Review Article

Joining of C_f/SiC Ceramic Matrix Composites: A Review

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Carbon fiber-reinforced silicon carbide (C_f/SiC) ceramic matrix composites have promising engineering applications in many fields, and they are usually geometrically complex in shape and always need to join with other materials to form a certain engineering part. Up to date, various joining technologies of C_f/SiC composites are reported, including the joining of C_f/SiC-C_f/SiC and C_f/SiC-metal. In this paper, a systematic review of the joining of C_f/SiC composites is conducted, and the aim of this paper is to provide some reference for researchers working on this field.

1. Introduction

With the rapid development of high-tech in aerospace and other industry fields, the demands for new materials, which can work in extreme harsh working environment of high temperatures, are growing. The needs for better efficiency and higher thrust-to-weight ratio promote the development of advanced materials at high temperatures, such as superalloys [1–3], ceramics [4–6], composites [7–10], and so on. Among these advanced materials, ceramic matrix composites (CMCs) are drawn great attentions for their engineering applications under extreme conditions because they can maintain low density, high strength, wear resistance, oxidation resistance, thermal shock resistance, corrosion resistance, and some other functions together [11].

Carbon fiber-reinforced silicon carbide (C_f/SiC) ceramic matrix composites, one of the most famous CMCs, are becoming the most promising candidates for high-temperature structural applications (as illustrated in Figure 1), such as sharp leading edges, nose cones, aeronautic jet engines, thermal protection systems for reusable atmosphere reentry vehicles [12, 13], as well as optical components [14] and nuclear fusion/fission reactors [15, 16], owing to their relatively low density ($\sim 2 \text{ g/cm}^3$), high thermal conductivity ($\sim 67 \text{ W/(m}\cdot\text{K)}$), high strength (300–800 MPa) [17–19], low

coefficient of thermal expansion (CTE, $3.0\text{--}3.1 \times 10^{-6} \cdot \text{K}^{-1}$), especially good stability and excellent oxidation and creep resistance at elevated temperatures [13, 21–23, 25]. In particular, C_f/SiC composites have shown significant improvements in fracture toughness and thermal shock resistance. These improvements in mechanical properties are dependent on the specific properties of the carbon fiber and the silicon carbide. According to the type of carbon fiber, it can be divided into 1D C_f/SiC, 2D C_f/SiC, 2.5D C_f/SiC, and 3D C_f/SiC and applied in different fields.

For aerospace applications, as reported by NASA, the X-37B and X-38 aircrafts employed a large number of C_f/SiC composites in their nose cone [25], leading edge wing and engine components [11, 26, 27, 29]. For nuclear applications, C_f/SiC composites are used as the cladding materials in pressurized water reactors and flow channel insert materials in thermonuclear fusion reactors [29, 30, 32]. In most cases, typically, C_f/SiC composite components are usually geometrically complex in shape and always need to join with other materials to form a certain engineering part. However, unfortunately, due to their poor machinability and toughness, C_f/SiC composites lack good processing performance like metal material and thus cannot be processed into complex-shaped components by forging, extrusion molding, and other traditional methods. It is very difficult to produce

FIGURE 1: Various engineering applications of C_f/SiC composites.

large-size C_f/SiC composite components with complex shapes, resulting in they must be joined with themselves or other materials by appropriate joining technologies [32–34, 37]. There have been numerous reports on the joining of C_f/SiC composites in the past two decades, including self-joining of C_f/SiC composites [36, 37, 39], and joining of C_f/SiC composite to dissimilar materials, such as Ti [39, 40], Nb [41, 42, 45], Ni [44, 45, 48], TiAl alloys [47], and so on.

Up to date, various joining technologies of C_f/SiC composites are reported, including the joining of C_f/SiC - C_f/SiC and C_f/SiC -metal. Table 1 lists commonly used joining technologies, such as direct bonding of C_f/SiC - C_f/SiC , indirect bonding of C_f/SiC - C_f/SiC , brazing of C_f/SiC -metal, diffusion bonding of C_f/SiC -metal, online liquid infiltration of C_f/SiC -metal, ultrasonic-assisted joining of C_f/SiC -metal, and electric-assisted joining of C_f/SiC -metal. To the best knowledge of the authors, however, there has been no systematic summary of the joining of C_f/SiC composites. Therefore, we herein conduct a systematic review of the joining of C_f/SiC composites, and the aim of this paper is to provide some reference for researchers working on this field.

2. Self-Joining of C_f/SiC Composites

In some conditions, in order to obtain large size and complex-shaped C_f/SiC composite components, it is necessary that C_f/SiC composites should be joined with C_f/SiC composites themselves, named as “self-joining.” There have been many reports about the self-joining of C_f/SiC composites in the last decades, usually including direct bonding and indirect bonding method.

2.1. Direct Bonding. Direct bonding method is a self-joining of C_f/SiC composites by solid-phase diffusion without any other materials (Figure 2(a)). As reported in previous papers,

TABLE 1: Commonly used joining methods of C_f/SiC composites.

Joining materials	Joining methods
C_f/SiC - C_f/SiC	Direct bonding
	Indirect bonding
C_f/SiC -metal	Brazing
	Diffusion bonding
	Online liquid infiltration
	Ultrasonic-assisted joining
	Electric-assisted joining

the main procedure of direct bonding usually includes three procedures: (1) plastic deformation, (2) diffusion, and (3) creep. Plastic deformation occurs on the interface because of heat and pressure; diffusion includes surface diffusion, bulk diffusion, grain boundary diffusion, and interfacial diffusion to achieve C_f/SiC bonding. Creep refers to the permanent movement or deformation of metal.

However, the bonding strength of the directly joined C_f/SiC composite is usually very low because a strong bonding of C_f/SiC composite is difficult to obtain without any other transition phases and because the diffusion between C_f/SiC composites is not easy owing to the strong covalent bond and the poor deformation ability of the SiC in the composites. Rizzo et al. [48] reported that a CVD- SiC coated C_f/SiC composite was directly joined to its counterparts using spark plasma sintering (SPS) technology. The results showed that the cracks in the CVD- SiC coating were visible among the interface and propagated from the SiC coating through the joint area (as is shown in Figure 3), due to the CTE mismatch between SiC coating and C_f/SiC substrate (as is shown in Table 2), and the apparent shear strength was as low as 5.6 MPa.

Therefore, direct bonding method is merely used owing to the low bonding strength. However, it is still very promising for direct bonding method of C_f/SiC composites, especially for extreme applications where it demands to avoid a second material.

2.2. Indirect Bonding. It is well known that it is very difficult to form diffusion between C_f/SiC composites owing to the strong covalent bond and the poor deformation ability of the SiC in C_f/SiC composites, thus resulting in a weak bonding strength of direct bonding joint (Figure 2(b)). Therefore, second-phase materials with plastic deformability, such as Ag-Cu-Ti [30, 49], Ti-Zr-Be [50], Ni [31, 51, 52, 55], calcia-alumina (CA) glass-ceramic [54], Ti_3SiC_2 [16, 36, 55, 56] and Si resin [57], and $MoSi_2$ [58], were widely reported to be used for the joining of C_f/SiC composites. These kinds of joining are known as indirect bonding method, always including using metal filler or nonmetal filler.

2.2.1. Metal Fillers. This method means that C_f/SiC composites are bonded with C_f/SiC composites using metal fillers, such as pure metal or alloys. Table 3 lists some typical reports on the self-joining of C_f/SiC composites using metal fillers.

FIGURE 2: The diagram of (a) direct bonding and (b) indirect bonding.

FIGURE 3: Scanning electron microscopy of polished cross sections of C_f/SiC specimens joined by SPS: direct bonding [48].

TABLE 2: CTE of typical materials (room temperature).

Materials	CTE ($\times 10^{-6} \cdot K^{-1}$)
C_f/SiC	3.0–3.1
Ti	8
Al	23.5
Cu	16.5
Ni	13
Ag	19.5
Nb	7.2
Mo	5.2
W	4.43
Zr	5.2
Co	6.8
Ta	6.7
C	1.5
TiAl	10.8
CrMo	12.5
SiC	4.8
Ti_3SiC_2	9.1
TiC	7.4

The low-temperature active filler is a relatively mature technology and widely used in C_f/SiC composites; however, the joint phase such as Ag, Cu, and other metals, usually with low melting point, leads to poor high-temperature strength and oxidation resistance. Therefore, C_f/SiC composites

joined by metal fillers can only be used in low-temperature environment ($<500^\circ C$).

Liu et al. [30] reported the C_f/SiC composites joined by ternary Ag-35.25 wt% Cu-1.75 wt% Ti and demonstrated that the mechanical strength decreased with the increase in temperature owing to the softening of filler. The flexural strength decreased to 46% and 26% at 300 and $500^\circ C$ compared with that at room temperature, respectively. Stefano et al. [48] fabricated C_f/SiC -Ti- C_f/SiC sandwich by SPS and used pure Ti foils as filler. They also found that a Ti-Si-C-based phase (Ti_3SiC_2 , as is shown in Figure 4) was the main reaction product, usually induced to strength decrease.

High-temperature metal fillers, such as Ni and its alloys, are reported and found to greatly improve the high-temperature resistance of the joint [61, 62]. Cheng [51, 52, 55] developed a novel joining process to join the 2D/3D C_f/SiC composites. Porous C_f/SiC composites were fabricated through chemical vapor infiltration (CVI) process, and Ni alloy was used to join the C_f/SiC composites together. Figure 5 shows the diagram of this joining process. Because the Ni alloy had a favorable wettability with C_f/SiC composites, melted Ni alloy easily infiltrated into the pores among C_f/SiC composites. Hence, the contact surface between Ni alloy and C_f/SiC composites matrix was greatly increased, thereby improved the bonding strength. Besides, Ni alloy had a higher melting point; hence, the joint was expected to be used at high temperatures ($>1000^\circ C$).

Table 4 lists some typical reports on the self-joining of C_f/SiC composites with high-temperature fillers (Ni alloy). As a nontraditional joining method, the self-joining process using Ni alloy is usually carried out during composite preparation procedure, and the damage is minimal. And after the joining process, an afterward CVD process is conducted, which not only densify the porous composites but also provides antioxidation coating for the matrix and the joint.

2.2.2. Nonmetal Fillers. Nonmetal fillers, such as MAX ceramic [16, 36, 55, 56, 63], ceramic precursors [64], Si resin [57], and $MoSi_2$ [58], are also reported to be used in the self-joining of C_f/SiC composites (as listed in Table 5).

MAX phase ceramics are reported to exhibit not only high-temperature performance, thermal shock resistance,

TABLE 3: Self-joining of C_f/SiC composites using metal filler (SS = shear strength).

CMCs	Basic information	Metal filler	Process parameters	Bend strength (MPa)	Ref.
C_f/SiC	CVD-SiC	Ti	1700°C, 3 min, 60 MPa, vacuum	24.6 (SS)	[48]
C_f/SiC	3D, 10.0 vol.%, PIP	Cu-Au-Pd-V	1170°C, 10 min, 1.5×10^{-3} Pa	135	[59]
C_f/SiC	3D	Pd-Co-V	1250°C, 20 min, $3.0-7.0 \times 10^{-3}$ Pa	—	[60]
C_f/SiC	3D, PIP, 10.0 vol.%	Cu-Pd-V	1170°C, 10 min, $3.0-7.0 \times 10^{-3}$ Pa	128	[61]

(a)

(b)

FIGURE 4: (a) Backscattered electron images of polished cross sections and (b) micro-XRD on the fracture surfaces of C_f/SiC joined by SPS with Ti foil [48].

FIGURE 5: The diagram of self-joining using Ni alloy.

and wear resistance but also a good plastic deformation capacity. Among various MAX phase ceramics, Ti_3SiC_2 presents a suitable wettability and CTE toward C_f/SiC composite matrix (as is shown in Table 2) and is thus believed to be a promising candidate for the self-joining of C_f/SiC composites [16, 55, 56]. Dong et al. [55] used Ti_3SiC_2 as the nonmetal filler to join C_f/SiC composite together

through hot pressing. The shear strength of the joint was reported as high as 110.4 MPa (56.7% of the C_f/SiC composite matrix). Chemical reactions took place at the interface between Ti_3SiC_2 and C_f/SiC , and residual thermal stress was investigated. The phase compositions of the fracture surfaces for the C_f/SiC joints joined at various temperatures were also analyzed by XRD (as is shown in Figure 6). In addition, the fracture behavior of joining interface and brazing application was explored in previous articles [9, 65, 66, 69]. Interfacial reactions can affect the formation of a joint from the onset of bonding through the development of equilibrated microstructure and to the optimization of the mechanical properties. It has been demonstrated that an adequate joining interface could lead to improvements of the composite wettability by C_f/SiC [39].

Besides, ceramic precursors are also used as nonmetal fillers for the self-joining of C_f/SiC composites. The ceramic precursor is transformed into amorphous ceramic at a certain temperature, and the composition and structure of the precursor are similar to those of the composite matrix. At the same time, the pyrolysis products are directly bonded with the composite matrix by chemical bonds. The thermodynamic properties of the joining layer obtained by this method are similar to those of the matrix [64]. And it has good compatibility with the composite matrix. Therefore,

TABLE 4: Self-joining of C_f/SiC composites with high-temperature fillers.

CMCs	Basic information	Joining material	Process parameters	Bend strength (MPa)	Ref.
C _f /SiC	3D, CVI	Ni alloy	1300°C, 45 min, 20 MPa, vacuum	260.3	[52]
C _f /SiC	2D, CVI	Ni alloy	1300°C, 45 min, 20 MPa, vacuum	60	[51]
C _f /SiC	2D, CVI	Ni alloy	1300°C, 15 MPa, vacuum	58	[53]

TABLE 5: Self-joining of C_f/SiC composites using inorganic filler (BS = bend strength).

CMCs	Basic information	Joining material	Process parameters	Shear strength (MPa)	Ref.
C _f /SiC	2D, CVI, 2.05 g/cm ³ , 40 MPa	Ti ₃ SiC ₂	1600°C, 30 min, 20–40 MPa, Ar	110.4 (BS)	[55]
C _f /SiC	3D, CVI	PSZ	1300°C, N ₂	29.6	[64]
C _f /SiC	3D, PIP, 1.9 g/cm ³	Si resin	1400°C, 5 h, Ar	3.51	[57]
C _f /SiC	2D, CVI, 1.7–2.2 g/cm ³	MoSi ₂ /Si	1450°C, 5 min, Ar	—	[58]

FIGURE 6: (a) The backscattered electron images and (b) XRD patterns of the fracture surfaces of the C_f/SiC joints [55].

the joint exhibits good mechanical strength. Previous reports showed that C_f/SiC composite was joined using Si-O-C ceramic precursor as filler [57].

Si resin is transformed into Si-O-C ceramic at low temperature; the Si-O-C ceramics infiltrating into the substrate improve the filler contact with the substrate closely and increase the connection area. Moreover, the Si-O-C ceramics infiltrating into the pits can form tiny “pins,” thus increasing the shear strength of the joints. Gianchandani et al. [58] reported that a MoSi₂/Si composite obtained in situ by reaction of silicon and molybdenum at 1450°C in Ar flow is proposed as pressure-less joining material for C_f/SiC composites.

To sum up, we can know that the application of non-metal fillers method due to the phase consistency of joining material and matrix was similar, which not only avoid the CTE mismatch between the joining material and the matrix (CTE of typical materials is shown in Table 2) but also inhibit the adverse reactions of interface. It will be a very promising method in the future.

3. Joining of C_f/SiC Composites to Metals

In order to obtain large size and complex-shaped components, the joining of C_f/SiC composites to metals such as Ti

[40], Nb [42, 68, 69], Ni [70], and TiAl alloys [30, 46, 71] is necessary. Due to the differences in physical, chemical and mechanical properties between C_f/SiC composites and metals, there are several problems for the joining of C_f/SiC composites to metals: firstly, the chemical bonds of C_f/SiC composites are ionic bond and covalent bond and the valence state is stable, whereas metals mostly are metal bond and therefore it is difficult to wet the surface of C_f/SiC composites by metal [40]. Secondly, the CTE mismatch between metals and C_f/SiC composites is very large, which will produce residual stress at the joint interface; hence, cracks, pores, and other defects exist after cooling [41, 72, 73]. At last, a variety of chemical reactions occur in the interface, resulting in brittle compounds with high hardness, which usually is the reason for the brittle fracture of the joint during working [30].

At present, there are many technologies solving the above problems during the joining process. Brazing and diffusion bonding are the most commonly used methods. In addition, online liquid infiltration joining, ultrasonic-assisted joining, and electric-assisted field joining are also reported.

3.1. Brazing. Brazing is one of the earliest and most commonly used methods for joining CMCs to metals

FIGURE 7: The schematic diagram of (a) brazing method and (b) diffusion bonding method.

(Figure 7(a)). It is divided into two kinds as follows: (1) metallizing the C_f/SiC composite surface and then brazing with ordinary brazing filler metals, usually known as indirect brazing, and (2) wetting CMCs surface directly using active metal, known as reactive brazing. Compared with indirect brazing, the scopes of application of reactive brazing are more extensive. Usually, metals and alloys with lower melting points are selected as the brazing fillers, and then the joint is heated to a certain temperature, which is higher than the melting point of brazing filler, and then brazing is conducted [74].

3.1.1. Low-Temperature Fillers. Low-temperature filler is a kind of metal with low melting point, such as Ag and Cu, which can form brazing filler at lower temperature to realize the joining of metal. Due to the low joining temperature, the damage is low.

Brazing method is simple and convenient; however, the brazing filler is mainly active metal elements, so it is necessary to protect the active metal elements from oxidation. Once the active element is oxidized, it is difficult to react with C_f/SiC composites and to form a reliable joint; consequently, the joint strength is low. Therefore, brazing method is generally carried out in vacuum conditions or inert protective gases [39, 75]. Feng et al. [72, 76] investigated the microstructural evolution and joint strength of between TiAl alloys and C_f/SiC composite via vacuum brazing using Ag-Cu and Ag-Cu-Ti fillers. The diffusion of Al and Ti from TiAl to the matrix had an important effect on the structure and strength of joints. When active element Ti diffused into C_f/SiC composite, the formation of AlCu₂Ti and Ag solid solution was detected with the dissolved Ti and Al; moreover, Ti₅Si₃ phase and TiC also formed adjacent to the composite (as is shown in Figure 8). The maximum shear strength achieved 85 MPa with the thickness of TiC layer of 4–5 μm. The fracture of the joint went through the TiC layer adjacent to its interface with the Ag solid solution and TiC bond layer.

As is shown in Table 6, Ag-Cu, Ag-Cu-Ti, and others are low-temperature fillers (900°C) and have low yield strength and good deformation ability, which is helpful to alleviate the residual stress of the joint, thus increasing the shear strength of the joints.

3.1.2. High-Temperature Fillers. Ag-Cu-Ti alloys have good plastic deformation behaviors (as is shown in Table 7); nevertheless, they always have low melting points and can only be used in low-temperature environments (<800°C). Once the temperature increased, the strength of the joint drops sharply. Therefore, it is necessary to develop suitable high-temperature brazing filler for high-temperature conditions.

Huang et al. [46] joined C_f/SiC composite to TC₄ alloy using (Ti-Zr-Cu-Ni) and W powder as brazing fillers. Ti and Zr elements reacted with C, Cu, and Ni in the interlayer. As elements diffused to each other, a reaction layer was formed between the C_f/SiC composite and TC₄ alloy. The brazing parameters had a significant effect on the interfacial reaction between C_f/SiC composite and joining material, which affected the shear strength of the joints. A continuous reaction layer adjacent to C_f/SiC composite and a diffusion layer near TC₄ alloy can be clearly observed (Figures 9 and 10). The addition of appropriate W powder helped to relieve residual stress and improved the strength of the joints. The shear strength of the joint was 166 MPa and 96 MPa at room temperature and 800°C, respectively. Therefore, the joint can be used under high temperature.

However, the effect of W powder on the residual stress was small and the residual stress was still high. Ti-Zr-Cu-Ni alloy and pure Ti metals were used as joining materials [30]; the molten Ti-Zr-Cu-Ni reacted with solid Ti in the liquid-solid reaction to form an in situ alloy. The effects of Ti contents on the strength of joints were explored. With the increase in the Ti content, more tearing ridges appeared in the fracture surfaces, which indicated that the fracture possessed more plasticity. When the Ti content reached up to 40%, the shear strength of the joint reached up to 283 MPa, which was 79% higher than using Ti-Zr-Cu-Ni alone. The main reason was that the metal Ti had better plasticity, and the proper addition was beneficial for improving the interfacial reaction between C_f/SiC composite and Ti-6Al-4V alloy.

There are many research studies using brazing method for joining C_f/SiC to metals as listed in Table 7. The low-expansion material (W), the soft metal (Ni), and the high-temperature metal (Mo) as the reinforcing phase are added into the brazing filler, so that the CTE of the brazing filler is

FIGURE 8: (a) Microstructures and (b) XRD patterns of the joint from C/SiC composites to TiAl brazed at 900°C for 10 min [72].

TABLE 6: Brazing of C_f/SiC composites to metals with low-temperature fillers.

CMCs	Basic information	Metal	Brazing material	Process parameters	Shear strength (MPa)	Ref.
C _f /SiC	3D, PIP, 1.86 g/cm ³	Ti Al alloys	Ag-Cu	900°C, 10 min, 5×10^{-3} Pa	85	[72]
C _f /SiC	3D, CVI	TC ₄ alloys	Ag-Cu-Ti	900°C, 5 min, 10^{-4} Pa	102	[77]
C _f /SiC	—	Nb alloys	Ag-Cu-Ti	930°C, 15 min, 2×10^{-3} Pa	—	[68]
C _f /SiC	3D, 1.8 g/cm ³ , 10–15%	Ti alloys	C _f /Ag-Cu-Ti	900°C, 30 min, 2.2×10^{-3} MPa, 6×10^{-3} Pa	84	[40]

TABLE 7: Brazing of C_f/SiC composites to metals with high-temperature fillers.

CMCs	Basic information	Metal	Brazing material	Process parameters	Shear strength (MPa)	Ref.
C _f /SiC	3D, 2.0–2.1 g/cm ³ , 10–15 vol.%, 400 MPa	Ti alloys	Ag-Cu-Ti + 15 vol.% W	900°C, 5 min, 2.2×10^{-3} MPa, 6×10^{-3} Pa	180	[38]
C _f /SiC	3D, PIP, 1.7–1.8 g/cm ³ , 10–15 vol.%, 400 MPa	TC ₄ alloys	Ti-Zr-Cu-Ni + 15 vol.% W	930°C, 20 min, 6×10^{-3} Pa	166	[46]
C _f /SiC	3D	42CrMo	Ag-Cu-Ti + 5 vol.% Mo	900°C, 10 min, vacuum	587 (BS)	[78]
C _f /SiC	3D, PIP	Nb	Ti-Cu-Ni-Zr	930°C, 10 min, 5×10^{-3} Pa	124	[69]
C _f /SiC	3D	Ti-6Al-4V	Ti + (Ti-Cu-Ni-Zr)	940°C, 20 min, 5×10^{-3} Pa	283	[47]
C _f /SiC	3D, PIP, 1.98 g/cm ³ , 21.5 vol.%	Nb-1Zr	Ti-Co-Nb	1280°C, 10 min, $1.0\text{--}3.0 \times 10^{-3}$ Pa	242	[43]
C _f /SiC	3D, PIP, 1.86 g/cm ³ , 11.7 vol.%	Ti Al alloys	TiH ₂ -Ni-B	1180°C, 10 min, 5×10^{-3} Pa	105	[71]

reduced and the residual stress of the joint is facilitated. However, there are still some shortcomings for brazing process, such as the interface reaction is intense, to produce brittle compounds, which requires the appropriate adjustment of brazing filler and process parameters. More importantly, avoiding bad excessive interface reaction and accessing to excellent mechanical properties of joints are essential.

3.2. Diffusion Bonding. In mid-1950s, the former Soviet Union scientists proposed a diffusion bonding method

which was widely used to join ceramic to metals, including the joint of C_f/SiC composites to metals (as shown in Figure 7(b)). C_f/SiC composites and metals are contacted with each other under high temperatures, vacuum or inert atmospheres and pressures, and the plastic formation of connected surfaces is close to each other. After a certain period of soaking time, the intermolecular diffusion and chemical reaction are realized. During the diffusion bonding process, the interface is bonded by plastic deformation, diffusion, and creep mechanism. The joining temperature is high, the CTE and elastic modulus of the composites and

FIGURE 9: BSE images of the joint: (a) micrograph of the joint; (b) interface between C_f/SiC composite and interlayer [46].

FIGURE 10: XRD pattern of the joint: (a) interface between C_f/SiC composite and interlayer; (b) interlayer [46].

metals are mismatch, and it is easy to induce high residual stress. Due to sharp structural transition near the interface and the lack of a buffer layer to relax the stress, the residual stress is high enough to lead to a lower joint strength.

Simply, diffusion bonding method is a solid-state bonding process, which has been demonstrated as a viable method to overcome the problems encountered in welding. There are many reports on the diffusion bonding C_f/SiC composites to metals. In order to join 3D/2D C_f/SiC composite to Nb alloy, Xiong et al. [41, 42] used Ti-Cu foil as the joining material to join C_f/SiC composite to Nb alloy through a two-stage joining process: solid-phase diffusion bonding and transient liquid-phase diffusion bonding. It was found that the Ti-Cu liquid eutectic alloy was formed by the reaction of Ti and Cu, not only infiltrated into open pores and microcracks as a nail but also reacted with ceramic coating. The remaining Cu was deformed by own plastic deformation and released the residual stress. In addition, the liquid layer formed by interlayer in the TLP-DB process had good wettability to C_f/SiC composite and can infiltrate into

C_f/SiC composite matrix and encapsulated C_f between the interlayer and C_f/SiC interface region. These processes were very beneficial for the mechanical strength of the joint. The shear strength of the joint between 2D C_f/SiC composite and Nb alloy was 14.1 MPa, and the shear strength of the joint between 3D C_f/SiC composite and Nb alloy reached up to 34.1 MPa. To our best knowledge, there were mainly two factors leading to a low shear strength of the joint between 2D C_f/SiC composite and Nb alloy: the CTE mismatch between 2D C_f/SiC composite and Nb alloy was larger compared with 3D C_f/SiC composite and Nb, resulting in a large residual stress, and the fiber direction among 2D C_f/SiC composite was parallel to the joining interface, whereas the fiber direction among 3D C_f/SiC composite was perpendicular to the joining interface. When the fiber was perpendicular to the joining interface, “nail effect” formed between reaction layer and C_f and shared more load than other regions in fracture test (as is shown in Figure 11). These results demonstrated that the direction of fiber was directly related to the interface structure of the joint, which

FIGURE 11: SEM micrograph of the joint: (a) 3D C_f/SiC and (b) 2D C_f/SiC [41, 42].

in turn affected the shear strength of joint. In this kind of research work, the influence of fiber must be considered; however, this interesting topic has not yet been studied systematically.

In addition, the reactions between joining material and composite matrix have been recently recognized as critical factors for determining the strength of the joint. C_f/SiC composite and Ti-6Al-4V alloy were joined by Ban et al. [79] with the mixed powder of Cu, Ti, and graphite under vacuum environment. In situ synthetic TiC that reduced the thermal stress significantly was synthesized by interdiffusing of C element in the graphite particle and Ti element in the liquid bonding layer (as is shown in Figure 12). The positive effect of TiC on joint strength was also described in other papers [56, 72, 80]. Table 8 summarizes the data of diffusion bonded joining. The utility model has the advantages of high strength, stable joint quality, and good corrosion resistance, especially for the joining of C_f/SiC composites and metals for high-temperature and corrosion-resistance application.

3.3. Online Liquid Infiltration Joining. Online liquid infiltration joining is a novel technology, which is applied to the joining of fiber-reinforced ceramic matrix composites. C_f/SiC composites are usually porous both for CVI and PIP processing. An online liquid infiltration joining method that is suitable for the composites was reported. The porosity of C_f/SiC composites was controlled and then the compact process was carried out after the joining has finished, which reduced the damage of joints as much as possible. The wettability between the joining material and C_f/SiC composite was improved; moreover, the joining material could be melted and infiltrated into the C_f/SiC matrix, which increased the joining area and reinforced the joint strength [81, 82]. In addition, a root-like morphology was formed in C_f/SiC composite substrate, which could greatly enhance the reliability of joint [83].

The only paper that attempts to join C_f/SiC composite to metal via online liquid infiltration joining was presented in 2004 [84]. The authors joined 2D/3D C_f/SiC composites to Nb with Ni-based filler by the online liquid infiltration

joining method (as shown in Figure 13). The joint between 2D C_f/SiC composite and Nb was failure and separated during the cooling. However, the favorable joint between 3D C_f/SiC composite and Nb was obtained. Approaches such as reactive brazed [68, 69] and diffusion bonding [41, 42] have also been successfully used to join C_f/SiC composites to Nb alloy. Unfortunately, the bonding processes above were usually conducted after the preparation of the composite matrix, which damaged the strength of the matrix. Online liquid infiltration joining, which is completed in the preparation process, is different from the above methods. Afterward, chemical vapor deposition (CVD) process not only complete the preparation of materials but also can provide antioxidation coating for the matrix and the joint, reflects the joining, preparation, and processing integration [51, 85].

3.4. Ultrasonic-Assisted Joining. Ultrasonic-assisted joining is employed to join aluminum alloy structural parts at first. Afterward, ultrasonic is used for copper and alloy, gradually widely used in CMCs and metals, as shown in Figure 14 [86]. Since ultrasound exists as an energy form, it produces some unique ultrasonic effects when it propagates in the medium. The ultrasonic-assisted joining utilizes ultrasonic vibrations to interact the contact area of the CMCs with the metal. The ultrasonic effect causes the liquid joining material to spread on the surface of the matrix and form a joint with the metal [87]. In 1990s, ultrasonic-assisted joining technology facilitated the wetting of materials with poor wetting properties such as ceramics, glass, and stainless steel [88–90, 94]. The liquid-connecting materials spread and moisten, through the ultrasonic wave effect that from the vibrations of ultrasonic, the surface of the CMCs and metal to achieve good connection. Moreover, it is worth mentioning that ultrasonic-assisted joining technology can improve the wettability of connection materials on the surface of matrixes such as ceramics, glass, and stainless steel. Therefore, this technology has been widely applied in many fields.

The joining of SiC and Ti-6Al-4V alloy via ultrasonic-assisted joining was conducted by Chen et al. [91, 92]. SiC

FIGURE 12: (a) Micrographs and (b) XRD pattern of the interface [79].

TABLE 8: Diffusion bonding of C_f/SiC composites to metals.

CMCs	Basic information	Metal	Joining material	Process parameter	Shear strength (MPa)	Ref.
C_f/SiC	3D, CVI, 2.1 g/cm ³	Nb alloy	Ti-Cu bi-foil	800°C, 30 min, 6 MPa; 1020°C, 60 min, 0.05 MPa, 3.2×10^{-3} Pa	34.1	[41]
C_f/SiC	2D, CVI, 16 vol.%	Nb alloy	Ti-Cu-Cu	850°C, 40 min, 8 MPa; 980°C, 30 min, 0.05 MPa, 3.2×10^{-3} Pa	14.1	[42]
C_f/SiC	3D, 2.0–2.1 g/cm ³ , 10–15 vol.%, 400 MPa	TC ₄ alloy	Cu-Ti-C	900–950°C, 5–30 min, 6.0×10^{-3} Pa	—	[79]
C_f/SiC	3D, 15 vol.%, 500 MPa	Ni alloy	Zr/Ta	1050°C, 10 min, 40.8 MPa, 10^{-2} Pa	110.89 (BS)	[70]

FIGURE 13: The diagram of specimens before being joined.

FIGURE 14: The diagram of capillary process that filler gets into clearance by action of ultrasonic vibration.

was employed by a joining material with an Al-12Si alloy at low temperature (620°C), and the shear strength of the joint was 84–94 MPa. In their study, the oxide layer of the matrix was broken by the ultrasonic, and the joining material can form a good interface between SiC and Ti-6Al-4V alloy. However, cracks were observed in SiC material and the

propagation direction was parallel to joint. The main reason was that the nonuniform shrinkage of material at the joint and residual stress, which leads to crack formation in the SiC substrate, was produced during the cooling process. They obtained an integrated joint when using the novel joining

material in their study. SiC and Ti-6Al-4V alloy were joined with AlSnSiZnMg mixed metal, which reduced the joining temperature and the residual stress of the joint, inhibiting the occurrence of cracks and other defects. Unfortunately, the shear strength of the joint was not improved (77.8 MPa).

On the other hand, ultrasonic-assisted joining technology can also be used to join oxide ceramics to metals. Naka et al. [88] joined Al_2O_3 to Cu with Zn, Zn-5Al, and $\text{Zn}_{100-x}(\text{Al}_{0.6} + \text{Cu}_{0.4})_x$ ($x = 0-30$) as the joining materials. It was shown that with the time and joining temperature increased, the shear strength of the joint with Zn-6Al-4Cu filler was improved and reached ~62 MPa. In the above literatures, some of them were reported that the ultrasound was beneficial to improve the wettability of Al_2O_3 and metals.

The mechanism of ultrasonic effect on the joining process can be summarized as follows: (1) the macroscopic bubbles between the filled metal and the ceramic were removed by the ultrasonic cavitation; (2) the C_f/SiC substrate surface was subjected to high-speed impact of atoms under ultrasonic vibration; (3) the ultrasonic vibration and friction between the joining material and metal.

3.5. Electric-Assisted Field Joining. Although diffusion bonding is widely used to join CMCs and metals, generally, it requires high temperatures, high pressure, vacuum or inert atmosphere, and long joining time [93, 94, 98]. Electric-assisted field joining is an effective way to solve these above problems, as shown in Figure 15. Since the joining between CMCs and metal was realized by chemical reaction, interfacial structure formed by reaction determines the mechanical properties of the joint. Better joint can be obtained using the electric-assisted field method.

The interface between CMCs and metal were polarized under electrostatic field. On the one hand, it promotes atomic migration and vacancy diffusion. On the other hand, it accelerates the interface reaction, which reduces the joining temperature, the pressure, and the residual stress. Moreover, the interface reaction is easy to control, and joining time is very short [96–98, 101].

Initially, the electric-assisted field joining is mainly employed for joining ceramics to metals [100]. The interface composition and mechanical properties of joints between SiC and Ti were investigated by Wang et al. [98] in the electric field. It was shown that the external electric field reduced the joining temperature and time and improved the shear strength. It is important that the external electric field can improve the diffusion rate of interface atoms. Moreover, it promoted the interface reaction and improved the joining efficiency.

Owing to its simplicity and efficiency, electric-assisted field joining became a useful method employed for joining C_f/C composites [101] and C_f/SiC composites [48]. C_f/C composites were firstly joined by combining electric field-assisted sintering technology and using a Ti_3SiC_2 tape film as the interlayer [101]. In their work, the interdiffusion speed between the interlayer and the metal was accelerated by an electric field and the joining time was only 12 min. To our

FIGURE 15: The diagram of the experimental equipment under electric field.

knowledge, the Ti_3SiC_2 exhibited pseudoplastic at 1300°C or higher [102, 103]. Therefore, Ti_3SiC_2 infiltrated into the composite matrix and a “nail” that clamps the matrix was observed, as shown in Figure 16, which improved shear strength of the joint. In the joining process, two key factors affected the strength of the joint: (1) the interdiffusion between the joining material and the matrix was promoted by electric field and (2) Ti_3SiC_2 showed good plastic deformation ability in the electric field.

Atoms spread to the interface under electric field. It is necessary to pass through the potential through the gap, the original position occupied by their own formed a new space. The energy of the atoms across the barrier was provided by the electric field. At the same time, the atoms across the barrier potential energy are reduced by the electric field. Combined with these two effects, the diffusion activation of atoms can be greatly reduced, thereby increasing the diffusion rate of solute atoms and obtaining a uniform structure [104]. Therefore, the electric-assisted fields joining method has drawn great attention and is expected to become an important way for the joining of C_f/SiC composites in the future.

4. Summary

With the rapid development of high-tech in aerospace and other industry fields, carbon fiber-reinforced silicon carbide (C_f/SiC) ceramic matrix composites, one of the most famous CMCs, are becoming the most promising candidates for high-temperature structural applications. In most cases, typically, it is very difficult to produce large-size C_f/SiC composite components with complex shapes, resulting in that they must be joined with themselves or other materials by appropriate joining technologies. At present, various joining technologies of C_f/SiC composites are reported, including the joining of C_f/SiC - C_f/SiC and C_f/SiC -metal, such as direct bonding of C_f/SiC - C_f/SiC , indirect bonding of C_f/SiC - C_f/SiC , brazing of C_f/SiC -metal, diffusion bonding of C_f/SiC -metal, online liquid infiltration of C_f/SiC -metal, ultrasonic-assisted joining of C_f/SiC -metal, and electric-assisted joining of C_f/SiC -metal.

FIGURE 16: (a) The schematic diagram of “nail” like and (b) BSE image [101].

To the best knowledge of the authors, however, there has been no systematic summary of the joining of C_f/SiC composites. In this paper, a systematic review of the joining of C_f/SiC composites is conducted, and the aim of this paper is to provide some reference for researchers working on this field.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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