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Regulation of intermetallic compound layer in friction stir lap welding of aluminum/steel: a short review

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Abstract: In this paper, the research on control of intermetallic compound during aluminum/steel friction stir lap welding is reviewed. Several means that improve the properties and quality of the joints are presented by controlling the IMCs layer. The thickness of IMCs layer is controlled by the processing parameters, tool structure and aided processing, and the types of the IMCs are controlled by the processing parameters and the addition of the interlayer design. Advantages and disadvantages of the above methods are discussed. A new research direction with a large-lift angle structure of the tool is also proposed for the development of the aluminum/steel welding technology in this paper.

Keywords: Aluminum; steel; Friction stir lap welding; Intermetallic compound; Control methods; Processing parameter

1. Introduction

With the increasing requirement for lightweight structures in aerospace, automotive, rail transit and other fields, aluminum/steel heterogeneous metal composite structures have attracted more and more attention for their characteristics of high quality, low cost, meeting different service conditions and energy saving and environmental protection[1-4]. The connection of dissimilar materials of aluminum and steel has been fully applied to some structural parts of aircraft, automobiles and ships. Therefore, solving the connection problem of aluminum/steel dissimilar materials is the key to realize the large-scale application of aluminum steel composite structural parts.

At present, the connection methods for aluminum/steel composite structural components mainly include bonding, riveting, and welding. However, there are some disadvantages for bonding and riveting, such as poor heat resistance and airtightness, increased structural weight, and low fatigue strength. It is difficult to achieve the requirements of lightweight and high-strength structure because of the above factors[5,6]. Welding technology with its high reliability, high strength, and good sealing properties has become the preferred method for aluminum/steel heterogeneous metal connections. The significant differences in thermal, physical, and chemical properties between aluminum and steel increase the difficulty of welding[7]. Therefore, the development of high-reliability welding methods becomes the important issue for obtaining the high-quality joint of aluminum/steel.

For the traditional fusion welding, high heat input leads to the difficulty of precise control, the formation of brittle intermetallic compounds and reduction of the joint properties. Brazing welding depends on the brazing filler metal, which reduces the heat input and the generation of intermetallic compounds, but the defects of porosity and slag inclusion are prone to forming[8-12]. Aluminum steel dissimilar metal connection is more inclined to solid phase welding.

Friction stir welding, as a typical solid phase connection technology, the most outstanding advantage of this technology is a lower heat input and a shorter high temperature residence time, which control the growth of intermetallic compounds, reduce the welding stress and avoid the defects such as cracks and pores. It has become an effective way to achieve high-quality joint[13-19]. Based on a large number of researches, it has been found that the high reliability and high-quality joints obtained by FSW are more dependent on the interfacial behavior, which is affected directly by the IMCs of aluminum/steel[20-23].

Therefore, the crucial issue of the connection of the aluminum/steel dissimilar metal is attributed to the control of the IMCs, that is, the control of IMCs layer thickness and IMCs types, as shown in Fig. 1. The thickness of IMCs layer is controlled by the processing parameters, tool structure and aided processing, and the types of the IMCs are controlled by the processing parameters and the addition of the interlayer design, as shown in Fig. 1. In this paper, the control means of IMCs in aluminum/steel dissimilar metal friction stir lap welding(FSLW) are reviewed, and the development is proposed based on the improvement of joint load capacity, which provides a new research direction for the improvement of aluminum/steel dissimilar metal welding technology.

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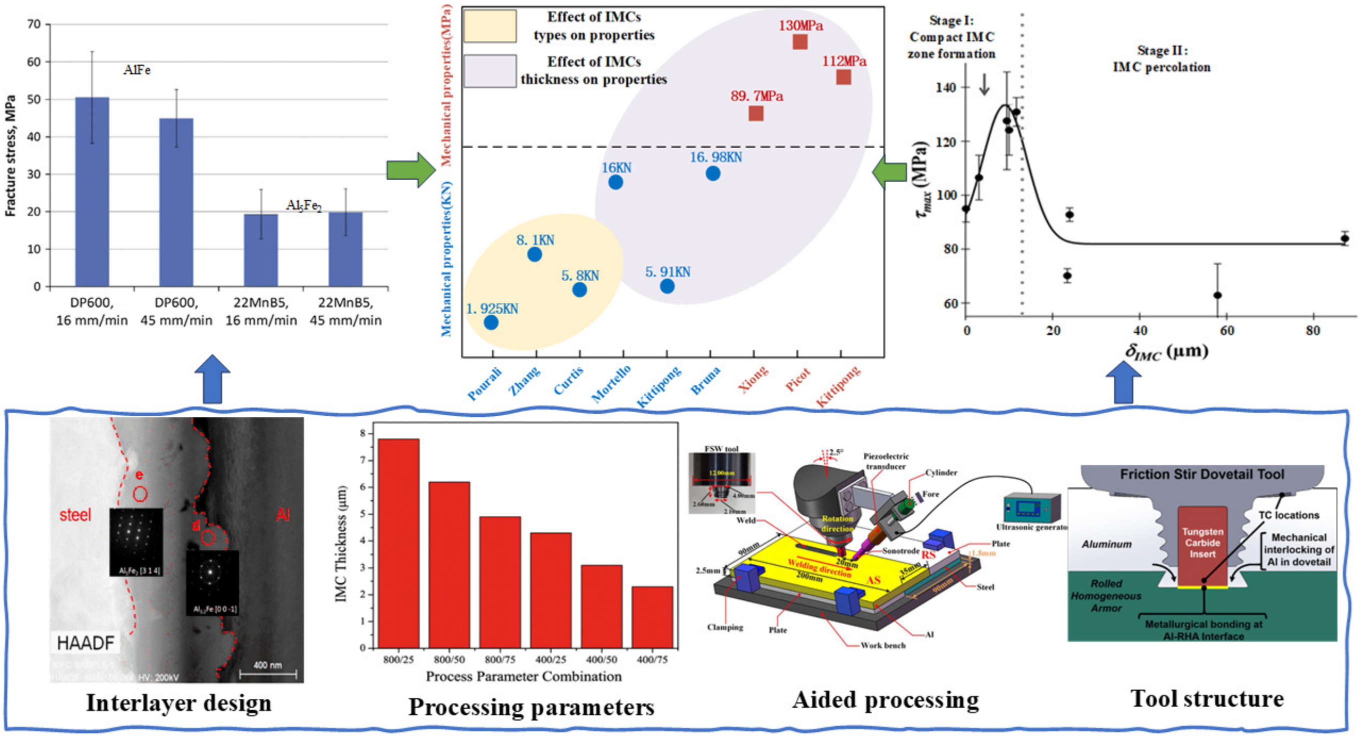

Fig. 1. Factors affecting mechanical properties.[24-37]

2. Way of lap welding

The hardness of steel is higher than that of aluminum and the upper layer is more affected by the tools. In order to reduce the damage and extend the service life of the tools, the tool without pin is chosen when the steel is on the upper side of aluminum during the friction stir lap welding, as shown in Fig.2. Fraction heat is transferred through the steel side to the aluminum side, causing the aluminum surface to melt and weld. However, in order to obtain a high-quality joint, as the upper plate, there are strict requirements on the thickness of steel because of its lower thermal conductivity. The thickness of the upper plate is less than 1 mm [38].

In order to promote the atom diffusion and material flow between the steel and aluminum, the aluminum is usually placed on the top of the steel, which is also benefit to deformation of aluminum and ensures a long service life of the tools. When the aluminum is on the upper side of steel during the friction stir lap welding, the schematic is shown in Fig.3.[39]

In addition, the low solubility of iron in aluminum leads to the formation of the brittle IMCs. Aluminum atoms are relatively more active, and the migration of aluminum to iron subjected by the pin of the tool is relatively sufficient during the friction stir lap welding. Iron-rich compound will be formed due to a long-time diffusion of the atom, which is subjected by the multiple action of the high temperature, shoulder pressure and pin[40,41]. Therefore, the aluminum placed on the top of the steel is usually used during the friction stir lap welding, and the IMCs layer is formed under the high temperature because of the limited solubility of the Al into Fe on the interface of overlap joint.

3. Effect of the IMCs layer thickness on properties

Comparing with the mechanical connection, metallurgical connection will be formed at the Aluminum/steel interface due to the production of the IMCs, enhancing the strength of the joints[42]. However, the volume of the phase will be changed because of the exces-

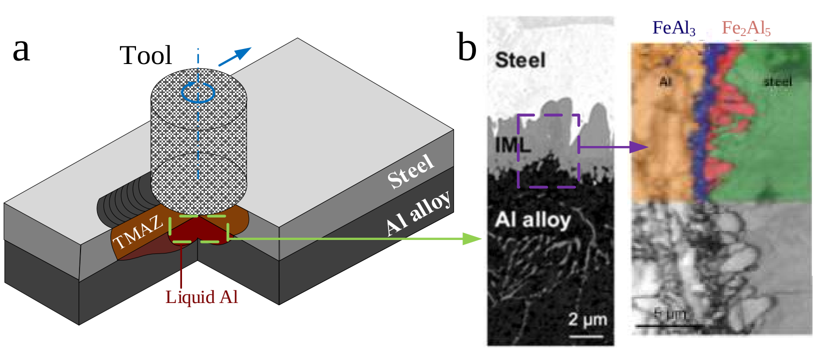

Fig. 2. Schematic diagram and microscopic morphology of welded structure steel upper and lower aluminum: a. schematic diagram; b. interface topography[38]**.**

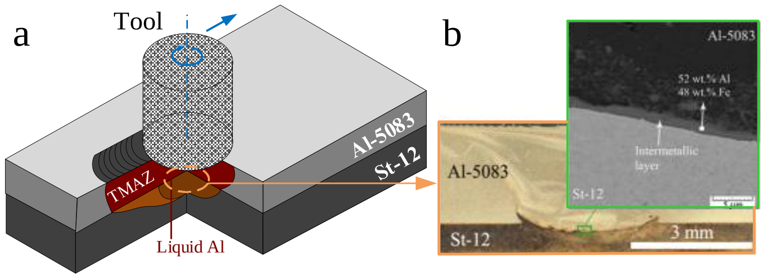

Fig. 3. Schematic diagram and microscopic morphology of welded structure under aluminum upper and lower steel: a. schematic diagram; b. interface topography[39].

sive IMCs layer thickness, resulting in the local stress and the crack propagation, reducing the load capacity of the joints. When the thickness of the IMCs layer is less than 2 μm during FSLW between 5083 aluminum alloy/steel, there is not any adverse effect for the quality of the joint[39]. The failure load increases with the increasing of the IMCs layer thickness. The thicker of the IMCs layer, the more likely to form the cracks and accelerate crack propagation[43,44].

Therefore, the thickness of the IMCs layer has an important effect on the properties of the joints. Superior joints properties are obtained by controlling the thickness of the IMCs layer. According to the current research status, the means of controlling the thickness of the IMCs layer include processing parameters, tool structures and aided process.

3.1 Control of the IMCs layer thickness by processing parameters

Heat input has great influence on the IMCs layer thickness and the weld forming[45-47]. When the heat input is lower, it is difficult for the material around the tool to plasticize with a poor flow ability, accompanying by the formation of various defects[48]. When the heat input is higher, there is a severe softening issue at the interface of the joints, resulting in a thicker IMCs layer. Controlling the heat input (including welding speed, rotational speed, insertion depth and inclination angle of the tool, etc.) contributes to an appropriate IMCs layer thickness, obtaining superior properties of the joints[25]. Table 1 records the research of different scholars about the effect of the rotational speed and welding speed on IMCs thickness.

Plastic deformation during aluminum/steel FSLW is affected by the changing of the rotational speed and welding speed[49]. The thickness of the IMCs layer at the interface decreases with increasing the welding speed, and increases with increasing the rotational speed[50]. Dehghani et al.[51] studied the welding speeds of 14 mm/min, 28 mm/min and 40 mm/min at a constant rotational speed, and found that at the lower welding speeds, a thicker IMCs layer was formed at the aluminum-steel interface, which was not good for the joint properties, as shown in Fig.4. When the welding speed was increased to 40 mm/min, the thickness of IMCs layer was reduced due to the decrease of heat input, and a better connection property was obtained. However, the IMCs layer cannot be formed at the aluminum/steel lap interface by reducing the ratio of the rotational speed to the welding speed blindly[52].

Based on the above researches, it is found that when the ratio of rotational speed to welding speed is too small, the thickness of the IMCs layer is too thin because of the low heat input, which cannot achieve the best performance or even leads to the invalid connection[53]. When the ratio of rotational speed to welding speed is too high, a thicker IMCs layer is formed by the higher heat input, causing the defects and the crack propagation. It is necessary to adjust the heat input by controlling the ratio of rotational speed to welding speed to obtain the most suitable IMCs layer thickness and the optimal joint performance.

Table 1 Summary of the effect of the rotational speed and welding speed on IMCs thickness.

Scholar	Experimental process		Conclusion
	Experimental material	Regulation means	
Ibrahim[52]	A516-70 steel and AA5052	Rational speed and welding speed	● Higher rotational speed is beneficial to the formation of IMCs. ● Lower welding speed will lead to connection failure.
Dehghani[51]	AA5186 and mild steel	Welding speed	● With the increase of welding speed, the IMCs layer will gradually become thinner. ● The joint will show higher tensile strength with increasing the welding speed.
Das[45]	AA6063 and zinc-coated steel	Rational speed	● The IMCs layer is an important structure to connect Al and steel. ● Good bonding performance can be obtained within a certain heat input range.
Boumerzoug[46]	AA6061-T6 and ultra-low carbon steel	Welding speed	● The thickness of the IMCs layer decreases with increasing welding speed. ● The shear strength increases by increasing the welding speed.
Kimapong[33]	AA5083 and SS400 steel	Welding speed	● Increasing the welding speed will obtain a thin IMCs layer, thereby obtaining good performance.
Wei[41]	AA1060 and SUS321 steel	Insertion depth	● The pin tip close to the steel will form a continuous and thin connection layer. ● The pin tip penetrating into the steel will generate thicker IMCs layer.
Chitturi[54]	AA5052 and 304 steel	Insertion depth	● The thickness of IMCs layer becomes thicker with increasing the insertion depth.
Chen[55]	AA6060-T5 and mild steel	Insertion depth	● The IMCs will become thicker with the pin inserted into the steel 0.1mm. ● The thickness of the IMCs layer less than 2.5 μm contributes to the superior joint.

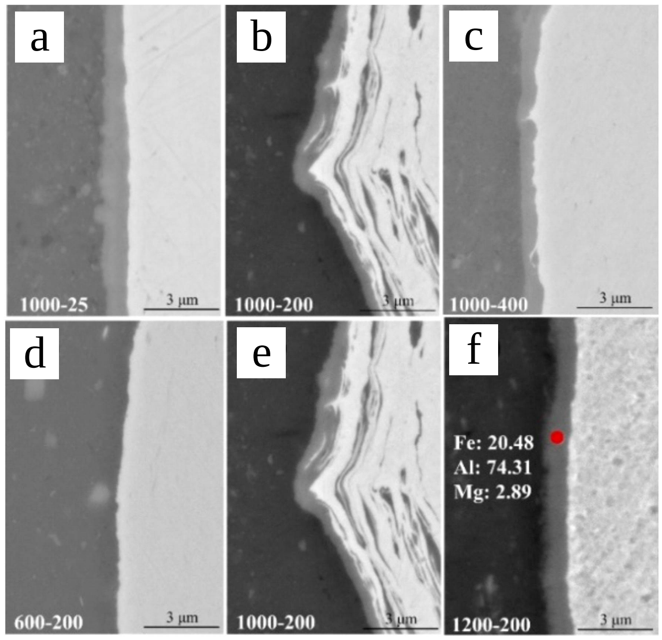

Fig. 4. Influence of different process parameters on thickness[51]

In addition to the rotational speed and welding speed, the insertion depth of the tools, as another an important factor controlling the heat input, also affects the thickness of the IMCs layer. The continuous IMCs layer is formed when the pin comes close to the steel surface[41,54], as shown in Fig. 5. On the contrary, when the pin is away from the steel, the effective IMCs layer cannot be formed or even leads to the invalid connection.

When the pin is inserted into the steel side, the steel is extruded into the aluminum side, forming a mechanical interlock connection which is beneficial for the joint properties[55]. A thicker IMCs layer will be formed due to the excessive insertion into the steel, which reduce the joint strength[56]. Furthermore, a reasonable range of the insertion depth of the pin has been provided, when the insertion depth of the pin into the steel is 0.1mm-0.5mm, a more significant flow of the material and a higher quality joint are presented[32]. With the increasing of the insertion depth of the pin, a hook-like structure is formed, resulting in a thicker IMCs layer[58], as shown in Fig.6.

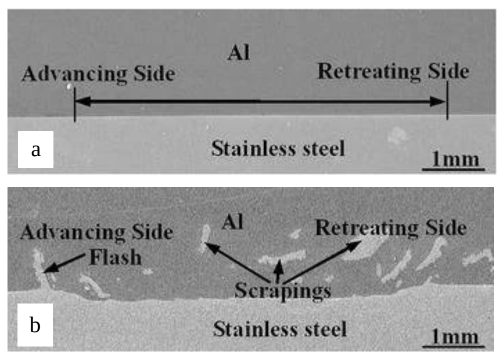

Fig. 5. Comparison of different depths.[41]

It has also been proved that as the insertion depth of the pin increases, the IMCs layer becomes discontinuous, resulting in a decline in the joint bearing capacity. When the pin is inserted into a suitable location, a microscopic zigzag interlocking structure and

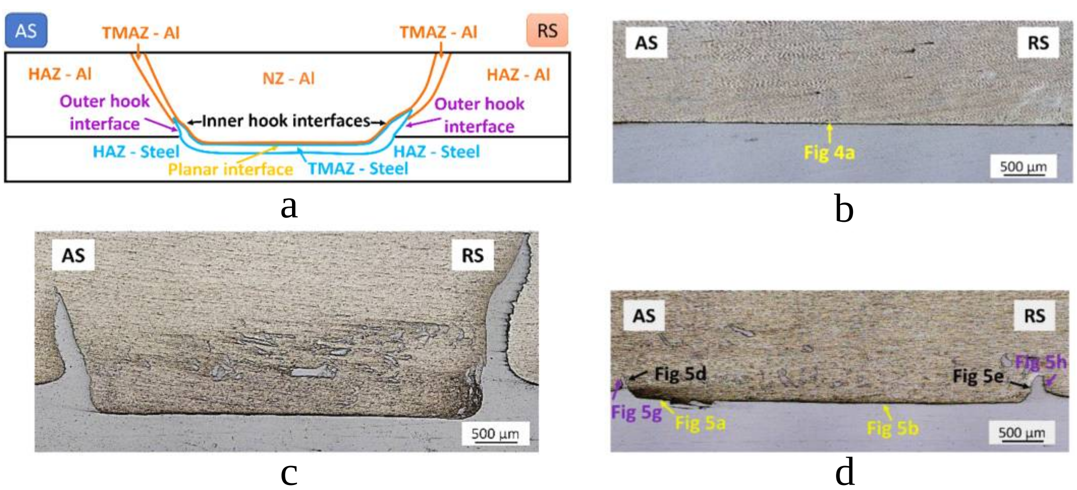

Fig. 6. a. A schematic representation of the interfaces and different depth: b. 0.05 mm; c. 0.2 mm; d. 0.4 mm.[58]

thinner IMCs layer are formed at the interface. It is necessary to set an optimal distance of the micro-insertion into the steel to obtain the mechanical interlock with good IMCs[33,57].

3.2 Control of the IMCs layer thickness by tool structures

Due to the insertion depth of the pin has a great influence on the IMCs layer thickness and it is not easy to precisely control the amount of insertion depth, improving the tool structures has been considered as an effective means to control the IMCs layer thickness, obtaining good results. In order to obtain a good connection effect, the researchers designed different shapes of pins based on cylindrical and conical shapes, as shown in Table 2.

Table 2 Summary of different shape pins

Scholar	Experimental process		Conclusion
	Experimental material	Regulation means	
Reza-E-Rabb[29]	AA6061-T651 and Rolled Homogeneous Armor	Dovetail-shaped pin	● The growth of IMCs in dovetail is inhibited. ● Mechanical interlocking and metallurgical bonding are formed.
Wang[59]	AA6022-T4 and mild steel	Pins with bumps	● The lap weld will fail along the aluminum above the aluminum/steel interface with a smaller hook height.
Wei[60]	AA1060 and SUS321	Cutting pin	● The cutting pin avoids the wear of the pin. ● Joints are formed by some serrated structures.
Ambrosio [62]	AA6061-T6 and SPCC steel	Hemispherical shape pin	● The growth of IMCs can be greatly inhibited by the hemispherical shape pin. ● The thickness of IMCs can reach 2-2.5 nm.

A superior effect in controlling the IMCs is provided by the different structures of the tools, promoting the material flow and forming the higher quality joints. The new needle modified according to the cylindrical and conical needle is shown in Fig.7.

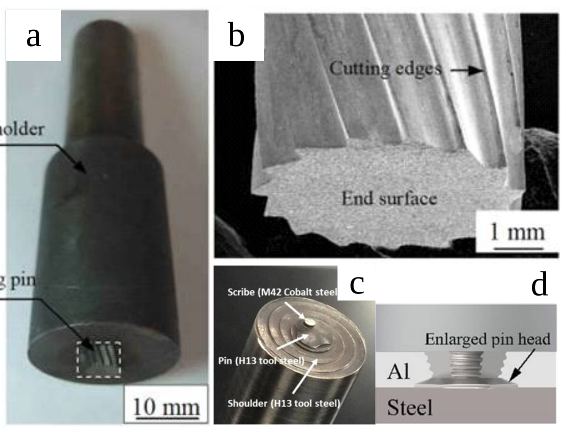

Fig. 7. Different shape pins.[59,60,63]

The tool structure with cutting pin changes the material flow by the small pump at the tip of the pin without increasing the heat input, reducing the hook-like structure and inhabiting the growth of the IMCs layer. However, the tip of the pin is prone to wear during welding by using this tool structure[59]. Cutting the thread on the pin does have the effect of enhancing the flow of the material, which is conducive to the impact of the aluminum material on the steel surface at the lap interface to form an effective metallurgical bonding[60]. Dovetail pin is developed to control the thickness of the IMCs layer and the over-combination between the Al and steel by using the thermocouple temperature sensor at the tip of the pin[61]. The continuous IMCs layer with complex composition is obtained by the tool structure with hemispherical pin inclining to the retreating side[62]. In addition, a new tool structure is proposed to control the penetration of steel to aluminum side and avoid the formation of the hook-like structure, obtaining a continuous interface with zigzag structure[63], as shown in Fig.8.

The special shape of the stirring pin can indeed obtain different joint interface morphologies and IMCs types by driving the flow of the material. The above scholars have studied the special shape of the stirring pin that is slightly inserted into the steel side; Through the shape of the stirring needle and the material driving effect of the thread pair on the needle, it is theoretically effective to design a stirring with a diversion tank on the surface for diffusion welding that does not penetrate the steel side.

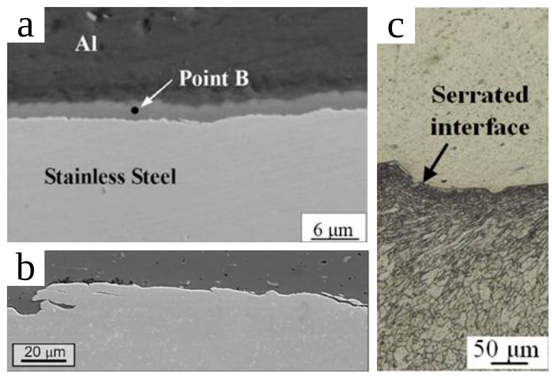

Fig. 8. Different shape needles and interfaces: a. the cutting pin; b. the hemispherical pin; c. the enlarged pin[60,62,63]

3.3 Control of the IMCs layer thickness by aided process

In order to obtain the continuous IMCs layer and improve the softening degree of the material, the aided process is introduced in the friction stir welding and all-right research results are achieved, such as, the ultrasonic vibration, friction stir brazing and fusion arc welding and other methods[60]. Table 3 summarizes the methods of adding other auxiliary processes for friction stir welding of aluminum steel.

Ultrasonic vibration has significant advantages in welding, including softening the base material, decreasing the load of welding, increasing the interface width of the mixing zone, improving the interface bonding capacity. Moreover, failure load and welding efficiency are also enhanced significantly. More importantly, the thickness of the brittle IMCs layer is reduced by the decrease of the peak welding temperature[64-66]as shown in Fig. 9 because of the addition of the ultrasonic vibration.

In addition to the external auxiliary device, the multi-pass weld-

Table 3 Summary of the aided process.

Scholar	Experimental process		Conclusion
	Experimental material	Regulation means	
Liu[30]	AA6061-T6 and Q235 steel	With or without ultrasonic	● The thickness of IMCs layer decreased to 0.71 mm with ultrasonic vibration. ● The plastic fluidity of the material is significantly improved.
Wang[58]	AA6061-T651 and galvanized steel	Single-pass and double-pass welding process	● Double-pass welding eliminates defects and the IMCs at key positions, forms a strong aluminum-steel interface adhesion, ● The welding strength is improved by double-pass welding
Leitao[67]	AA6082-T6 and S355J2 steel	Multipass welding	● The formation of IMCs in the bonding interface is inhibited.
Liu[69]	AA6061 and Q235 steel	By-passing current-metal inert gas welding	● The thickness of the IMCs layer can be reduced to less than 1.5 μm.
Zhou[70]	AA6061 and Q235 steel	Adding the Al interlayer.	● The FS interlayer is composed of highly refined and equiaxed grains. ● A defect-free Al/steel weld was obtained.

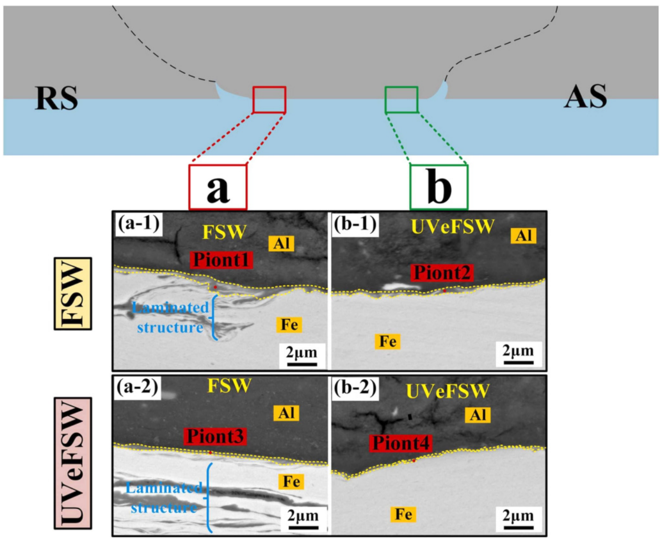

Fig. 9. The difference between with and without ultrasonic vibration[65]

ing process is also applied to aluminum steel welding with the repeated action on the weld. A good metallurgical connection is formed because of the welded material flow fully under the multiple action of the pin. However, due to a metallurgical connection cannot be formed with a small insertion, the insertion depth is strictly controlled under this process[58,67]. Although the friction stir brazing with pure aluminum as the middle layer solves the above problems and reduces the tool wear, aluminum is prone to deformation and fracture because of the insufficient heat input and large diameter shoulder without pin[68]. Arc and friction stir hybrid welding (AFSHW)is developed by combing the arc welding and the FSW. The steel surface is coated with a pure aluminum intermediate layer using MIG, and then FSLW multi-pass welding. The growth of the IMCs layer is inhabited by the appropriate heat input and a great mixture of the material is promoted, forming a good connecting interface[69]. Similarly, the IMCs layer can be thinned by welding the intermediate layer of aluminum by friction stir surfacing[70]. The results obtained by multipass welding, hybrid welding and friction stir surfacing are shown in Fig.10.

4. Effect of IMCs types on properties

Due to the formation of the IMCs types has an important effect on the toughness of the joint during aluminum/steel welding process, the IMCs types are another important factor affecting the properties of the joints except for the IMCs layer thickness[24].

The main types of the IMCs formed by aluminum/steel welding are classified as Al-rich IMCs ($FeAl_2$ $FeAl_3$, $FeAl_6$, Fe_4Al_{13} and so on) and Fe-rich IMCs (FeAl, Fe_3Al and so on). There are great different effects between these two types IMCs on the properties of the joints. When there is a high content of Al-rich IMCs types at the interface of aluminum/steel joint, the joint presents a high brittleness, resulting in crack propagation and reducing the joint strength. Fe-rich IMCs types often exhibit a higher toughness[72]. It has been proved that the Fe-rich IMCs types are superior to the Al-rich IMCs types for joint properties, improving the fracture toughness and interfacial strength[34,51,55,73]. Table 4 summarizes the research on how to obtain different types of IMCs.

Therefore, the researchers suggest that joints properties can be improved by adjusting the IMCs types, and optimizing the welding parameters is an important means to control the IMCs types. The researchers explored the formation of Fe-rich compounds under different process parameters, and concluded that with the increase of rotational speed, the temperature required for the formation of Fe-rich compounds was provided. The lower welding speed means that the interface has a relatively longer time to complete the transition from Al-rich to Fe-rich, but too large transfer ratio will accelerate the growth of the IMCs layer[74]. It is found that when the rotational speed of the needle and the welding speed reach a certain balance, the interface will change from Al-rich IMCs to Fe-rich IMCs, but when the heat input continues to increase on the balanced process parameters, it will be beneficial to the formation of Al-rich IMCs[33,57].

In addition, the researchers identify that IMCs types can also be controlled by introducing an intermediate layer in the aluminum-steel interface[75-77]. For example, it has been proved that the plastic flow ability of the aluminum-steel interface will be improved because of the addition of Zn interlayer. With the increase of Zn interlayer thickness, Al-rich IMCs types at the interface will be transformed into Fe-rich IMCs types[78,79].

4.1 Control of the IMCs types by processing parameters

A large number of studies have shown that the aluminum-steel interface at high welding speed is not enough to have enough heating time to generate IMCs. For the lap welding of aluminum and steel, All_3Fe_4 and Al_5Fe_2 were observed at the interface by reducing the welding speed[53,80]. Reducing the welding speed will prolong the holding time of welding, enhance the diffusion ability between atoms, and further transform into $FeAl_3$, while increasing the amount

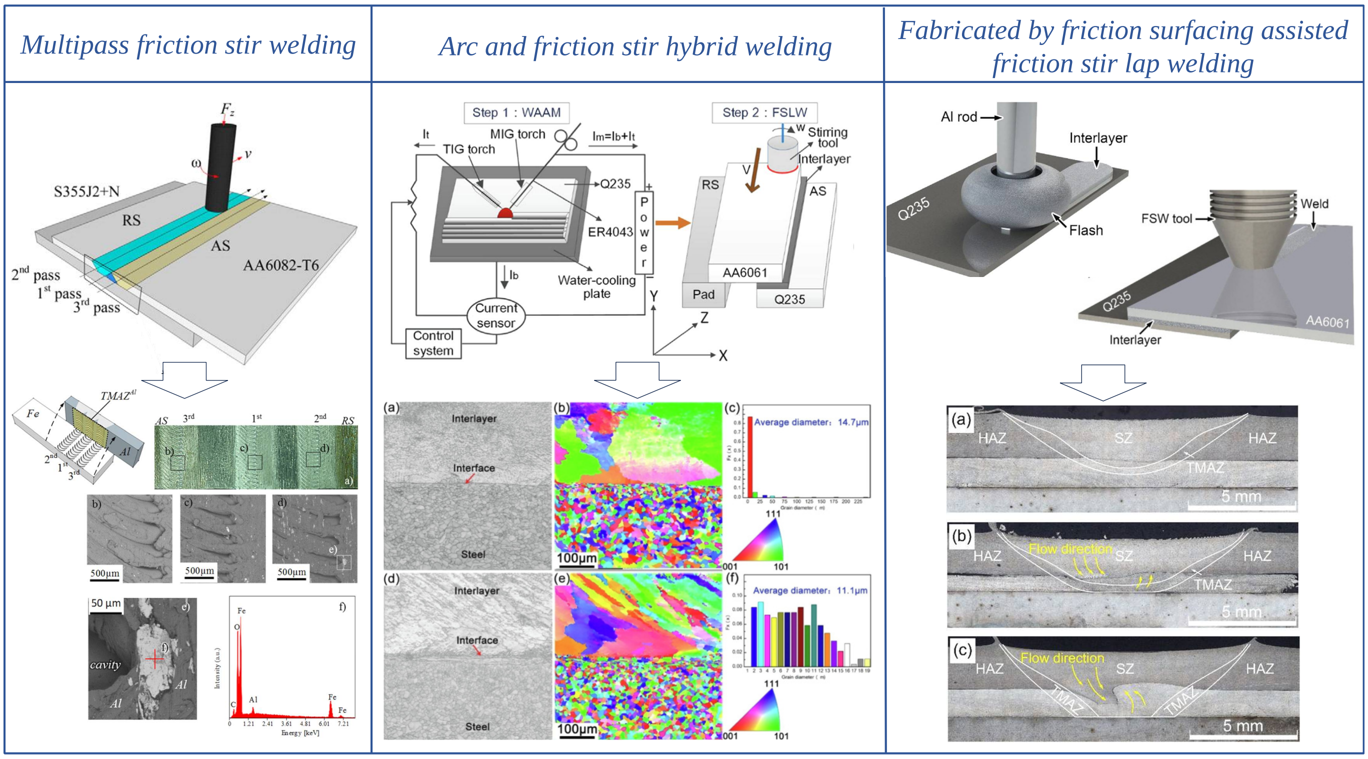

Fig. 10. A schematic diagram of the three processes.[67,69,70]

Table 4 Summary of the research on different types of IMCs.

Scholar	Experimental process		Conclusion
	Experimental material	Regulation means	
Tanaka[72]	Solid Fe and liquid Al	Temperature	● The thickness of $FeAl_3$ is much smaller than that of Fe_2Al_5, so the compound region is mainly composed of Fe_2Al_5.
Ratanathavorn[53]	AA5754 and DP800 steel	Processing parameters	● $Al_{13}Fe_4$, Al_5Fe_2 and Fe_3Zn_{10} were detected. ● Al-rich (Fe_2Al_5) IMCs is easier to form at high welding speed.
Meng[81]	AA6061-T6 and galvanized steel	Adding zinc foil	● The addition of zinc foil effectively greatly prevents the formation of Fe_3Al_{14}. ● The Al-Zn eutectic structure replaces the thicker IMCs.
Dong[82]	Al-Mg-Si and 301L steel	Adding Zn interlayer	● The tensile shear load of the Zn-added joint presented an obvious increase of 41.3%. ● Fe-Zn IMCs and Al-Zn eutectic are formed.
Zhou[70]	AA6061 and Q235 steel	Adding Al interlayer	● The diffusion layer was found at the interface, but not the IMCs layer. ● The atomic migration and related interface bonding were enhanced.
Li[75]	AA6022 and high strength steel	Adding Al interlayer	● A diffused layer with the thickness of 10 nm was generated at the interface. ● The IMCs was not found at the joint.
Chen[84]	AA5052 and stainless steel	Adding Ni interlayer	● $Al_{0.9}Ni_{1.1}$/Al_3Fe and Al_3Ni were formed. ● The properties of the joint were improved.

of pressure will not further transform $FeAl_3$ but thicken it[33,34,57], as shown in Fig. 11. The researchers conducted experiments with different reductions and found that the IMCs particles in the joint were distributed on the boundary of the fine equiaxed grains, which indicated that the region was more severely deformed, and then the slender grains were transformed into fine equiaxed grains through the dynamic recrystallization process[36].

Changing the rotational speed of the stirring head can greatly affect the heat input of the welding, and the welding speed can be seen as the action time and cooling time of the material to be welded. Some researchers have found that slowing down the cooling time at the interface will be beneficial to the transition from Al-rich to Fe-rich.

4.2 Control of the IMCs types by interlayer design

In the experiment of adding Zn interlayer, it was found that when the joint with Zn interlayer and pin did not penetrate the upper aluminum plate, the interface diffusion layer changed from continuous diffusion layer to uneven diffusion layer. Compared with the single Fe-Al IMCs in the diffusion layer of the joint without Zn addition, Fe-Zn IMCs and Al-Zn eutectic were formed in the joint with Zn addition, as shown in Fig. 12. The combination of galvanized layer and low welding speed is more conducive to the formation of Fe-

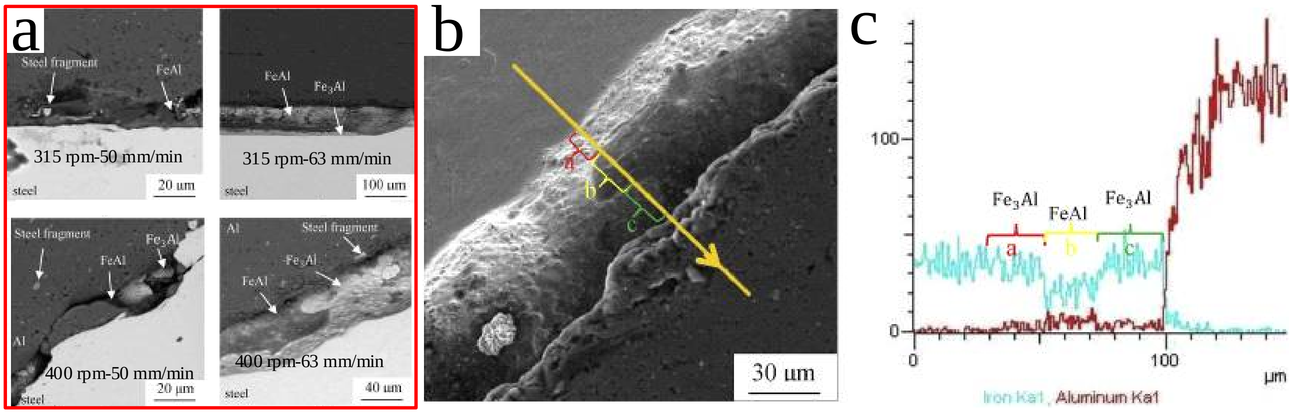

Fig. 11. a. thickness and type of IMCs layer generated under different process parameters; b. enlarged image of IMCs; c. curve of EDS.[34]

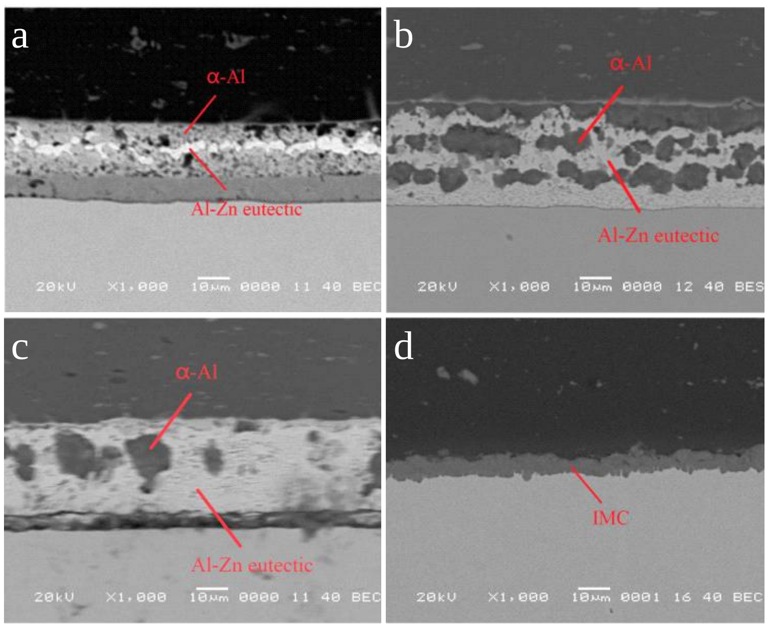

Fig. 12. a. without addition; b. 50 μm Zn interlayer; c. 100 μm Zn interlayer; d. 200 μm Zn interlayer.[82]

rich intermetallic compounds (FeAl)[81].

Some scholars believe that pure aluminum can be used to inhibit the formation of aluminum-rich compounds[70,75]. However, the diffusion layer was found at the interface but no metal compounds were found. The test of adding Ni interlayer proves that the IMCs types are $Al1_3Fe_4$, Al_5Fe_2 and $AlFe_3$ without Ni interlayer, which are Al_3Ni, $Al3Ni_2$ and AlNi with Ni interlayer, respectively as shown in Fig. 13. The joints of Al-Fe IMCs type are very brittle, while the joints of Al-Ni IMCs type are mostly ductile. The bonding strength between aluminum alloy and steel is improved by the Al-Ni phase with better toughness. It effectively prevents crack propagation and changes the crack propagation path, thereby improving the fatigue strength of the joint[26,83-85].

5. Conclusion and prospect

A lot of research had been done on friction stir welding of aluminum and steel, but the core problem (increasing the joint load capacity) was still needed to be solved. According to the above references, the strength of the aluminum-steel joint mainly depended on the thickness of the IMCs layer. The load capacity of the joint was reduced and prone to fracture because of the thicker brittle IMCs layer. It was difficult to obtain the thinner IMCs layer. In addition, the effective connection could not be formed because of that continually reducing the heat input caused the incomplete diffusion of atoms.

In order to accurately control the thickness of the IMCs layer generated by the interface, it was necessary to accurately control the temperature of the interface (heating time, peak temperature, cooling time, etc.). For friction stir welding, the precise temperature parameters were controlled by the rotational speed, welding speed, clamping mode, environmental temperature and other parameters, which was complicated and difficult in the conventional process. Therefore, the composite process of optimizing joints by adding other auxiliary processes based on friction stir welding has been developed, and the auxiliary process of adding ultrasonic vibration is more mature. Ultrasonic assisted technology is aimed to achieve a good metallurgical connection of aluminum steel interface under low heat input, but the process becomes complexity because of the new equipment and the high frequency oscillation of ultrasonic has serious pollution to the working environment. Moreover, its practical application in engineering field remains to be proved.

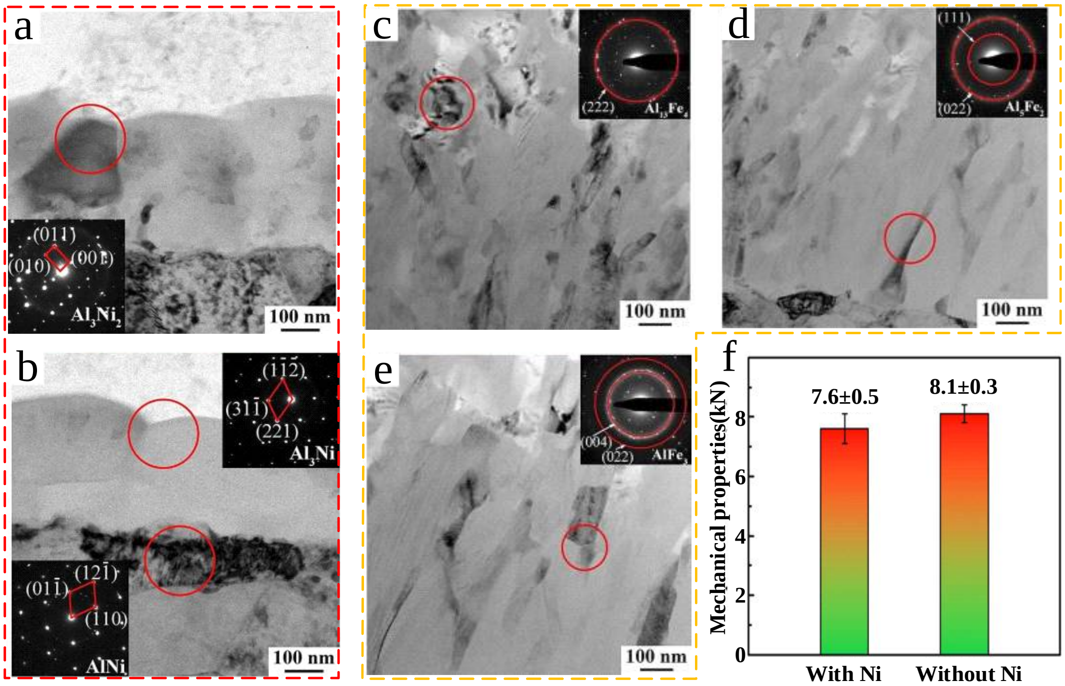

Fig. 13. a, b. with Ni intermediate layer; c, d, e. without Ni intermediate layer; f. comparison of carrying capacity.[26]

Micro-insertion process has been studied more in recent years. Compared with traditional process, micro-insertion process has many advantages. For example, a small length insertion into the lower plate will destroy the original interface and form a continuous and serrated mechanical interlock. In addition, the thicker IMCs generated by the interface will be extruded into the welding core with the insertion of the pin, resulting in the reduction of the IMCs layer thickness and enhancing the load capacity of the joint. However, hook defects are easy formed and the pin will be destroyed under this condition. There is still a certain distance between the micro-insertion process and the application in the engineering field. According to the investigation of this paper, the main factors affecting the formation of compounds are components, temperature, pressure and flow, as shown in Fig.14.

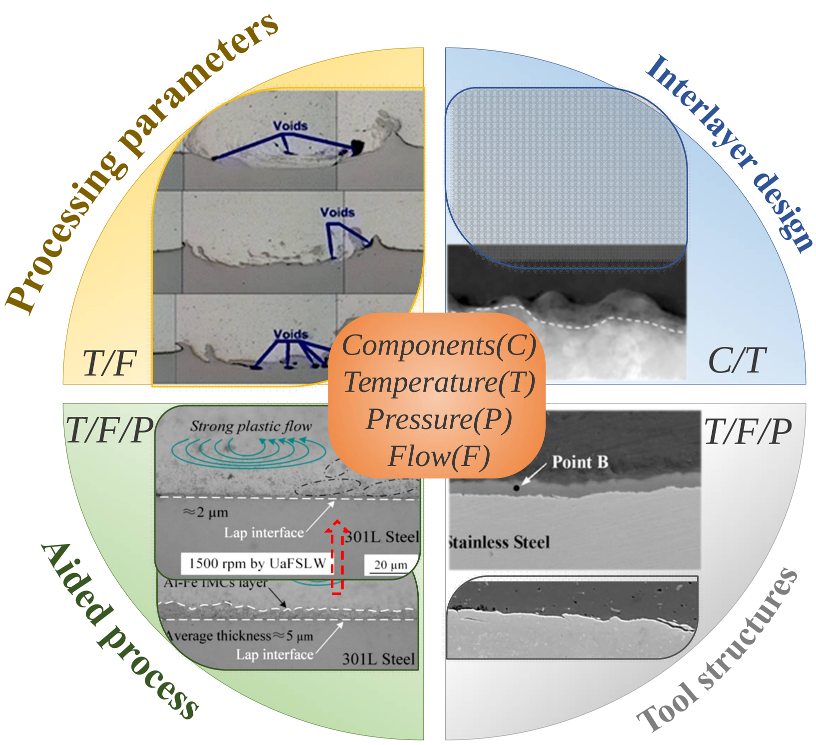

Fig. 14. Summary of methods.[34,75,83,86]

In addition to the above researches, it is also worth noting that the shape and thread of the stirring pin play an important role in the flow of the driving material[87-89]. According to the effect of cutting on the interface of aluminum and steel[60], whether a conical stirring pin with similar thread can be envisaged to further optimize the interface effect. In the study of micro-penetration and non-penetration of aluminum steel, the pin with this large-angle thread is used as a pin to reduce the wear of the pin by driving the material instead of increasing the penetration amount. Through the special design of the screw groove of pin, the downward vertical flow on the aluminum side is formed. The thickness of the IMCs layer is reduced and mechanical interlock is formed by the impact of material flow on the interface.

In summary, since the formation of IMCs is the main factor affecting the properties of Al-steel joints, the research on the control of IMCs Al-steel joints is summarized in this paper. The results show that the type of IMCs can be adjusted by adding intermediate layer and joint with superior properties is obtained. For example, the thickness of IMCs layer is reduced by adding Zn layer appropriately, the formation of Al-rich Zn-Al eutectic is promoted and the properties is improved. The distribution of IMCs can be controlled by changing the welding parameters. For example, the formation of brittle IMCs can be avoided and a thinner IMCs layer is obtained by increasing the rotational speed and reducing the welding speed. In addition, the IMCs also can be controlled by adjusting the insertion depth of the tool. The macroscopic mechanical interlocking and the microscopic saw tooth mechanical locking are enhanced by the proper insertion depth, the retention of brittle IMCs is avoided. Based on the summary of friction stir lap welding of aluminum and steel, good results can be obtained by using special shape tools and other process optimization. Therefore, in the case of non-penetrated aluminum plate, our team has designed and proposed a tool with diversion groove for the characteristics of vertical flow. This structure can theoretically obtain continuous IMCs, which is of great help to the follow-up study of non-penetrated aluminum plate.

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Reference

1. Boitsov AG, Kuritsyn DN, Siluyanova MV, et al. Friction stir welding in the aerospace industry. *Russian Engineering Research* 2018; 38: 1029-1033.
2. Shah LH, Ishak M. Review of research progress on aluminum – steel dissimilar welding. *Materials and Manufacturing Processes* 2014; 29 (8):928-933.
3. Wan L, Huang YX. Friction stir welding of dissimilar aluminum alloys and steels: a review. *International Journal of Advanced Manufacturing Technology* 2018;99(5-8):1781-1811.
4. Martinsen K, Hu SJ, Carlson BE. Joining of dissimilar materials. *The CIRP Annals* 2015;64(2):679-699.
5. Barnes TA, Pashby IR. Joining techniques for aluminium spaceframes used in automobiles: Part I—solid and liquid phase welding. *Journal of Materials Processing Technology* 2000;99(1-3):62-71.
6. Sun X, Stephens EV, Khaleel MA. Fatigue behaviors of self-piercing rivets joining similar and dissimilar sheet metals. *International Journal of Fatigue* 2007;29(2):370-386.
7. Pouranvari M, Abbasi M. Dissimilar gas tungsten arc weld-brazing of Al/steel using Al-Si filler metal: Microstructure and strengthening mechanisms. *Journal of Alloys and Compounds* 2018;749:121-127.
8. Hasanniah A, Movahedi M. Gas tungsten arc lap welding of aluminum/steel hybrid structures. *Marine Structures* 2019;64:295-304.
9. Singh J, Arora KS, Shukla DK. Lap weld-brazing of aluminium to steel using novel cold metal transfer process. *Journal of Materials Processing Technology* 2020;283:116728.
10. Qin G, Lei Z, Su Y, et al. Large spot laser assisted GMA brazing – fusion welding of aluminum alloy to galvanized steel. *Journal of Materials Processing Technology* 2014;214(11):2684-2692.
11. Ma H, Qin G, Ao Z, et al. Interfacial microstructure and shear properties of aluminum alloy to steel fusion-brazed welded joint. *Journal of Materials Processing Technology* 2018;252:595-603.
12. Fedorov V, Uhlig T, Wagner G. Investigation of fatigue damage in aluminum/stainless steel brazed joints. *Welding in the World* 2018;62:609-616.
13. Maji P, Karmakar R, Nath RK, et al. An overview on friction stir welding/processing tools. *Materials Today: Proceedings* 2022;58:57-64.
14. Sezhian MV, Ramadoss R, Giridharan K, et al. Comparative study of friction stir welding process and its variables. *Materials Today: Proceedings* 2020;33:4842-4847.
15. Soori M, Asmael M, Solyalı D. Recent development in friction stir welding process. *SAE International Journal of Materials and Manufacturing* 2021;14(1):63-80.
16. Cam G, Mistikoglu S. Recent developments in friction stir welding of Al-alloys. *Journal of Materials Engineering and Performance* 2014; 23:1936-1953.
17. Golezani AS, Barenji RV, Heidarzadeh A, et al. Elucidating of tool rotational speed in friction stir welding of 7020-T6 aluminum alloy. *International Journal of Advanced Manufacturing Technology* 2015; 81: 1155-1164.
18. Dong WJ, Meng XC, Xie YM, et al. Wire-feeding friction stir welding for large-gap width tolerances. Science and Technology of Welding and Joining 2024;29(4):291-295.
19. Meng XC, Xie YM, Sun SM, et al. Lightweight design: friction-based welding between metal and polymer. *Acta Metallurgica Sinica* 2023: 36:881-898.
20. Kar A, Vicharapu B, Morisada Y, et al. Elucidation of interfacial microstructure and properties in friction stir lap welding of aluminium alloy and mild steel. *Materials Characterization* 2020;168:110572.
21. Ma Y, Lou M, Li Y, et al. Effect of rivet and die on self piercing rivetability of AA6061-T6 and mild steel CR4 of different gauges. *Journal of Materials Processing Technology* 2018;251:282-294.
22. Chitturi V, Pedapati SR, Awang M. Investigation of weld zone and fracture surface of friction stir lap welded 5052 aluminum alloy and 304 stainless steel joints. *Coatings* 2020;10(11):1062.
23. Gao K, Soumyabrata B, Zhang S, et al. Effects of the microstructure on the fatigue fracture of friction stir lap welded Al-clad Al and Al-clad steel sheets. *Journal of Materials Research and Technology* 2023; 22:2518-2531.
24. Haghshenas M, Abdel-Gwad A, Omran AM, et al. Friction stir weld assisted diffusion bonding of 5754 aluminum alloy to coated high strength steels. *Materials & Design* 2014;55:442-449.
25. Picot F, Gueydan A, Martinez M, et al. A Correlation between the ultimate shear stress and the thickness affected by intermetallic compounds in friction stir welding of dissimilar aluminum alloy – stainless steel joints. *Metals* 2018;8(3):179.
26. Zhang T, Hao Z, Wang K, et al. Effect of Ni interlayer on interfacial microstructure and fatigue behavior of friction stir lap welded 6061 aluminum alloy and QP1180 steel. *International Journal of Fatigue* 2024;180:108096.
27. Li SH , Chen YH, Kang JD, et al. Effect of revolutionary pitch on interface microstructure and mechanical behavior of friction stir lap welds of AA6082-T6 to galvanized DP800. *Metals* 2018;8:925
28. Liu Y, Pang Q, Zhang Z, et al. Formation and evolution mechanism of intermetallic compounds of friction stir lap welded steel/aluminum joints. *Materials* 2023;16(18):6118.

29. Reza-E-Rabby M, Ross KA, Overman N R, et al. Joining thick section aluminum to steel with suppressed FeAl intermetallic formation via friction stir dovetailing. *Scripta Materialia* 2018;148:63-67.
30. Liu T, Gao S, Ye W, et al. Achievement of high-quality joints and regulation of intermetallic compounds in ultrasonic vibration enhanced friction stir lap welding of aluminum/steel. *Journal of Materials Research and Technology* 2023;25:5096-5109.
31. Nguyen VN, Nguyen QM, Thi HTD, *et al.* Investigation on lap-joint friction stir welding between AA6351 alloys and DP800 steel sheets. *Sādhanā* 2018;43:160.
32. Xiong JT, Li JL, Qian JW, et al. High strength lap joint of aluminium and stainless steels fabricated by friction stir welding with cutting pin. *Science and Technology of Welding and Joining* 2012;17(3):196-201.
33. Kimapong K, Watanabe T. Lap joint of A5083 aluminum alloy and SS400 steel by friction stir welding. *Materials Transactions* 2005;46: 835-841.
34. Pourali M, Abdollah-Zadeh A, Saeid T, et al. Influence of welding parameters on intermetallic compounds formation in dissimilar steel/aluminum friction stir welds. *Journal of Alloys and Compounds* 2017;715: 1-8.
35. Curtis T, Widener C, West M, et al. Friction stir scribe welding of dissimilar aluminum to steel lap joints. *Friction Stir Welding and Processing* 2015;8:163-169
36. Mortello M, Pedemonte M, Contuzzi N, et al. Experimental investigation of material properties in FSW dissimilar aluminum-steel lap joints. *Metals* 2021;11(9):1474.
37. Bruna FB , Luciano AB , Piter G, et al. Characterization of dissimilar friction stir welded lap joints of AA5083 and GL D36 steel. *Journal of Materials Research and Technology* 2020;9(6):15132-15142.
38. Van der Rest C, Jacques PJ, Simar A. On the joining of steel and aluminium by means of a new friction melt bonding process. *Scripta Mater* 2014;77:25-28.
39. Movahedi M, Kokabi AH, Reihani SMS, et al. Effect of tool travel and rotation speeds on weld zone defects and joint strength of aluminium steel lap joints made by friction stir welding. *Science and Technology of Welding and Joining* 2012;17(2):162-167.
40. Ma ZY, Pilchak AL, Juhas MC, et al. Micro structural refinement and property enhancement of cast light alloys via friction stir processing. *Scripta Materialia* 2008;58(5):361-366.
41. Wei Y, Li J, Xiong J, et al. Effect of tool pin insertion depth on friction stir lap welding of aluminum to stainless steel. *Journal of Materials Engineering and Performance* 2013;22:3005-3013.
42. Wan L, Huang Y, Liu X, et al. Study progress on friction stir welding of aluminum/steel dissimilar materials. *Welding & Joining* 2018;12(1): 19-24.
43. Bozzi S, Helbert-Etter A L, Baudin T, et al. Intermetallic compounds in Al 6016/IF-steel friction stir spot welds. Materials Science and Engineering: A 2010;527(16-17):4505-4509.
44. Hsieh MJ, Lee RT, Chiou YC. Friction stir spot fusion welding of low-carbon steel to aluminum alloy. *Journal of Materials Processing Technology* 2016;240:118-125.
45. Das H, Basak S, Das G, et al. Influence of energy induced from processing parameters on the mechanical properties of friction stir welded lap joint of aluminum to coated steel sheet. *International Journal of Advanced Manufacturing Technology* 2013;64:1653-1661.
46. Boumerzoug Z, Helal Y. Friction stir welding of dissimilar materials aluminum Al6061-T6 to ultra low carbon steel. *Metals* 2017;7:42.
47. Mahto RP, Kumar R, Pal SK, et al. A comprehensive study on force, temperature, mechanical properties and micro-structural characterizations in friction stir lap welding of dissimilar materials (AA6061-T6 & AISI304). *Journal of Manufacturing Processes* 2018;31:624-639.
48. Ramachandran KK, Murugan N, Kumar SS. Effect of tool axis offset and geometry of tool pin profile on the characteristics of friction stir welded dissimilar joints of aluminum alloy AA5052 and HSLA steel. *Materials Science and Engineering:A* 2015;639(15):219-233.
49. Geng P, Morimura M, Ma H, et al. Elucidation of intermetallic compounds and mechanical properties of dissimilar friction stir lap welded 5052 Al alloy and DP590 steel. *Journal of Alloys and Compounds* 2022;906:164381.
50. Wan L, Huang Y. Microstructure and mechanical properties of Al/steel friction stir lap weld. *Metals* 2017;7(12):542.
51. Dehghani M, Amadeh A, Akbari Mousavi SAA. Investigations on the effects of friction stir welding parameters on intermetallic and defect formation in joining aluminum alloy to mild steel. *Materials & Design* 2013;49:433-441.
52. Ibrahim AB, Al-Badour FA, Adesina AY, et al. Effect of process parameters on microstructural and mechanical properties of friction stir diffusion cladded ASTM A516-70 steel using 5052 Al alloy. *Journal of Manufacturing Processes* 2018;34:451-462.
53. Ratanathavorn W, Melander A, Magnusson H. Intermetallic compounds in friction stirred lap joints between AA5754/galvanised ultra-high strength steel. *Science and Technology of Welding and Joining* 2016;21(8):653.
54. Chitturi V, Pedapati SR, Awang M. Effect of tilt angle and pin depth on dissimilar friction stir lap welded joints of aluminum and steel alloys. *Materials* 2019;12:3901.
55. Chen ZW, Yazdanian S, Littlefair G. Effects of tool positioning on joint interface microstructure and fracture strength of friction stir lap Al-to-steel welds. *Journal of Materials Science* 2013;48:2624-2634.
56. Sorger G, Wang H, Vilaça P, et al. FSW of aluminum AA5754 to steel DX54 with innovative overlap joint. *Welding in the World* 2017; 61: 257-268.
57. Kimapong K, Watanabe T. Effect of welding process parameters on mechanical property of FSW lap joint between aluminum alloy and steel. *Materials Transactions* 2005;46:2211-2217.
58. Wang X, Lados DA. Optimization of aluminum-to-steel friction stir lap welding for the fabrication of high-integrity structural components. *Journal of Advanced Joining Processes* 2022;5:100114.
59. Wang TH, Sidhar H, Mishra RS, et al. Friction stir scribe welding technique for dissimilar joining of aluminium and galvanised steel. *Science and Technology of Welding and Joining* 2018;23(3):249-255.
60. Wei Y, Xiong J, Li J, et al. Microstructure and enhanced atomic diffusion of friction stir welding aluminium/steel joints. *Materials Science And Technology* 2017;33:1208-1214.
61. Reza-E-Rabby M, Ross K, McDonnell M, et al. Numerical simulation and experimental validation of joint performance in aluminum-steel lap welds formed by friction stir dovetailing. *Journal of Materials Processing Technology* 2019;277:116459.
62. Ambrosio D, Morisada Y, Ushioda K, et al. Extremely thin intermetallic layer in dissimilar AA6061-T6 and mild steel friction stir lap welding using a hemispherical tool. *Scientific Reports* 2024;14:1718.
63. Liu JL, Hao ZL, Xie YM, et al. Interface stability and fracture mechanism of Al/Steel friction stir lap joints by novel designed tool. *Journal of Materials Processing Technology* 2022;300:117425.
64. Liu T, Gao S, Shen X, Sun Z, et al. Acoustic effect on the joint quality and process of friction stir lap welding of aluminum to steel. *Materials Today Communications* 2023;35:106184.
65. Han L, Yu Z, Yan D, Rao Y , et al. Improved Interface Morphology and Failure Load of Ultrasonic-Assisted Friction Stir Lap Welding Joint of 2024 Aluminum Alloy to 304 Stainless Steel. *Metals* 2024;14:267.
66. Liu T, Gao S, Shi L, et al. Welding load, temperature, and material flow in ultrasonic vibration enhanced friction stir lap welding of aluminum alloy to steel. *Materials Today Communications* 2024; 40: 2352-4928.
67. Leitao C, Ekaitz A, Egoitz A, et al. Aluminium-steel lap joining by multipass friction stir welding. *Materials & Design* 2016;106:153-160.
68. Zhang G, Yang X, Zhu D, et al. Cladding thick Al plate onto strong steel substrate using a novel process of multilayer-friction stir brazing (ML-FSB). *Materials & Design* 2020;185:108232.
69. Liu J, Wu B, Wang Z, et al. Microstructure and Mechanical Properties of Aluminum-Steel Dissimilar Metal Welded Using Arc and Friction Stir Hybrid Welding. *Materials & Design* 2023;225:111520.

70. Zhou L, Yu M, Liu B, et al. Microstructure and mechanical properties of Al/steel dissimilar welds fabricated by friction surfacing assisted friction stir lap welding. *Journal of Materials Research and Technology* 2020;9(1):212-221.
71. Baligidad RG, Radhakrishna A. Effect of alloying additions on structure and mechanical properties of high carbon Fe-16 wt.% Al alloy. *Materials Science and Engineering:A* 2000;287:17-24.
72. Tanaka Y, Kajihara M. Morphology of compounds formed by isothermal reactive diffusion between solid Fe and liquid Al. *Materials Transactions* 2009;50(9):2212-2220.
73. Zhang G, Qie X, Gong W, et al. Microstruc ture and properties of friction stir welding interface of steel and aluminum dissimilar materials. *Transactions of Materials and Heat Treatment* 2018;39(5):159-164.
74. Chen Z. Effects of Si addition on the growth behvior of intermetallic compound layer at aluminum/steel rolling interface[dissertation]. Changsha: Central South University. 2013.
75. Li S, Chen Y, Kang J, et al. Friction stir lap welding of aluminum alloy to advanced high strength steel using a cold-spray deposition as an interlayer. *Materials Letters* 2019;239:212-215.
76. Niu S, Ji S, Yan D, et al. AZ31B/7075-T6 alloys friction stir lap welding with a zinc interlayer. *Journal of Materials Processing Technology* 2019;263:82-90.
77. Zheng Q, Feng X, Shen Y, et al. Dissimilar friction stir welding of 6061 Al to 316 stainless steel using Zn as a filler metal. *Journal of Alloys and Compounds* 2016;686:693-701.
78. Gao P, Xu H, Li T, et al. Lap friction stir brazing of galvanized steel sheet and 6061 aluminum alloy. J*ournal of Netshape Forming Engineering* 2018;10(2):113-116.
79. Gao P, Xu H, Li M, et al. Study on friction stir welding of steel and aluminum matrix composite with Zn interme diate layer. *Hot Working Technology* 2019;48(3):73-76.
80. Chen YC, Komazaki T, Kim YG, et al. Friction stir lap joining of AC4C cast aluminum alloy and zinc-coated steel. *Materials Science Forum* 2008;580-582:371-374.
81. Meng L, Chen S, Zhang J, et al. Study on friction stir lap welding of aluminium to steel sheets. *Metals* 2019;9(5):498.
82. Dong JH, Liu H, Ji SD, et al. Diffusion bonding of Al-Mg-Si alloy and 301L stainless steel by friction stir lap welding using a Zn interlayer. *Materials* 2022;15(3):696.
83. Liu J, Guo R, Gong P, et al. Interface characteristics and mechanical properties of 2024 aluminum alloy and 304 stainless steel dissimilar alloys FSLW joint with Ni interlayer. *Metals* 2022;12(10):1574.
84. Chen S, Huang J, Ma K, et al. Microstructures and mechanical properties of laser penetration welding joint with/without Ni-foil in an overlap steel-on-aluminum configuration. *Metallurgical and Materials Transactions A* 2014;45:3064-73.
85. Xu T, Zhou S, Wu H, et al. Effect of nickel interlayer thickness on lap joint laser welding for aluminium-steel dissimilar materials. *Science and Technology of Welding and Joining* 2022;27(3):166-75.
86. Hong K, Wang Y, Zhou J, et al. Investigation on ultrasonic assisted friction stir welding of aluminum/steel dissimilar alloys. *High Temperature Materials and Processes* 2021;40(1):45-52.
87. Kumar K, Kailas SV. The role of friction stir welding tool on material flow and weld formation. *Materials Science and Engineering A* 2008; 485:367-374.
88. Geng P, Ma H, Zhao P, et al. Effect of tool revolutionary pitch on heat transfer and material flow in Al/steel friction stir lap welding. *Journal of Materials Processing Technology* 2024; 325: 118306.
89. Geng P, Ma Y, Ma N, et al. Effects of rotation tool-induced heat and material flow behaviour on friction stir lapped Al/steel joint formation and resultant microstructure. *International Journal of Machine Tools and Manufacture* 2022;174: 103858.