Additional heat is produced as the materials undergo severe plastic deformation due to the combined rotation and translation of the tool [13]. Despite its multiple benefits, FSW has some limitations, including difficulties in welding complex shapes and the inevitable introduction of an exit hole.

Micro-Friction Stir Welding (μFSW) refers to FSW applied to sheets with a thickness of 1000 μm or less [14]. It is useful for joining soft metals and metal alloys with lower melting points [15]. A typical μFSW setup is illustrated in Figure 1. Similar to FSW, it consists of workpieces (e.g. copper and aluminum sheets) placed between top cover plates (e.g. Bakelite) and support plates (e.g. ceramic and steel) using clamps or fixtures. The FSW tool, positioned at the center of Figure 1, contacts the workpieces, traverses, and stirs along a designated path.

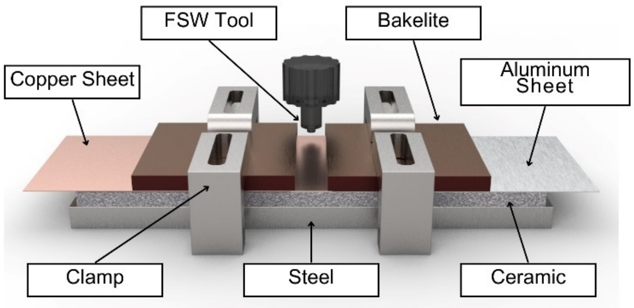

Fig. 1. A typical μFSW setup.

When workpieces are downscaled, the smaller volume of material available for stirring leads to challenges not usually observed in conventional FSW. Specifically, the precision in plunge depth becomes much more critical. In addition, the downscaling of the tool size due to the limitations of sheet thickness makes it much more difficult to fabricate intricate features on its probe or pin. A smaller apparatus size translates to a smaller heat source. In thin sheets, heat dissipates faster because of the relatively larger surface-to-volume ratio of the workpiece. The combination of a smaller heat source and a greater heat dissipation can often result in improper mixing and subsequently welding defects, the elimination of which requires tight control of the welding parameters. In other words, a narrowing processing window of welding parameters is expected when downscaling from FSW to μFSW. Moreover, thin sheets can shear easily. Micro-defects that can be often overlooked in a thick workpiece, now exert a domineering role in degrading the mechanical and electrical properties of the weld joint [13]. The aforementioned challenges are presented in Figure 2. Numerical analysis has been attempted to simulate some of these challenges [16].

To reduce heat loss, clamping fixtures and back materials with low thermal conductivity are often utilized [17, 18]. However, when welding dissimilar materials, inherent differences in mechanical and thermal properties further complicate the FSW process. The disparity in flow characteristics can hinder homogeneous material mixing, while the material with a lower softening temperature is more likely to produce flashes [13].

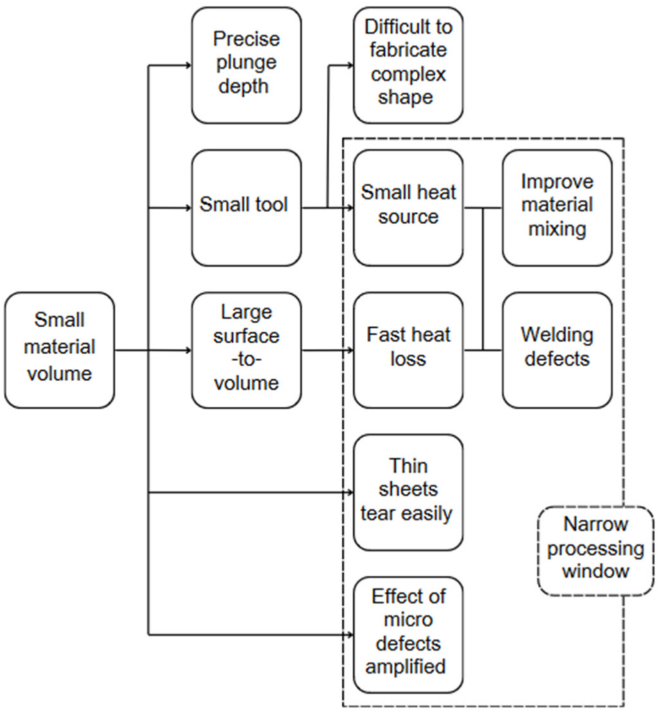

Fig. 2. Challenges of downsizing from FSW to μFSW.

B. *Micro Friction Stir Butt Welding*

Micro Friction Stir Butt Welding (μFSBW) refers to friction stir butt welding of sheets with a thickness of 1 mm or less. Successful μFSBW experiments on dissimilar aluminum alloys, aluminum-copper alloys, aluminum-magnesium alloys, and brass-copper alloys have been reported [13]. Specifically, the μFSBW of Al-Cu was extensively studied, and joints without microstructural defects were obtained [19-22]. Al-Cu sheets that underwent μFSBW could further be cold-rolled to make welded blanks and coils [23]. The mechanical joint strength is often measured in terms of Joint Efficiency (JE) by comparing the joint strength with that of the base material.

$$JE = \frac{Ultimate\ Joint\ Strength}{Ultimate\ Base\ Metal\ Strength} \quad (1)$$

With regard to dissimilar aluminum alloys, authors in [24] reported a peak tensile joint strength that is 69% of that of the AA 6082-T6 base material (330 MPa), when welding it to AA 2024-T3, both 0.8 mm thick. In [25], μFSBW was produced between 1 mm thick AA5052-H32 and 1 mm thick AA 6061-T6 with a peak tensile strength of 172.4 MPa. Similarly, the dissimilar 0.8 mm thick AA 2024-T3 and AA 6082-T6 μFSBW joint was reported to be 260 MPa [26]. Authors in [27] managed to obtain welding of the same materials, and the sample's peak tensile strength was 86.7% of the base AA 5052 material strength or 222.63 MPa. Authors in [28] reported a peak tensile strength of 236.2 MPa (or 82.9% of Cu base material) in the butt joints of 1 mm thick AA 6061-T6 and T2 copper. A peak tensile strength of 42.5% of the base material strength was calculated in [22], by joining 0.8 mm thick AA 5052 and pure copper. In [29], μFSBW was obtained between 0.6 mm thick H62 brass and T2 copper, and the sample's tensile strength was 194 MPa, equivalent to 82.6% of the T2 copper strength. In butt welding, it may be difficult to achieve uniform thickness on both sides of the sheets and obtain a good surface finish due to the differences in material flow [13].

C. *Micro Friction Stir Lap Welding*

μFSLW refers to FSLW of sheets with a thickness of 1 mm or less. Despite its potential advantages, very few published studies have reported successful Al-Cu μFSLW, and microstructural defects are almost always present in these joints. Moreover, in this kind of research, joint strength is significantly lower than that of μFSBW and lap welding of thicker plates (i.e. peak tensile strength of 38 MPa [5]), or is not reported at all. Some attempts at Al-Cu lap welding have combined both lap and butt joint configurations [30-32]. Table I summarizes the μFSLW reports on joining thin Al-Cu sheets published in the last 21 years. Other published works on Al-Cu FSLW involved workpieces with thicknesses of more than 1 mm, and therefore were not considered μFSLW. Most FSLW works before downscaling Al-Cu had aluminum placed on top of the copper [12, 33], and could include an interlayer between the top and bottom plates [34]. It had been argued that such configurations resulted in greater heat input when lap-welding thicker aluminum alloy and copper plates, due to the lower thermal conductivity, and hence lower frictional heat dissipation in the aluminum alloy in direct contact with the tool shoulder [5]. It was also claimed that the harder material (i.e. copper) is mostly placed beneath the softer material in the lap configuration [3]. Nevertheless, successful Al-Cu μFSLW was more often reported when copper was placed on the top. The past successes in placing aluminum at the top do not seem to carry over when the workpieces are downscaled, probably due to the challenges related to the reduced thickness of the workpieces.

II. IMPORTANT PARAMETERS IN FRICTION STIR WELDING AND MICRO-FRICTION STIR LAP WELDING

A. *Tool Materials*

The FSW tool influences the heat generated during the process, the acceptable range of the operation parameters, and therefore, the mechanical properties of the weld joint. It needs to maintain its geometry and features during the process. A wear-resistant and easy-to-machine tool that remains hard at the welding temperature, which has great fracture toughness and does not react with the workpiece is desirable. Heat-treated high-speed steel and hardened tool steels are common choices, although the latter can wear out due to low thermal stability [5]. Among the summarized μFSLW works, as displayed in Table I, those in [12, 35, 38] did not specify the tool materials, those in [11] did not specify the type of tool steel. In [36], SKD61 tool steel was utilized, while in [39], the H13 tool steel was used.

TABLE I. SUMMARY OF SHEET THICKNESS, PROCESS PARAMETERS, AND JOINT EFFICIENCY IN MICRO-FSLW OF DISSIMILAR AL-CU MATERIALS

Sheet thickness (mm)	Process parameters	Test type, JE, and peak load	Reference
1.9 Pure Cu 0.9 Pure Al	Rotation: 800 rpm Welding: 50 mm/min Dwell: 25 s Tilt angle: 0^o	-	[35]
2.0 Pure Al A1100H24 (with and without 50 µm zinc interlayer) 1.0 tough pitch copper	Rotation: 41.7 s-1 (~1255 rpm) with interlayer 33.3 s-1 (~1002 rpm) with interlayer Welding: 5 mm/s (~300 mm/min) without an interlayer 3.3 mm/s (~198 mm/min) with an interlayer Tilt angle: 3^o	Peel test, About 2.1% and 4.0% (Assuming A1100H24 ultimate tensile strength of 130 MPa) Peak loads at 276 N and 526 N, with and without interlayer, respectively.	[36, 37]
1 Cu-DHP (R240) 6 heat-treatable AA6082-T6	Rotation: 600 rpm Welding: 50 mm/min Tilt angle: 0^o	-	[12]
1 Cu-DHP (R240) 6 non-heat-treatable AA5083-H111 or heat-treatable AA6082-T6	Rotation: 750 rpm Welding: 160 mm/min Tilt angle: 0^o	-	[38]
0.3 Pure Cu 0.2 Al alloy	Rotation: 2500-3000 rpm Welding: 50-60 mm/min Plunge Depth: 0.4 Dwell: 5 s Tilt angle: 0^o	-	[11]
0.5 T2 Cu 0.5 AA5052	Rotation: 1500 rpm Welding: 50-70 mm/min Plunge Depth: 0.55 Tilt angle: 0^o	Tensile test, 7.8% - 8.7% 2.4 – 2.7 kN or 18.3 to 20.3 MPa	[39]

B. Tool Geometry

An ideal tool geometry design can be utilized to enhance the process parameter window. Previous studies on FSW of Al-Cu materials indicate that shoulder geometry, diameter, surface profile, and pin characteristics affect plasticized materials during welding. Shoulder diameter directly influences frictional heat generation, whereas pin affects the formation of IMCs. The strength of the joint can be optimized by employing a thicker, shorter pin [5]. Generally, the pin length is 0.2 - 0.3 mm shorter than the workpiece thickness [7].The geometry of the tool also impacts the formation of defects. A narrow shoulder combined with a large pin can cause tunnel defects, and a narrow shoulder at high welding speed can cause surface cracks. The material flow, the size of the stir zone nuggets, and the joint microstructure (i.e. shape and size of the stir zone, type, amount, and distribution of IMCs) are strongly related to the shoulder's surface profile. A concave shoulder (with an angle of 2^o-10^o) with a smooth surface, as illustrated in Figure 3, is proposed as optimal to obtain defect-free joints.

However, the above observations may not be applied to the µFSLW of Al-Cu materials. The size of tools is limited by the workpiece sheet thickness, which makes their features difficult to machine. Table II presents a summary of the tool geometry that was reported to have produced the optimal Al-Cu joints of ultra-thin (≤ 1 mm thick) sheets, in terms of either mechanical joint strength or any quality highlighted by the authors. These tools have cylindrical shoulders and featureless pins. The end surface profiles of the shoulders can be flat or concave. No successful micro-scaled joints have been reported using scrolled features (i.e. protrusion in "S" shape), unlike the ones in µFSLW of Al-Cu [38].

TABLE II. TOOL GEOMETRY, PIN GEOMETRY, AND PIN TIP PENETRATION THAT PRODUCED THE BEST MICRO-FSLW AL-CU JOINTS

Tool geometry (mm)	Pin geometry (mm)	Shoulder-to-pin diameter ratio	Pin tip penetration into the bottom workpiece (mm)	Reference
Diameter: 12 Flat end surface	Diameter: 2.8 Length: 2.6	4.29	-	[35]
Diameter: 10 Concave shoulder angled about 4.9^o	Diameter: 3.0 Length: 1.7	3.33	0 to 0.1	[36, 37]
Diameter: 9.5 Concave shoulder angled about 8^o	Diameter: 3.0 Length: 1.0	3.17	- (at a tool axial force of 4.5 kN)	[12]
Diameter: 10 Concave shoulder angled about 8^o	Diameter: 3.0 Length: -	3.33	-	[38]
Diameter: 6 Flat end surface	Diameter: 3.0 Length: 0.3	2.00	0.1	[11]
Diameter: 6 Flat end surface	Diameter: 2.0 Length: 0.35	3.00	0.05	[39]

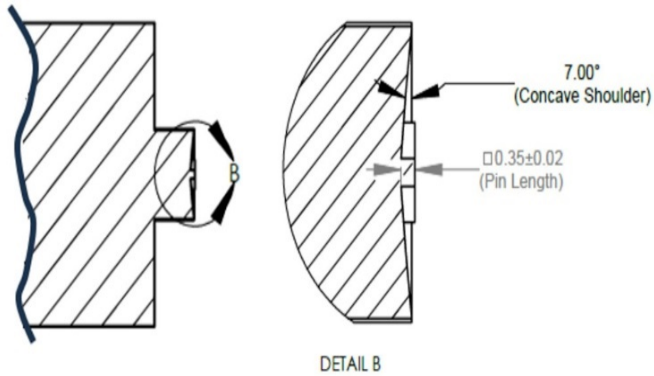

Fig. 3. A typical tool with a concave but featureless shoulder.

It is worth noting that the reported penetration into the bottom workpiece ranges from 0.0 to 0.1 mm. This slight penetration seems to enable better joining, consistent with [36]. In all the successful μFSLW, the ratio of tool shoulder diameter to pin diameter ranges from 2 to 4.29, which encompasses and extends slightly beyond the recommended range of 3 to 4 [13], but still within 2 to 5 [7]. No successful μFSLW has been reported on the use of a tool without pins.

C. Processing Parameters

The most commonly used μFSLW processing parameters are plunge depth, welding speed, tool rotational speed, and tilt angle. Plunge depth must be precise and is usually fixed; otherwise, a viable joint may not form. Higher welding speed leads to lower heat input, whereas increased rotational speed results in more heat. An optimum heat input is often desired. Excessive heat can lead to thick IMCs formation, which are susceptible to macro-cracking, flashes, high residual stress, and grain coarsening, all of which negatively affect the mechanical properties of the joint. However, insufficient heat (i.e. "cold weld") impedes proper material mixing, leading to various joint defects [5, 7, 11-13].

1) Plunge Depth

Plunge depth, also known as pin insertion depth, is better referred to as the geometrical position of the tool pin tip into the bottom workpiece during the FSLW. In pinless tools, it is a measure of the distance that the shoulder extends into the upper workpiece, rather than just contacting it. For aluminum/steel FSLW, a pin penetration depth of 0.1, 0.2, or even 0.4 mm into the bottom steel has led to better material mixing [3]. Slight penetration usually promotes Al-Cu joining, but in some cases, sound joints were reported even without pin penetration [5]. In μFSLW of Al-Cu, plunge depths are typically ≤ 0.1 mm. At this scale, material penetration may or may not happen at a plunge depth of 0.1 mm, as the tool plunge deforms the top workpiece rather than piercing through it. Excessive plunge depth often causes penetration, leading to unsuccessful joining and torn top workpieces.

2) Welding Speed

The welding speeds reported on successful Al-Cu μFSLW in Table I range from 50 to 70 mm/min, except those reported in [38] (160 mm/min). In [36], the welding speeds varied (i.e. 3.3, 4.2, and 5 mm/min) and a general decrease was observed in the fracture load as the welding speed increased. This trend aligns with the findings in [5], where 6-mm thick Al-Cu butt welding was performedat 50 to 80 mm/min. Similarly, authors in [37] reported sound lap joining of 0.5 mm thick Al-Cu sheets at 50 and 70 mm/min, with samples at 50 mm/min having fewer defects and less joint resistance but similar tensile strength to those at 70 mm/min.

3) Rotational Speed

Unlike welding speed, the range of acceptable rotational speeds is much wider, namely from 600 - 3000 rpm. Rotational speed may be the last process parameter to fine-tune as it is probably the most forgiving in μFSLW Al-Cu sheets. Higher rotational speeds generate more heat, softening the workpieces for a larger mixed material zone inside the nugget, causing more uniform material mixing [5]. Authors in [36] increased the rotational speeds from 16.7 s^{-1} to 41.7 s^{-1} at different welding speeds and observed a general increase in the fracture load. Peel test specimens produced at rotation speeds between 25.0 s^{-1} and 41.7 s^{-1} had joints fractured at the IMC sites -the weakest link. It has been remarked that FSW Al-Cu joint electrical resistivity is proportional to heat input [6]. This seems to remain true after downscaling, as authors in [11] found that lower rotational speed produced more electrically conductive Cu-rich IMCs, which are corrosive resistant.

4) Tilt Angle

Among the studies summarized in Table I, a zero-tilt angle was used, except for [36], where a 3^{o} tilt was applied. A slight tilt is believed to increase forging for better material flow through vertical and horizontal stirring of plasticized material [3].

III. JOINT QUALITY

The required mechanical and electrical properties of Al-Cu joints depend on their intended applications. Generally, it is desirable to have a joint with high strength and low electrical resistance to ensure an effective electrical connection. The microstructure and hardness are often analyzed as they are strongly related to mechanical strength and electrical conductivity. The presence of IMCs and voids in weld joints can reduce mechanical strength, ductility, and electrical conductivity [40]. No studies have reported so far achieving defect-free Al-Cu joints utilizing μFSLW, except for [35], where butt joining was combined with lap joining employing a 1.9 mm thick copper plate over a 0.9 mm thick aluminum sheet. Although authors in [36-37] did not report any microstructural defects, they also did not account for variations in peel strength observed in their welded joints. Furthermore, their top aluminum plate was 2 mm thick.

A. Mechanical Joint Strength

High mechanical joint strength is often associated with adequate material mixing, interlocking at the interface, a thin IMC layer, and no defects. Joint strength is often evaluated using tensile shear tests [5]. However, no test standards exist for varying joint widths, which depends on the tool shoulder diameter when existing test standards for adhesive bond, such as ISO 4587:2003, DIN EN-1465, and ASTM D1002, are usually adopted.

In FSLW of Al-Cu plates, peak joint strength efficiency can reach 78% of Cu or 74% of Al parent materials [41]. In case of μFSLW of Al-Cu sheets, the peak joint strength efficiency is rarely reported and is lower than 10% [37].

B. Electrical Conductivity

An electrical characterization test is usually conducted by using a high-precision ohmmeter [42] or four-wire measuring techniques [11]. Al_2Cu and Al-Cu IMCs decrease mechanical joint strength, while electrical resistivity is increased. In a previous FSBW study, authors indicated that strong Al-Cu joints exhibit better electrical conductivity, as fewer defects prevent crack propagation, which would otherwise increase electrical resistance [5]. In μFSLW, authors in [10] reported the effects microstructural variations in the weld zone had on the electrical resistance of the joint. Although the Kirkendall void formation at the copper side under extreme heat increased, the joint electrical resistance, charge-carrying Cu-rich IMCs, such as Al_4Cu_9 and $AlCu_4$, formed at lower heat, exhibited the opposite and desirable effect. Unfortunately, the mechanical joint strength was not measured in [10], and therefore the electrical conductivity was not related to the mechanical performance of the joints. Authors in [37] suggested that higher joint strength does not necessarily lead to increased conductivity, as the latter also depends on defect volume, grain size, and IMCs composition (i.e., Cu-rich or Al-rich). They also reported that some samples displayed electrical conductivity that was slightly greater than the average of the parent materials (i.e. average joint electrical resistance of 0.155 mΩ compared to aluminum's 0.227 mΩ). This is in contrast with the findings of [42], where FSBW Al-Cu plate joints displayed lower and closer conductivity to the aluminum parent.

C. Microstructure

When joining different materials, a brittle and hard IMC layer often forms at the interface. This layer should be minimized, as it reduces ductility and electrical conductivity, hinders material mixing, and serves as a corrosion initiation site [5, 13]. Thin IMCs can improve joint strength and hardness [3, 5]. IMCs are typically revealed by metallographic etching [43]. The IMC formation was supposed to depend on the welding temperature, as different IMCs have different melting points. $CuAl_2$ melts at around 660 °C, while Cu_9Al_4 melts at 1030 °C. Common phases detected in previous studies, ranked by low-to-high activation energy, include: Al_2Cu, AlCu, Al_3Cu_4, Al_2Cu_3, and Al_4Cu_9 [3, 4]. It is observed that Al_2Cu and AlCu are often traced together, which leads to increased electrical conductivity. They are formed above the recrystallization temperature of Cu, they dissipate heat faster, and are generally harder [5, 11]. Although welding temperatures remain much lower than the melting points, IMC formation is attributed to interdiffusion under extreme deformation and mechanical stirring, resulting in a complex microstructure [7, 13]. Authors in [5] observed the strengthening effect of Al_4Cu_9 IMC at the interface of Al-Cu lap joint when welding the 3 mm thick aluminum alloy and copper plates. IMCs was detected using a microhardness test and Energy-dispersive X-ray Spectroscopy (EDS) analysis. Upon annealing, new IMC phases may form and their thickness may grow. Most published literature has focused on the stirred zone and the Thermal-Mechanically Affected Zone (TMAZ) when reporting the microstructure of Al-Cu FSW joints [4]. The interactions of the base materials mostly occurred in the pin zone, which is evident in micrographs even when not explicitly stated in the reports. The sketches in Figure 4 portray the important features of the microstructure reported in the published literature of Al-Cu μFSLW.

Authors in [11] observed micron-sized grains in the nuggets and nano-grains in the aluminum layer due to the use of a small pin, the occurrence of recrystallization, and insufficient heat input for grain growth. Authors in [36] reported grain coarsening in the advancing side of the aluminum top sheet and did not discuss the TMAZ issue. In [11, 38] the material interaction was restricted to the pin zone, as can be seen in Figure 4(a), where a larger TMAZ appeared in joining copper and heat-treatable aluminum alloy, compared to non-heat-treatable aluminum alloy. Complex intercalated lamellae of copper and aluminum were detected in the stirred zone, as depicted in Figure 4(b), similarly to those found in butt joints. However, significant weld defects, like voids or tunnels, were also observed. This is consistent with the findings of authors in [39], who noticed intercalated lamellae of copper and aluminum in the microstructure of welds produced at 50 mm/min, along with significant tunnel defects in the lamella band and the copper layer close to the Al-Cu interface, as illustrated in Figure 4(c). These defects became more severe and were shifted further from the interface, as the lamella bands diminished and were replaced by a very thin layer of lamellar IMC at the Al-Cu interface when the welding speed increased to 70 mm/min. Interestingly, the lamella structures reappeared at 80 mm/min, together with hook defects, voids, and tunnel defects. At welding speeds of 50 mm/min and 80 mm/min, the stirred zone appeared in the pin zone and was discontinuous. Nuggets appeared at both the advancing and the retreating sides. No obvious stirred zone was evidenced at a welding speed of 70 mm/min.

In [36], joints produced with a rotational tool speed of 25.0 s^{-1} or higher exhibited brittle fractures, mainly at the grey IMC structure consisting of Al_4Cu_9 and AlCu. Joints formed at rotational speeds between 25.0 s^{-1} and 41.7 s^{-1} displayed a black microstructure, mostly in the aluminum top sheets close to the Al-Cu interface. The microstructure extended in the direction of the advancing side to the surface of the top sheet, as the welding speed increased, as presented in Figure 4 (d). Additionally, on the copper side, a thin, Al-Cu-rich dark layered structure, as displayed in Figure 4(e), appeared simultaneously with the grey IMC structure, which was distinct from the black microstructure in the aluminum sheet. The stirred zone consisting of refined grains was located in the aluminum top sheet, while the heat-affected zone, was observed next to the stirred zone at both the advancing and the retreating sides. Fragments of copper were exposed embedded in the aluminum near the interface, as shown in Figure 4 (f), which is also demonstrated in [39]. These fragments often had sharp edges that could lead to voids and microcracks [6].

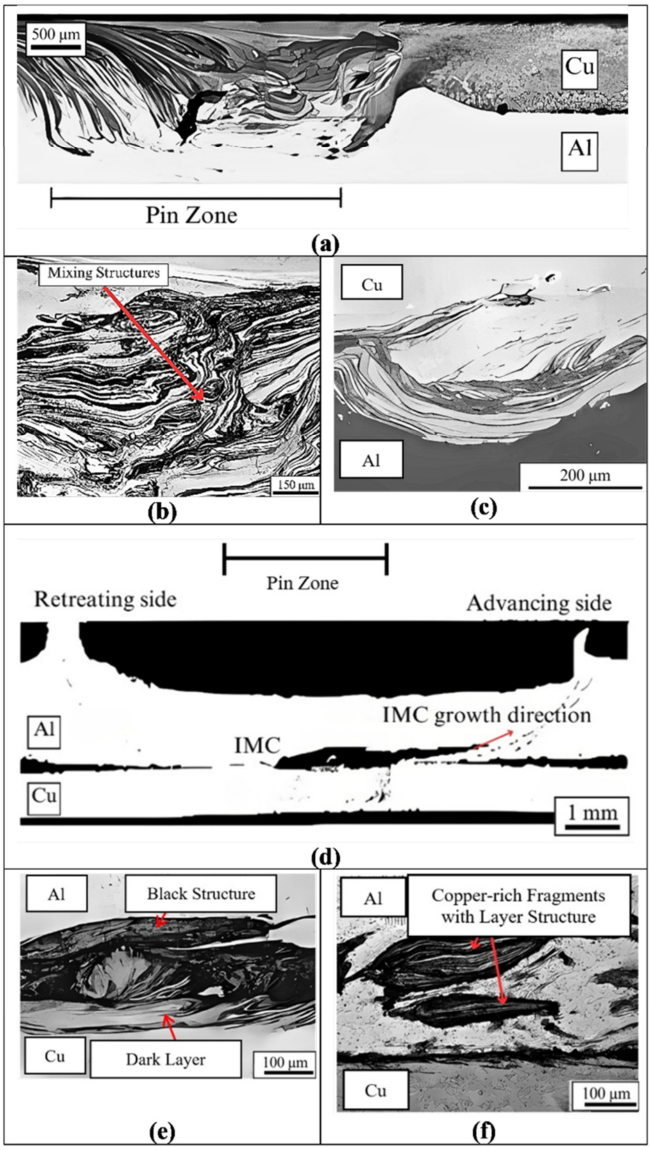

Fig. 4. Microstructure sketches: (a), (b) intermixing of top copper and bottom aluminum material in the pin zone, respectively [11], (c) similar banded structure in [39], (d), (e) Al-Cu black structure and dark layer, and (f) copper-rich fragment with layer structure in [36].

Authors in [30] observed a copper-rich banded structure interspersed with aluminum in the stirred zone on the advancing side. On the retreating side, the boundary of the copper layer moved downwards, forming a significant copper hook-like extension within the aluminum side. The mixing of layers of aluminum and copper due to the mechanical stirring of the pin and elongated grains could be seen at the bottom of the stirred zone at the retreating side [35]. It is safe to say that among the three classes of Al-Cu interactions -known as lamellar intercalated features, homogeneous mixtures, and composite-like structures [4]- the former is the dominant feature observed in µFSLW of Al-Cu, followed by a composite-like structure.

Authors in [4] demonstrated that the presence of hooks is a key feature in FSLW. They are formed when the plunge force pushes the materials underneath the pin upwards, stirring out a hook-like microstructure made up mainly of the base material with some intermixing. A hook was claimed to promote joint strength, since it serves as a mechanical lock at the interface [5]. However, in [39], such hooks were reported as defects that degraded joint strength. The length of the hooks may be of great influence and shorter hooks, such as those in [44], may be desirable. Table III summarizes the defects observed in µFSLW of Al-Cu.

TABLE III. DEFECTS IN MICRO-FSLW OF DIFFERENT AL-CU MATERIALS

Reference	Observed Defects
[35]	Defect-free joint was reported in the combined butt-lap welding.
[36, 37]	Surface flashes were observed. No obvious microstructural defects were reported. Aluminum top plate thickness was 2 mm (> 1 mm).
[12,38]	Volumetric defects were large voids between non-heat-treatable Al and Cu, and small voids at the nuggets in heat-treatable Al, as shown in the black strip in Figure 4(a). Surface defects included massive flashes when using heat-treatable Al, but little flashes when using non-heat-treatable Al.
[11]	Volumetric defects included Kirkendall voids, partial detachment of copper from Al at the interface. Surface defects were massive flashes.
[39]	Volumetric defects were voids, tunnels, gaps near the interface. Surface defects included minor flashes at the sides of the weld line and grooves along the weld.

Common defects in µFSLW include tunnel defects and cavities, owing to either excessive heat input leading to thermal stresses or limited heat input causing insufficient material flow, besides contributing factors, such as plate positioning, tool pin offset, and profile [5, 45]. In the µFSLW of 0.5 mm thick Al-Cu, severe tunnel defects were noticed in samples prepared at a medium weld speed (i.e., 70 mm/min) relative to those found at a low speed (i.e., 50 mm/min), and flashes when the welding speed was below 100 mm/min [39]. Unlike the excellent surface finish typically achieved in FSW of similar materials, FSW of Al-Cu does not always produce consistent surface quality [4]. The surface finish of FSLW Al-Cu joints tends to deteriorate with increasing rotational speed and decreasing welding speed [41].

D. Hardness

Microhardness tests are commonly conducted to identify the presence of hard and brittle IMCs in the weld joint, the distribution of Cu fragments within the Al base, and the distinction between the stirred zone, TMAZ, Heat Affected Zone (HAZ), and base materials [5]. These tests are typically performed using Vicker hardness settings, such as 100 g load for 15 s or 200 g load for 15 s. Table IV summarizes the Hardness Values (HV) obtained through these methods, with indentation performed either along the interface or from top to bottom.

Authors in [39] conducted indentation tests on the top workpiece to infer the microstructure beneath. In the FSW joint of dissimilar materials, the harness profile typically indicates an inverted U-shape when traced from the advancing side to the retreating side, rather than a "W" shape commonly seen in the welding of similar materials. The peak hardness in the middle is attributed to the stir zone, where refined grain increases hardness due to the Hall-Petch effect. Similarly, the HAZ exhibits the lowest hardness owing to grain coarsening [7]. This remains true in μFSLW of Al-Cu, although the profile can show variance due to the presence of defects (i.e. void and tunnel), the uncontrolled distribution of copper fragments within aluminum matrix [39]. In [34], authors indicated the highest HV within the stirred zone, mainly at the advancing side, due to the presence of hard IMCs at the banded structure. Hardness fluctuations at the advancing side are also notable, as alternating coarse and fine copper grains interspersed with softer aluminum traces in the banded structure. On the retreating side, hardness increased where/and Al-Cu mixing resulted in hard IMC formation. Grain refinement due to the frictional contact between the tool shoulder and the copper top sheet can make certain locales harder than those closer to the interface. In [11], the presence of micro and nano-sized grains in the stirred aluminum region, rather than the intercalated IMC lamellae led to peak hardness in the non-heat-treatable aluminum alloy.

TABLE IV. HV REPORTED AT BASE MATERIALS AND IMCS

Reference	Measurement setting, indentation path	HV of base materials	HV at IMCs
[35]	Vickers at 100 g load for 15 s Along the interface	76 to 95 away from the nugget zone/ IMC	110 to 150
[36, 37]	- Top Al to bottom Cu	Al: Average at 30 Cu: Average at 65	38 to 69
[12]	Vickers at 200 g load for 15 s Along the interface	Al: 85 to 215 Cu:-	Peak around 400
[11]	Nano-indenter at 10 mN and 10 s indentation 3 indentations points, i.e. at Al, Cu, and near Al-Cu interface (IMC)	Al: 66-75 Cu:157-160	Peak around 120
[39]	Indentation at the top	-	-

IV. INCORPORATION OF ENGINEERING MATERIALS

The degradation of joint strength caused by brittle IMC formation in Al-Cu FSLW can be diminished by introducing reinforcement materials. It is evident that many different nanoparticles can enhance FSW joint's properties [46]. Table V highlights the findings of the incorporation of engineering materials in Al-Cu μFSLW. A 0.2 mm zinc foil utilized as an interlayer between a 2 mm thick aluminum top plate and a 2 mm thick copper bottom plate, successfully produced a defect-free joint with a peak shear strength of 28.5 MPa. This finding was attributed to enhanced interdiffusion between Al and molten Zn, along with the extrusion of the Zn-Al liquid phase, containing a slight amount of copper [47].

TABLE V. EFFECTS OF THE INCORPORATION OF ENGINEERING MATERIALS INTO AL-CU JOINTS

Study focus	Results	Reference
Investigation of the effect of a zinc interlayer in FSLW of Al-Cu thin sheets.	Zinc interlayer improved joint strength and shifted failure mode from brittle to ductile. Peak loads increased significantly.	[36]
The use of zinc as a filler metal for Al-Cu joints in friction stir welding.	Achieved defect-free joints with enhanced interdiffusion and extrusion of zinc-aluminum liquid phase.	[47]
Graphene utilization in spot welding of Al-Cu thin sheets.	Improved joint shear strength, microhardness, and electrical conductivity by at least 15%.	[48]
Incorporated graphene nanoparticles in Al-Cu FSW using eccentric tool motion.	Enhanced material mixing and joint strength, but noted agglomeration issues with graphene.	[49]
Analyzed graphene's effect on Al-Cu mixing and joint properties in friction stir welding.	Improved electrical resistance due to better mixing, but no significant change in mechanical strength due to particle agglomeration.	[50]

In μFSLW of Al-Cu sheets, the use of a 0.05 mm thick zinc foil between a top aluminum sheet and a bottom copper sheet almost tripled its mechanical joint strength [36]. The zinc layer inhibited the thickening of the grey IMC structure, which was the major brittle failure site when the zinc layer was absent. It also prevented the growth of the black IMC at the aluminum top sheet near the interface and the deposition of copper fragments into the aluminum. Additionally, the presence of zinc shifted the crack path formed at the Al-Cu-rich layered structure at the copper side instead of the grey structure at the aluminum side. Fractography demonstrated a larger ductile fracture area with mostly copper content, indicating a transition from brittle to ductile failure. The Cu-Zn IMCs (i.e. $CuZn_2$, $CuZn_5$, and Cu_5Zn_8) were mostly found in the aluminum top sheet, whereas fracture-prone Al-Cu IMCs (i.e. Al_4Cu_9, AlCu, Al_2Cu) were particularly observed in the copper bottom sheet.

Graphene additives enhance mechanical properties by preventing grain growth through Zener's pinning effect. Movement restrictions cause local dislocation accumulation, promoting dynamic recrystallization, and subsequently improved mechanical properties [48]. Authors in [49] incorporated graphene nanoparticles into the butt joint of 6 mm thick Al and Cu plates through eccentric weave friction stirring tool motion. The findings indicated uniform dispersion of the particles, adequate mixing of the materials in the joints, and increased joint strength. Similarly, authors in [50] observed that the addition of graphene enhanced Al-Cu mixing by detaching copper fragments. Both materials were then deposited into the aluminum matrix, forming intermixing layers, thereby reducing the electrical resistance of Al-Cu friction stir joints. However, the matrix did not change their mechanical strength, probably due to the presence of agglomerated graphene particles. The closest trial at incorporating graphene into Al-Cu joints via μFSLW was attempted in [48],where a spot welding was utilized to join 0.5 mm thick copper to 1.5 mm aluminum alloy.

The joint shear strength, microhardness, and electrical conductivity of the resulting joints were improved by at least 15%, attributable to grain growth prevention by the finely distributed particles.

V. RESEARCH GAP

This review highlights several research gaps in Al-Cu μFSLW that need to be addressed. Specifically, the effects of tool tilt angles and complex tool profiles on the mechanical and electrical joint properties remain unexplored, as the potential benefits of assistive technologies, such as ultrasonic vibration, assistive heating/cooling, and assistive magnetic field in μFSLW. In addition, the investigations involving thrust force, torque, stress flow on the top and bottom sides, temperature distribution on the workpieces, and the resulting tool wear will greatly enhance the existing understanding of the μFSLW mechanism, which can be eventually harvested for a technological breakthrough.

In terms of relating the microstructure to the mechanical joint strength and electrical conductivity, it will be desirable to understand the relative contribution and significance of grain size, Cu-rich IMCs, and the presence of defects, such as voids, tunnels, hooks, and cracks. It remains unclear whether the morphology of hooks in the microstructure has much role in making them beneficial or detrimental to the mechanical joint strength. Methods to effectively incorporate different nanoparticles into the joints of thin sheets and the types of nanoparticles that improve the mechanical and electrical properties of the joints need to be identified. Since very few simulations or modeling efforts have been reported about Al-Cu μFSLW, such techniques should be used to generate predictions of weld joint qualities and identifying the suitable window of processing parameters upon downscaling from macro to micro friction stir lap welding.

VI. CONCLUSION

Micro-friction Stir Lap Welding (μFSLW) of aluminum-copper sheets presents significant challenges due to the miniaturization of process parameters, the formation of brittle Intermetallic Compounds (IMCs), and tool geometry limitations. None of the previous μFSLW studies that used aluminum and copper sheets of 1 mm thick or less reported defect-free joints, compared to macro-scale Friction Stir Lap Welding (FSLW), with common defects including tunnels, voids, and hooks.

The mechanical joint strength of μFSLW Al-Cu, with peak tensile shear strength ranging from 18.3 MPa to 20.3 MPa and joint efficiency of 7.8%-8.7% is much lower than the 38 MPa tensile strength in macro-lap welding and joint efficiency of 69%-87% in butt welding of micro-scale sheets. However, μFSLW joints may exhibit better electrical conductivity than that of base aluminum, with a joint electrical resistance of 0.155 mΩ compared to 0.227 mΩ in aluminum. The most common pattern of Al-Cu interaction in the μFSLW is the lamellar intercalated feature. Many approaches have been studied to improve the quality of μFSLW joints. Zinc foil and other interlayers have shown potential in preventing IMC development, reducing brittleness, and improving joint strength. Furthermore, graphene and other nanoparticles have shown benefits in electrical conductivity, mechanical characteristics, and grain fragmentation. Future studies should concentrate on creating predictive models for μFSLW of Al-Cu, investigating intricate tool geometries, and optimizing process parameters.

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