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ARTICLE

Review on Joining Process of Carbon Fiber-Reinforced Polymer and Metal: Methods and Joining Process

Zhang Dawei[1], **Zhang Qi**[1], **Fan Xiaoguang**[2], **Zhao Shengdun**[1]

[1] Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Xi'an 710049, China; [2] State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an 710072, China

Abstract: The use of carbon fiber-reinforced polymer (CFRP) in aviation, automobile, marine and offshore, etc. increases sharply. The metals such as aluminum alloy are still widely used in these industries. Then, the joining technology of CFRP-metal is one of the key problems urgently to be solved and developed in these industries, especially in aviation industries. Thus, this paper gives a review on the joining processes of carbon fiber-reinforced polymer and metal. The implementation processes and joining material types of adhesive bonding, bolt connection, riveting, welding, "z-pin" (pin inserts), and joining (such as self-pierce riveting, hot riveting, mechanical clinching, friction welding) by plastic deformation, were summarized.

Key words: carbon fiber-reinforced polymer; metal; joining; finite element method

Pursuing high-reliability, light-weight, high-efficiency is unchanging forever for aviation industry, and light-weight material, light-structure and advanced forming process are the efficient approach to meet these demands[1-3]. Carbon fiber-reinforced polymer (CFRP) with high specific strength, high specific modulus, excellent fatigue resistance, etc., has been widely used in aviation industry[3-5]. The production of CFRP is expected to over 0.2 million tonnes in 2020[6].

The ratio of composite material to material used in new generation of aircraft increases sharply, such as the using of composite material is more than that of aluminum alloy in Boeing 787 and Airbus 350XWB[6-8]. The metals as a high-performance and light-weight material, such as aluminum alloy and titanium alloy, are still used in aerospace and aircraft industries. Thus, the joining processes of CFRP-CFRP and CFRP-metal is one of the key problems urgently to be solved and developed in aerospace and aircraft industries. Moreover, the hybrid structures of CFRP and metal have been widely used in automobile, marine and offshore, leisure spots.

Adhesive bonding, mechanical fastening (bolt connection and riveting) and welding all have the application in composite material joining[8-15]. Although mechanical fastening has the stress concentrating and weight increasing problems, the mechanical fastening is also widely used due to simply process, easy maintenance and non-sensitive to working environment. Such as the riveting is still used in newest Airbus 350[9]. Generally, adhesive bonding has excellent fatigue strength and high corrosion resistance, but the surface treatment of joining material is careful, and the cured time of adhesively bonded joint is long such as several days, and the strength of adhesively bonded joint is sensitive to working environment such as humidity, temperature, and oil pollution. Resistance welding, ultrasonic welding, laser welding, and so on, are all used in composite material joining, but the application range is limited.

The joining technology of composite material is dominated by mechanical fastening, adhesive bonding, and hybrid joining method combining mechanical fastening with adhesive bonding at present. However, joining by "z-pin" (i.e. pin inserts), welding and joining by plastic deformation such as self-pierce riveting, mechanical clinching, friction welding and hot riveting have been used more and more in CFRP-metal joining. Thus, the joining methods and their joining process, especially the joining process by plastic deformation, for CFRP-metal hybrid

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Corresponding author: Zhang Dawei, Ph. D., Associate Professor, School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, P. R. China, Tel: 0086-29-82668607, E-mail: zhangdawei2000@mail.xjtu.edu.cn

joint were summarized in the present paper.

1 Advances on Joining Technologies

1.1 Adhesive bonding

Adhesive bonding (AB) is a process that two partners are joined by mechanical interlock, physical adsorption and chemical binding, and it has been widely used in composite material joining[10-12]. Adhesive bonding has a high flexibility, but it needs careful surface treatment before joining and a long curing time in joining process. Up to now, research on AB is mainly focused on surface treatment before bonding, influence of adhesive property, detection and evaluation of bonded joint[9,13,14].

The epoxy adhesive was adopted by most of research due to polymer characteristic in CFRP. The modified epoxy adhesive was also expanded to join CFRP and metal such as aluminum alloy[12]. However, most adhesive bonding processes for CFRP-metal are used in strengthening steel structure and repairing steel part fields[15-17].

In order to improve gap-filling and interfacial wetting between two joining materials, an ultrasonic vibration was exerted on the joint in the adhesive bonding process, which named ultrasonic vibration-assisted adhesive bonding (UVAB), as shown in Fig.1[18,19]. The developed bonding method with ultrasonic vibration has been used to join CFRP tube and aluminum alloy bar together. Compared with traditional adhesive bonded joint, the strength of the joint by novel process increases notably.

1.2 Mechanical fastening

Mechanical fastening of composite material has a wide range of application at initial stage. It includes two types: bolt connection and rivet connection (riveting)[20,21], as shown in Fig.2. The joining partners need a hole by machining such as drilling, and this will result in delamination damage in CFRP and stress concentration around the hole, and then the strength of the joint will be reduced[22]. Bolt connection is easy to assemble and disassemble, and has a good airworthiness certification, so the bolted joint is still used in aerospace and aircraft structure[23], especially in heavy load structure[24]. The riveting process is easy to achieve automation and the riveting efficiency is high, and thus the riveted joint is also an important joining method. For example, the riveting process is still an important part of joining technology in newest Airbus 350[9].

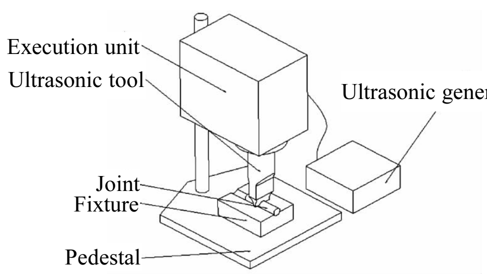

Fig.1 Sketch of ultrasonic vibration-assisted adhesive bonding process[18]

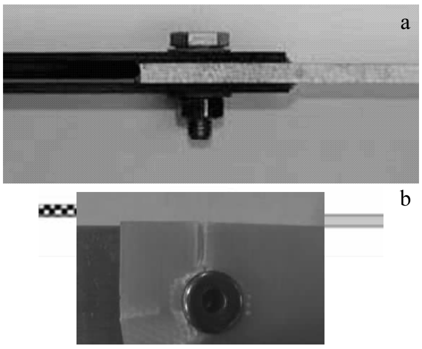

Fig.2 Mechanical fastening: (a) bolt[20] and (b) rivet[21]

The blind rivet body consisting of hollow rivet and rivet mandrel is put in the drilling hole, and then the rivet mandrel is pulled to form another head of hollow rivet, and then the rivet mandrel is broken, as shown in Fig.3a. Stand blind riveting (BR) process was also used in joining CFRP and metal[25], as shown in Fig.3b.

The mechanical joint needs a drilling hole and it brings low sealing performance and some damages for composite[26]. The strength of the bonded joint is sensitive to working environment, and it tends to fail instantaneously[20]. A hybrid joining method, such as bolted-bonded joint (as shown in Fig.4), can increase sealing effect of mechanical joining and improve potential weakness of adhesive bonding. The hybrid jointing method has been widely used in composite material connection including composite-composite joint and composite-metal joint[20,24,27].

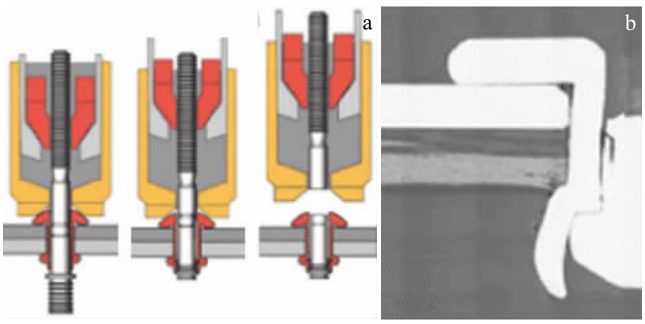

Fig.3 Sketch of blind riveting: (a) riveting process and (b) cross section of joint[25]

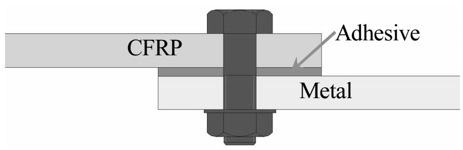

Fig.4 Sketch of bolted-bonded joint

For traditional mechanical fastening, the fastening depends on nut in bolted joint or formed rivet-head in riveted joint. However, in the laser riveting (LR) developed by Kashaev et al.[28], the metal rivet is welded to metal partner. During the laser riveting process, the metal rivet is pushed in the drilled holes of metal and CFRP sheets, and the head of rivet contacts with free surface of CFRP sheet, then CFRP sheet is pressed to metal sheet, and then the end of rivet is fused with metal sheet, as shown in Fig.5a. The heat affected zone of CFRP decreases with the increasing of laser power[28]. In order to improve bolted joint, some pyramids were milled into surface of metal sheet in lap zone, as shown in Fig.5b[28].

1.3 Joining by "z-pin" (pin inserts)

The z-pinning technology is a novel technology for reinforcement of polymer laminated composite in through-thickness direction[29,30], as shown in Fig.6. It was developed for joining composite to composite[30,31]. The pin is made from titanium alloy, steel, fibrous carbon and the diameter of the pin is 0.2~1.0 mm[30], and the diameter is often less than 0.6 mm[29], such as 0.28 mm being used[31,32].

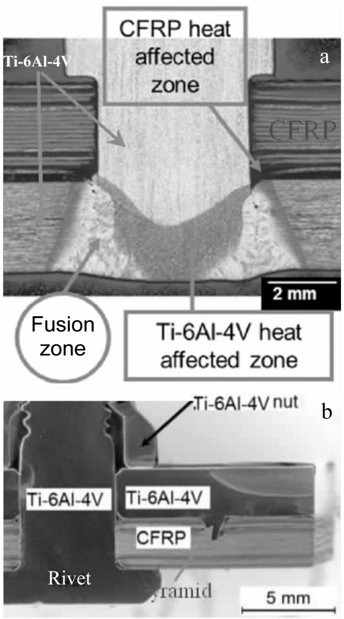

Fig.5 Some new mechanical joining methods[28]: (a) laser riveting and (b) bolt combining with surface structuring of metal sheet

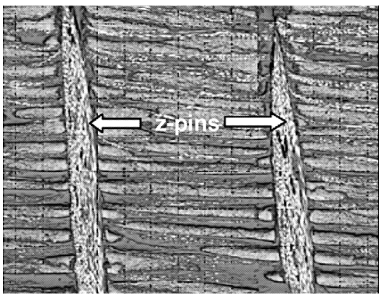

Fig.6 z-pinned composite[30]

However, the current z-pinning technology is difficult to achieve joining between CFRP and metal. A technology of joining composite to metal sheet with some "pins" was developed via mechanical locking by pin[33], as shown in Fig.7. In the joining region, the shape of metal is a plate[33,34], as shown in Fig.7; and the scarf shape and stepped shape were also used in the joining region[35,36], as shown in Fig.8. The pins with different shapes such as spike, cylinder, ball-head, and wedge were adopted[33-36]. Generally, the pins are perpendicular to surface of metal, but the tilted pins were also investigated[34,35]. The diameter of pins is often larger than that in z-pining technology, such as 0.8~1.5 mm being used[33,34].

Cold metal transfer (CMT) that allows a wire to be welded onto surface of metal is often used to produce the pins[33]. Metal injection molding was also used to produce the metal with pins[37], such as forming with electron beam melting (EBM) [34], and this method is often used for titanium alloy. Micro machining method was also used to produce the pins[35], where the surface-pin was generated by chip removal.

In general, the co-curing processing method was used to join CFRP to metal with pins[33,35]. The process is complex and needs a long time. Thus, the metal with pins was inserted into uncured composite by ultrasonication and then was cured in an autoclave[34,38]. However, the curing process is needed for the joining process, which consumes the additional resources such as equipment and time. The direct joining method (named as ultrasonic joining) using ultrasonic energy was developed by Feistauer et al[37], as shown in Fig.9.

During the ultrasonic joining process, the clamping pressure and ultrasonic vibration are applied by the sonotrode (step 2 in Fig.9); the vibration combined pressure produces friction heat at the metal-composite interface, which softens the polymer;

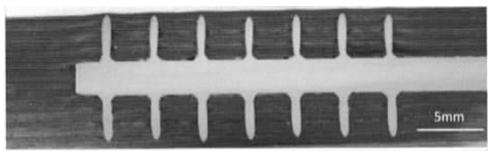

Fig.7 "Pinning" composite-metal joint[34]

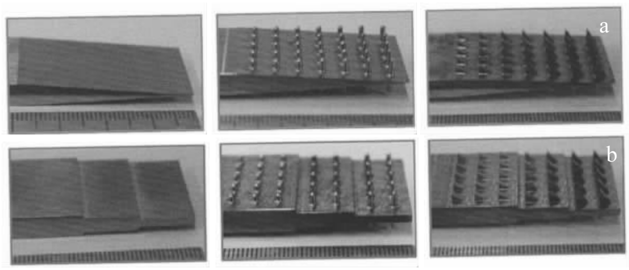

Fig.8 Shapes of metal in joining region[35]: (a) scarfed insert and (b) stepped insert

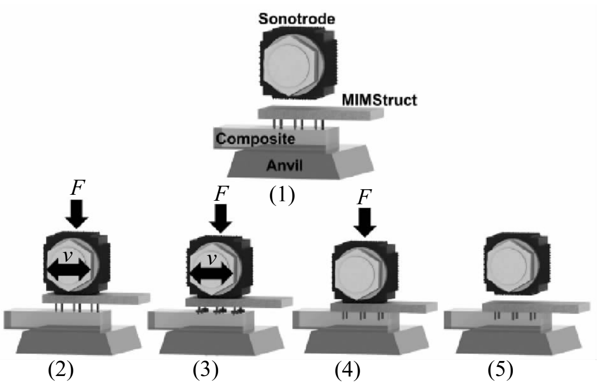

Fig.9 Process of ultrasonic joining (MIMStruct: metal injection molded parts with reinforced surfaces)[37]

and then pins are inserted into the polymer (step 3 in Fig.9); the metal surface will be wetted by the polymer after the pins are completely inserted (step 4 in Fig.9). The method has been applied to Ti-6Al-4V alloy and glass fiber-reinforced polymer (GFRP).

1.4 Welding

The CFRP and metal are also joined by improved braze welding and resistance welding. Moreover, contactless joining methods such as by laser, infrared and induction heating are also used in composite material joining. The solid-state welding method such as welding combining friction and plastic deformation will be discussed in next section (Section 1.5).

In general, joining surface of CFRP is covered by a layer metal before brazing by means of plating, sintering and depositing, or active metals such as titanium and zirconium are adopted as brazing filler directly[39]. And the vacuum brazing is often used for the CFRP-metal joint. The vacuum brazing with active brazing filler included Ti has been used to join CFRP and titanium alloy or niobium alloy[40], as shown in Fig.10.

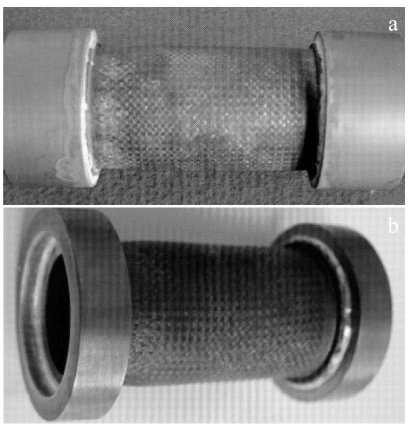

Fig.10 Brazed hybrid joint[40]: (a) CFRP-titanium alloy and (b) CFRP-niobium alloy

The aluminum alloy and CFRP joined by resistance welding (RW)[41], induction heated joining (IHJ)[42] and ultrasonic welding (UW)[43,44] have been achieved, respectively. The laser joining (LJ) process has been used to join steel and CFRP[45,46]. Essentially, these welding processes of CFRP and metal are the bonding process between metal and CFRP in overlap region under certain temperature and pressure. The induction heat, ultrasonic and laser are applied to metal partner of hybrid joint, and polymer matrices of CFRP in overlap or joining zone is melted because of heat conduction. For example, Fig.11 illustrates the characteristics of heat transfer and section feature of CFRP-stainless steel 304 joint by laser joining process.

Essentially, the welding process of CFRP and metal is a process to form bonding between metal and CFRP in overlap region under certain temperature and pressure. Thus, the surface treatment before welding is very important, especially for metal. In resistance welding process, the micro-porosity of surface should be created on aluminum alloy substrate, and standard surface treatment for adhesive bonding was often adopted[41]. In induction heated joining process, mechanical and chemical treatment methods were used to increase surface roughness and surface concentration[42].

The ultrasonic welding process is characterized by short welding time and low energy input. The amplitude of oscillation applied to welding zone is 5~50 μm, and the thickness of upper joining partner (i.e. metal partner) is up to 3 mm[43,44]. Surface roughness is also important for weldability, but higher roughness will result in localized hot spots and thermos-shock provoked factures are caused by this hot spots[44].

The mechanical bonding and chemical bonding are the joining mechanism of laser joining between metal and CFRP[45,47]. In order to increase melted polymer matrices to strengthen bonding effect, the same polymer laminae was added between CFRP and stainless steel[48]. The Cr-coated layer can strengthen chemical bonding during laser joining process, increasing the strength of CFRP-mild steel joint[45].

1.5 Joining by plastic deformation

Self-pierce riveting (SPR) and mechanical clinching (MC) processes are wieldy used in connection of metal sheets, especially in joining process of light-wright materials such as aluminum alloy and magnesium alloys[49,50]. Essentially, self-pierce riveting and mechanical clinching processes are a cold forming process, and the sheets are without pre-hole

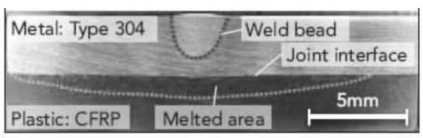

Fig.11 Heat transfer and section feature of hybrid joint by laser joining[46]

before joining. The SPR, MC and other joining methods by plastic deformation also have an application in hybrid joint between CFRP and metal, but have some improvements, even innovative ways.

1.5.1 Self-pierce riveting

A stainless steel semi-tubular rivet was used in self-piercing riveting process of CFRP and aluminum alloy[51,52], as shown in Fig.12. The riveting process is similar to the process for metal-metal joint, but CFRP sheet should be placed at the top[52]. The rivet pierced the upper sheet and formed/flared in lower sheet to form/create a mechanical interlock. The lower metal sheet ensured the formation of interlock and keeping certain strength. In order to join lower CFRP sheet, the modified self-piercing riveting process by adding two flat washers was developed[53], where the rivet pierces the upper and lower sheets and is flared between lower washer and lower die. The delamination in CFRP can be suppressed by the washers[53].

Based on the stand blind riveting process, friction stir blind riveting (FSBR) was developed and was expanded to join CFRP and metal[54]. Fig.13 illustrates the process of FSBR. During the FSBR, the blind rivet rotates and pierces the softened sheets by frictional heat, and the end of rivet body is also heated by the frictional heat, and then rivet mandrel is pulled to fasten sheets and broken. There is no special requirement for the relative position of metal or CFRP sheet.

In order to improve the hybrid joint, the adhesive bonding was also introduced in SPR process. The SPR-bonded joint between CFRP and AA 2024 was performed by Franco et al[51]. The SPR-bonded joint is better than simple SPR joint or simple bonding.

Connection of different materials by rivet inserting into CFRP named friction riveting (FR) was developed by Amancio-Filho et al[55], as shown in Fig.14. During the friction riveting process, metal rivet rotates and moves down, and then the end of rivet begins to plastically deform, forming a flash due to increase in temperature, and finally, the rivet is anchored in thermoplastic CFRP as a metallic-insert. But the principle of joining shows a difference for different positions of metal sheet. If metal is placed at bottom, the rivet penetrates the CFRP sheet and is against the surface of metal sheet, and the welded point between rivet and metal sheet will be formed by frictional heat and pressure, as shown in Fig.14a. If metal is placed at top, the metal has a through-hole, and the rivet is across the hole and is inserted and anchored in lower CFRP, as shown in Fig.14b. Deformation of rivet in CFRP by friction riveting and pull-out performance were investigated in the study[56,57].

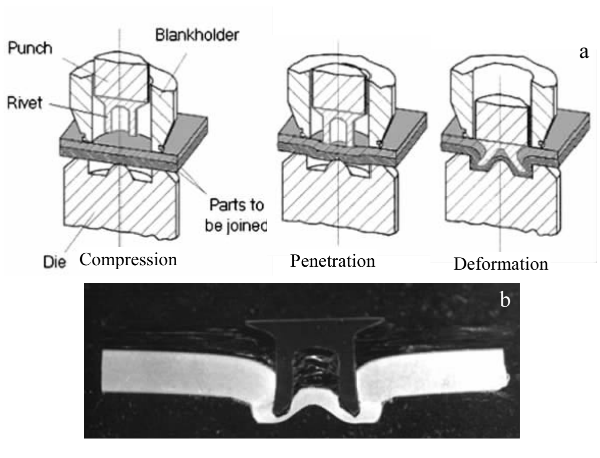

Fig.12 Sketch of self-piercing riveting: (a) riveting process[51] and (b) cross section of joint [52]

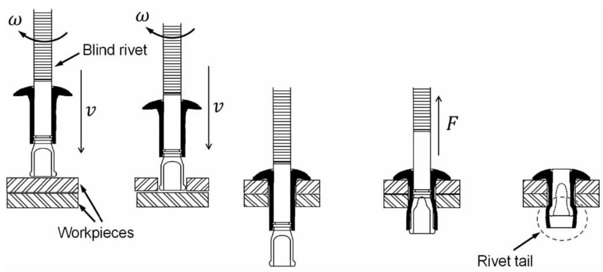

Fig.13 Sketch of friction stir blind riveting[54]

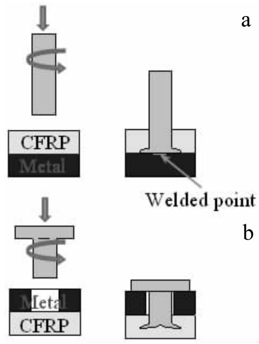

Fig.14 Sketch of friction riveting: (a) CFRP at top and (b) CFRP at bottom

1.5.2 Hot riveting

A rivet is needed in above riveting process, and the materials of rivet are stainless steel, mild steel, titanium, etc. in general. The rivet increases the weight of joint and causes corrosion between rivet and sheets. These problems can be solved by adopting a composite rivet or no rivet, and the hot riveting (HR) and mechanical clinching are the corresponding joining processes, respectively.

Based on staking, injecting and bonding technologies, an injection clinching joining (ICJ) process was developed[58], as shown in Fig.15. The polymer-based partner is with a protruding stud and the metal partner is with a hole, and the stud is similar to the rivet. During ICJ process, the stud is heated to molten/soften, and then is filled into cavity in metal

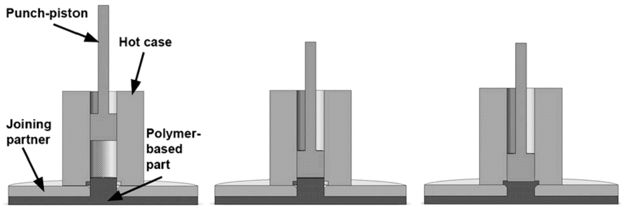

Fig.15 Sketch of injection clinching joining[59]

partner, and the joint is cooled under certain pressure. The ICJ process was successfully used to join GFRP and aluminum alloy 2024[58,59].

However, the polymer-based partner with a stud in ICJ was machined from a tick plate, such as the 10 mm thick extruded GFRP was machined to 3 mm thick sheet in the study[58]. So, material lost and damage may occur during much machining work for polymer-based partner. Thus, a new hot riveting process was developed in Xi'an Jiaotong University[60], as shown in Fig.16. During hot riveting, the metal rivet is replaced by CFRP rivet, the CFRP rivet is heated to aggregation state between elastomeric state and viscous state, and then the CFRP rivet is pressed to form hat-shape ends.

1.5.3 Mechanical clinching

The mechanical clinching processes does not need an additional rivet and there is no fracture of material in the clinching process, and the interlock of joint is formed by plastic deformation.

The poor formability is one of disadvantages for CFRP, so the clinching process should be improved before introducing to join metal and CFRP. A dummy metal sheet is set between CFRP sheet and die in order to enhance the formability of CFRP[61], as shown in Fig.17a. Furthermore, the high temperature, such as 100 °C, can be used in mechanical clinching between CFRP and metal[61]. A better hybrid joint of CFRP and aluminum alloy was obtained by clinching combining adhesive bonding, as shown in Fig.17b. The CFRP lay-up has an influence on the surface of clinched-bonded joint of CFRP and metal. The experiments in the study[61] indicated that the surface is smooth for cross lay-up CFRP ([0°/90°/0°/0°/90°/0°]), and is wrinkle for quasi-isotropic lay-up ([0°/60°/120°/120°/60°/0°]).

There exists a protrusion on the clinched sheet, and the reshaping methods[50,62] were developed to reduce the protrusion height of clinched joints. The mechanical clinching with reshaping (MCR) process includes two steps: the first step is a conventional clinching process; and the second step is a reshaping process; and the reshaping force was applied along opposite direction of clinching force. This two-step clinching process was also introduced into connecting process

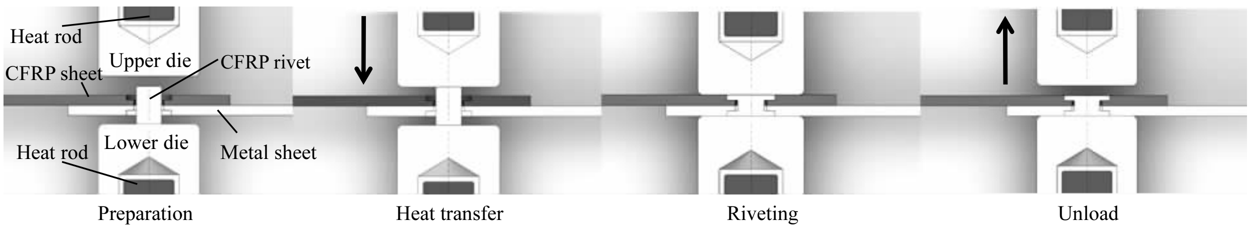

Fig.16 Sketch of hot riveting

between metal and CFRP[63], but the reshaping process was used to improve the geometrical parameters (such as neck thickness and undercut thickness) of CFRP-metal joint.

The CFRP may be damaged in SPR and clinching processes due to poor formability. Hole-(mechanical)-clinching (HMC) process is one of mechanical clinching process, as shown in Fig.18a. The lower sheet needs a pre-hole and has little deformation during the hole-clinching process, so the method is suitable to join brittle lower sheet. A hybrid joint of high-strength steel (SPRC440) and CFRP was performed by hole-clinching in the study[64], and the desired joint strength can be obtained.

1.5.4 Friction welding

Friction stir welding (FSW) is a well-known solid-state welding technique using plastic deformation, as shown in Fig.19a[65]. The tool including shoulder and stir pin rotates and moves along the seam during FSW process, where the

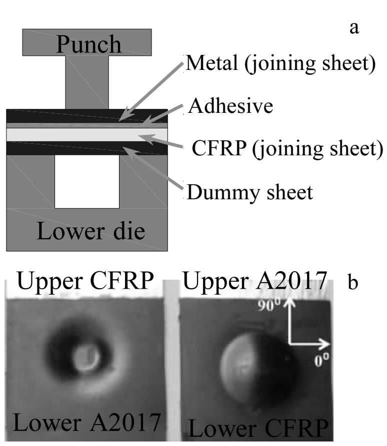

Fig.17 Sketch of clinched-bonded joining process: (a) clinching process and (b) top view of joint [61]

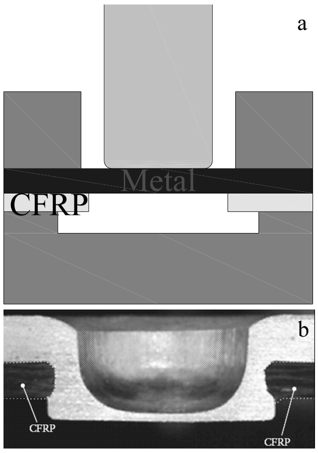

Fig.18 Sketch of hole-clinching: (a) clinching process and (b) cross section of joint[64]

shoulder contacts with the surface of sheet while the pin inserts in the sheet. Butt joint and lap joint of metal can be obtained by FSW. Several variations, such as friction lap welding (FLW) and friction stir spot welding (FSSW), are also developed in composite joining process, as shown in Fig.19b and 19c.

The FSW process has been successfully used to join different metal sheets. However, some quality problems will be caused by the motion of fiber-reinforced polymer from front to back of the stir pin under rotating combined moving. Thus so far, the traditional FSW has not been used to join polymer and metal.

A new friction lap welding similar to FSW was developed to join polymer and metal according to the material features, as shown in Fig.19b[66]. The FLW tool only has shoulder without stir pin. The friction heat produced between shoulder and metal sheet was transferred to polymer, and then melted polymer joined with metal substrate. The FLW has been used to join the polymer such as polyamide (PA 6) and the aluminum alloy, magnesium alloy and carbon steel[66,68,69]. The FLW was also successfully used to join CFRP and aluminum alloy (AA5052)[70,71].

Friction stir spot welding is another variation based on standard FSW, and it is an alternative for resistance spot welding[65]. The FSSW has been directly used to join polymers and the process includes four stages[67], as shown in Fig.19c. During FSSW process, the tool rotates and inserts in the sheet; and then the tool only rotates to generate friction heat; and then rotation stops and the material is cooled under certain pressure; finally, stir tool retracts. CFRP and aluminum alloy (AA5052) was successfully joined by the FSSW[72].

And several variations of FSSW, such as friction spot welding (FSpW)[73], are developed, as shown in Fig.20. The sleeve and pin rotate in the same direction, and the sleeve inserts in the metal partner, and then the sleeve retracts while the pin pushes softened metal to refill, and then tool retracts and molten polymer is cooled under pressure. The joining mechanisms of FSpW are the mechanical interlock by the nub and the adhesion by molten polymer filling metal surface[73-75]. During the FSpW, the tool inserting phase only occurs in the metal partner, and thus, the damage to the fiber reinforcement would be reduced or avoided. The magnesium alloy (AZ31) or aluminum alloy (2xxx, 6xxx) can be joined with CFRP by the FSpW. In order to improve the strength of hybrid joint, an additional polymer film was inserted between CFRP and metal before FSSW or FSpW according to advantages in weld-bonding technology[72,76].

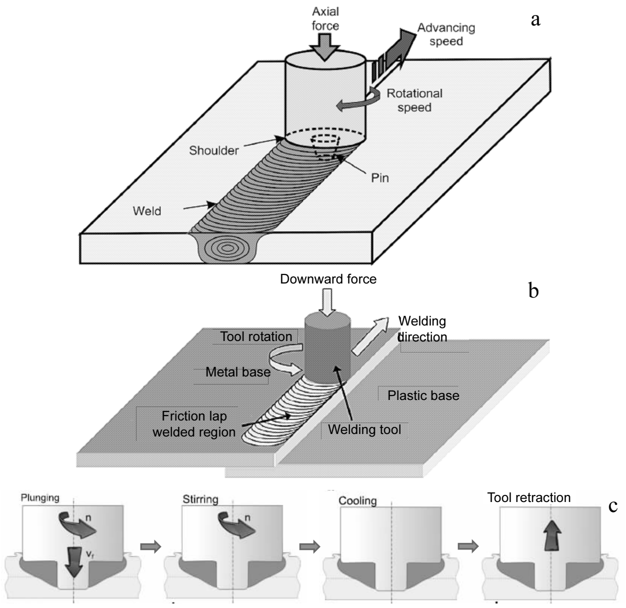

Fig.19 Variations of friction stir welding: (a) standard FSW process[65], (b) FLW process[66], and (c) FSSW process[67]

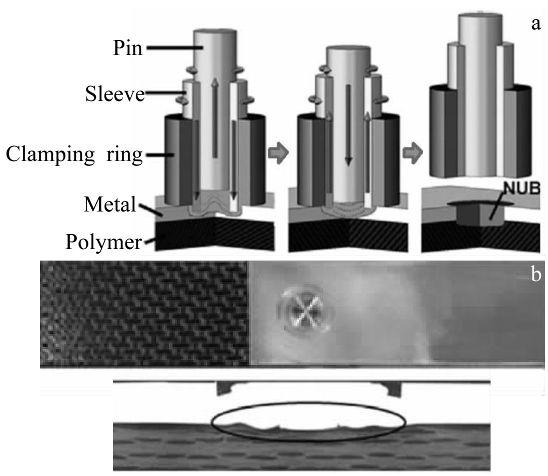

Fig.20 Sketch of friction spot welding: (a) joining process[73] and (b) cross section of CFRP-AA2024 joint[74]

2 Numerical Analysis of Plastic Deformation During Joining Process

It is difficult to describe the plastic deformation of polymer coupled fiber. Numerical analysis only focuses on the displacement/deformation of fiber in hot stamping of composite with obvious fiber orientation[77,78]. The extruded CFRP with short-cut fibers or CFRP with woven fibers is treated as a homogenous/isotropic material in reported numerical analyses on the CFRP-metal joining process by plastic deformation, and the fiber orientation and fiber deformation were not considered.

In the finite element (FE) model of SRP between CFRP and aluminum alloy, the CFRP ([0°±45°]) was considered as a homogenous/isotropic material and the normalized Cockcroft & Latham was used to describe the fracture of CFRP by Franco et al[52]. The shear friction model was used in the FE model, but different friction factors were used for different contact relations. The developed FE model by DEFORM 2D can predict the fracture of CFRP sheet and the deformation of aluminum alloy sheet, as shown in Fig.21, but the deformation and fracture of fiber were not mentioned in the study[52].

The mechanical properties of CFRP sheet in hole-clinching process[64] were evaluated by tensile tests, as shown in Fig.22. Ultimate tensile stress for 0° direction is much greater than that for 45° direction, and even much greater than that of steel SPRC440. The stress-strain curve shows a plastic characteristic. The isotropic material was also adopted to describe the CFRP in the FE modeling of joining process, but the flow stress (Eq. (1)) of CFRP for 45° direction was used[64]. The FE model of hole-clinching was also developed based on DEFORM 2D, but Coulomb friction model was adopted by Lee et al[64].

$$\sigma = 102.3 - 1805.1\varepsilon \qquad (1)$$

The developed FE model can describe the deformation of materials during the hole-clinching process, and the predicted dimensions of interlock is less than 4.35% according to comparisons under three diameters of punch[64], as shown in Fig.23. The influence of diameters and corner radius of punch on the geometrical interlock were carried out by the FE model.

The extruded CFRP Peek 450CA30 was used in the hot riveting, and thus the CFRP rivet or partner was also considered as a homogenous/isotropic material. The isothermal compression test was adopted to evaluate the mechanical properties of Peek 450CA30, as shown in Fig.24. The FE model of hot riveting of CFRP and aluminum alloy was developed by software Abaqus[60] and Forge, respectively.

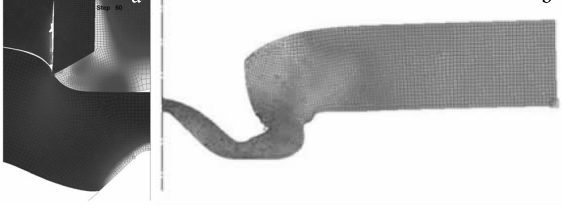

Fig.21 FE results of self-piercing riveting[52]: (a) fracture of CFRP sheet and (b) deformation of aluminum alloy sheet

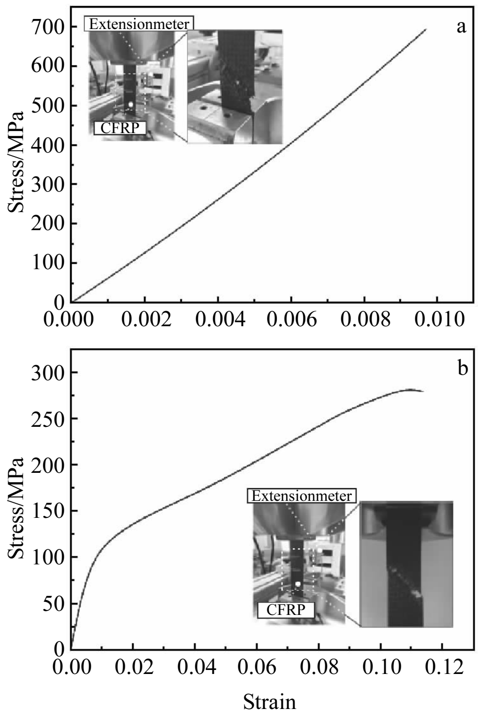

Fig.22 Stress-strain curves of CFRP[64]: (a) for 0° direction and (b) for 45° direction

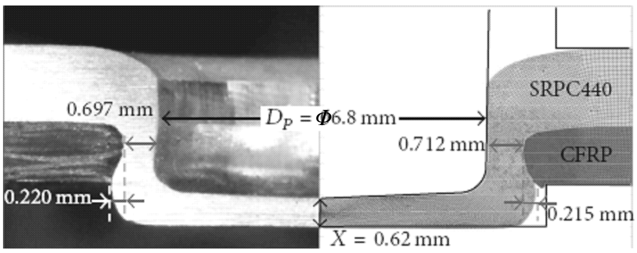

Fig.23 Comparison of geometrical interlock between FE prediction and experiment[64]

Fig.25 illustrates the comparison of joining load and joint shape by hot riveting between FE and experiment. The maximum difference of riveting load between FE and experiment is about 11.7% and the cross-section of the joint predicted by FE is also in agreement with the experimental result. Thus, the developed FE model of hot riveting can describe the riveting process using CFRP rivet. The FE results indicate that the stress of joint after hot riveting decreases with the increasing of joining temperature due to homogeneous material flow.

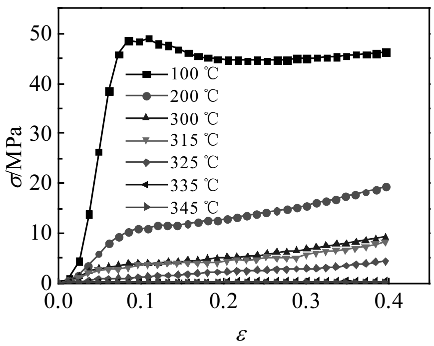

Fig.24 Stress-strain curves of CFRP Peek 450CA30

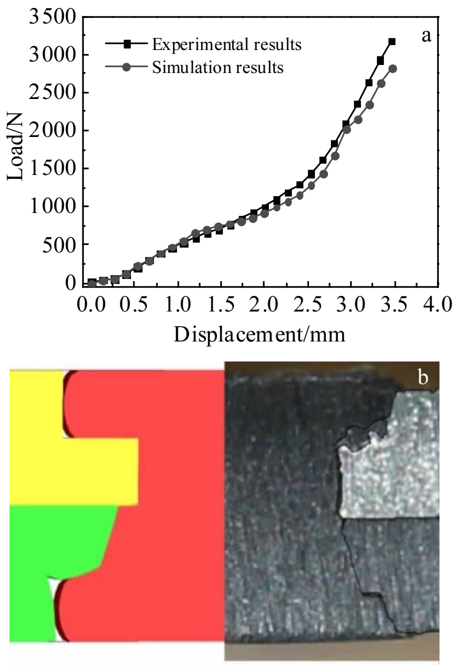

Fig.25 Comparison of FE results with experimental results: (a) riveting load (FE based on Abaqus) and (b) cross-section of joint (FE based on Forge)

3 Conclusions

1) The hybrid structures of CFRP and metal have been widely used in aviation, automobile (especially race car), marine and offshore, leisure spots. Mechanical fastening is suitable for CFRP and nearly all metals, although there are weight and corrosion problems.

2) The thermoplastic CFRP is adopted in the joining processes with plastic deformation or warming or both cases. The joining of CFRP to titanium alloy, niobium alloy, coated steel, stainless steel and aluminum alloy 1XXX, 2XXX, 5XXX, 7XXX has been achieved by welding at present. The joining by plastic deformation has been successfully used to join CFRP to high-strength steel, coated steel, magnesium alloy and aluminum alloy 2XXX, 5XXX, 6XXX.

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碳纤维增强树脂基复合材料和金属材料连接技术综述：方法和连接过程

张大伟 [1]，张　琦 [1]，樊晓光 [2]，赵升吨 [1]
(1. 西安交通大学 现代设计及转子轴承系统教育部重点实验室，陕西 西安 710049)
(2. 西北工业大学 凝固技术国家重点实验室，陕西 西安 710072)

摘　要：碳纤维增强树脂基复合材料（CFRP）在航空、汽车、舰船、海洋等工业中用量迅速增加。同时，如铝合金等金属材料在这些工业中仍然广泛应用。因此，CFRP 和金属材料之间的连接技术是航空、汽车等此类工业中所面临迫切需要解决和发展的关键问题之一。本文综述了 CFRP 和金属连接技术的一些研究成果。总结了胶接连接、螺栓连接、焊接、金属插入连接以及基于塑性变形连接（如自穿孔铆接、热铆接、无铆链接、摩擦焊接等）技术的实现和连接材料类型。

关键词：碳纤维增强树脂基复合材料；金属；连接；有限元法

作者简介：张大伟，男，1982 年生，博士，副教授，西安交通大学机械工程学院，陕西 西安 710049，电话：029-82668607，E-mail: zhangdawei2000@mail.xjtu.edu.cn