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Review Paper

Welding Process of CFRP and Metal: A Systematic Review

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Recently, the applications of carbon fiber reinforced polymer (CFRP) in marine, automobile, aerospace, and other industries have increased significantly. Due to great physical and chemical differences between CFRP and metal, it is not easy to join them together, and this is one of the key problems that many industries need to solve. Thus, a systematic review of the achievements in joining CFRP and metal by welding process is presented in this study to understand the joining mechanism of these materials. Different types of joining methods, such as supersonic welding, laser welding, friction welding, composite welding, and other techniques are studied. The research shows that all different welding methods have pros and cons, and the usage of hybrid joining will be the future trend to improve the joint performance with respect to the joining application of CFRP and metal. In the time ahead, these methods can provide some references for the development of technologies used in joining CFRP and metal.

Key words: carbon fiber reinforced polymer; metal; welding; review.

1. Introduction

Lightweight technology is one of the most important solutions to lower energy consumption and environmental problems [1]. The hybrid structure of composites and metal, which reduces weight effectively, can be used in many fields, such as automobile, aerospace and shipping. CFRP is a popular composite due to its low density, high specific strength, high specific modulus, large degree of freedom of design, etc. [2–4]. CFRP is an ideal material for designing the hybrid structures of composites and metal. A 10% reduction in vehicle weight can produce about 6% ∼ 8% fuel saving [5, 6]. The Lexus LFA research and development team used 65% CFRP and 35% aluminum in their cars, and the weight was reduced by 100 kg [7]. Li *et al.* [8] proposed the conceptual vehicle with composites, whose body mass was reduced by 20–50%. The hybrid joint of CFRP and metal has been widely applied in aerospace, vehicles, shipping, etc. [9]. The demand for joining of CFRP and metal is increasing sharply.

Due to great physical and chemical differences between CFRP and metal, adhesive bonding, mechanical connection and hybrid joining of the two above are often used to join these two materials [10–13]. However, Kweon *et al.* [10]

showed that this hybrid connection could improve joint strength only when the strength of mechanical fastening was greater than that of adhesive bonding. Although adhesive bonding has high fatigue resistance and can adapt to high technology requirements [14, 15], it also has limitations. For example, the curing of adhesive bonding takes long time, even several days. Besides, it is sensitive to the working environment, such as humidity, temperature, etc. Additionally, the surface preparation of joining materials also needs special attention [9]. The mechanical connection has some advantages, such as short production cycle, simple assembly and insensitivity to environmental factors [2]. However, mechanical connection can damage the fiber, induce stress concentration and increase weight due to adopted connectors.

Welding technology has been widely used to join dissimilar materials. This paper makes a systematic literature review of the welding process of CFRP and metal. In this study, the traditional welding technologies and some novel welding methods developed in recent years are introduced.

2. Welding

Welding is the processing method that produces atomic bonding between the welding parts by heating or pressing or combining both, with or without filling materials. This paper focuses on welding methods of joining CFRP and metal. As welding technology belongs to thermal processing, it is only suitable for CFRP based on the thermoplastic matrix [16]. There are various types of welding processes [17]: fusion welding, pressure welding and brazing, as shown in Fig. 1.

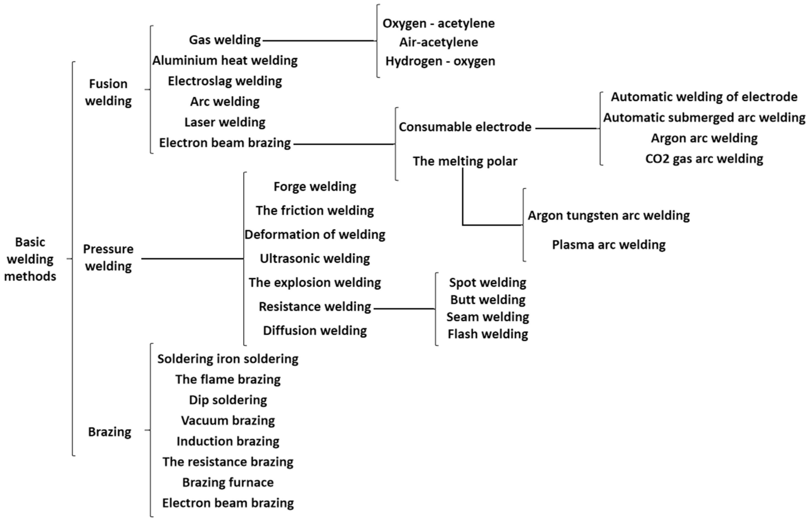

Fig. 1. Classification of welding methods.

A summary of applications of welding to CFRP and metal is shown in Table 1.

Table 1. Welding methods of CFRP and metal.

Method	Joining material		Pre-treatment	Joint strength F/τ	Remark	Ref.
	CFRP	Metal				
Ultrasonic welding	CF-PA66 (2 mm)	Al99.5 (1 mm)	–	2460 N /25 MPa	Lapping	[18]
		AA5754 (1 mm)	–	31.5 MPa		[19]
		AA1050 (1 mm)	–	2460 N /25 MPa		
		DC01 (1 mm)	–	30 MPa	Lapping; 100 µm thick Al as the middle layer	
		AA5754 (1 mm)	Corundum sandblasting + acid washing	50 MPa	Lapping	[20]
		AA2024 (1 mm)	–	33.5 MPa		
Laser welding	CFRP (3 mm)	Mild steel (1.2 mm)	–	2237.37 N /9.32 MPa	Lapping	[21]
			Chromium-plated layer	6127.81 N /22.14 MPa		
		Galvanized steel (0.7 mm)	–	3300 N	Lapping	[22]
	CFRTP (ø3 mm)	Al (2 mm)	–	5.2 MPa	Lapping; laser as induction; Al-Ti-C as the middle layer	[23]
	CFRP (3.5 mm)	AA7075 (2 mm)	–	8.5 MPa	Lapping	[24]
			Pre-treated by the laser Surfi-Sculpt	18.5 ∼39 MPa		
FSW	CF-PEEK (2.5 mm)	LF6 (2.5 mm)	–	18.65 MPa	Lapping	[25]
	SCF/PEEK (3 mm)	AA2060-T6 (2 mm)	–	33 MPa	Lapping; self-designed tool	[26]
FSSW	CFRP (2 mm)	AA5052 (2 mm)	–	1504 ± 317 N /6 ± 0.65 MPa	Resin as the middle layer	[27]
	PP-SCF (2 mm)		–	80% of composites	THFSW	[28]

Table 1. [Cont.]

Method	Joining material		Pre-treatment	Joint strength F/τ	Remark	Ref.
	CFRP	Metal				
FLW	CFRTP (3 mm)	AA5052 (2 mm)	–	1 kN	–	[29]
			Surface grinding on the Al plate	2.9 kN		
	CURV® (2 mm)	AA6082-T6 (3 mm)	–	2800 N	Punch design	[30]
			–	3000 N	The holes adopted special structures	
FSpJ	CF-PPS (2.17 mm)	AA2024-T3 (2 mm)	–	27 MPa	–	[31]
			Sandblasting aluminum surface	43 MPa		
		AA6181-T4 (up&middle: 1&1.5 mm)	–	2107–3523 N	Double-lap joint	[32]
		AA2024-T3 (2 mm)	–	Raising 20–55%	PPS middle layer	[33]
	CF-PPS (2.1 mm)	MgAZ31 (2 mm)	P1200 Sandpaper grinding + Acetone cleaning	20–28 MPa	–	[34]
Composite joining	CF-PEEK	AA5052	–	–	FSSW and self-propagating connection technology	[35]
	CFRP (2 mm)	AA6061 (1 mm)	① Al alloy: micro-grooving treatment ② CFRP: infrared laser radiation treatment, and then alcohol ultrasonic cleaning	1725 N	FSSW, adhesive bonding and ultrasonic aid technology	[36]
	CFRP (2.17 mm)	AA6181 (1 mm)		2760 N		
Resistance welding	PEI-CF (3.14 mm)	AA7075 (3 mm)	Standard surface treatment	25 MPa	Add middle layer	[37]

Abbreviations:

CF-PA66 – carbon fiber polyamide-66;

CF-PEEK – carbon fiber reinforced polyether ether ketone;

CF-PPS – carbon fiber reinforced polyphenylene sulfide;

CFRP – carbon fiber reinforced polymer;

CFRTP – carbon fiber reinforced thermoplastics;

Table 1. [Cont.]

CURV® – self-reinforced polypropylene;
FLW – friction lap welding;
FSpJ – friction spot joining;
FSSW – friction stir spot welding;
FSW – friction stir welding;
PEI-CF – carbon fiber reinforced polyetherimide;
PPS – polyphenylene sulfide;
PP-SCF – short carbon fiber reinforced polypropylene;
SCF/PEEK – short carbon fiber reinforced polyether ether ketone;
THFSW – threaded hole friction spot welding.

2.1. Ultrasonic welding

Ultrasonic welding takes advantage of high-frequency vibration waves that vibrate the surfaces of two welding partners, and as a result of heat generated by their rubbing friction, the surfaces of those objects form a welding between molecular layers under pressure [19]. Ultrasonic welding is divided into ultrasonic metal welding, in which the direction of oscillation amplitude is different from that of welding, and ultrasonic plastic welding, in which the direction of oscillation amplitude is the same as that of welding [19]. Sometimes, ultrasonic welding can also be assisted by other welding technologies.

According to the survey conducted by WKK (Institute of Materials Science and Engineering, Kaiserslautern University), ultrasonic metal welding is an effective way to realize high strength connection between CFRP and metal with two great advantages: short welding time (less than 5 s) and no damage of carbon fiber after welding [18]. As for the ultrasonic plastic welding, it is mainly used in welding between CFRPs or plastics [19]. High strength fabric of carbon fiber cannot be used to transfer directly mechanical load between CFRP and metal [18]. So, the former is selected. The ultrasonic metal welding system includes ultrasonic generator, frequency converter, booster, sonotrode, joining partners, anvil, and force transmission. The ultrasonic metal welding has three important parameters: welding force, welding energy and welding amplitude of ultrasonic generator.

Balle *et al.* [18] used ultrasonic metal spot welding to join Al99.5 ($20\times70\times1$ mm^3) and CF-PA66 ($30\times70\times2$ mm^3) in the form of lap welding. The size of the welding region was 10×10 mm^2. The results showed that the welding quality was fine. In this case, the central composite design circumscribed (CCC) method was employed to reduce the number of experiments. The range of test parameters included: welding force at $55\sim85$ N, welding energy at $1550\sim1850$ J and welding amplitude at $29\sim35$ μm. The welding specimen reached the maximum shear force of 2460 N and maximum tensile strength of

25 MPa under welding force at 65 N, welding energy at 1725 J and welding amplitude at 32 μm. On this basis, Balle *et al.* [19] successfully welded CF-PA66 with the following three different metals: AA1050, AA5754, and DC01. The maximum tensile shear strengths were 25 MPa, 31.5 MPa, and 30 MPa, respectively. Besides, Wagner *et al.* [20] carried out surface pre-treatment to welding partners, and it was found that tensile shear strength of CF-PA66 and AA5754 joint increased from 30 MPa to 50 MPa.

2.2. Laser welding

Laser welding converts the luminous energy of the laser into the thermal energy required for welding to make interface melt and form a welding joint [38]. The gradual innovation in this field has promoted the development of laser welding. Jung *et al.* [22] proposed a laser-assisted metal and plastic (LAMP) direct joining method. LAMP includes yttrium aluminum garnet (YAG), diode and disk/fiber laser. The joining mechanism is shown in Fig. 2. When the laser beam reaches the metal's surface, the metal will be melted through absorbing energy from the laser beam, and thus the melting pool can be produced.

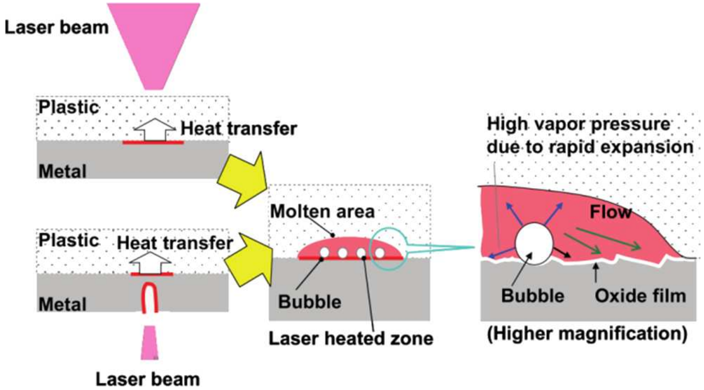

Fig. 2. The joining mechanism of LAMP [39].

Compared to supersonic welding, laser welding has the advantages of small deformation, low wear of welding tools, welding in closed environment, easy automation and no space restriction. However, the laser welding equipment is expensive, the position requirements of the welding parts need to be very accurate, and the energy conversion rate is low – usually less than 10%.

Laser welding has been successfully applied in joining of CFRP and metal. Tan *et al.* [21] adopted laser welding technology and lapping formation to join mild steel ($40 \times 30 \times 1.2$ mm^3) and CFRP ($35 \times 28 \times 3$ mm^3) successfully. Besides, in the same study, cases with and without a chromium coating on the metal plate were also compared. The experiment showed that chromium coating on the metal plate could greatly increase the shear force and shear strength of joint, as shear force increased from 2237.37 N to 6127.81 N and shear strength rose to 22.14 MPa from 9.32 MPa. ZHANG *et al.* [24] adopted this technology to join CFRP and AA7050, and carried out the study about surface treatment. It was found that higher strength can be obtained after pre-treatment, as shown in Table 1.

JUNG *et al.* [22] used LAMP to join CFRP ($20 \times 100 \times 3$ mm^3) and galvanized steel ($30 \times 70 \times 0.7$ mm^3). Scanning electron microscope (SEM) and transmission electron microscope image indicated that CFRP in the surface of metal could form small bubbles, especially in the joining interface [39]. The influence of welding speed and laser power on tensile shear load under different conditions is presented in Fig. 3. With the increase of traveling speed and laser power, the tensile shear load first increased and then decreased. The maximum load was observed around 3300 N.

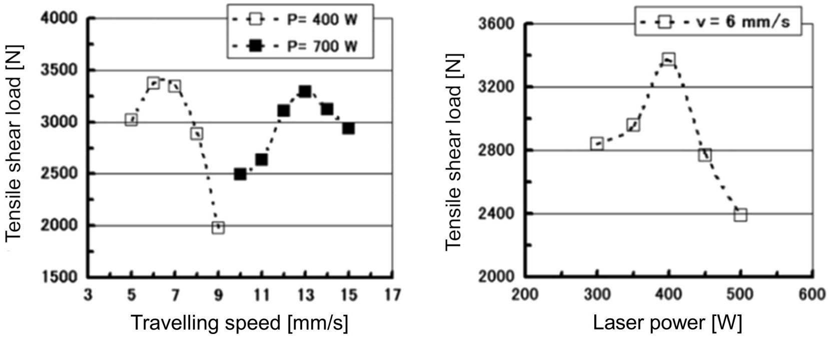

FIG. 3. Tensile shear test results of joints under different conditions [22].

LIU *et al.* [23] developed a laser-induced Al-Ti-C powder interlayer self-propagating welding technology to connect CFRTP and aluminum alloy, as shown in Fig. 4a, whereas the dimensions are shown in Fig. 4b. The interlayer

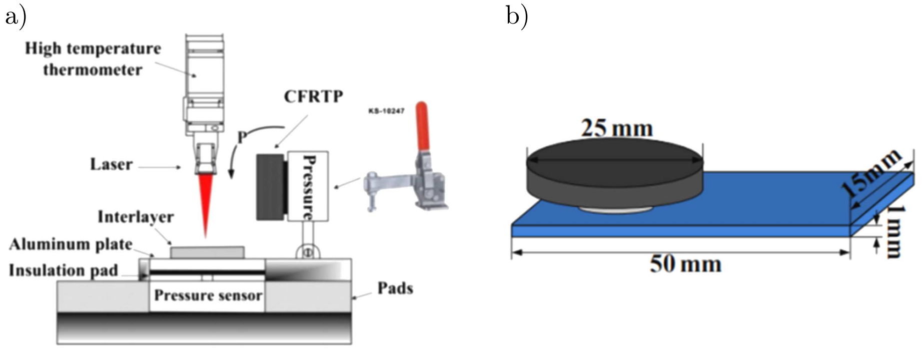

FIG. 4. Laser-induced self-propagation joining [23]:
a) assembly drawing, b) the size of the sample.

and aluminum had metallurgical reaction under laser heat. At the same time, CFRTP was melted and pressed into the micro-hole of the interlayer to form mechanical interlock.

2.3. *Friction welding*

Friction welding is a solid phase welding method, which uses the heat generated by friction under the pressure to join together materials. Friction welding can be divided into continuous drive friction welding, friction surfacing welding and FSW, etc. [17]. In ordinary fusion welding, it can cause defects such as air holes, and the fibers can also be damaged due to large physical and chemical differences between metal and composites. FSW is regarded as a good way to join CFRP and metal.

2.3.1. FSW. FSW was invented by The Welding Institute (TWI – Cambridge, UK) in the early 1990s [40–42] and has been widely applied in various fields [43], such as high-speed train [44], shipping [45] and aerospace [46].

The schematic diagram of FSW is shown in Fig. 5. The pin is inserted into the workpiece at a certain rotation speed until the shoulder contacts the workpiece surface, and then the tool moves along the joining line to complete the welding process.

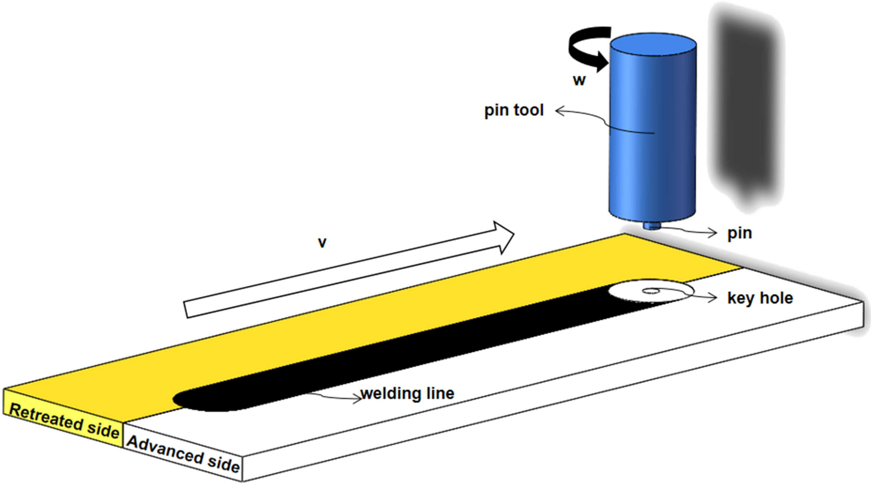

Fig. 5. Schematic diagram of FSW.

FSW is capable of joining the same or dissimilar metals regardless of lap or butt joint [42]. Xie [25] carried out tests for the lap and butt joints of CF-PEEK composites and LF6 aluminum alloy sheet, with the thickness of 2.5 mm. In the lap experiments, the joint's maximum tensile shear strength of 18.65 MPa was obtained when plunge depth, rotation speed and welding speed were 0.16 mm, 750 r/min, and 30 mm/min, respectively. The strength of the joint increased at first and then decreased as the shoulder pressure increased. In the butt welding, it was difficult to obtain a good joint [25].

Gao *et al.* [47] used an underwater FSW to successfully connect thermoplastics, as shown in Fig. 6. Compared with the traditional FSW, a more uniform temperature field was obtained, and the quality of the welding line was improved, which increased the strength of the joint [48]. When rotational speed, welding speed and plunge depth were respectively 1800 r/min, 45 mm/min, and 0.4 mm, the tensile strength of 12.3 MPa was obtained, whereas the conventional FSW had only 9.6 MPa. This provides a very good reference for connecting CFRP and metal.

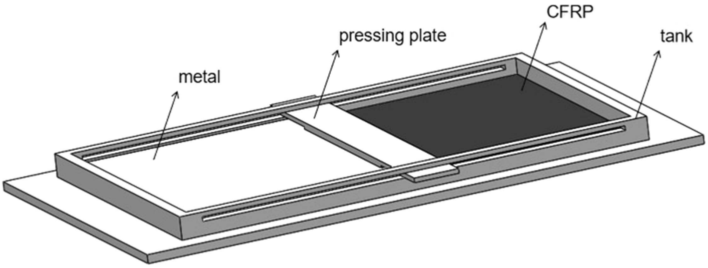

Fig. 6. The underwater joining.

Huang *et al.* [26, 49] used a special-made tool to carry out FSW in the formation of lapping for 2 mm thick AA2060-T6 and 3 mm thick SCF/PEEK. This tool had special design features of two shoulders: one that was fixed (this could prevent the material from spilling over the weld line and improve the integrity of the joint) and another one was rotating with following the tool- a tapered thread pin with the triple facets. The schematic diagram is shown in Fig. 7a. In this experiment, parameters were set as follows: rotational speed was 30 mm/min,

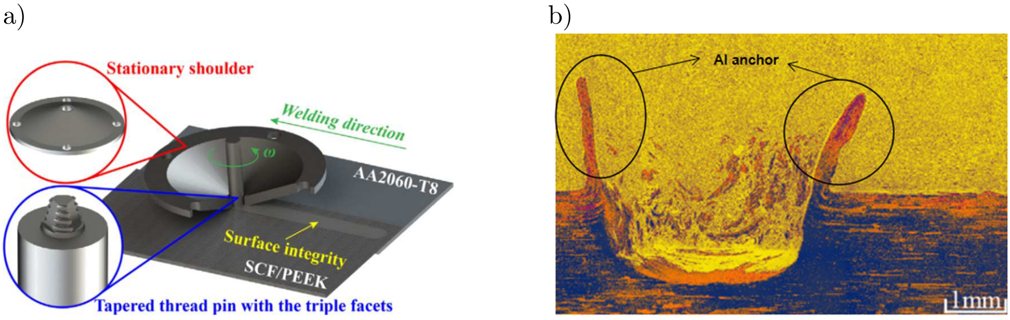

Fig. 7. a) Schematic picture for FSW based on the novel welding [26]; b) macro-structure in cross-section of typical joints under 1600 r/min.

tilt angle was 2°, plunge depth was 0.2 mm and the rotation speed was in the range of 1400–2000 r/min. When rotational speed was 1600 r/min, a good joint was obtained, and the shear strength reached 33 MPa. The aluminum anchor shown in Fig. 7b was produced using this method [26]. It was an inherent defect when FSW was carried out with metal and polymer. Therefore, the aluminum anchor was embedded in the polymer to finish the connection. This reduced mechanical properties of joints, but avoided kissing bonding effectively, providing a mechanical interlocking for metal and polymer, and it was helpful in transmitting load [49].

2.3.2. FSSW.

FSSW is a variant FSW. It is an important method to substitute resistance welding, because in the resistance welding, short welding time can induce incomplete filling of micro-porosity on the aluminum alloy substrate and long welding time can cause thermal degradation, and eventually these two factors decrease strength of joint [37]. FSSW has been used in the joining of the polymer [50, 51]. The process includes four steps [52]. First, the tool rotates and presses down into the workpiece, and then the tool rotates alone to produce friction heat. After that, the rotation is stopped and the material is allowed to cool under a certain pressure. Finally, the tool is retracted from the workpiece. As for FSSW of CFRP and metal, Tanaka *et al.* [27] used this method to weld AA5052 and CFRP together, while the tensile shear strength of 1922 ± 478 N was obtained.

However, there remains a pit after welding, which will reduce the bearing area and weaken the mechanical properties of joint. To this defect, Karami *et al.* [28] and Paidar *et al.* [53] proposed a new way – THFSW, which can make up for the defect of the pit. THFSW is different from FSSW, as its tool does not have a pin. During the welding process, a threaded hole is drilled in advance in the aluminum plate. Then, the tool rotates and presses down about 0.3 mm into the aluminum surface. After that, the tool contacts the aluminum plate and produces friction heat. The heat arrives at aluminum/polymer by conduction. Finally, the polymer at the interface is melted and it flows into the pre-punched hole with thread forming mechanical interlocking. Karami *et al.* [28] successfully welded AA5052 and PP-SCF. The formation of aluminum, carbon, oxide composite layer and mechanical interlocking between threaded holes and resolidified polymers was identified. The maximum shear-tensile strength of the joints reached 80% of composites when rotation was up to 2000 r/min. On the other hand, mechanical strength and fracture energy of the joints increased as the tool rotational speed increased.

2.3.3. FLW.

FLW is another variant based on FSW, and the tool used in FLW does not have a pin.

The welding of CFRP and metal completed successfully by using FLW was presented in [29, 54]. NAGATSUKA *et al.* [29] used FLW to join CFRTP (Polyamide 6 with 20% carbon fiber added) and AA5052, as shown in Fig. 8a. The results showed that CFRTP and AA5052 were linked together by a MgO oxide layer. After carrying out surface treatment of the aluminum alloy, $Al(OH)_3$ was produced instead, improving the joint's tensile shear strength from 1 kN to 2.9 kN. When the welding speed was increased from 100 mm/min to 1600 mm/min, the tensile shear strength increased first and then gradually decreased, as shown in Fig. 8b.

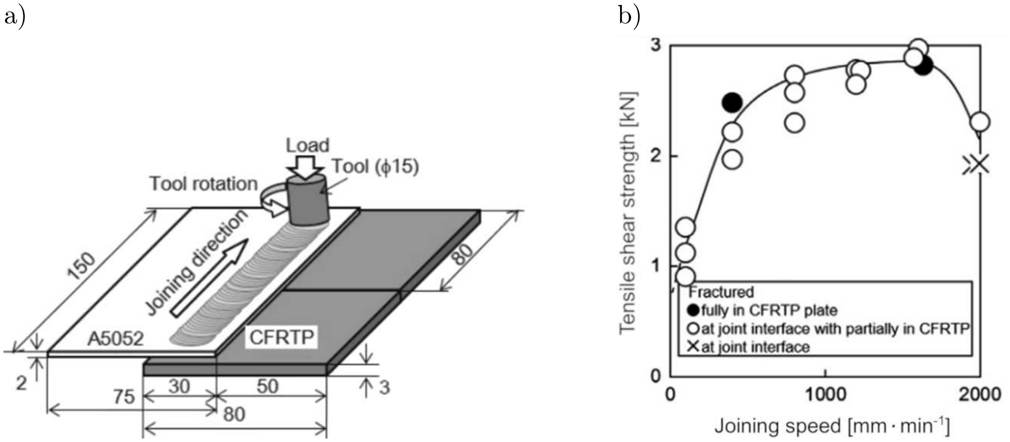

FIG. 8. a) Schematic illustration of FLW in AA5052-CFRTP [29]; b) the relationship of joining speed and tensile shear strength [29].

BUFFA *et al.* [30] drilled two rows of equally equidistant holes on both sides of the welding line in the 3 mm thick AA6082-T6, and the 2 mm thick CURV® composite was placed below the aluminum plate, as illustrated in Fig. 9. As a result of the vertical force imposed by the tool and the clamp, a reverse extrusion occurred in the lower plate, and the extruded polypropylene formed a mechanical bond between two plates. The cross-section and vertical-section diagrams of the joint are given in Fig. 10 and illustrate the generation of heat and material flow. The heat distribution was symmetric though the flow of materials was asymmetrical during the FSW [55]. Thus, the amount of extruded material on the advancing side was the same as that on the retreated side [30]. The experimental results showed that the size of the hole (d) and the interval size (p) had a certain influence on the shear force and the properties of the joint. When $d = 3$ mm or 5 mm and $p = 2d$, the maximum shear force was up to 2800 N.

To further improve the mechanical joint, BAFFARI *et al.* [56] investigated the structure of holes based on [55]. It was found that the sink-hole structure produced the joint with the best performance. Moreover, the stress concentration

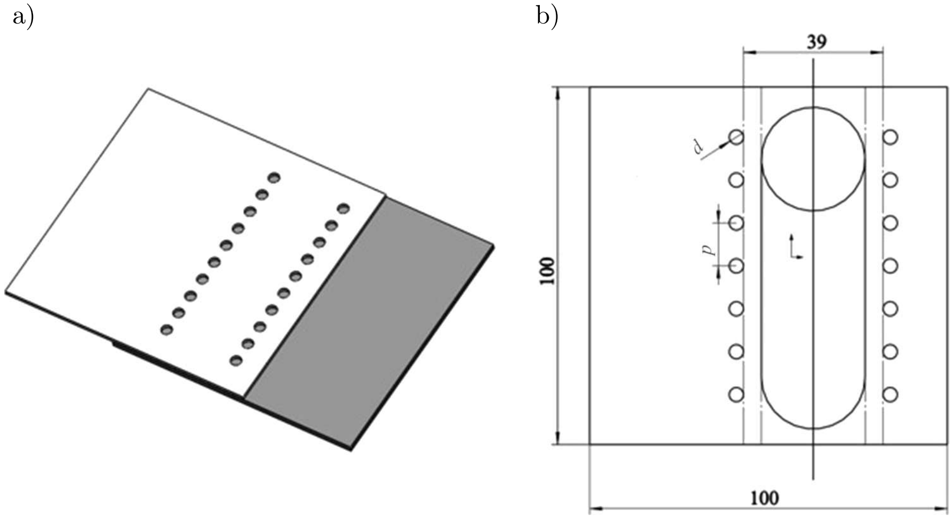

FIG. 9. a) 3D view of plates; b) sketch map of the aluminum sheet and location of holes.

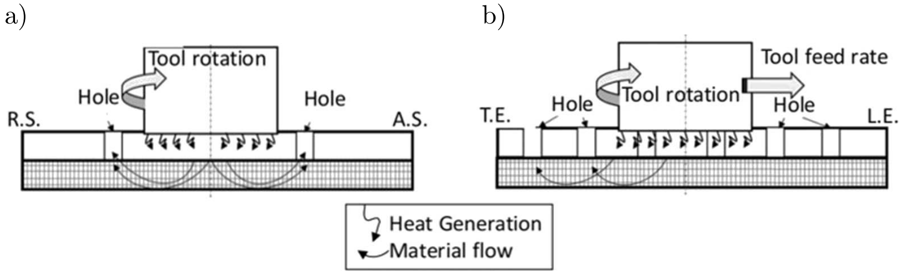

FIG. 10. Heat generation and material flow [30]: a) transverse section, b) longitudinal section.

in this area was reduced with the employment of the chamfer angle around the hole. Furthermore, the mechanical properties of the joint were improved.

2.3.4. FSpJ. FSpJ is a new technology derived and developed from FSSW, which produces the key- hole's spot welding defect. The tool used in FSpJ consists of a pin, a sleeve and a clamping ring [31], as shown in Fig. 11. The sleeve is rotated and inserted into the metal sheet with a predefined depth, and then the pin is pushed into the softened metal to fill the keyhole in the metal sheet. Finally, the pin is retracted, and the joint is reinforced under the pressure. It should be noted that the depth of the pin inserted into the metal parts should not be too deep to avoid any damage to the fiber. FSpJ was used to join CFRP and metal [31–34].

GOUSHEGIR *et al.* [31] performed FSpJ-experiment of 2 mm thick AA2024-T3 and 2.17 mm thick CF-PPS. They found that with rotation speed at 1900 r/min,

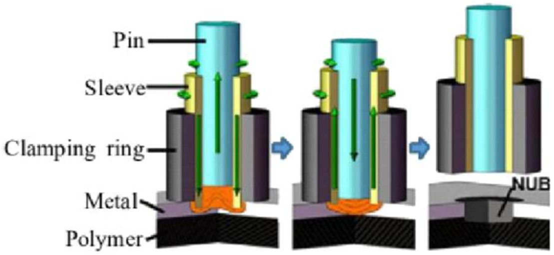

FIG. 11. Tool components and joining process of FSpJ [31].

sleeve plunge at 0.5 mm, welding time at 4.8 s and pressure at 8.5 kN, good welds were obtained and the tensile shear strength reached 27 MPa. Mechanical interlocking and adhesion were the main bonding mechanisms. GOUSHEGIR *et al.* [31] divided the joint zone into three zones [57]: adhesion zone (AZ), transition zone (TZ), and plastic deforming zone (PDZ), shown in Fig. 12. The main process parameters affecting the bonding area were joining pressure, rotational speed and joining time. Rotational speed and joining pressure had the greatest influence on the joint's mechanical properties [57]. The fracture morphology showed a brittle-ductile mixed fracture. The radial crack nucleated around the bonding zone and propagated rapidly until the bonding zone failed. The crack propagated to TZ and PDZ, which led to the decrease of the joint's stiffness [58].

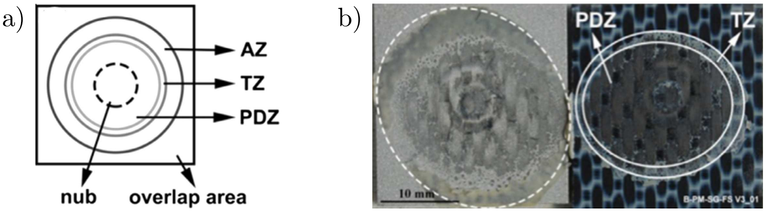

FIG. 12. a) Illustration of fracture surface; b) a real fracture.

To improve performance of joint, a double-lap connection to weld AA6181-T4 ($25.4 \times 100 \times 1$ mm^3) and CF-PPS ($25.4 \times 100 \times 2.17$ mm^3) was used by ESTEVES *et al.* [32], as shown in Fig. 13. This welding design reduced the rotation in the whole joint, and a shear load ranging from 2107 N to 3523 N was obtained. Among the welding parameters, the rotational speed had the largest effects on the shear strength of double-lap joints, followed by joining time and lap depth.

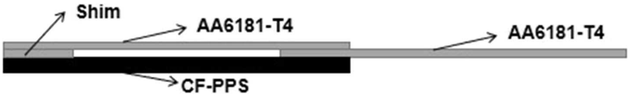

FIG. 13. Double-lap joint.

The increase of the bonding force made the molten polymer expand better at the interface and reduced cracks and pore at the metal surface [32].

Adding the middle layer is a good way to improve the properties of the joint. On the basis of FSpJ, André *et al.* [33] studied the joint's microstructure and mechanical properties by adding the middle layer (PPS film) between 2 mm thick AA2024 and 2.17 mm thick CF-PPS, whose plane dimension was 25.4×100 mm^2. Compared to experiments without PPS film, the ultimate lap shear force of the joint was increased by 20–55% and fatigue life was increased nearly three times. The existence of the middle layer greatly improved the adhesion area of the joint, made the stress distribution more uniform, and also made the load distribution better which was the main reason for this phenomenon. Besides, there was a micro-mechanical chimerism between the middle layer and the aluminum alloy plate, and between the middle layer and the CF-PPS plate. Its linkage property was better, which was especially apparent for the improvement of joint strength.

2.4. Hybrid welding

Nowadays, single welding technology sometimes may not satisfy the requirement of strength. Thus, hybrid welding methods have been developed.

Hu *et al.* [35] combined FSSW with self-propagating bonding technology to carry out a welding experiment for CFRP and metal, as shown in Fig. 14a. This hybrid joining overcame the shortcoming of poor airtightness for spot welding joint and realized rapid and high strength joint of CFRP and metal. In Fig. 14a, numbers represent as follows: 1 – metal, 2 – self-propagating reaction powder, 3 – CFRP, 4 – tool. The reactive powder was a mixed powder obtained by ball milling of carbon nanometer powder, aluminum powder, tin powder and copper powder under argon protection. Through carrying out spot welding in adjacent two reactive powders, the self-propagating reaction of powder on both sides was induced due to generating friction heat, and then the tool carried out

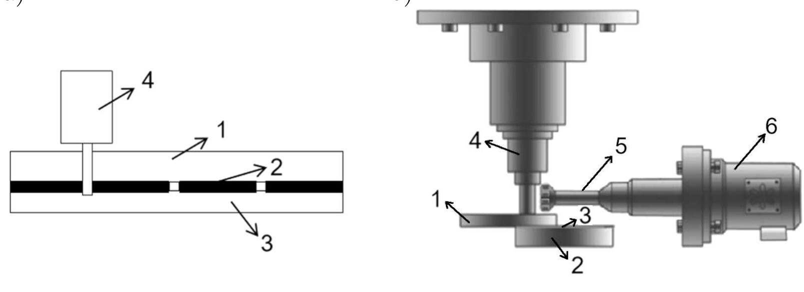

Fig. 14. Composite joining: a) FSSW and self-spreading joining, b) adhesive bonding and FSSW under ultrasonic assistance.

spot welding in the powder interval in turn to finish welding. Finally, the good joints of AA5052 and CF-PEEK were obtained.

To overcome defects such as poor mobility in the process of spot welding, Hong *et al.* [36] proposed a new method including three kinds of welding technologies: FSSW, adhesive bonding and ultrasonic-assisted technology, as shown in Fig. 14b. They also performed the connection of metal and composites successfully. In this figure, every number represents as follows: 1 – Al alloy, 2 – composites, 3 – middle layer (in their study it was mentioned that when composites were carbon fiber, polyamide-6 material was used, and when composites were glass fiber, polyphenylene sulfide material was used), 4 – machine used in FSSW, 5 – amplitude rod, 6 – energy converter. The ultrasonic-assisted technology does not only improve the uniformity of adhesive when it starts spreading but also enhances the mobility of materials. Several good joints such as AA6061 and CFRP, AA6181 and CFRP were obtained using the ultrasonic-assisted technology.

3. Conclusions and outlooks

There are many methods of joining different materials. This review provided a systematic study on the welding of CFRP and metal. The following points summarize this study:

1) Although adhesive bonding and mechanical connection are the common methods for joining CFRP and metal, solid-phase welding such as friction welding is regarded as an appropriate approach in applications.
2) Lapping weld is the preferable weld design, compared with the butt joint of CFRP and metal.
3) In order to improve joint quality, surface pretreatment, adding a middle layer and hybrid welding are employed. In Fig. 15, the tensile shear strength of materials before and after surface treatment is presented. A better weld-

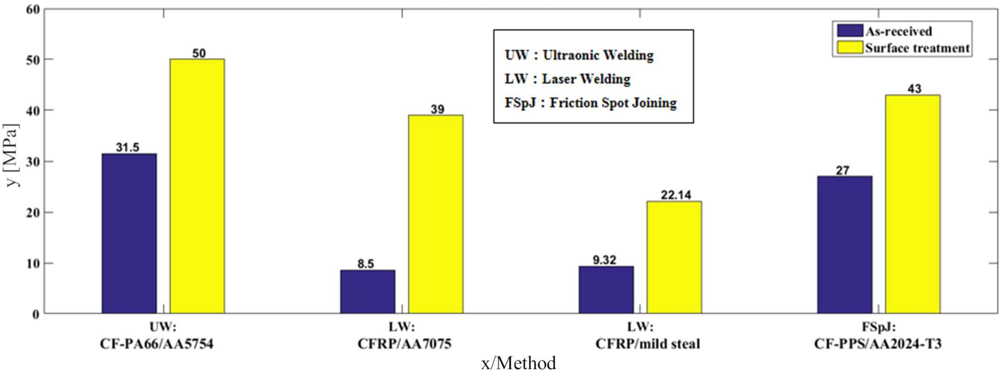

Fig. 15. Contrast diagram between treatment and non-treatment [18, 20, 21, 24, 31].

ing effect is generally obtained after carrying out surface pretreatment of materials.

4) For continuous development of joining technologies, comprehensive understanding of the process and weldment properties such as strength, performance and sustainability [59] is required. The feasibility of connecting CFRP and metal has been proved, but there are many factors affecting the joint. The finding of suitable process parameters is a key problem among those factors. Advanced experimental techniques and multi-physical modeling are expected to extract details on joint formation mechanisms and the effect of process parameters on the mechanical behavior of material connections.
5) At present, the composite connection is used in connecting CFRP and metal. The hybrid joining can compensate for some defects of single joining technology and exert its advantages fully. So, researchers can attempt to diversify joining experiments in different joining technologies. In addition, it is also important to establish models for different joining techniques to better observe the mechanical behavior of the joints.
6) The internal material flow at the interface between CFRP and metal needs further theoretical discussion, and the bonding mechanism is also a key point that researchers need to understand.
7) A reference guide and performance evaluation can be made for different connection technologies and junctions of different CFRPs and metals.

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