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Review

A Review of the Friction Stir Welding of Dissimilar Materials between Aluminum Alloys and Copper

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Abstract: With the rapid development of various industries, the connection of copper and aluminum is in high demand. However, as a solid-phase connection technology, friction stir welding has a potential application prospect in the connection of copper and aluminum. This paper comprehensively summarizes the most recent 20 years of the literature related to the friction stir welding of copper and aluminum. The application significance of copper and aluminum connectors is introduced, and the research field of the friction stir welding of copper and aluminum is analyzed and explored from the aspects of welding technology, microstructure and mechanical properties, as well as innovations and improvements in the welding process. In view of the research status of this field, the authors put forward their views and prospects for its future, aiming to provide a basis for researchers in this field.

Keywords: copper; aluminum alloys; friction stir welding; research status

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Citation: Sun, Y.; Gong, W.; Feng, J.; Lu, G.; Zhu, R.; Li, Y. A Review of the Friction Stir Welding of Dissimilar Materials between Aluminum Alloys and Copper. *Metals* **2022**, *12*, 675. https://doi.org/10.3390/met12040675

Academic Editor: Sergey Malopheyev

Received: 1 March 2022
Accepted: 7 April 2022
Published: 14 April 2022

1. Introduction

The welding of materials has been a significant concern of various industries. In the past, the field of material welding has been limited to the welding of similar materials. However, with the rapid development of various industries and the demand for complex parts in engineering, the welding of similar materials has been far from meeting the needs of the industry, and the welding of dissimilar materials has gradually attracted the interest of researchers. Composite parts joined using dissimilar materials can maximize the advantages of both materials [1]. This can meet the various performance requirements of the parts, but also reduce costs [2]. Because of the technical and economic advantages of dissimilar material connectors, it is of great significance to study the welding of dissimilar materials, which holds great promise [3], and will become the development trend of welding problems in various industries [4]. At present, the welding of dissimilar materials has been employed in many industries, such as power generation, chemical, petrochemical, nuclear, aerospace, transportation, electronics industry and military [5–11]. Specifically, the welding of dissimilar materials is used in aero-engines, aerospace propulsion systems, metal ducting structures, ceramic metal structures, bimetal components for aerospace instruments, advanced Al/Cu radiators, Al/St joint structures for the automotive industry, etc. [12]. To date, researchers have studied the welding of dissimilar materials, such as aluminum alloy (AA)–steel, AA–magnesium alloy, AA–copper, AA with different series and AA–titanium [13–16].

It is well known that copper (Cu) has a good electrical conductivity, ductility, low temperature plasticity and corrosion resistance [2,16]. However, the prices of Cu and Cu alloy have become expensive and unstable in recent years [2,17]. For structural parts, because of the high density of Cu and Cu alloys, the use of Cu and Cu alloys alone is not conducive to reducing the weight of structural parts. The density of aluminum (Al) is only one third that of Cu; Al and AA also have the advantages of high strength, good corrosion resistance, high thermal conductivity, good processing performance, etc. [2].

If Al and AA can replace the part of Cu in the structural parts, when Cu and Al are welded together, the resulting structural parts can play to the advantages of Cu and Al [18–20]. The Al–Cu welding joint combines the advantages of the two, not only having good electrical conductivity, thermal conductivity, corrosion resistance and mechanical properties, but also it can reduce the weight of the structure parts, so, it is widely used in engineering structures [21–25]. For example, in the power industry, Cu–Al transition pieces can replace the bolt joining widely used in transmission [13,14,26]. There are Cu–Al high-power components, large power transformers, and so on. In the electrical industry, Cu–Al connectors can be used as refrigeration tubes and capacitors [27–29]. Heat exchanger tubes in thermal applications are also Cu–Al connectors [1]. In addition, they are also widely used in the transportation industry and aerospace [1,19].

Although the welding of Cu and Al dissimilar materials has a wide range of practical applications, there are still some problems in the welding process. Table 1 shows the basic properties of Al and Cu. We can evidently see, from Table 1, that the basic properties of Al and Cu differ significantly, especially the melting point difference of 400 °C and the mutual solubility being very limited [30]. First, these differences lead to a variety of intermetallic compounds (IMCs) due to the high temperature in the welding process of Cu and Al, especially in fusion welding [11,18,22,23,30–32]. As it is well known, although some IMCs have the characteristics of being hard and brittle, the generation of IMCs in the welded joints of dissimilar materials is a normal phenomenon [33,34], but thicker IMCs will make the Cu and Al atoms in the joints, which work in high temperature environments and vibrate for a long time, to continue to diffuse, thus continuously thickening the IMCs [35]. Second, Al and AA are easy to oxidize to form an oxide film with a melting point up to 2050 °C [34] due to their strong oxidizing properties [36,37], regardless of being in a solid or liquid state, which can hinder further reactions between Al and Cu. Measures should be taken to prevent oxidation during fusion welding and to remove oxides from the molten pool. Third, the difference in the coefficient of the linear expansion between the two materials leads to deformation and stress after welding [37], which leads to defects, such as cracks in the weld joint [22,30,36]. In general, the traditional fusion welding is not completely suitable for Al/Cu dissimilar materials welding, so the research focuses on solid-state welding technology.

Table 1. Crystal structure and main physical parameters of Al and Cu.

Materials	Density (g/cm^3)	Melting Point (°C)	Coefficient of Linear Expansion (/°C)	Crystal Structure	Resistivity (Ω·m)	Thermal Conductivity (W/mK)
Al	2.7	660	2.3×10^{-5}	FCC	2.83×10^{-8}	237
Cu	8.92	1083	1.7×10^{-5}	FCC	1.75×10^{-8}	401

There are many methods of solid-state welding for dissimilar materials, such as explosion welding, diffusion welding, soldering and brazing, friction stir welding, upset welding, flash butt welding, friction welding and ultrasonic welding [20,30,38]. Soldering and brazing have the characteristics of having a short period, needing simple equipment, as well as having low heat temperature, low production cost and small deformation after welding. For Cu and Al welding, a corrosive flux must remove the oxide film from the Al surface. However, because of the absorption of water by the flux residue, it is easy to find the phenomenon of intergranular corrosion. There is a large potential difference between Cu and Al, thus brittle IMCs are generated in the weld and the mechanical properties of the joint are reduced [36,39]. Both Cu and Al are faced-centered cubic structure with good ductility. The joint with good properties can be obtained by upset welding, but it forms a large number of IMCs at the interface [21] and lacks a certain universality [13]. Additionally, for smaller parts, impulse welding would be a better choice, because it is more controllable. Explosion welding uses the tremendous energy generated at the moment of explosive explosion as the power to make atoms bond with each other and make the material produce a plastic deformation, which allows the materials to be connected [13,14]. This method is simple to operate and the welding process is faster, but it lacks a certain security [13]. During friction welding, the material closes and is pressurized to prevent deformation and the loss of material. For large sizes, it is difficult to ensure the size accuracy of thin-walled Al and Cu. For the laser welding of Cu and Al, the heat generated during laser welding changes some properties of the base material [40,41]. In addition, due to the high heat input, this welding method produces a large number of IMCs in the joint, thus reducing the mechanical properties of the welded joint.

Because of the particularity of Cu and Al dissimilar materials welding, the above solid welding methods are more or less related to the geometric limitations of the materials, high process cost, special welding equipment, safety and other issues [42]. So, they are not the preferred welding methods of Cu and Al.

In addition to the solid-state welding methods mentioned above, friction stir welding (FSW) is the latest welding method that has been widely used in the past 20 years. FSW was invented by TWI in Britain in 1991 [43–47]. As shown in Figure 1a, the principle of FSW is to insert a high-speed rotating tool into the work pieces for welding. As the tool rotates, it moves in the direction of welding; at this point, the material to be welded under the action of rotation, friction and extrusion of the tool reaches the shape of the state and, through dynamic recrystallization, forms the weld [48–53].

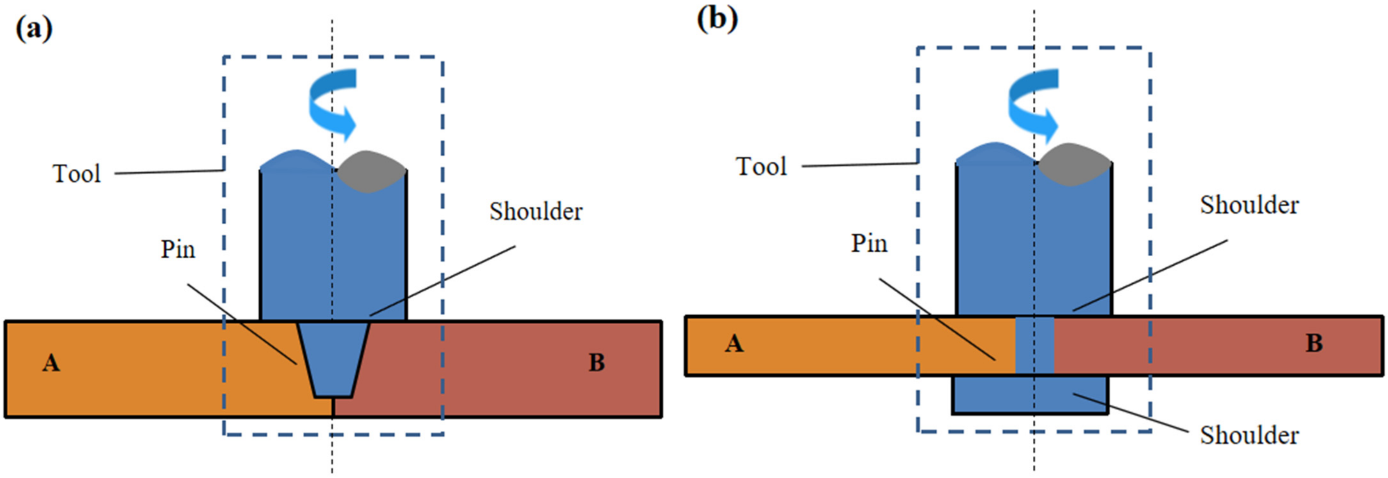


Figure 1. Principle of FSW: (**a**) single-shaft shoulder FSW; (**b**) bobbin tool FSW.

Because of the special principle of FSW, the temperature in the welding process is far lower than that of fusion welding [7,17], which avoids a series of problems, such as cracks and pores, caused by the metallurgical reaction [54]. Moreover, FSW does not need protective gas, no smoke and dust, and is easy to operate. FSW is considered as a green technology due to its energy efficiency and environmental friendliness [24]. The development of FSW for decades, because of its unique advantages, not only has successfully connected similar materials, such as aluminum alloy, steel, magnesium alloy and titanium alloy, but also completed the dissimilar materials connection of Al–steel, Al–Mg and so on [16]. Based on the principle of FSW, FSW technologies, such as friction stir spot welding (FSSW), refill friction stir spot welding (RFSSW) and bobbin tool friction stir welding (BT-FSW), have been derived. The principle of BT-FSW technology is shown in Figure 1b. This FSW technology is widely used in aerospace, rail transit industry, ships, nuclear power, electrical technology, etc. [55,56], which raises engineering industry of technological change, and has brought social and economic benefits for the country. With the development of various industries, the process of FSW is being constantly improved [57,58], and its application is expanding and gradually moving towards high-level engineering and industrial applications [54]. In summary, FSW is the most promising method for welding dissimilar metal materials.

Several researchers have studied the FSW of Cu–Al dissimilar materials, focusing on the welding process, joint mechanical properties, joint microstructure, material flow pattern and numerical simulations. In addition, the research on the FSW of Cu and Al has only found relevant data for the common single-shoulder FSW, but no researchers have reported on the bobbin tool friction stir welding. This paper summarizes the research results of the FSW of Cu and Al dissimilar materials that have been obtained in the most recent 20 years, classifies and summarizes the problems mentioned above, and puts forward our own views on the development of the FSW of Cu and Al. This review paper has a very professional guiding significance for researchers who are new to this field, because this paper clearly explains the development process and basic scientific knowledge of this field. For researchers already engaged in this field, in this paper, some new ideas are proposed for the future development of this field in view of the current development status of this field, hoping to give some inspiration to researchers in this field. It is hoped that this paper, as the base point for Cu–Al dissimilar material FSW technology, will arouse the interest of more researchers and develop more innovative research methods to further study the inherent scientific problems.

2. Research on FSW Process

The welding process is the most basic part in the FSW process, which determines the forming and performance of welding joints. According to the existing literature, the current research on the FSW process of Cu and Al dissimilar materials can be divided into the following aspects: the study of the tool, the study of Cu/Al configuration, the study of the tool offset, and the selection of welding parameters. The welding process of the butt joint and lap joint FSW of Cu and Al dissimilar materials in the past 20 years is described, as shown in Tables 2 and 3, respectively. Blanks in the table are not mentioned in the references.

Table 2. The welding process of butt joint FSW of Cu and Al dissimilar materials.

Ref.	Materials		PT (mm)	SD (mm)	SS	PS	PD (mm)	PDth (mm)	Materials in the AS
	Cu	Al							
[3]	Cu	1060 AA	5	-	-	-	-	-	Al
[4]	Cu	6063 AA	4	18	-	-	7	3.7	Cu
[5]	Cu	6061 AA	12.7	-	-	-	12	-	Cu
[9]	Cu	5083 AA	5	20	concave	cylindrical	5	4.7	5083 AA
[10]	Cu	5086 AA	6.3	18	concave	tapered thread	6	5.9	Cu
[13]	Cu	1060 AA	5	20	-	-	6	4.8	Cu
[14]	Cu	6101 AA	3	20	-	-	7	2.7	Cu
[15]	Cu	1050 AA	4	-	-	cylindrical	-	-	Cu
[16]	Cu	1350 AA	3	16	concave	tapered thread	5.2	2.75	Cu
[20]	Cu	5A06 AA	2	-	-	-	-	-	Cu
[21]	Cu-T2	5A06 AA	3	-	-	-	-	-	5A06 AA
[22]	Cu	5052 AA	3	12	concave	tapered thread	3	-	Cu
[25]	Cu-T2	5A06 AA	4	18	-	tapered thread	-	-	5A06 AA
[31]	Cu	5052 AA	3	-	concave	tapered thread	-	-	Cu
[32]	Cu	6061 AA	3	18	flat	-	4	2.75	Cu/Al
[35]	Cu-T2	5A06 AA	4	20	-	tapered thread	5	3.6	-
[36]	Cu-T2	5A06 AA	4	20	concave	cylindrical	-	3.5	5A06 AA
[39]	Cu-T2	5A06 AA	4	20	truncated cone	cylindrical	-	-	5A06 AA
[41]	Cu	5052 AA	0.8	6	-	tapered thread	1.5	0.6	5052 AA
[42]	CuZn30	1050 AA	3	15	-	tapered thread	4	-	CuZn30
[54]	Cu	1100 AA	6	18	concave	tapered thread	7.2	5.8	Cu
[58]	Cu	5754 AA	3.175	18	concave	tapered thread	5	-	Cu
[59]	Cu	6082 AA	5	15	concave	tapered thread	9.7	4.8	Cu
[60]	Cu	5083 AA	1	14	-	-	3	-	Cu

Table 2. *Cont.*

Ref.	Materials		PT (mm)	SD (mm)	SS	PS	PD (mm)	PDth (mm)	Materials in the AS
	Cu	Al							
[61]	Cu	2024 AA	5	20	flat	-	4	2.75	2024 AA
[62]	Cu-T2	6061 AA	3	15	-	-	5	2.5	6061 Al
[63]	C1100	5A05 AA	4	14	-	-	-	4	-

Note: SD—shoulder diameter; SS—shoulder shape; PS—pin shape; PD—pin diameter; PDth—pin depth; AS—advancing side; PT—plate thickness; AA—aluminum alloy.

Table 3. The welding process of lap joint FSW of Cu and Al dissimilar materials.

Ref.	Materials		PT (mm)	SD (mm)	SS	PS	PD (mm)	PDth (mm)	Materials in the Top
	Cu	Al							
[6]	Cu	1060 AA	3 + 3	15	-	-	5	6.5	1060 AA
[11]	Cu	7070 AA	2 + 2	17.7	concave	cylindrical	5	3.5	7070 AA
[25]	Cu-T2	6061 AA	1.6 + 1.6	10	concave	tapered thread	4	1.6	6061 AA
[26]	Cu	1060 AA	3 + 3	20	-	-	8	4	1060 AA
[64]	Cu	1100 AA	1 + 2	10	-	cylindrical	3	1.7	1100 Al
[65]	Cu	Al	3 + 1.5	12	flat	cylindrical	2.9	2.6	Al

Note: SD—shoulder diameter; SS—shoulder shape; PS—pin shape; PD—pin diameter; PDth—pin depth; AS—advancing side; PT—plate thickness; AA—aluminum alloy.

2.1. The Study of the Tool

The welding tool, which is the heart of FSW, plays an important role in the FSW process [1]; it keeps the material at a high strain rate [66] and is the most important source of heat in the welding process. The structure of the welding tool is shown in Figure 2. At present, the most common ones are the common FSW tool (Figure 2a) and BT-FSW tool (Figure 2b). The tool is mainly composed of the shoulder and the pin. The shoulder of BT-FSW includes the upper shoulder and the lower shoulder.

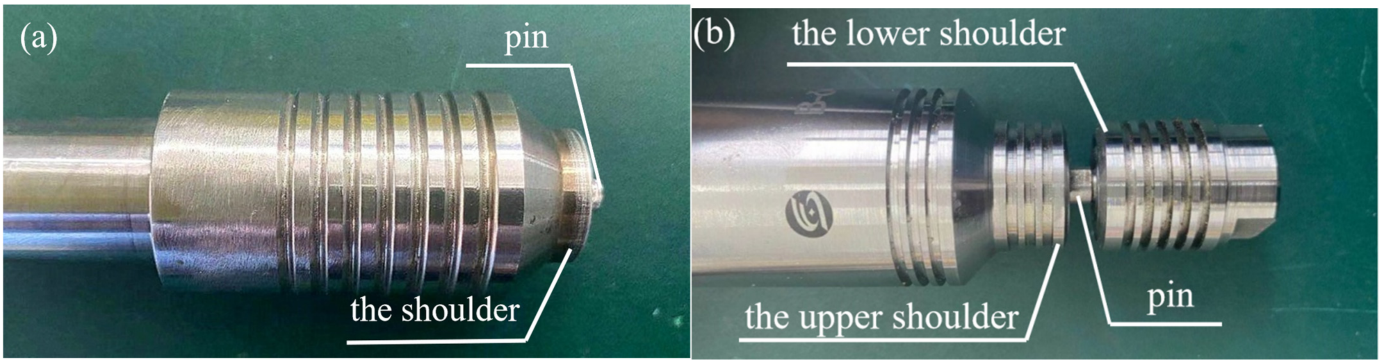


Figure 2. Tool structure: (**a**) the common FSW tool; (**b**) BT-FSW tool.

First of all, the choice of material is very important for the welding tool. In the process of FSW, the welding tool needs to bear the heat load, force load and friction wear in the welding process; this requires that the tool material has high melting points, strength and hardness, as well as good wear resistance. Some common welding tool materials and their characteristics and applications are listed in Table 4. In Mishra's opinion [67], if a material with a large difference in friction coefficient with Cu and Al is selected as the tool material, more heat input will be generated during the welding process and the material flow will be more sufficient. At present, common tool materials used for welding Cu and Al dissimilar materials are tool steel, carbon steel, stainless steel and nickel alloy.

Table 4. Common materials for the friction stir welding tool and their applications.

Material	Advantages	Disadvantages	Applicable Temperature Range	Applicable Welding Materials
Tool steel	Good machinability; cheap; high strength	Easy to tear	<500 °C	Aluminum alloy; magnesium alloy
High-temperature alloys	High strength; high toughness; high temperature resistance	Expensive	<900 °C	Copper alloy; titanium alloy; steel
Tungsten alloy	High strength; high temperature resistance	Difficult to process	600–800 °C	Aluminum alloy; magnesium alloy; titanium alloy; steel
PCBN	Good high temperature stability; high hardness	Expensive; Difficult to process	800–1000 °C	Wear-resistant material

PCBN: Polycrystalline Cubic Boron Nitride.

Secondly, some scholars have also studied the influence of shoulder diameter and shoulder geometry on welded joints. The shoulder is reported to contribute from 70 to 87 percent of the heat in the FSW process [1,30]. In addition to heat production, the shoulder can also prevent the overflow of softened materials, which is conducive to weld forming [30]. The choice of the geometry of the shoulder is also important for weld forming; the shape of shoulder generally takes the form of a concave shoulder, which can make the material subject to inward force in the FSW process and fill the cavity formed behind the pin with the rotation of the pin. There are many shapes of shoulder suitable for FSW as shown in Figure 3, but for Cu–Al dissimilar material FSW, most researchers use the common concave annular shoulder as shown in Figure 4.

Figure 3. Shapes of shoulder suitable for FSW.

Finally, some researchers have studied the effect of pin depth, the diameter and the geometry of the pin on the forming of the joint. In the process of FSW, the pin plays a role in providing part of the heat and mechanical stirring to the welded material, so the geometry and the size of the pin affect the mechanical properties of the joint. In the decades of development of FSW, in order to adapt to different welding states, different geometric shapes of pin were invented, such as cylindrical pin, tapered thread pin, tapered thread pin with three slots, eccentric circle pin, outside thread pin, manually retractable pin and automatic retractable pin. However, as shown in Tables 2 and 3, most researchers choose the cylindrical pin or tapered thread pin. The length of the pin reflects the depth of the stirring zone. Generally, the length of pin should be less than 0.2–0.3 mm of the workpiece thickness, and the relative length of the pin must be correlated to the joint geometry [30,68]. Xue P. et al. pointed out that a larger diameter of the pin will produce a larger joint area, which can improve the joint bonding strength. Additionally, the diameter of the pin is 0.9–1.1 times of plate thickness [48].

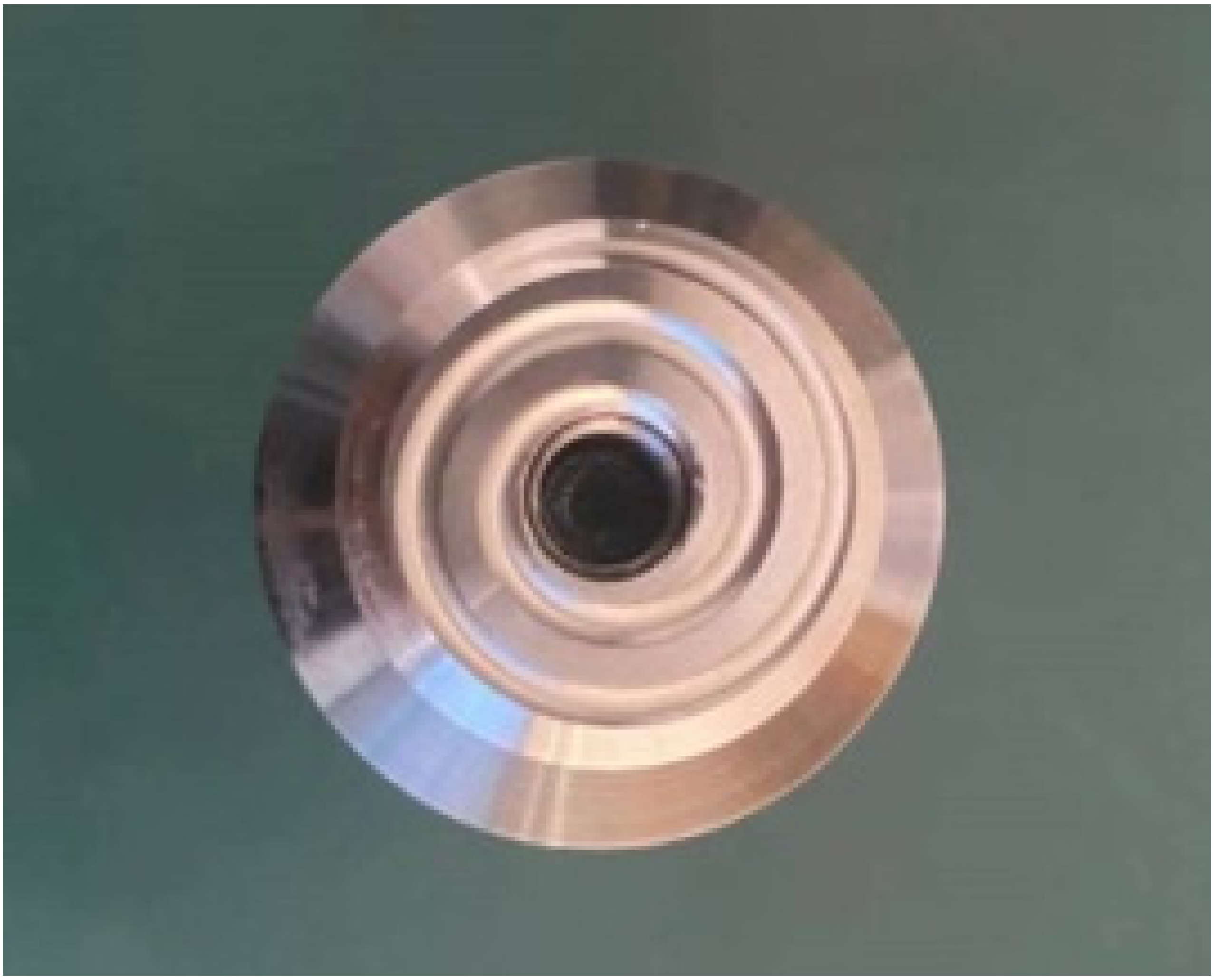


Figure 4. Concave annular shoulder.

The welding tool plays a key role in the welding of dissimilar materials. Different welding tools should be designed according to different materials to be welded and plate thickness. However, according to the current research results, there is no research on the tool of FSW with different materials of Cu and Al, including the choice of the tool material, the design of shoulder and the pin, especially the choice of the welding tool material. Ke Liming et al. [20] found through research that, in the process of Cu and Al FSW, the plugging of the tool is very likely to occur, that is, the material sticks to the surface of the shoulder and the pin, which destroys the original morphology of the tool and leads to the failure of the normal welding process, resulting in groove and other defects or even failure to weld. The author has also studied the BT-FSW of Cu and Al. The structure of the BT-FSW shoulder differs from that of the ordinary shoulder, which is more likely to produce the phenomenon of the adhesion of the tool, as shown in Figure 5, which leads to the loss of the original function of the tool. The author suggests that, in the subsequent research on the FSW of Cu and Al, the problem of the adhesion of the tool should be mainly solved, and new materials and structures of the tool also should be studied to adapt to the FSW system of Cu and Al dissimilar materials.

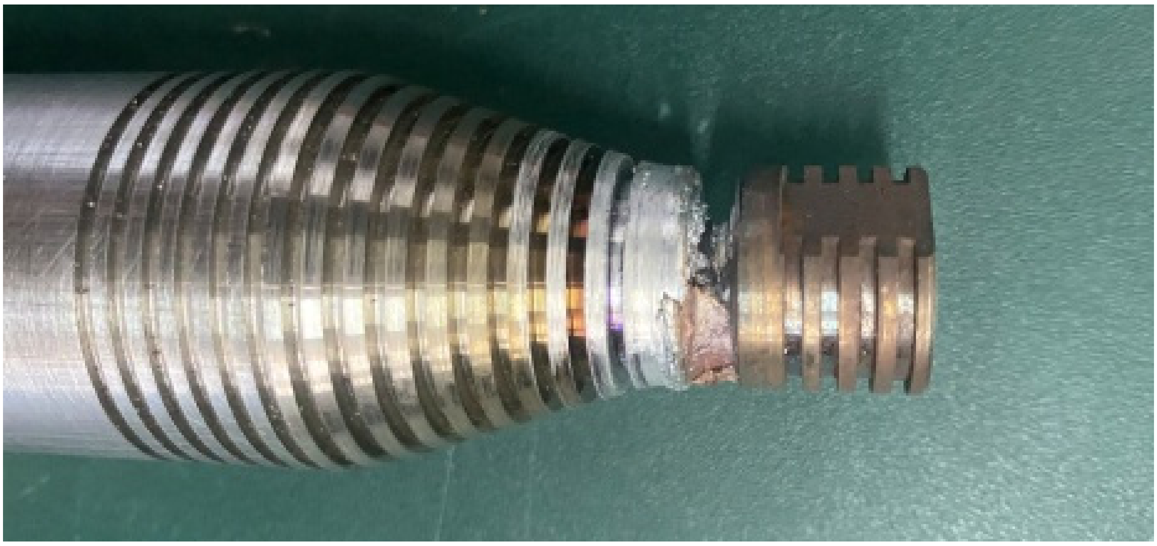


Figure 5. The phenomenon of the material adhesion in the tool.

2.2. The Study of Welding Configuration

According to the characteristics of FSW, the form of the welded joint is divided into butt joint and lap joint. Compared with the FSW of similar materials, due to the asymmetry of the welding of dissimilar materials, the FSW of dissimilar materials is more complicated [7,69]. In addition, the physical and chemical properties of Cu and Al are very different, so, in the lap welding, the choice of Al plate or Cu plate on the top is worth studying. Additionally, in butt welding, in addition to the different properties of the materials themselves, in the FSW process, the material at different positions also has different flow modes. Usually, the thermo-mechanically affected zone (TMAZ) is divided into the advancing side (AS) and the retreating side (RS). The AS refers to the side with the same rotation direction and the travel direction of the tool, and the direction in which the tool rotates and moves in the opposite direction is called the RS. Therefore, in the butt joint, it is very important to choose what material to place on the AS and RS. Almost all researchers are aware of this problem and have performed some research. M. Akbari et al. [11] found that different positions of Cu and Al would affect the heat input in the FSW process, and there are defects within the joint when the heat distribution is uneven. For lap joints, there are two positions in which the Cu and Al can be placed: the Cu placed on the top, or on the bottom, as shown in Figure 6a,b. For butt joints, Cu can be placed on the AS or RS, as shown in Figure 6c,d.

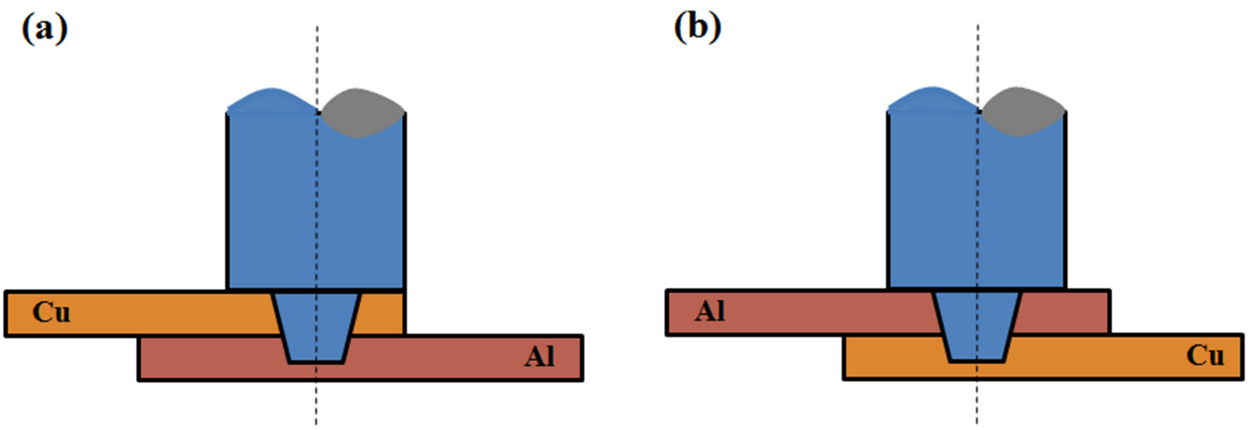


Figure 6. *Cont.*

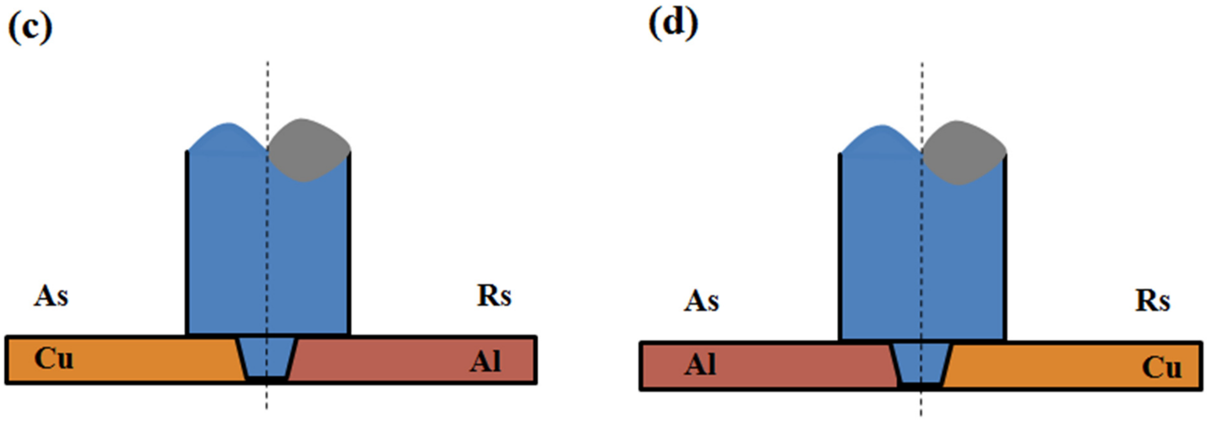


Figure 6. Material placement position of (**a**) Cu on the top; (**b**) Al on the top; (**c**) Cu on the AS; (**d**) Al on the AS.

In the study of the Cu–Al lap joint FSW, researchers have basically reached a consensus on the placement of Cu–Al, that is, the Al plate placed on the Cu plate for welding. Saeid et al. [6], Bisadi et al. [70], Xue et al. [26], Abdollah-Zadeh et al. [71], Vahid Firouzdor et al. [72] and Elrefaey et al. [64,73] placed the Al on the upper side in their research on the Cu–Al lap joint FSW. The upper material is in direct contact with the welding tool. If the material with a lower melting point is placed on the upper side, the welding process will be smoother, and a better combination with the lower plate will be achieved with a larger welding area. Xue et al. [26] found no difference in placing either copper or aluminum on the advancing side when placing aluminum on the top side. Similarly, in other studies of the FSW of dissimilar materials, most of the softer materials are placed on the upper side. When Al is placed above Cu, due to its lower thermal conductivity, it generates more heat at the top, which is more beneficial to the welding process [1].

For the Cu–Al butt joint FSW, researchers have different views on the placement of Cu and Al, and there is no consensus. Liu Huijie et al. [18] think that there are two views on the placement of Cu and Al. One is determined by the melting point, and the material with a high melting point is placed on the side with a high temperature; the other is determined by hardness. Dong Fengbo et al. [36] specifically studied the effect of Al and Cu placement on joint appearance and mechanical properties. They believe that the placement should be determined by the melting point, and the material with a high melting point should be placed on the side with a high temperature, so that both sides of the material are in a suitable plastic state, which can achieve an effective combination.

Wang Xijing et al. [74] believed that Al had a better plastic fluidity at high temperature. When Al was placed on the RS, Al was more likely to stick to the root of the shoulder, which would lead to changes in the geometric structure of the tool and tunnel-type defects in the welding process. So, Al should be placed on the AS. Meng Qiang et al. [62] found that the plastic flow of Cu was better than that of 6061 AA, and Cu was more likely to flow from the RS to AS to form in the process of FSW. Dong Fengbo et al. [36] studied the influence of the relative placement of Cu and Al on the performance of the FSW joint of Cu and Al dissimilar materials, and they found that, when Al was placed on the AS, the tensile strength of the joint was 1.36 times that of when Cu was placed on the AS. In addition, the specific tensile strengths are listed in Table 5. Correspondingly, when Al was placed on the AS, the microstructure is more compact (spacing between alternative layers of Al and Cu were smaller), showing the alternating layered distribution of Cu and Al; when Cu was placed in the AS, however, Cu and Al were combined in a disordered, not dense, state and some micro pores existed. In the experiments of other researchers, such as Murr et al. [68], Liu Peng et al. [21], Wang Chengguo et al. [39], Moneer H. Tolephin et al. [61], Jawdat et al. [32], Fotoohi et al. [9,75] and Yusof et al. [41], Al was placed on the AS for the FSW test, and also obtained welded joints with good appearance and performance.

Table 5. Tensile strength of a dissimilar Al/Cu joint according to the different parameters of welds (from reference [36]).

Number	The Location of Copper Plate	Fracture Location	Strength R_m (MPa)
1	AS	HAZ (Cu)	144
2	AS	HAZ (Cu)	167
3	AS	NZ	142
4	AS	HAZ (Cu)	140
5	AS	HAZ (Cu)	160
6	AS	NZ	166
7	AS	HAZ (Cu)	132
8	RS	HAZ (Al)	205
9	RS	NZ	214
10	RS	HAZ (Al)	190
11	RS	HAZ (Al)	201
12	RS	HAZ (Al)	225
13	RS	HAZ (Al)	206
14	RS	HAZ (Al)	189

On the contrary, many researchers believe Cu should be placed on the AS and Al on the RS during welding. Xue Peng et al. [13] carried out FSW butt tests on 5 mm thick Cu and Al, and the results showed that a better appearance of the joint could be obtained when Cu was on the AS, as shown in Figure 7. They believed that, in the process of FSW, the flow direction of the material was from the RS to the AS, and the material formed a tight weld on the AS. Since the hardness of Cu or steel is greater than that of Al, most of the material flow occurs in the Al matrix, and correspondingly, the Al should be placed on the RS. On the contrary, if the material with higher hardness is placed on the RS, the material on the RS is difficult to transfer to the AS, and a good weld cannot be formed. Additionally, Pratik Agarwal et al. [4] carried out a FSW test on 4 mm thick pure Cu and 6063 AA and analyzed the joint. They found that, when Cu was placed on the RS, it did not react with 6063 AA on the AS. In a number of FSW butt tests involving Cu and Al dissimilar materials, the researchers placed the Cu on the AS and obtained a joint with a good appearance and performance, such as Jiahu Ouyang et al. [5], Akbri et al. [10], Rathesh et al. [14], Genevois et al. [15], Li Xiawei et al. [16], Ke Liming et al. [20], Liu et al. [22], Esmaeili et al. [42], Felix. Xavier et al. [54], Akinlabi et al. [58], Avettand et al. [59] and Galvão et al. [60,76].

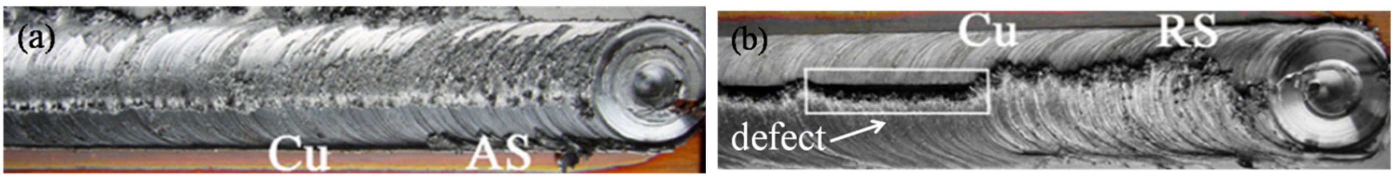


Figure 7. Surface morphologies of the FSW Al–Cu joints: (**a**) Cu plate fixed at AS; (**b**) Cu plate fixed at RS (adapted from [13], with permission from Elsevier, 2011).

To conclude, the placement of Cu and Al is a problem that must be studied when FSW is carried out between the dissimilar materials Cu and Al. However, it can be seen from the summary of the previous studies that there is no unified conclusion regarding the placement of Cu and Al in butt welding. The material flow in FSW is a complicated process, especially the mixing of different materials. The formation of a perfect joint is the result of many aspects, including the geometry, size and material of the tool and welding process parameters. The authors suggest that modeling should be carried out for different Cu and Al placement positions, and welding process windows should be established to systematize the welding process.

In the case of butt joints, the problem of the tool offset is also involved. Due to the large difference between Al and Cu in properties and the different plastic flow capacity, the offset of the tool insertion position relative to the center of the weld has a significant influence on the performance of the Al/Cu dissimilar joint. The schematic diagram of the tool offset is shown in Figure 8. Figure 8a shows the tool biased to the Cu side, and Figure 8b shows the tool biased to the Al side. Liu Huijie et al. [18] believe that whether the tool should be offset is not certain and should be considered with the location of the material and welding parameters. Dong Fengbo et al. [36] showed in his paper that, when other welding parameters are constant, the offset of the tool is of great significance to the research on the FSW of Al and Cu, which can change the proportion of different materials in the weld, thus controlling the type and quantity of IMCs. Debroy et al. [7] think that it is necessary to offset the tool relative to the weld in the FSW process of Cu and Al dissimilar materials. Only in this way, better joints with better mechanical properties can be obtained. However, in the actual experiment, almost all researchers adopted the tool offset technique and believed that the tool should be offset to the aluminum side.

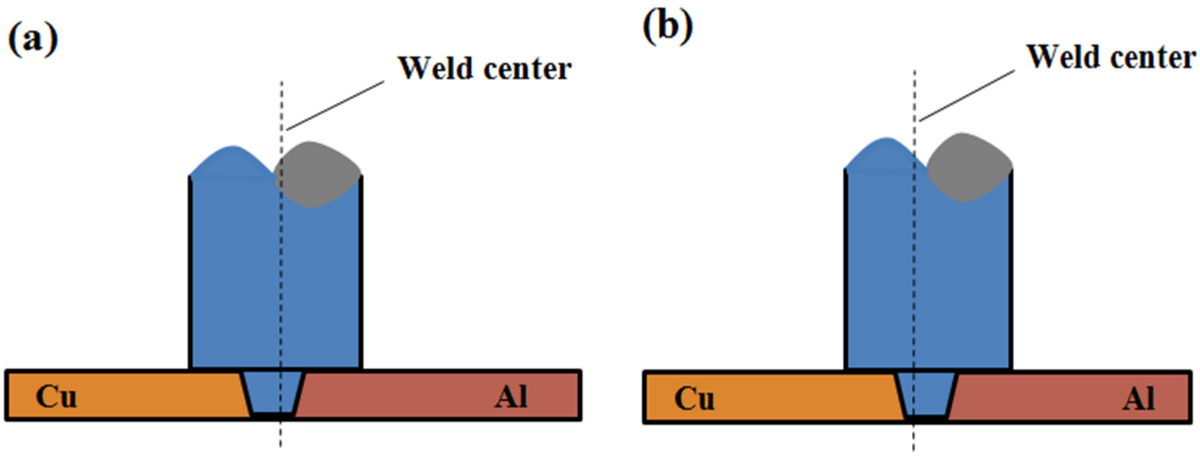


Figure 8. The tool bias principle: (**a**) the tool biased to the Cu side; (**b**) the tool biased to the Al side.

It is well known that Cu has a high coefficient of thermal expansion. If the tool is placed on the Al side, the Al side will receive more heat, which will make the thermal stress distribution more reasonable and the mixing of the material will be sufficient. In Liu's experiment [31], he found that, when the tool was offset to the Cu side, the content of Cu in the weld increased and the probability of IMC formation increased. In his opinion, under the same thermal and mechanical conditions, Al has better fluidity compared with Cu, and the overall material fluidity increases. In this case, holes and other defects caused by welding will be filled in time, which can reduce the occurrence of defects. Kush P. et al. [1] believed that, when the tool was offset to the Al side away from the Cu side, less heat would be taken away due to the higher thermal expansion coefficient of Cu, and the thermal stress would be reasonably distributed. The researchers almost reached a consensus on the placement of the tool on the Al side in the Cu–Al FSW, and further explored the issue of offset distance. Pratik Agarwal et al. [4] proved through experiments that better joints with better macroscopic morphology could be obtained when the offset distance of the tool was small. This is because when the pin offsets are small, large Cu pieces are scratched off the metal plate and are mixed into the Al matrix. Xue Peng et al. [13] believe that the distance of the tool to offset the Al should be larger, because the large chunks of Cu that peel off from the Cu matrix do not flow easily, and mixing Cu and Al too much would form eutectic structure, resulting in brittle IMCs and a poor performance. On the contrary, a small amount of Cu shedding would form a good combination in the Al matrix. Figure 9 shows the macroscopic morphology of the welded joint and the microscopic morphology of the joint section under different offsets of the pin; a smaller pin offset results in a better-looking weld joint. Li Xiawei et al. [16] found that, if the tool is placed completely on the Al side, it is difficult to achieve the perfect welding with Cu through diffusion, resulting in defects, such as grooves.

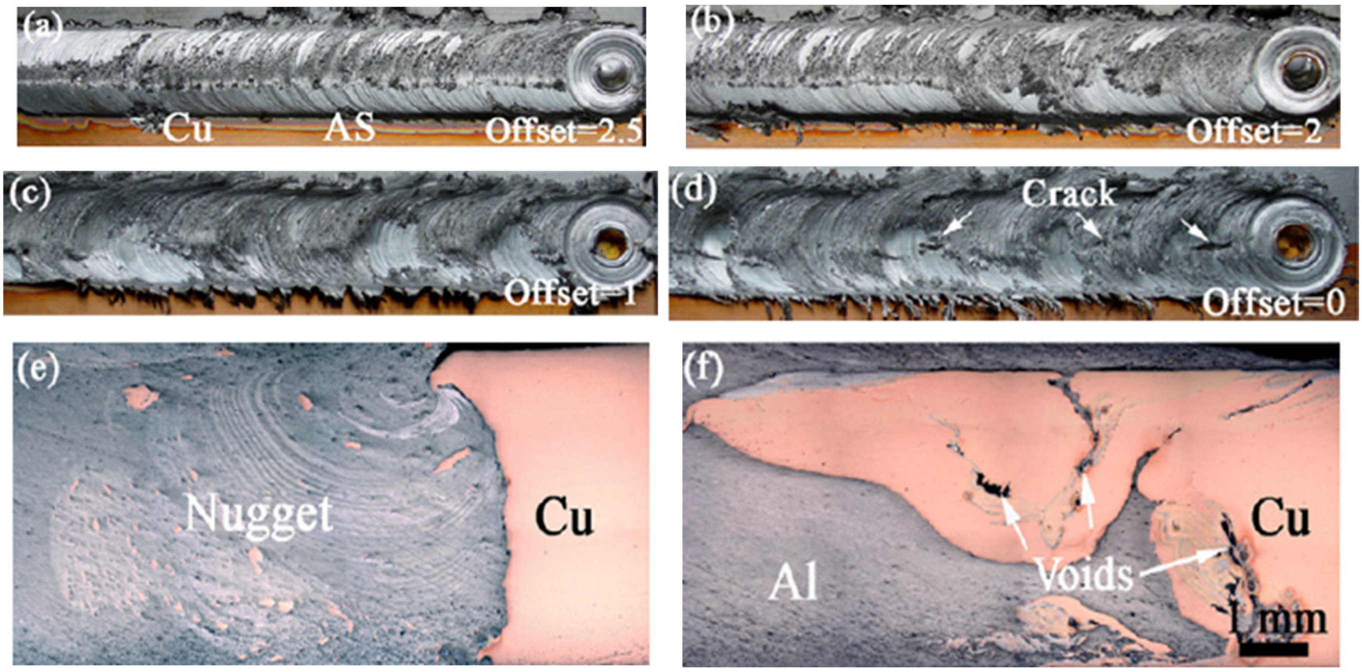


Figure 9. Surface morphologies of the FSW Al–Cu joints for pin offsets of (**a**) 2.5 mm; (**b**) 2 mm; (**c**) 1 mm; and (**d**) 0 mm. Cross-sectional macrostructure of the joints for pin offset of (**e**) 2.5 mm and (**f**) 1 mm (adapted from [13], with permission from Elsevier, 2011).

2.3. The Study of Welding Parameters

In the process of FSW, the most important welding parameters are rotation speed and travel speed, which are, respectively, called R and TS in this paper. The purpose of these two welding parameters is to provide heat of friction and generate sufficient shear stress. It has been reported that the R provides 40% of the heat during the welding process [30]. The choice of R and TS directly affects the appearance and mechanical properties of the joint. Moreover, the choice of R and TS should meet both the thickness direction and the requirements of the plastic flow of materials around the tool, and the generation of IMCs should also be reduced [60]. Therefore, the R and TS are issues that must be studied in each experiment. Earlier in the literature, researchers preferred to separate the R and TS for separate studies, while in recent years, they prefer to analyze and study the R and TS as a whole.

Researchers generally believe that in the FSW of Cu–Al dissimilar materials, when TS is constant, the larger the R is, the more heat is generated in the welding process, and conversely, the smaller the R is, the less heat is generated in the welding process. However, when the R is constant, the larger the TS is, and the less heat will be generated in the welding process, and the smaller TS is, the more heat will be generated [13,20,42,49,75]. The same conclusion was reached not only in the FSW of Cu and Al dissimilar materials, but also in the study of the welding parameters of the FSW of similar materials. In fact, according to some reports, in the early stages of the invention of FSW, in order to study the influence and mechanism of the R and TS on welded joints, researchers tended to fix one parameter and explore the influence of another parameter on the appearance and performance of the joint, including the generation of defects and the mechanical properties of the joint. After exploring the basic laws, more researchers prefer to think of the R and TS as a whole to represent heat input. Ke Liming et al. [20] believe that R/TS could be defined as the heat generated on the weld per unit length, and the heat increased as the value of the R/TS increased. They also believe that a good R/TS match could guarantee the densification of the joint and determine the mechanical properties of the joint microstructure [49]. Similarly, several researchers have also defined the R/TS as heat input [77–80].

By looking at, sorting and analyzing the previous literature, the authors found that, compared with the average of the FSW of similar materials, the FSW of the Cu and Al dissimilar materials has a smaller welding parameter window. Few researchers have carried out systematic research on the welding parameter window, so the authors suggest that a systematic welding parameter window should be established first during the FSW of Cu and Al, and then the following research should be carried out: R and TS, as the most convenient and intuitive welding parameters to adjust in the process of FSW, should be considered as a whole in the current status of research.

3. Research on the Microstructure and Mechanical Properties of Joints

In the field of welding, researchers often analyze the microstructure and mechanical properties of welded joints through research methods in order to explore the mechanism of microstructure evolution, the formation and causes of defects, and the influence of parameters on mechanical properties during welding. In the previous studies on the FSW of Cu and Al dissimilar materials, the researchers selected the welding technology and the appropriate welding parameter window on the basis of the macroscopic morphology and tensile strength of the welded joint and analyzed and studied the microstructure and mechanical properties of the welded joint. According to the current research status, it can be concluded that current research is mainly focused on the following aspects: the study on the microstructure of the joint, the interface IMCs of the joint, the tensile strength and the micro-hardness.

3.1. Microstructure Characteristics

In the analysis of the material structure and properties, the analysis of the microstructure is the most basic research, which affects the mechanical properties. In the literature, researchers observed and analyzed the microstructure of Al–Cu dissimilar FSW joint by means of optical microscope (OM), scanning electron microscope (SEM) and transmission electron microscope (TEM), etc. The authors will not elaborate on them in this paper, but will only analyze some typical cases.

In the case of the lap joint, Figure 10 shows the macroscopic morphology of the typical Cu–Al dissimilar material FSW lap joint. As with the majority of the microstructures of the FSW joints, the microstructure of Al–Cu dissimilar material FSW joints consists of the stir zone (SZ), the thermal mechanical affected zone (TMAZ), the heat affected zone (HAZ) and the base material (BM) on the Cu and Al sides. Xue Peng et al. [26], A. Abdollah-Zadeh et al. [71], Ahmed elrefaey et al. [64] and Akbari et al. [11] observed a similar macroscopic morphology in the FSW lap experiment of Cu and Al.

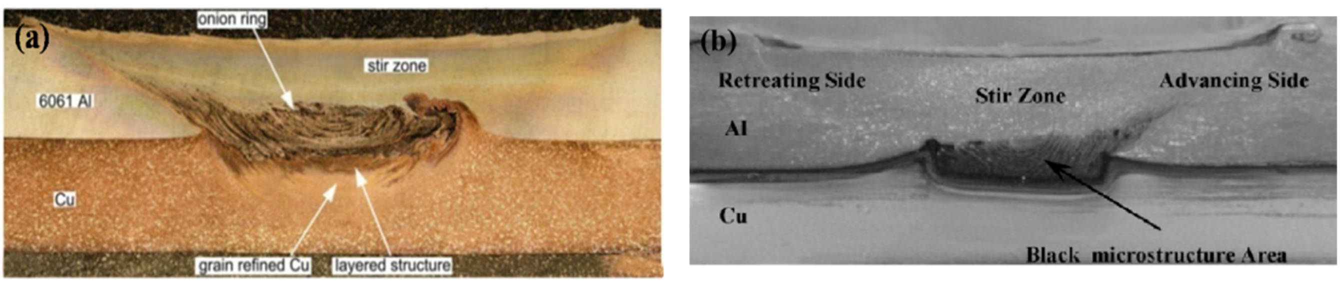


Figure 10. Macroscopic morphology of Cu–Al FSW lap joint: (**a**) (adapted from [72], with permission from Springer, 2011); (**b**) (adapted from [71], with permission from Elsevier, 2007).

We found the following characteristics in Abdollah-Zadeh's observation [71] of the microstructure of Al–Cu FSW lap joint. First of all, just as the microstructure of common FSW joint, the grains in the SZ are smaller than the BM because of the effect of dynamic recrystallization, and the grains in the TMAZ appear to be elongated due to the heat cycling and the stirring of the tool. The grain size in the HAZ is relatively large because of the action of thermal cycling, and the grain size near the Cu–Al interface is even smaller, as shown in Figure 11. In the observation of the microstructure by Ahmed Elrefaey et al. [64], no evident onion ring structure or TMAZ structure was found on one side of Al. However, Xue et al. [26] divided the SZ region into the upper and lower regions. The upper region had only the presence of Cu, while the lower region mainly had Al matrix and Cu fragments. Vahid Firouzdors et al. [72] believe that the material on the top is corroded 6061 AA and the material on the bottom has a complex Cu–Al interlaced onion ring shape.

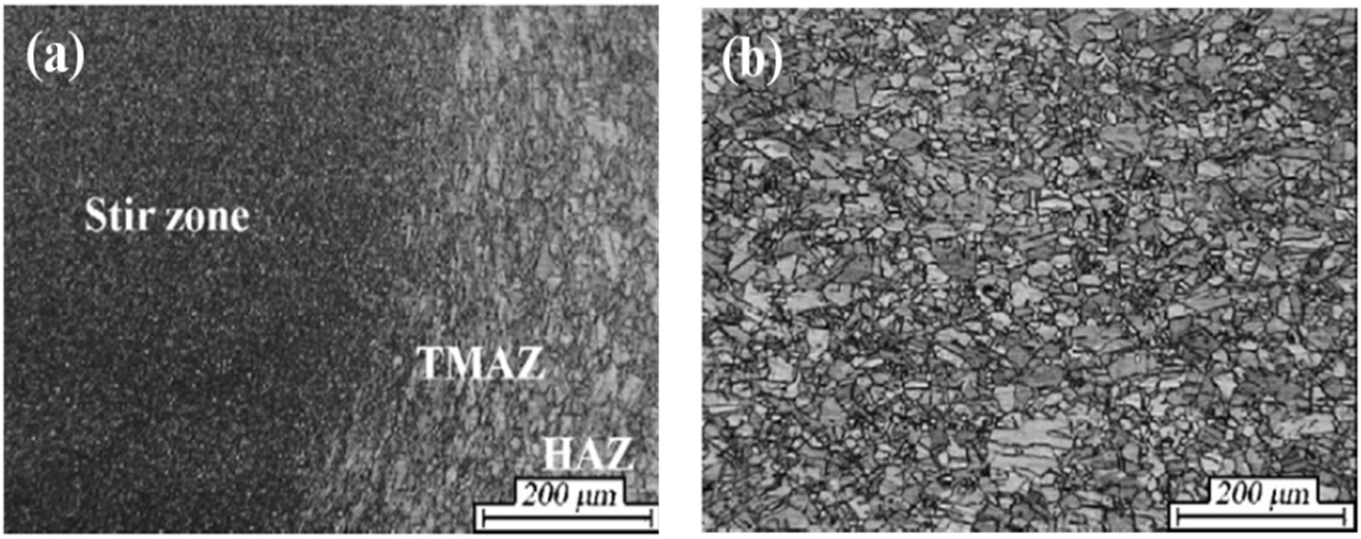


Figure 11. (**a**) Stir zone, TMAZ and HAZ of copper in the advancing side of the joint; (**b**) HAZ in the copper side (adapted from [71], with permission from Elsevier, 2007).

Secondly, the material is transported from the RS to the AS, and the thread on the pin causes the material to move vertically. The same phenomenon was observed in Saeid's study [6], which he explained to be related to the eddy flow generated by the conical thread of the pin during welding. He also found that the larger the TS, the less material was transported vertically.

Finally, dark areas are observed at the interface of Al and Cu, and extended to AS. Saeid et al. [6] also observed this dark region, in which Cu particles with different shapes were observed to be unevenly distributed in the Al matrix, and through experiments, it was found that, when V increased, the dark region extended toward the forward side. Figure 12 shows the different morphologies of the welded joint at different welding speeds. The authors believe that the different reactions of the interface to the etchant caused the dark areas to be observed under the OM.

In addition to the above, Xue et al. [26] observed the hook structure near the RS region, which is inevitable in the FSW lap joint of dissimilar materials, especially when the pressure of the tool is very high. This phenomenon is related to the material moving from the RS to the AS.

In the case of the Cu–Al dissimilar materials FSW butt joint, the macroscopic morphology of the typical welded joints is shown in Figure 13. Liu et al. [22] observed intercalation structures with different light and dark shapes on the interface. These intercalation structures are composed of parallel and alternating lamella, which are distributed at the interface of Cu and Al and the lower part of the SZ. The components of these structures were also detected as IMCs. Liu Peng et al. [21] found several features in their research on Cu–Al FSW butt joints. First, the boundary between Cu and Al is evident, which is the structure of plastic flow, and the onion ring structure can also be clearly observed. Second, due to the different thermal conductivity of Cu and Al, the heat loss on the Cu side is more serious, which leads to different microstructures on both sides and evident asymmetry. However, Genevois et al. [15] observed some characteristics of microstructure by TEM, as shown in Figure 14. The SZ presents equiaxial grains and a low dislocation density due to dynamic recrystallization, and TMAZ consists of small equiaxial grains and elongated grains along the plastic flow direction, also with a low dislocation density.

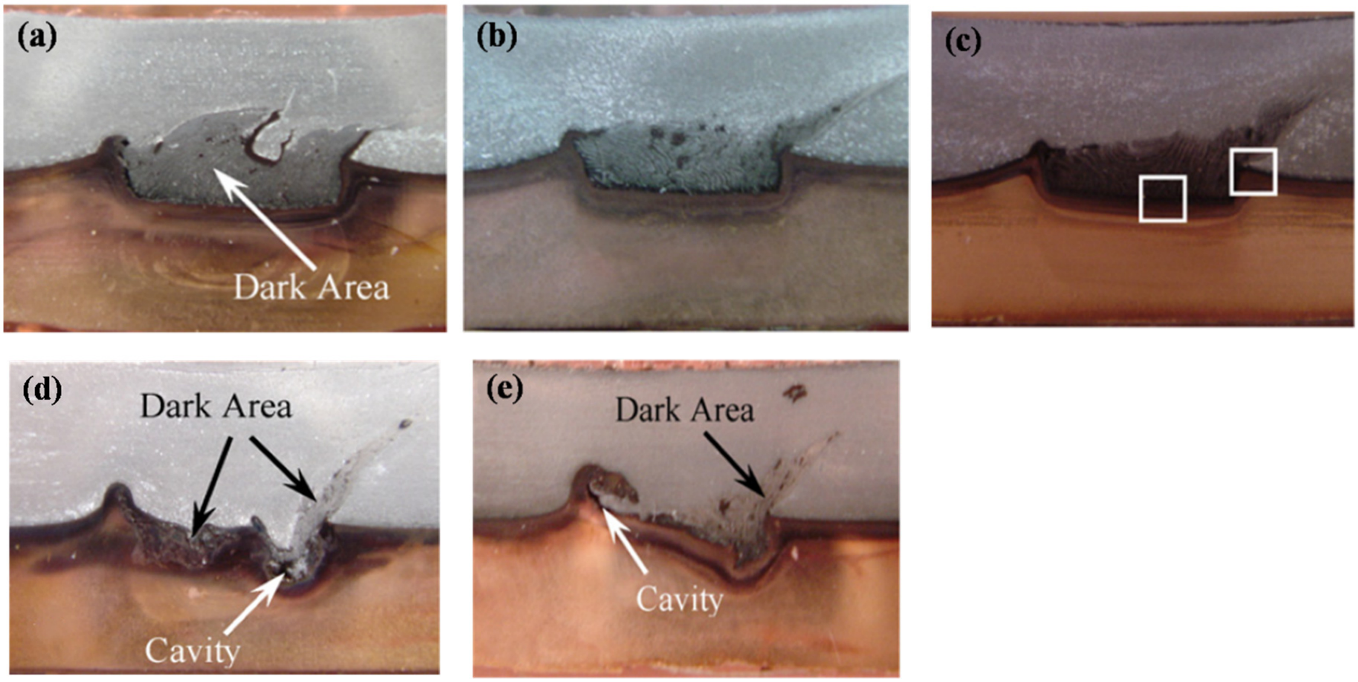


Figure 12. Macroscopic overviews of the FSW joint cross sections at the constant tool rotational speed of 1180 rpm and welding speeds of (**a**) 30, (**b**) 60, (**c**) 95, (**d**) 118 and (**e**) 190 mm/min (adapted from [6], with permission from Elsevier, 2010).

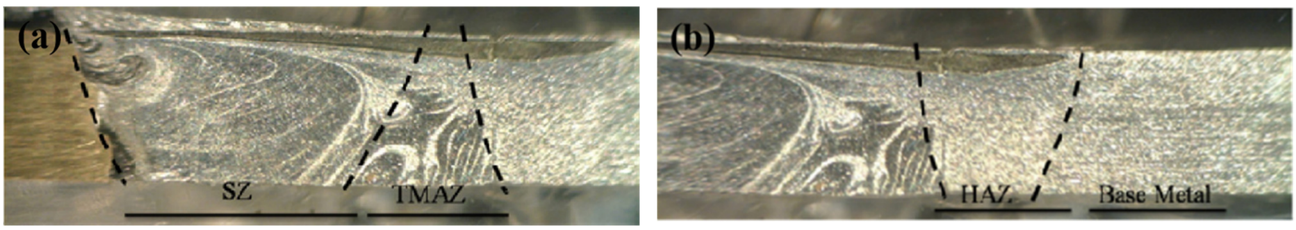


Figure 13. Macroscopic morphology of the Cu–Al FSW butt joint (**a**) SZ and TMAZ; (**b**) HAZ and base metal (adapted from [42], with permission from Elsevier, 2011).

Finally, Cu and Al achieve a close bond at the Al side, showing a mixed lamellar staggered microstructure. However, Xue Peng et al. [3] observed through SEM, as shown in Figure 15a, that the SZ is mainly composed of Al matrix and Cu particles with uneven size, shape and distribution, and the bottom of the SZ is a rich area of Cu. This is due to the stirring action of the pin, which results in the stripping, crushing and dispersion of copper particles. They believe that the SZ mainly contains aluminum matrix composites. In the experiment of Galvão et al. [60], it was observed that the upper structure of the SZ was mostly Al and the lower structure was mostly Cu, and the homogeneity of the mixing region of Cu and Al was better with the increase in heat input. Meng Qiang et al. [62] also believe that the SZ had an aluminum-matrix composite structure, because under the action of the tool, the Cu block and fine Cu particles were stripped from the Cu matrix, transported from RS to AS, and the Al matrix in the Al composite structure was formed on the SZ. The morphology of the welded joint obtained by their experiment under SEM is shown in Figure 15b.

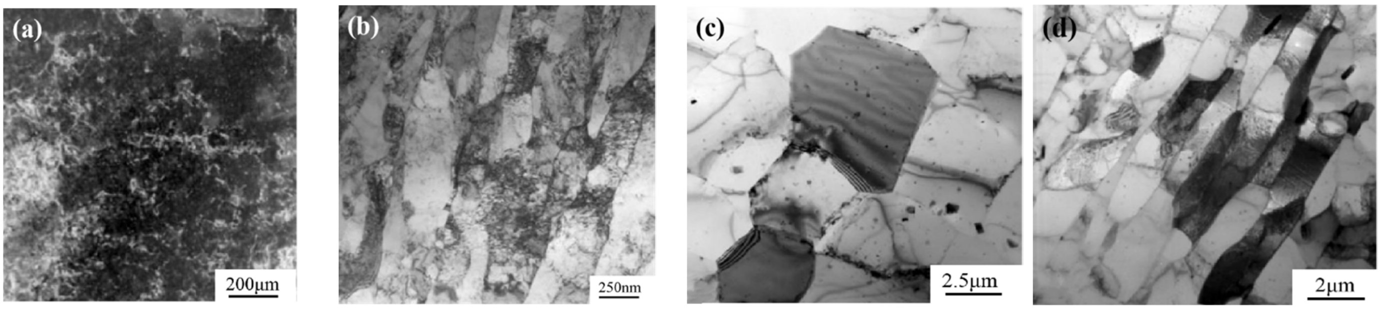


Figure 14. (**a**) TEM bright field of the dislocation organization in the copper base material; (**b**) bright-field TEM micrograph showing the grain and the dislocation structures in the TMAZ in the copper side, close to the Al/Cu interface; (**c**) bright field showing the microstructure in the stir zone; (**d**) bright field of the grain structure in the TMAZ (adapted from [15], with permission from Springer, 2011).

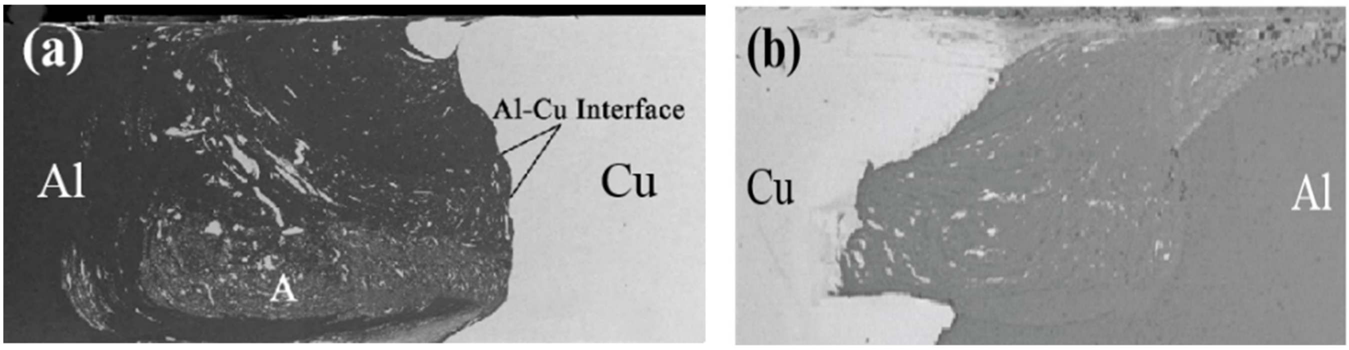


Figure 15. (**a**) SEM backscattered electron images (BEI) of the FSW Al–Cu joint (from ref. [3]); (**b**) SEM microstructures of the FSW Al–Cu welded joint in NZ (from ref. [62]).

3.2. The Study of the IMCs

Regarding the microstructure of the joint described above, many researchers have observed the darkness of the Al–Cu layer in a crisscross complex structure, a kind of special structure that has also aroused the interest of researchers. Researched have detected and analyzed the composition of IMCs by X-ray diffraction (XRD) combined with Cu–Al binary phase diagrams and observed the morphology of IMCs by means of SEM and TEM. Additionally, as shown in Figure 16b–d, Meng Qiang et al. also used the method of selected area diffraction (SAED) pattern in TEM to identify and distinguish the phases of IMCs. To date, the research on the IMCs of the FSW of Cu–Al dissimilar materials mainly focuses on the following aspects: composition analysis, formation mechanism and influence on the mechanical properties of joints.

First of all, regarding the IMCs generated in the process of the FSW of Cu–Al dissimilar materials, the common IMCs are Al_4Cu_9, AlCu, Al_2Cu and $AlCu_3$. The components of IMCs are usually detected by line scanning, XRD and other methods. Although the results of each individual study are different, the IMCs that researchers have detected are all made up of a combination of these five IMCs. The morphology of a typical IMCs under a microscope is shown in Figure 16a. For example, in the study of al-Roubaiy et al. [10], only one kind of IMC, Al_2Cu, was detected. Two IMCs, Al_2Cu and Al_4Cu_9, were detected by Avettand-fenoel et al. [59], Saeid et al. [6], Genevois et al. [15], Xue et al. [3,26], Akinlabi et al. [58], Ahmed Elrefaey et al. [64], Beygi et al. [65] and Fotoohi et al. [9]. Three IMCs, AlCu, Al_2Cu and Al_4Cu_9, were found in the research of Jiahu Ouyang et al. [5], Liu. et al. [31], Abdollah-Zadeh et al. [71], Meng Qiang et al. [62] and Vahid Firouzdor et al. [72]. In Liu's study [22] on the IMCs of the FSW of Cu–Al dissimilar materials, four IMCs were found, namely, AlCu, Al_2Cu, Al_4Cu_9 and $AlCu_3$. However, the existence of IMCs was not detected in the study of Liu Peng [21] and Li Xiawei et al. [16]. Liu Peng [21] believes that no chemical changes occurred in the process of the FSW of Cu–Al and no phase transition reaction occurred. In a recent study on the lap joints of Al and Cu FSW technology, Kota Kurabayashi et al. [81] added Ni to the superlayer metal. In their study of IMCs, they found that the addition of 3 at.% Ni changed the IMC phases from $CuAl_2/Cu_9Al_4$ into (Ni,Cu) $Al/CuAl/Cu_9Al_4$ from the Al side. This provides a new idea for our future research, that is, we can try to add elements between Cu and Al and change the content, so as to achieve the purpose of changing the composition of IMCs. As can be seen from the above summary, there are many circumstances for the existence of IMCs. This is due to the complexity of the causes of IMCs, which are caused by a variety of factors.

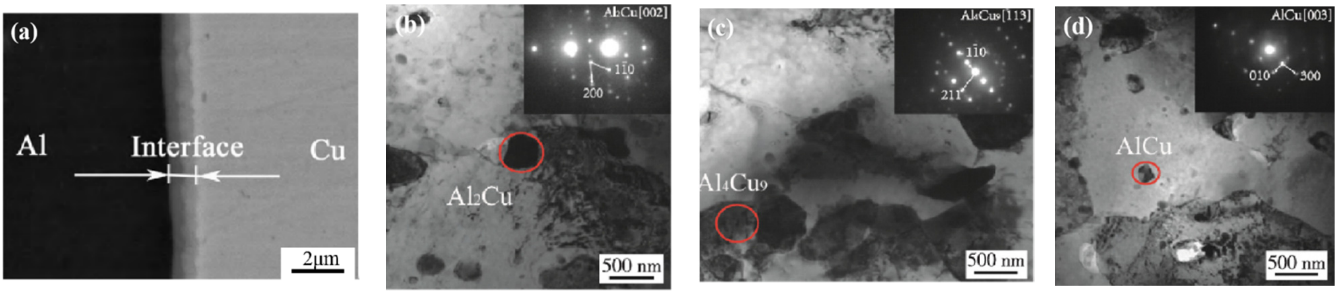


Figure 16. (**a**) Microscope image of a typical IMC (adapted from [3], with permission from Elsevier, 2010); (**b**) $Al_2Cu_{[2]}$ phase; (**c**) $Al4Cu9_{[113]}$ phase; (**d**) $AlCu_{[3]}$ phase (adapted from [62], with permission from CNKI, 2019).

Secondly, the mechanism of IMC generation was also discussed and analyzed. Li Xiawei et al. [16] believe that welding parameters, base material composition and temperature affect the generation of IMCs. The difference between each experiment lies in the different dynamic conditions in the FSW process, which will lead to different IMCs generated in the welding process of each experiment. For example, the thin plate has a short reaction time and a relatively high cooling rate, which makes it difficult to generate IMCs. Liu et al. [22] found that most of the IMCs were detected at the junction of the SZ and Cu, and he speculated that the production of IMCs was caused by the diffusion between Al–Cu due to the extreme deformation. Abdollah-Zadeh et al. [71] and Akinlabi et al. [58] both believe that a higher rotational speed would increase the temperature of the Cu–Al interface, so the formation of IMCs was due to thermal activation. Felix Xavier Muthu et al. [54] believe that the generation and growth mechanism of IMCs was related to the temperature and holding time. At a certain temperature, the atomic activation energy leads to the diffusion between Cu and Al atoms. Jiahu Ouyang et al. [5] also believe that solid-state diffusion is the formation mechanism of IMCs, which is the solidification transition and solid-state phase transition caused by higher welding temperatures. At the same time, he proposed a specific mechanism. In the process of FSW, the high strain rate and the fine crystal structure of dynamic recrystallization promote the diffusion between atoms, the sub-structure of the dislocation provides a fast channel for diffusion, and the layered structure of Cu and Al shortens the diffusion distance between atoms. Li Mingshen et al. [27] proposed the growth mechanism of specific IMCs through qualitative and quantitative detection. They believe that, when the heat in the growing area is insufficient, Al_2Cu is formed first. With the increase in temperature, AlCu is nucleated on the surface of Al_2Cu and grow. With the continuous increase in temperature, Al_4Cu_9 is nucleated on the AlCu layer. By microscopic observation and the quantitative detection of the interface, some new ideas have been proposed by I. Galvão et al. [60] on the specific formation mechanism of IMCs. The formation of Al_2Cu is due to the solid-state diffusion. According to the Cu–Al binary phase diagram, the peritectic reaction of Al_2Cu occurs at 590 °C; although the welding temperature is close to the melting temperature, they did not observe the primary dendritic structure of Al or Al_2Cu through SEM. However, they believe that the formation of Al_4Cu_9 was a mechanical process. Cu and Al were combined from AS and RS to form a layered structure under the action of the pin, respectively. Al_4Cu_9 with appropriate atomic concentration can be formed even if the temperature is not high and the diffusibility is relatively high, and Al_4Cu_9 appears at the bottom where Cu is enriched.

Finally, it is also worth discussing how the existence of IMCs affects the welded joints. Researchers also have different views on this issue. Yan Qiang et al. [63] considered that the mutual solubility of Al and Cu was limited. When the joint works in a high temperature and vibration environment for a long time, Al and Cu atoms continue to diffuse, leading to the formation of thicker IMCs, which affects the strength of the joint. Jean Pierre Bergmann et al. [17] believe that IMCs cause the joint to fail during cooling from the melting point to room temperature. Xue Peng et al. [13], however, believe that continuous thin layers of IMCs are necessary for the FSW of Cu–Al to produce good joints. In another paper [26], they also proposed that IMCs can be easily generated at higher temperatures, and IMCs with a continuous thin layer can be generated at lower temperatures. Such IMCs will enhance the metallurgical bonding between Cu–Al, thus improving the mechanical properties of the joint.

3.3. The Study of Tensile Strength and Micro-Hardness

Tensile strength is the most basic mechanical property of the FSW of Cu–Al dissimilar materials, whether in the lap or butt joint forms. Researchers took the tensile strength as the most basic standard to judge the mechanical properties. In each experiment, the tensile strength of the welded joint was tested. They mainly recorded the tensile strength, the tensile fracture position of the specimen and observed the fracture morphology by using SEM. Because the basic conditions of each experiment are different, whether it is the thickness, the material of the specimen, or the welding parameters of the test, the results obtained are all different, and there is no rule to follow. Therefore, the authors will not enumerate the results of each tensile test in this paper, but there are several results that are worth thinking about and will be of further help in the following research.

Felix Xavier Muthu et al. [54] carried out FSW of 6 mm thick pure Cu and 1100 AA. Under the different welding parameters they set, the lowest joint efficiency reached 42.5%, while the highest reached 70.62%. Faced with such an enormous gap in data, the reason for this was analyzed in combination with the shape, thickness and composition of IMCs. They observed IMCs in tensile fractures and assumed that the tensile strength decreased as the thickness of the IMCs increased, due to the brittleness of the IMCs between Cu and Al. In addition, according to the TEM image shown in Figure 17, they also concluded that, due to the Orowan mechanism, the presence of Cu particles in the welded joint could hinder the dislocation movement and lead to the increase in tensile strength. In the research of Liu Xiaowen et al. [82] on FSW of brass and Cu, they found that the tensile fracture is located on the brass side, which is because the organization in HAZ is inhomogeneity, appearing with the phenomenon of segregation. Through the SEM observation of the welded joint, the upper metal is uniform and sufficient, with defects existing in the underlying metal, which leads to the ductile fracture of the upper material and the brittle fracture of the lower metal, reducing the strength of the joint as a whole. This situation is also common in the FSW lap of dissimilar materials, because the single shoulder FSW is prone to a lack of penetration when welding the plate. The authors suggest that the BT-FSW can solve this problem.

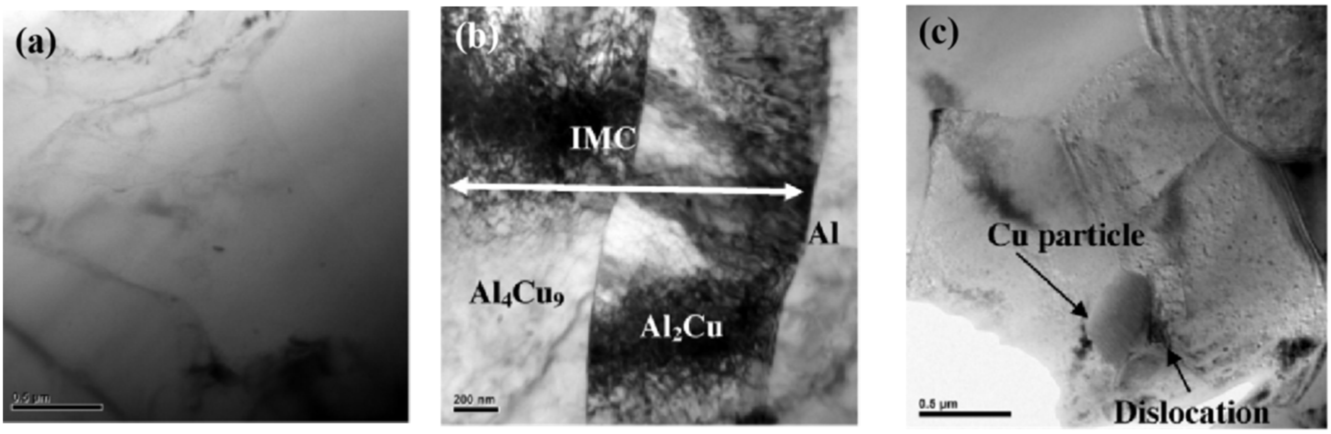


Figure 17. TEM investigation of the various regions of the stir zone microstructure at the tool travel speed of 80 mm/min: (**a**) SZ (Cu side); (**b**) intermetallic layer; and (**c**) SZ (Al side) (from ref. [54]).

The hardness test is also a basic mechanical property test, which includes the Rockwell hardness (HRC), Brinell hardness (HB) and Vickers hardness (HV). In the FSW of Cu–Al dissimilar materials, most researchers adopt the Vickers hardness method. It can measure the hardness and softness of the material, and combine the microstructure to explain some problems. Researchers usually take a cross section of the welded joint to test for microhardness. In the previous FSW test on Cu–Al dissimilar materials, all researchers carried out microhardness tests on welded joints. The specific microhardness values obtained from each experiment were different, but similar rules could be found. Li Xiawei et al. [16] and Liu Peng [3] et al. conducted microhardness tests on the joints and found that the joints bottom and Cu side had relatively high hardness, as shown in Figure 18a,c. Through the microscopic metallographic structure, Li Xiawei et al. [16] found that Cu fragments exist at the bottom of the welded joint SZ, which was the reason for the high hardness of the SZ. On the contrary, Liu Peng et al. [3] believe that the increased hardness at the bottom of the SZ is due to the presence of IMCs, not Cu fragments. In contrast to the above results, Qiuzheng Zhang et al. [83] carried out microhardness tests on the upper, middle and lower layers of the FSW of joints of Cu–Al dissimilar materials, and our research group also obtained a similar trend of hardness values in the previous microhardness study of the FSW of Al–Cu dissimilar materials, as shown in Figure 18b. Through analyses, it is known that the upper material is subjected to the extrusion and friction of the shoulder, which makes the two materials in this region more likely to form IMCs under the action of heat and force than the middle and bottom materials. The presence of IMCs increases the hardness of the area.

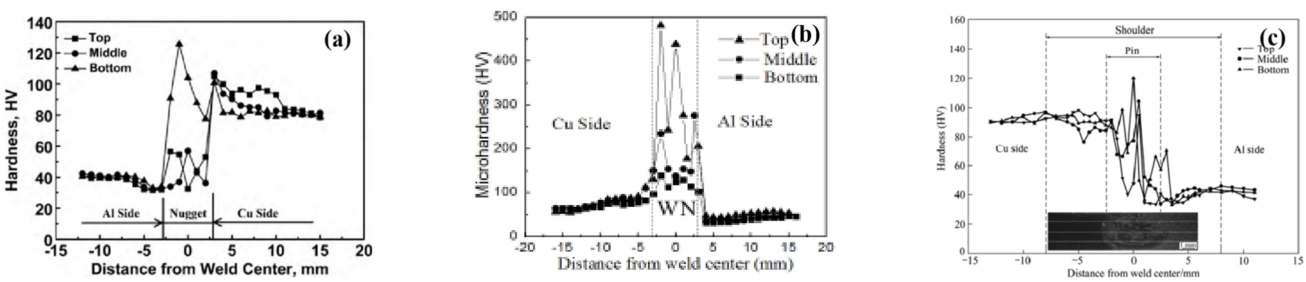


Figure 18. Microhardness profile: (**a**) from ref. [3]; (**b**) from ref. [84]; and (**c**) from ref. [16].

It was found that the hardness of the upper layer is greater than that of the middle layer and the bottom layer. Liu Peng et al. [3] and Yusof et al. [41] found that the hardness of the SZ was higher than that of the base metal, and they all believed that the co-existence of Cu particles and IMCs in the SZ resulted in the increased hardness of the SZ. Another interesting research result is that of Pratik Agarwal et al. [4], which found a sudden increase in hardness value at the interface through experiments, which is caused by the production of IMCs, such as Al_4Cu_9 and Al_2Cu, at the interface. Similarly, Dong Fengbo et al. [2] found that the SZ hardness value fluctuated greatly in the microhardness test of the 5A06 AA and Cu FSW joints, which was also caused by IMCs produced during welding. In addition to the mechanical properties mentioned above, Rasoul Khajeh et al. [84] have also tested the electrical properties in the recent study. Although there are not many analyses, this is of great significance and can also be taken as a research direction in the future research.

4. The Study of Numerical Simulation

On the basis of experimental research, the numerical simulation of the welding process is also very important, which requires researchers to establish a suitable mathematical model, use a numerical simulation method to analyze the research object and verify whether the experimental results are accurate. At present, the content of numerical simulation research on FSW mainly includes temperature simulation, stress simulation and plastic flow simulation in the welding process. Although many researchers have performed many numerical simulation analyses of FSW experiments, there are few reports on the numerical simulation analysis of Cu–Al dissimilar materials. The numerical simulation for the FSW of dissimilar materials is difficult, and its complexity lies in that the heat generation process between the tool and the two materials [48]. In addition, because few researchers have performed research in this field, there is a lack of reference data, and a lot of assumptions need to be made in the process of modeling. However, Ahmed O. Al-Roubaiy et al. [10] numerically simulated the temperature field of the FSW of Cu–Al dissimilar materials using the COMSOL Multiphysics software. They split a region into several finite regions, divided the number of nodes and determined the unit volume, and then defined approximations of the controlling boundary conditions affecting the nodes and surrounding nodes. Then, they made many assumptions in the simulation process. They ignored the radiation heat flow, the heat transfer between the tool and the workpiece, the friction coefficient, and assumed that the material did not melt during the welding process, and the material was isotropic and uniform. The model they used in their research is based on 3D geometry with a Lagrange-T2J1 element.

They put the numerical simulation on the temperature analysis and the actual temperature test results together and found that the Cu side conducts heat faster, and the actual results are basically consistent with the simulation results. Although they did not conduct an in-depth numerical simulation of the FSW of Cu–Al dissimilar materials, their results have opened a door for researchers in this field and are of great reference value. It can be seen from the existing literature that the research on the FSW of Cu–Al dissimilar materials still remains to be conducted regarding basic parameter research and performance research, and no real numerical simulation research has been carried out. The authors suggest that, on the basis of the study of parameters and mechanical properties, researchers can try to conduct the numerical simulation analysis of the welding process, including the temperature field, stress field and material plastic flow.

5. The Study of the Improvement of the Welding Process

Since Murr et al. [68] studied the FSW of the Cu–Al dissimilar materials in 1998, a large number of researchers have also started to conduct studies in this field. Those mentioned above are some of the research results. However, there are still some problems in the welding Cu–Al dissimilar materials by using FSW. For example, the welding parameter window is small, it is difficult to obtain a joint without defects, and the welding joint is very prone to flash, hole and tunnel defects. From the above analysis, it can be concluded that, due to the characteristics of the two materials, the welding of dissimilar materials cannot eliminate some of the problems just by changing the welding parameters, such as the welding of the similar materials. That is to say, the welding process needs some treatment. Of course, some researchers have made improvements in the welding process.

Liu et al. [31] proposed an alternated process, friction stir butt barrier welding (FSBBW), whose principle is to place a barrier between the Cu-5052 AA butt joint and the shoulder of the tool to prevent the direct contact between the shoulder and the surface of the workpiece to be welded. We show the schematic diagram in Figure 19. They performed FSBBW on Cu-5052 AA dissimilar materials, and reached some interesting conclusions by observing the macroscopic morphology, microstructure and XRD detection. First of all, they found that the macrocosmic and microscopic morphology of the 5052 AA barrier was better than that of the Cu barrier, and when Cu is the barrier, the material sticks to the shoulder of the tool, and the presence of Cu does not prevent the direct contact between the shoulder and the material. This is because 5052 AA has a better plastic fluidity and can fill the defects caused by the lower Cu-5052 AA butt joint in time during the welding process. Secondly, they also performed a comparative study on the thickness of the barrier and found that the better joint was obtained when the barrier was 1.5 mm thick. Finally, when they studied the influence of the welding parameters on the joint performance, they found that too high a rotational speed would make the barrier lose its function. The study of Liu HJ et al. provided a good idea for the improvement of the FSW process of Cu–Al dissimilar materials, but the comparison was only conducted through the observation of macroscopic and microscopic methods, without the data of mechanical properties to support the conclusion.

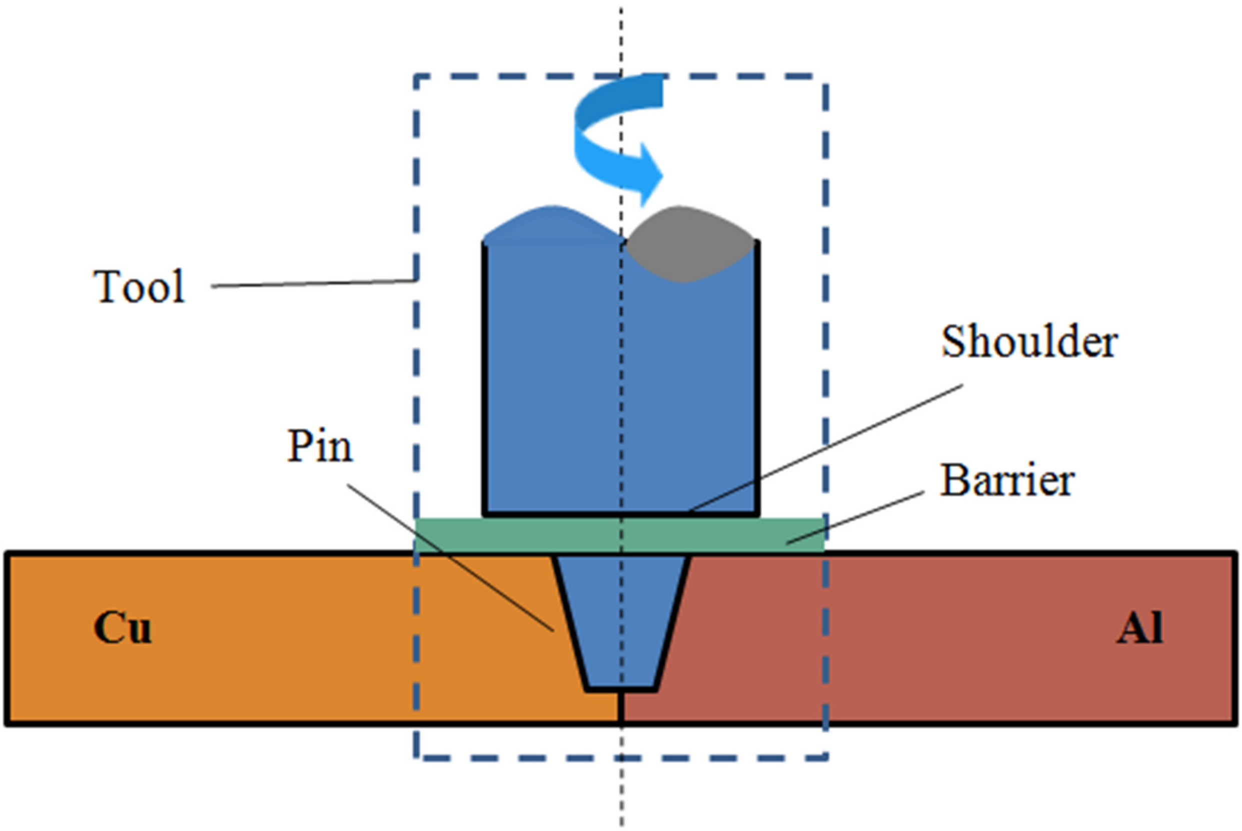
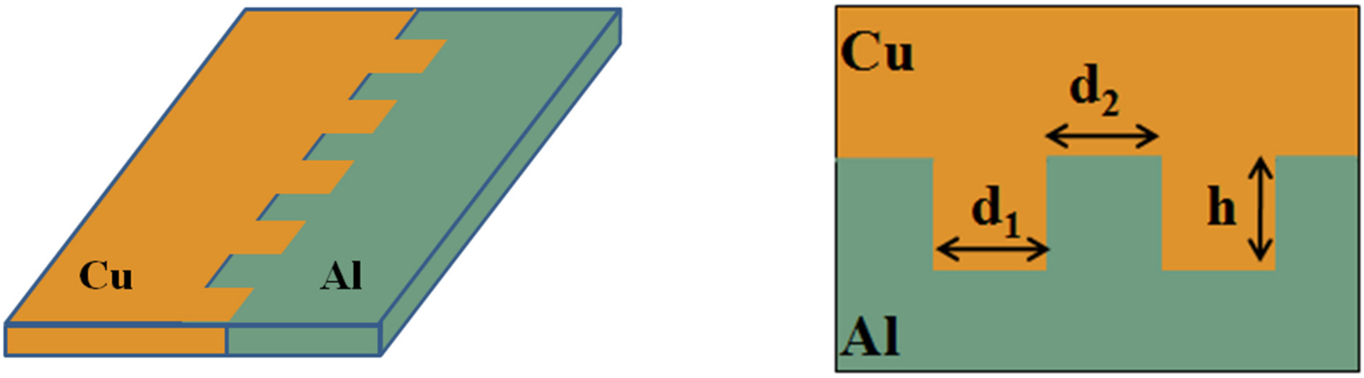


Figure 19. FSBBW schematic diagram.

Elrefaey et al. [73] adopted the method of adding a 50 µm zinc intermediate layer to the Cu-1100Al lap joint and then conducting FSW. They compared the welded joint with the zinc intermediate layer and without the zinc intermediate layer from macroscopic and microscopic morphology, tensile strength, tensile fracture and other aspects. As mentioned above, a dark black structure occurs at the interface of the Cu-Al FSW lap joint; however, when they observed the microstructure of the zinc intermediate layer joint, they found that the dark structure became thinner, and the disordered, layered Al–Cu alternating structure at the interface moved down into the Cu matrix, indicating that the presence of the zinc intermediate layer hindered the development of the dark structure. They also conducted tensile strength tests and found that the tensile strength of the joint with the zinc intermediate layer was three times that of the joint without the zinc intermediate layer, and the fracture paths and fracture modes of the two joints were also different. The joint with zinc intermediate layer was ductile fracture, and the joint without zinc intermediate layer was a brittle fracture. Additionally, by XRD detection, they found that there were more Cu–Zn IMCs near the Al side, and more Al–Cu IMCs near the Cu side. Their method of adding the zinc intermediate layer between the two materials was verified by experiments, and the macroscopic morphology and mechanical properties of Cu–Al have been improved and enhanced. Moreover, their next research direction is to study the influence of the zinc intermediate layer thickness on the joint properties.

Rasoul Khajeh et al. [85] studied the effect of the Zn layer on the microstructure and properties on the FSWed butt joint of Cu and 2024 aluminum alloy. From the perspective of the microstructure, after the addition of the Zn layer, the original IMCs, Al_2Cu and Al_4Cu_9, disappeared and turned into "$Al_{4.2}Cu_{3.2}Zn_{0.7}$, $CuZn_5$ and Cu_5Zn_8", and the complex wavy structure appeared in the welded joint. This inhibited the formation of brittle IMCs and increased the tensile strength and ductility of the welded joint. In addition, without Zn layer, the microstructure of tensile fracture showed clear cleavage steps, but after the Zn layer was added, there were a lot of dimples in the port morphology.

Instead of adding materials to the welds for process improvement, Zhang Wei et al. [86] chose to treat the form of the joint. They used FSW technology for the butt welding of 6061 AA and Cu. Different from previous studies, they chose the form of tooth-shaped butt joint in the joint form. Its processing diagram is shown in Figure 20, where d1 is the tooth width of the 6061 AA side and d2 is the tooth width of the Cu side, and h is the tooth length. In the experiment, they controlled h as a constant and changed d1 and d2, which meant that they wanted to control the content ratio of 6061 AA and Cu in the weld by changing d1 and d2. For example, when d1/d2 is 1/4, the volume ratio of 6061 AA to Cu in the weld was 1/4.



(**a**) (**b**)

Figure 20. (**a**) schematic diagram of tooth-shaped butt joint; (**b**) Dimension diagram.

They made microscopic observations, composition measurements, and obtained some mechanical properties of both common butt joints and tooth-shaped joints, and came to some interesting conclusions. First of all, they found that, compared with the ordinary butt joint, the tooth-shaped joint was less prone to defects, because the Cu–Al of the toothed joint were interlaced with each other, and the holes and other defects generated in the welding process were filled in time. Secondly, through the analysis of the microstructure and mechanical properties, it was found that, when d1/d2 is 3/2, the microstructure of the joint is more uniform and the mechanical properties are better, which indicates that the excessive Cu content in the weld is not conducive to being formed. Finally, they found that there were two sublayers in the interface microstructure of the tooth-shaped joint, and that each sublayer was very uniform and thin, which is different from a normal butt joint. Overall, the experiment of Zhang Wei et al. was a bold innovation, with a large change in the joint form and a change in the proportion of the material by changing the tooth width. In this way, the structure and performance of the Cu-Al butt joint were also improved.

6. Conclusions

From the above, we can see that, since 1998, many researchers have investigated this area of FSW of Cu–Al. The authors made a summary of the research and put forward the following ideas and suggestions:

1. At present, most of the studies on the FSW of Cu-Al are limited to the observation of the microstructure and the analysis of basic mechanical properties, including tensile strength and microhardness. However, as the FSW of Cu and Al dissimilar materials has practical applications, it should involve fatigue properties, corrosion resistance and even electrical properties. The next research on FSW of Cu-Al dissimilar materials should be richer and more complete in terms of mechanical properties;
2. The single shaft shoulder FSW process of Cu–Al dissimilar materials has been studied relatively thoroughly and has relatively perfect welding parameters during welding. However, in previous studies, the single shaft shoulder FSW process was prone to weld defects where the root was not welded through. It can only use this method for butt and lap jointed plates and not for hollow type plates. Therefore, the authors believe that the next development direction of the FSW of Cu–Al dissimilar material technology is to use the derivative technology of FSW, namely BTFSW, FSSW and RFSSW, to weld Cu–Al dissimilar materials, and continue to expand this field;
3. At present, there are relatively few studies on the FSW numerical simulation of Cu–Al dissimilar materials, including the simulation of temperature field, stress field and plastic flow model in the welding process. In subsequent studies, numerical simulations of the FSW process for Cu–Al dissimilar materials should be attempted with different software and finite element models;
4. Although many researchers have successfully welded Cu–Al dissimilar materials by using the FSW process, there are still many problems in the FSW of Cu–Al dissimilar materials. For example, the welding parameter window is small, and the mechanical properties of the welded joint are not high. Therefore, the next step is to continuously improve the FSW welding process to achieve the purpose of improving the mechanical properties of the joint, so that the FSW technology of Cu–Al dissimilar materials can be more widely used in various industries.

Author Contributions: Conceptualization, writing—review and editing, writing—original draft preparation, Y.S.; funding acquisition, resources, W.G.; visualization, J.F.; software, investigation, G.L.; validation, data curation, R.Z.; supervision, project administration, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Jilin Province Development and Reform Commission industrial technology research and development project, grant number X2019C046-7.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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