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ARTICLE

Review on Joining Technology of Aluminum Alloy and Resin Matrix Composites

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Abstract: The hybrid structures of metal-composites are widely used in the field of aerospace, marine and vehicle industry due to the advantages of high specific modulus and high specific strength of aluminum alloy and resin matrix composites. Therefore, the joining technology between metal and composites as one of the crucial factors in these industries has been paid more attention. In this research, the connection mechanism and influencing factors of the joining processes of resin matrix composites and aluminum alloy were reviewed. At present, bolt connection, rivet connection, adhesive bonding, injection molded direct joining and welding were studied for the connecting between aluminum alloy and resin matrix composites. The processes of bolt connection and rivet connection are simple, however, it is easy to produce the stress concentration around the hole. The cost of adhesive bonding is low, but the anti-impact and anti-stripping strengths of the interface are low. The production cycle in the process of injection molded direct joining is short, but the strength of the joint is also low. The degree of automation of the welding technology is high, however, the required equipment is expensive. Finally, the development direction of joining technology between aluminum alloy and resin matrix composites which can obtain the joints with high performance and high reliability is pointed out according to the current research results.

Key words: composites; aluminum alloys; processing technology; strength; connection

High-reliability, light-weight and energy-saving are the goals of the continuous development of manufacturing industry. Therefore, light-weight materials, light structure and advanced processing technology are effective ways to meet these needs[1-4]. The metal pieces (such as aluminum alloy) as high-performance and light-weight material are still employed in aerospace and aircraft industries. Furthermore, the resin matrix composites (such as carbon fiber-reinforced polymer, CFRP) with high specific modulus, high specific strength, excellent fatigue resistance, etc, have been widely used in aviation industry. However, the composites are hard to completely replace the aluminum alloy. Therefore, it is necessary to seek a dependable technology to connect the aluminum alloy and resin matrix composites under the premise of ensuring safety[5,6]. In addition, the joining processes of metal-composites are one of the key problems to be solved urgently and in need of further developing in the aviation industries. Moreover, the hybrid structures of metal-composites have been widely used in various industries. The joining processes of aluminum alloy and resin matrix composites through bolt connection, rivet connection, adhesive bonding, injection molded direct joining and welding have the application in composite material joining. In order to improve the joining quality, many researchers still do in-depth research on these techniques[7-10]. The structure of the bolt joint is simple and easy to operate in the production process. However, it is necessary to process through holes on the aluminum alloy and resin matrix composite which can damage the composite ma-

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terial. Self-piercing riveting technique does not require pre-drilling, the automation degree of which is high and the operation is simple in the process with protrusion under the lower plate surface of riveting. The bonding structure of metal-composites has the advantages of smooth appearance, good sealing and low cost after the necessary and careful surface treatment. The injection molded direct joining technique has the advantages of simple process, low cost and low sensitivity to the environment. However, it cannot be used for high-strength structures. The welding technique divides into friction stir welding, laser welding and ultrasonic welding[11-13]. In this study, the influence factors on the quality of joints were discussed to clarify the advantages and disadvantages of the joining processes.

1 Traditional Connection Method

1.1 Bolt connection

Bolt connection is easy to assemble and disassemble during the process, therefore it becomes the most common detachable connection method in the applications[14]. The connecting process is: the through holes on the both workpieces are machined and then the bolt passes through the through holes to tighten the workpieces with nuts[15,16]. As shown in Fig.1, the joint is subjected to the tension force when the applied load is parallel to the bolt. Meanwhile, it suffers the shear force when the applied load is perpendicular to the bolt[17]. Bolt connection can be used for structures subjected to tensile loads, shear loads, and both loads.

The strength of the bolt joint is related to not only the material of the bolt, but also the tightening torque of the bolt. The mechanical performance of hybrid double-lap aluminum-glass fiber reinforced polymer (GFRP) bonded bolt joints was investigated. The hybrid joint exhibits the static tensile strength in practice equalling the sum of relative strengths of the simply bonded joint and the simply bolted joint. The relationship of the tensile failure load of a bolted Al-GFRP double-lap joint shows a non-monotonic function of the tightening torque[18]. Furthermore, the single lap composite-to-aluminum bolted joints experiment was carried out to discuss the influence of lateral displacement of the grip using different models[19]. The structure of the joint is simple and easy to operate in the production process. Although there are many advantages of the bolt joint, it is necessary to process through holes on the aluminum alloy and resin matrix composite which can damage the composite material. The matrix fibers of composite material can be cut off, and cause stress concentration to the composite material[18]. If there is a potential difference between aluminum alloy and composite material, the life of joints would decrease due to the electrochemical corrosion[20].

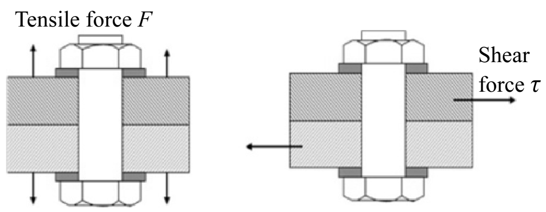

Fig.1 Stress of bolted joints[17]

1.2 Self-piercing riveting

The forming of holes during bolt connection process increases the processing time resulting in the rising cost, therefore, the self-piercing riveting is proposed to solve this problem[21]. The self-piercing riveting, requiring no pre-punching, is a cold forming mechanical connection process which is widely used in the fields of automobiles and aerospace. As shown in Fig.2, the process of self-piecing riveting is divided into four steps: (1) forcing the rivet on the top element by a flat punch; (2) drilling the top element and forcing the bottom sheet into deformation by the rivet shank; (3) plastic deformation of the lower sheet and getting the rivet into the die; (4) creation of the mechanical interlocks between the elements in the die, and end of the punch progress until the satisfaction of predetermined value of load[22,23].

In the self-piercing riveting process of connecting aluminum alloy and polymer-based composite materials, the main factors that affect the performance of the joint are: the stacking sequence of specimen[22,24], rivet pressure[22], temperature[25,26], rivet shape[25-27], load form[28,29], etc. Through the research about self-piercing riveting of AA6022-T4 aluminum alloy and CFRP[22], it is found that the maximum tensile load of joint of the composite plate in the upper layer is 48% higher than that of the composite plate in the lower layer. Because it is difficult for rivet to expand and deform due to the low plasticity of the composite plate resulting in the fact that rivet cannot flow to the center of the rivet. The maximum tensile load of the joint is low because of poor mechanical interlocking between the rivet and the CFRP with the composite plate in the lower layer. Therefore, during the self-piercing riveting process of composite materials and metal materials, the metal plate should be placed at the under layer in order to improve

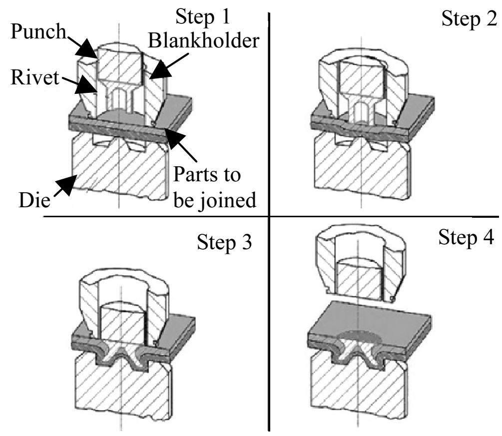

Fig.2 Self-piercing riveting process[23]

the strength of the joint. In addition, this phenomenon can be found in the self-piercing riveting process of three-layer plates of AA5052 aluminum alloy and CFRP[24]. The joint can form better mechanical interlocking when the intermediate layer is the CFRP plate.

The change of temperature can also affect the joint performance if the used polymer is sensitive to temperature. The fatigue of aluminum/glass fiber reinforced polymer composite assembly jointed by the self-piercing riveting was discussed by Gay[25,26]. The results show that the fatigue strength of the joint decreases by 30% when the temperature rises from −40 °C to 23 °C, because the polyamide resin is sensitive to the temperature.

Gay et al[25,26] also studied the influence of rivet head shape on joint performance. The results indicate that the performance of joint formed by domed head rivet (Fig.3a) is better than that of joint formed by countersunk head rivet (Fig.3b). This is because the countersunk head rivet breaks the fiber around the rivet on GFRP plate during the pressing process, resulting in the poor performance of joint. When the hollow tubular rivets (Fig.3c)[27] were used, the rivet head was fully pressed into the upper plate surface which causes more serious local damage on the CFRP plate, and the performance is also poor.

The failure forms of the joints in the self-piercing riveting process change with various load forms. In the fatigue load test, the failure of the joint is caused by the fracture of the aluminum alloy plate at the lower layer[28]. Because the property of plastic and toughness at the interface of the joint decreases with the increase of the plastic deformation of the aluminum alloy after introducing the work hardening. Besides, in the static tensile test, the failure is related to not only the thickness and width of the CFRP plate but also the diameter of rivet. The joint is damaged on the upper CFRP plate when the diameter of rivet is large and the thickness and width of the CFRP plate are small. When the diameter of rivet is small and the thickness and width of the CFRP plate are large, the joint is damaged by the falling-out rivet[22].

Self-piercing riveting technique can connect the difficult-to-weld-or-bond materials. In addition, no pre-drilling or blanking of the workpiece are achieved, the degree of automation is high and the operation is simple in the process[29]. Furthermore, it can be used with adhesive bonding technique[22]. Although the self-piercing riveting technique has many advantages, it also has some disadvantages: protrusion under the lower plate surface of riveting, requiring heavy equipment, and possible electrochemical corrosion[30].

1.3 Adhesive bonding

Adhesive bonding is a process of connecting two workpieces through mechanical interlocking, physical adsorption, chemical bonding and other mechanisms with appropriate adhesives. In aviation, automobile and construction industries, adhesives are usually used to connect components made of different materials[31] (Fig.4). The joint of bonded aluminum alloy and resin matrix composite can be divided into two distinct bonding interfaces, i.e., the adhesive-aluminum alloy contact interface and the adhesive-resin matrix composite contact interface[32].

During processing and transportation, the surface of aluminum alloy is easy to form an oxide film and have dust, oil and other impurities. If it directly bonds with the polymer, it is easy to fall off. Therefore, the surface of the aluminum alloy is often treated (such as sanding treatment, coupling agent treatment[32], anodizing treatment, sandblasting treatment[33], etc) before bonding to improve the strength of the joint. After the surface treatment with silicon coupling agent, AA2139-T4 aluminum alloy was connected with GFRP through epoxy adhesive. Results show that the strength of the joint greatly improves, and the fracture mode of the joint changes from the bonding fracture between the interfaces to the shear fracture within the adhesive layer[32]. After sandblasting the 5052 aluminum alloy surface and bonding it with the carbon fiber material, the shear strength

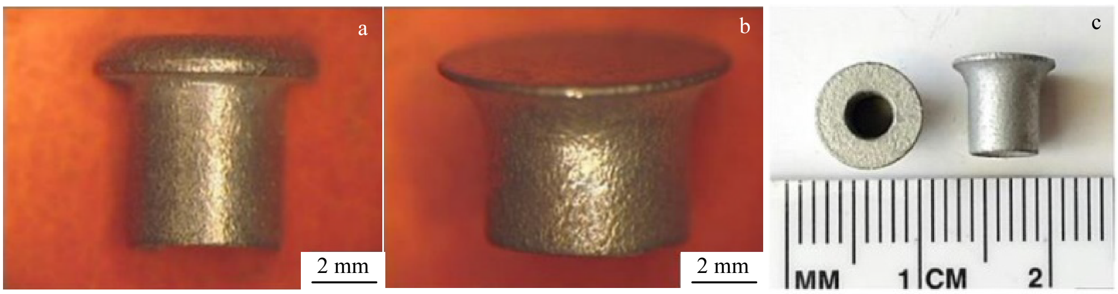

Fig.3 Appearances of different rivet head shapes: (a) domed head self-piercing rivet[24], (b) countersunk head self-piercing rivet[24], and (c) hollow tubular rivet[27]

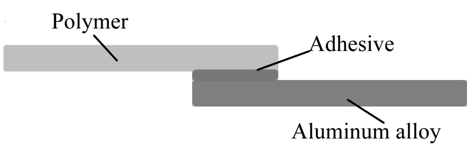

Fig.4 Schematic diagram of adhesive bonding[31]

of the joint greatly improves. The joint strength is nearly doubled when surface of the 5052 aluminum alloy is treated with a reasonable sandblasting time[33] (Table 1).

In addition to the treatment of aluminum alloys, factors such as the thickness of the polymer material[34] and the layup sequence[35] also affect the strength of the joint. Through the quantitative analysis of peeling stress of CFRP and L-shaped aluminum alloy bonded composite structure[34], it is found that the peak peeling stress decreases with the increase of CFRP plate thickness. In the single overlap of polymer and aluminum alloy, the eccentricity caused by the tensile force has a bending moment at the joint, causing the joint part to undergo lateral displacement bending, i.e., the secondary bending effect[36]. The secondary bending effect has a large effect on the peeling stress of the glued joint[35]. The greater the stiffness of the polymer sheet, the smaller the secondary bending effect and the smaller the corresponding peeling stress. In addition, the stiffness of the polymer sheet increases by adjusting the laying direction and the laying order to achieve the purpose of reducing the secondary bending.

The bonding structure of aluminum alloy and resin matrix composite has the advantages of uniform stress distribution, no reduction of workpiece strength, smooth appearance, good sealing, low cost, etc[37]. However, the bonding of adhesives also has some restrictions. In order to achieve high-quality bonding, careful surface treatment is necessary[38], long curing time is required, the bonding joint is sensitive to the environmental conditions, and the impact and peel strength of the bonding interface are relatively low. In order to obtain better connection performance, aluminum alloy/resin matrix composite bonding frequently uses the combination of bolt connection[39], riveting[23] and welding[40].

2 Injection Molded Direct Joining

Fig.5 shows the injection molded direct joining process of aluminum alloy and resin matrix composites. Firstly, the surface of metal piece (such as aluminum alloy) is pre-processed by chemical or physical method to form micro/nano holes or grooves on the surface. Afterwards, the pre-processed metal piece is put into a mold, and then the molten composite injecting into the mold invades into the holes or grooves on the surface. Finally, the molten composites solidify to connect the metal piece and resin matrix composites through mechanical anchoring, intermolecular binding force or chemical bonding[41].

Table 1 Tensile shear strength of 5052 aluminum alloy-composite joint under different sandblasting time[33]

Sandblasting time/s(15 cm^2)	0	10	15	180
Tensile shear strength/MPa	7.98	13.38	15.33	15.18

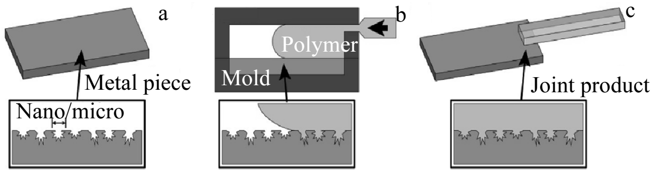

Fig.5 Injection molded direct joining process[41]

The strength of the aluminum alloy with the composite material joints using the injection molded direct joining connection technique is related to the pre-processed surface and processing parameters (such as injection speed[42,43] and injection/pack pressure[43,44]). The strength of joint improves with the increase of injection pressure which can make the polymer deeply penetrate the micro/nano holes or grooves on the surface of aluminum alloy. In addition, the strength increases with the increase of injection speed when the size of holes or grooves on the aluminum alloy surface is about tens or hundreds of microns. However, when the holes or grooves with a diameter of several tens of nanometers form on the surface of the aluminum alloy, the joint strength decreases with the increase of injection speed and pack pressure[42] (Fig.6). This is because the higher injection pressure and injection speed increase the peak temperature in the mold (Fig.7) resulting in the thermal degradation of polymer. Thus, the joint's bonding strength decreases.

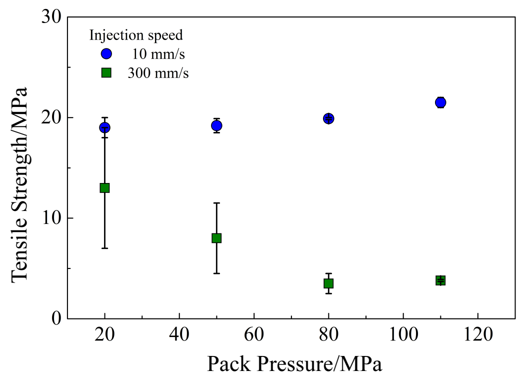

Fig.6 Relationship of tensile shear strength and pack pressure with different injection speeds[42]

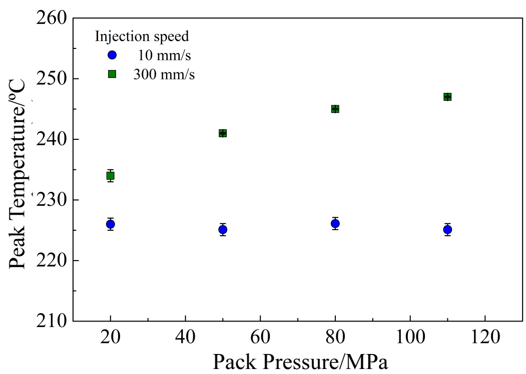

Fig.7 Relationship between peak temperature and pack pressure during the injection process[42]

The injection molded direct joining technique of aluminum alloy and resin matrix composites has various advantages, such as simple process, short production cycle, low cost, no adhesive, and low sensitivity to the environment. The structural integrity can be maintained without making through holes in metal pieces during the process[42,45]. However, the bonding strength is restricted. So this technique cannot be used in connection of high-strength structures. And the bonding surface cannot be too large because the thermal expansion coefficients of composites and aluminum alloy are quite different[46].

3 Welding

The above connection methods of aluminum alloy and resin matrix composites, such as bolt connection, riveting, adhesive bonding, etc, all belong to cold connection techniques. However, welding process belongs to thermal connection technique[22]. Therefore, the welding method is only applicable to the thermoplastic resin matrix composites which can be locally melted by heating, such as friction[47], laser[48] and ultrasonic vibration[49]. And then a mechanical interlock is established on the surface of the aluminum alloy to realize the connection between the aluminum alloy and resin matrix composites.

3.1 Friction stir welding

Friction stir welding (FSW) is a solid phase welding technique by plastic deformation, which has the characters of high efficiency and energy-saving[50]. The FSW process is shown in Fig.8. The rotating tool is inserted into the workpiece which rapidly rotates and moves along the weld seam for generating friction heat to form the connection.

FSW technique is mainly used to join the metal materials. Most of the researchers focus on the effects of process parameters on the mechanical properties and microstructure of welded joints. For example, the effect of process parameters of FSW, such as the rotational speed and moving speed of the stirring head, on the mechanical properties and microstructure of the aluminum alloy and resin matrix composites joint connected by FSW technique was studied. Moshwan et al[51] successfully realized the connection between AA 7075 aluminum alloy and polycarbonate (PC) by FSW technique. Meanwhile, Patel et al[52] used FSW to connect AA 6061 aluminum alloy and PC. The effects of the rotating speed and moving speed of the stirring head on the mechanical properties and microstructure of the joint were studied[51,52]. The results show that: (1) no mixing occurs and no ceramic-type compound forms at the joint interface, which shows that the connection is formed by mechanical interlocking; (2) the fluidity of the material is affected due to the variation of the temperature at the joint induced by the difference of rotational speed and moving speed of the stirring head which results in the degrees of mechanical interlocking between the two materials; (3) at the interface of the joint, the polymer softens through thermal degradation by the friction heat. Therefore, the dispersed particles and voids were detected at the interface, resulting in lower tensile strength and hardness at the joint. In conclusion, the performance of the joint changes with different process parameters.

The solid phase welding technique can avoid many metallurgical reactions between different materials because the temperature is lower than the melting temperature of the material[53]. Therefore, FSW can be used to join dissimilar materials with significant performance differences. In addition, equipment of FSW process is simple and safe, with high degree of automation and low energy consumption[54]. However, holes leave in the tail after welding, and the stirring head is worn and consumed quickly. At present, there are a few researches on FSW of polymer and aluminum alloy which still need further research to implement it into engineering.

3.2 Laser assisted welding

Fig.9 shows the schematic diagram of the laser welding setup. It can be observed that the polymer at the contact interface absorbing the heat of laser becomes molten state during the welding process, indicating that the mechanical connecting of aluminum alloy and resin matrix composites is achieved.

In laser assisted welding process, the joint strength of aluminum alloy and resin matrix composites is related to the surface state of aluminum alloy and the laser parameters. A novel laser beam joining process for hybrid polyamide-aluminum structures was reported by Lamberti et al[56]. The results in Fig.10 show that the electro-chemical laser pre-treatment of EN-AW1050A aluminum substrate surface has a distinctive effect on the shear strength of the joint. Nevertheless, the joint quality does not correspond to the change of surface roughness R_a, indicating

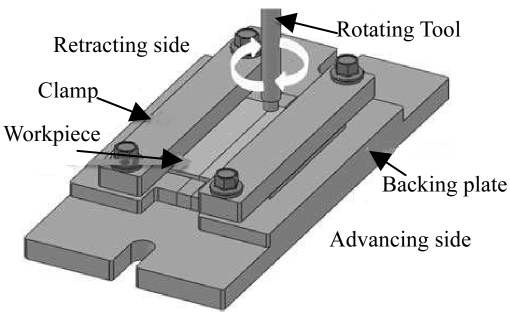

Fig.8 Schematic diagram of experimental setup in the FSW process[51]

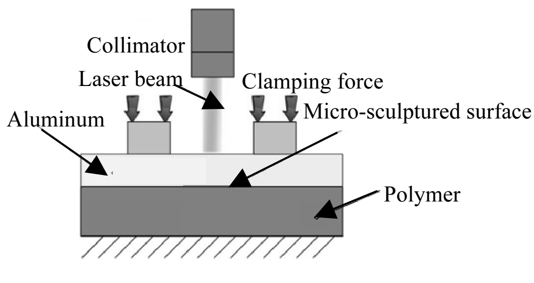

Fig.9 Schematic diagram of the laser welding setup[55]

that the mechanism of the interface bonding is not only the mechanical interlocking but also the physicochemical interaction. Zhang et al[57] used fiber laser to join the carbon fiber reinforced plastic and aluminum alloy A6061 treated by phosphate anodizing pretreatment. With optimized experimental parameters, the shear strength reaches 41.8 MPa, which is approximately 8 times as high as that of sample without anodizing pretreatment. A new chemical bonding of Al-O-PA6 is detected in the joint of CFRP and A6061 which strengthens the mechanical anchoring effect at the interface. In addition to the surface state of aluminum alloy, the joint property is also affected by the laser parameters. The effects of laser power and scanning speed on the mechanical properties of joint between AA5053 aluminum alloy and polyvinyl chloride (PVC) were investigated[55]. It is found that the joint strength reduces with the increase of the laser power and the decrease of the scanning speed due to the PVC degradation induced by the high temperature at the joint. Besides, the joint strength reduces with the decrease of temperature because the PVC at the interface melts deficiently.

The laser assist welding technique has advantages of high energy density, low heat input, small deformation and no electrode wear[55,56]. However, the laser welding equipment is expensive which severely handicaps its application. Furthermore, the welding efficiency reduces due to the high reflectivity of aluminum alloy to laser beam[58].

3.3 Ultrasonic welding

Ultrasonic welding includes ultrasonic plastic welding (UPW) and ultrasonic metal welding (UMW). As shown in Fig.11, UPW process is to connect the workpieces and molten plastic by the welding force and the ultrasonic with amplitude whose direction is perpendicular to the interface of the joint, respectively. Meanwhile, UMW process proceeds by the metallurgical combination at the contact interface under the action of friction heat using the ultrasonic with amplitude whose direction is parallel to the interface[59].

The UMW technique was applied successfully to join AA5754 aluminum alloy and CFRP by Wagner et al[60]. The

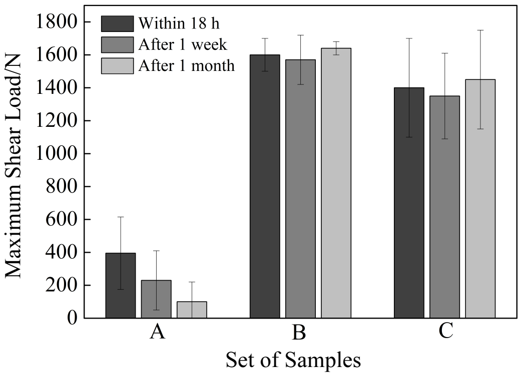

Fig.10 Shear loads of samples with different Al surface treatments[56]

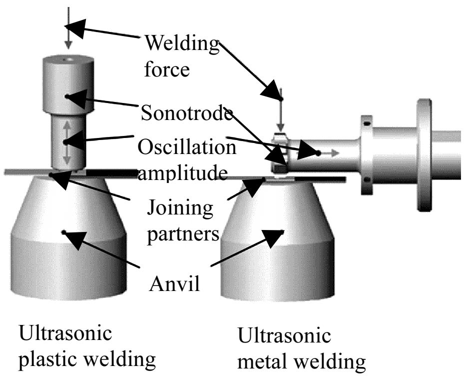

Fig.11 Schematic diagram of ultrasonic welding[59]

tensile shear strength of the welded joint using aluminum alloy after sandblasting and pickling pretreatment can reach 50 MPa. In addition, the shear strength can increase to 58 MPa when the aluminum alloy is pre-treated with the occurrence of precipitation hardening. These results prove that UMW can achieve good bonding effect between aluminum alloy and resin matrix composites structure. At present, aluminum alloy and thermoplastic composite materials can be connected. However, it is difficult to connect aluminum alloy and thermosetting materials by the common welding techniques. Using UMW technique, Lionetto et al[61] successfully joined AA5754 aluminum alloy and thermosetting material, such as carbon fiber reinforced epoxy resin. In the preparing process of thermosetting epoxy resin, the thermoplastic PA6 film with the thickness of 100 μm was decorated on the surface. During welding process, the relative movement at the interface between the aluminum alloy plate and the composite plate causes the temperature to rise rapidly, resulting in the melting of PA6 layer and realizing the connection. Therefore, the principle of welding process is related to the aluminum alloy and thermoplastic composite materials.

Compared to other joining techniques, ultrasonic welding is very attractive for composite processing and joining since it is characterized by short welding time, low energy input, low cost and ease of automation[62]. However, only overlap joint can use the ultrasonic welding technique. Furthermore, the thinner workpiece is suitable for connection because the attenuation of ultrasonic energy increases with the increase of the thickness of workpiece which restricts its application.

4 Discussion

Several techniques for connecting aluminum alloy and composites were introduced. The characteristics of these connection processes are summarized in Table 2.

Table 2 Characteristics of various connection methods

Method	Advantage	Disadvantage
Bolted joints	Simple; easy assembly and disassembly	Stress concentration; electrochemical corrosion
Self-piercing riveting	Connecting difficult-to-weld-or-bond materials; low cost; no need for pre-drilling and blanking; no waste; high degree of automation; simple operation	Protrusions at lower deck; cumbersome equipment; if there is a potential difference in the material, galvanic corrosion may occur in direct contact
Adhesive bonding	Uniform stress distribution; no reduction in workpiece strength; smooth shape; good sealing; low cost	Surface-treated materials only; long curing time; joints are sensitive to the environmental conditions; relatively low impact resistance and peel strength
Injection molded direct joining	Simple process; short production cycle; low cost; maintaining structural integrity	Restricted bonding strength; cannot be used for high strength structures; the bonding surface should not be too large
Friction stir welding	Simple equipment; high degree of automation; low energy consumption; safe welding process	Hole appears in the tail of the welding; friction head wears out quickly; difficult practical application
Laser assisted welding	High energy density; low heat input; small deformation; no electrode wear	Expensive equipment; reduced efficiency
Ultrasonic welding	Short welding time; low energy input; low cost; no impurities	Materials can only be lapped; apply for only thin workpieces

5 Summary and Prospect

In this research, several connection technologies between dissimilar materials were reviewed, focusing on the connection mechanisms, the influencing factors and the characteristics. Although the connection mechanism and performance of each method are different, all connection structures have definite bearing capacity.

At present, the research on bolt connection, self-piercing riveting, adhesive bonding and injection molded direct joining is relatively mature and these techniques are widely applied in practice, but the research on the connection of aluminum alloy and resin matrix composite remains at an early stage. These methods have great potential in the field of engineering application. The further research direction is proposed as the following points:

1) Use computer simulation technology to study and optimize the influence of process parameters of different welding techniques on joint performance. The application scope of different methods can be better determined.

2) The welding principle and failure mechanism of aluminum alloy and resin matrix composites need to be further explored.

3) Combine different connection technologies (such as riveting and adhesive bonding) to study hybrid connection technologies. Disadvantages of single method can be eliminated. Advantages of various methods can combine, thus improving the performance of composite joints.

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铝合金与树脂基复合材料连接技术综述

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摘 要：在航空航天、海洋运输和车辆制造等领域，制造材料朝着轻量化、复合化和高性能化的方向发展。由于铝合金和树脂基复合材料具有高比模量和高比强度等优点，其复合结构的连接技术也受到越来越多的关注。本文针对铝合金与树脂基复合材料连接技术的连接机理和影响因素进行综述。目前，铝合金和树脂基复合材料的连接方法主要为螺栓连接、铆接、胶接、注塑连接和焊接。其中螺栓连接和铆接工艺简单，但孔洞易产生应力集中；胶接成本低，但界面的抗冲击和抗剥离强度较低；注塑连接周期短，但强度有限；焊接自动化程度高，但设备昂贵。最后本文基于当前研究成果，指出高性能、高可靠性的铝合金与树脂基复合材料接头进一步的研究发展方向。

关键词：复合材料；铝合金；加工工艺；强度；连接技术

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