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The research on oxidation resistance ability and mechanical properties of carbon fiber reinforced phenolic resin composites

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Abstract

Carbon fiber reinforced composite (CFRP) has been widely used in a lot of areas with its distinguished properties, especially mechanical properties. However, both carbon fibers and polymer substrate cannot resist high air temperature environment, limiting the application of CFRP, such as in the aerospace fields. The paper proposes two kinds of carbon fiber with oxidation resistance coatings, which are used as reinforced components to make phenolic resin substrate composites. Weight difference method, mechanical test machine and scanning electron microscope are used to characterize the antioxidation ability, mechanical properties, and surface morphology of composites. The results show that SiC/SiO 2 coated carbon fibers and SiC–ZrO 2 –MoSi 2 /Ni coated carbon fibers can increase the anti-oxidation ability without decreasing the mechanical properties of composites. The failure temperature is around 1200 °C and 1600 °C respectively.

1. Introduction

The rapid development of aerospace fields puts tough demands on the special properties of materials. Carbon fiber has been used to make varies of structure parts in this field because it is characterized by excellent mechanical properties, high specific modulus, high specific strength, low coefficient of thermal expansion and good toughness [1, 2]. It has been reported that carbon fiber can be oxidized gradually with the increase of temperature in the air environment, and the properties of carbon fiber decrease accordingly. The ultimate heat-resistant temperature of carbon fiber is about 400 °C [3, 4]. When the oxidation temperature exceeds 400 °C, the carbon fiber can be destroyed rapidly [5], which leads to fiber failure. Such properties limit the application of carbon fiber in the aerospace fields [6], as carbon fiber reinforced composites are very suitable for the preparation of various parts with high strength, large modulus, low density and a small coefficient of linear expansion [7–9]. However, the working condition for spacecraft parts is quite different from that of normal environment. Since such parts as rocket fairing and engine cover need to be used in high-temperature environment, certain oxidation resistance ability is a must-have for them to stand high temperature produced by engine operation or high-speed friction. Therefore, the better anti-oxidation performance of carbon fiber in the air environment can greatly improve the stability of carbon fiber reinforced composites to make spacecraft [10].

Coating method is one of the most widely used methods to improve the oxidation resistance ability for carbon fibers. Researchers have come up with kinds of different coating methods to improve the antioxidation ability of carbon fibers [11–15]. Among all kinds of carbon fiber reinforced polymers (CFRP), phenolic resin is the most commonly used polymer to prepare high-temperature resistant CFRP because of its good thermal stability, flame retardancy and insulation [16]. However, when it comes to making spacecraft parts, the initial oxidation temperature of traditional phenolic resin is too low, and the unstable end group phenolic hydroxyl and methylene in its molecules will produce small molecule volatiles after high-temperature treatment, which can lead to a large number of holes in the phenolic resin to destroy the internal structure of CFRP, which seriously affects the ablation performance of ablation composites [17, 18]. There are two common methods to
improve the heat resistance of phenolic resin. One is introducing structure with higher thermal stability, such as imide group, triazine ring and polysulfone, another one is introducing the inorganic nano-particles or compounds containing inorganic elements, such as boron, silicon, phosphorous, zirconium, titanium and so on [19–21].

In the present research, two kinds of carbon fibers with composite anti-oxidation coating are prepared by different coating methods. SiC/SiO2 coated carbon fibers are prepared by the sol-gel method and SiC–ZrO2–MoSi2/Ni coated carbon fibers are prepared by composite electroplating method. Two kinds of coated carbon fibers are used to make boron modified phenolic resin-based composites, and the oxidation resistance property and mechanical property of each composite have been tested. Also, with the surface and section analysis of composites, the mechanism of oxidation has been discussed.

2. Experimental plan

2.1. The pre-treatment and coating process of carbon fibers

The type of carbon fiber is bidirectional carbon fiber woven from Toray, Japan, with filament count being 3000 and sizing type 4. The fiber properties of this product are listed in Table 1.

Fiber properties of this product are listed in Table 2, together with the manufacturers and specifications of major raw materials that have been used in the paper. First, carbon fibers are put into a tube furnace with nitrogen environment and heated at 400 °C for 1 h to remove the protective films. Then transfer the carbon fibers into 65 wt% nitric acid solution for ultrasonic treatment for 40 min to increase the active functional groups on the surface of the fiber and improve the interface bonding strength between the coating and the fiber.

The coating process of carbon fiber has been described in the other two articles [23, 24], including factors that affect the performance of coated carbon fiber. The SiC/SiO2 coating is prepared by modified sol-gel method and the SiC–ZrO2–MoSi2/Ni coating is prepared by composite electroplating. In this paper, the optimal formula has been used to prepare SiC/SiO2 coated carbon fibers and SiC–ZrO2–MoSi2/Ni coated carbon fibers. When it comes to the modified sol-gel method: the ratio of ethanol, distilled water and TEOS is 5:1:3. The pH of this system should be adjusted to 3 by hydrochloric. After stirring the solution for 2 h, the sol is stood for 10 h at 60 °C to obtain transparent SiO2 sol. Then, the polydimethylsiloxane, SiO2 sol and distilled water are mixed with the ratio 1:1:1, and 5 wt% Tween–80 has been used as emulsifier. The SiC nanoparticles have been added into the emulsion (24 g/200 ml) and mixed with homogenizer (15000 rpm). The optimum coating parameters of composite plating are as follows. The carbon fiber woven has been cut into 30 mm × 30 mm square. The plating conditions are as follows: (1) The pH of plating bath was 3.5; (2) The temperature of plating bath was 45 °C; (3) The electrical current density of plating was 4 A dm−2 and the plating time was 10 min; (4) The ratio of each

| Table 1. The fiber properties. |
|---|---|---|
| Properties | Metric | Method |
| Tensile Strength | 3,530 MPa | TY-030B-01 |
| Tensile Modulus | 230 GPa | TY-030B-02 |
| Strain at Failure | 1.50% | TY-030B-03 |
| Density | 1.76 g cm−3 | TY-030B-02 |
| Filament Diameter | 7 μm | |

| Table 2. The manufacturer and specification of raw materials. |
|---|---|---|
| Raw materials | Manufacturer | Specification/Ite m number |
| carbon fiber | Toray, Japan | T300 |
| TEOS(tetraethoxysilane) | Shanghai Aladdin biological technology co., LTD | N-110595 |
| silane coupling agent KH560 | Shanghai Aladdin biological technology co., LTD | 97%, G-107576 |
| dimethicone | Shanghai Aladdin biological technology co., LTD | 10 mPa.s, neat, S104472 |
| Tween-80 | Shanghai Aladdin biological technology co., LTD | T104866 |
| SiC | Shanghai Aladdin biological technology co., LTD | S-104653(40 nm) |
| NiSO4 | Shanghai Aladdin biological technology co., LTD | N-100216 |
| NiCl4 | Shanghai Aladdin biological technology co., LTD | N-112126 |
| MoSi2 | Shanghai Aladdin biological technology co., LTD | S100522(50 nm) |
| ZrO2 | Shanghai Aladdin biological technology co., LTD | Z104402(40 nm) |
| boron-silicon modified phenolic resin | self-made[22] | |
nanoparticles in the plating bath: SiC $120 \text{ g l}^{-1}$, MoSi$_2$ $80 \text{ g l}^{-1}$ and ZrO$_2$ $120 \text{ g l}^{-1}$. During the plating process, mechanical agitation (600 rpm) was applied to keep nanoparticles disperse uniformly.

2.2. The preparation of carbon fiber prepreg with composite coating

The preparation of carbon fiber cloth prepreg is an important step to make carbon fiber reinforced composite by molding process. The matrix resin is boron silicon modified phenolic resin [22]. Hydroxymethyl phenol is synthesized first, then boron modifier (boric acid) and silicone modifier (phenyltriethoxysilane) are added to synthesize double modified phenolic resin.

(1) Boron modified phenolic resin is introduced into the dip tank. The carbon fiber cloth is cut into a certain size with a laser cutting machine. Then the cut carbon fiber cloth is put into the dip tank and fully mixed with phenolic resin for 1 h.

(2) Spread the carbon fiber cloth soaked with resin on the polyester thin film, and brush it with phenolic resin. In this way, the phenolic resin can be distributed evenly on the surface of the carbon fiber cloth without any air bubble.

(3) The carbon fiber cloth coated with boron modified phenolic resin is dried in an oven at $90^\circ \text{C}$ for 12 h, and the prepreg can be obtained after the volatile content is less than 5%.

2.3. Cutting and molding of carbon fiber prepreg

The thickness of standard bending specimen is 2.5 mm. So, there are 12 layers of carbon fiber cloth have been used to prepare the composites, the molding process is as follows:

(1) The initial temperature of the flat vulcanizer is set at $60^\circ \text{C}$. Take out the prepreg from the oven and put it into the metal mold with release agent, and close the mold;

(2) To improve the fluidity of the matrix and remove small molecules such as ethanol from the prepreg, it is necessary to raise the temperature of the flat vulcanizer to $120^\circ \text{C}$ and keep it for 1 h without applying any pressure to the prepreg;

(3) After step 2, the temperature is maintained at $120^\circ \text{C}$, and the prepreg is applied with 15 MPa pressure for 20 min;

(4) Keep the pressure unchanged, and raise the temperature of the flat vulcanizer to $160^\circ \text{C}$. Then, keep the temperature for 3 h;

(5) Finally, the temperature of the flat vulcanizer was raised to $180^\circ \text{C}$. The sample was cured for 1 h and then cooled to $60^\circ \text{C}$ naturally to obtain the phenolic resin composite reinforced by coated carbon fiber.

2.4. Characterization

2.4.1. Mechanical properties

The bending and tensile properties of carbon fiber reinforced phenolic resin composite are tested through a universal material test machine (M-4100, Shenzhen Ruigeer Instrument Co., Ltd). In order to clarify the effect of different oxidation temperatures on the mechanical properties of the material, this paper uses a muffle furnace to reach the specific temperature treatment on the sample for 10 min. After cooling to room temperature, the mechanical properties of composites are tested. The standards for the preparation and testing of bending properties refer to ISO-14125-1998. There are 5 test samples in each group with the test speed being 10 mm min$^{-1}$ and the gauge distance 64 mm. The sample size is shown in figure 1.

The methods that are used to calculate the bending strength and elastic modulus are as follows.

Bending strength

$$\sigma = \frac{F}{b \cdot d}$$

$\sigma$-bending strength, Mpa
$F$-yield load, N
$b$-the width of specimen, mm
$d$-the thickness of specimen, mm
Elastic modulus

\[ E = \frac{L_0 \cdot \Delta F}{b \cdot d \cdot \Delta L} \]

- \( E \) - elastic modulus, Mpa
- \( L_0 \) - the gauge distance, mm
- \( b \) - the width of specimen, mm
- \( d \) - the thickness of specimen, mm
- \( \Delta F \) - load increment, N
- \( \Delta L \) - The deformation increment corresponding to the load increment, mm

2.4.2. Oxidation resistances

The oxidation resistance ability has been measured by comparing the weight changes of phenolic resin reinforced by carbon fiber with and without anti-oxidation coating after treatment at different high temperatures. The residual weight ratio of different samples has been compared to investigate the anti-oxidation performance of each composite. KSL-1800X-S muffle furnace is used for high temperature static burning. The test temperature is 600 °C, 800 °C, 1000 °C, 1200 °C, 1400 °C and 1600 °C in the air environment. All the samples are put into the furnace with a certain test temperature. Then, cut off the heating power and cool down to room temperature in the closed furnace. The oxidation time is set to 10 min because when such composites are applied on aerospace crafts, many of them are used as ablative materials. It means that the heat generated by atmospheric friction in 10 min is mainly carried away through the ablative material falling off. Besides, 10 min is enough to distinguish the differences of oxidation resistance property. After testing 5 samples in each group, record the change of residual weight of the sample (Precision Balance ME3002T/00, METTLER TOLEDO, maximum capacity 3200 g, readability 0.01 g) and take the average value for comparison.

2.4.3. Surface and section morphology analysis

Ultra plus-43-13 field emission scanning electron microscope (FESEM) produced by Zeiss Optical Instruments Company in Germany is used as the test instrument to characterize the surface morphology of different samples. The influence of high temperature oxidation treatment on the morphology of carbon fiber reinforced phenolic resin composite with and without coating is analyzed. At the same time, the microstructure of bending section has also been studied. The oxidation process and fracture mechanism of the composite have been discussed.

3. Experimental results and discussion

3.1. Oxidation resistance performance

The residual weight of carbon fiber reinforced phenolic resin composite with and without anti-oxidation coating after 10 min oxidation treatment has been shown in Table 3.

Table 3 shows that the residual weight of composites without anti-oxidation coating is 64.94% after 800 °C treatment. However, because of the good anti-oxidation property of boron modified phenolic resin, the composite maintains certain integrity under such temperature. The hardness of sample is quite low and some parts of the composite have been powdered. It can be deduced that the composite reinforced by carbon fiber without anti-oxidation coating has no resistance to high temperature oxidation as the carbon fiber exposed to air has been completely oxidized. So, when the oxidation temperature exceeds 1000 °C, the residual weight of this sample decreases rapidly, and once the temperature is 1600 °C, the residual weight of the sample will be less than 10%. When it comes to the composites with anti-oxidation coatings, both two coatings increase the oxidation resistance property of composites, and SiC–ZrO2–MoSi2/Ni coated CF/PR shows much better performance when the temperature is over 1200 °C. The reason is that SiC can be quickly decomposed to SiO2 and CO2 gas. CO2 gas can cause the inner crevices of composites. However, the coating that contains ZrO2 and MoSi2 can
prevent such a phenomenon. ZrSiO$_4$ can be formed by the reaction of SiO$_2$ and ZrO$_2$. As the coefficient of thermal expansion (CTE) of ZrSiO$_4$ is very close to the CTE of carbon fiber at 1000 °C, the separation process of coating from the fiber can be slowed down. Besides, ZrSiO$_4$ has good fluidity and can fill the pores and small cracks on the coating surface.

### 3.2. Mechanical properties

In this paper, the bending mechanical properties of carbon fiber reinforced phenolic resin with and without coating are tested. The test temperature conditions are room temperature (20 °C), 600 °C, 800 °C, 1000 °C, 1200 °C, 1400 °C and 1600 °C respectively. The bending strength and modulus of elasticity are shown in figures 2 and 3.

Before the high-temperature oxidation treatment, the initial bending strength and elasticity modulus of phenolic resin composites without coated carbon fiber are 145.43 MPa and 11.9 GPa respectively, while the features of the coated fiber reinforced composites are very close to these numbers. The results show that the coating decreases both bending strength and elastic modulus of composites, which are in line with the anticipation. The decreases are acceptable and reasonable for the main components of anti-oxidation coating for each composite are ceramics. These coatings have low toughness. It can deduce that the coating on the surface of carbon fiber has little effect on the initial mechanical properties of the fiber. With the increase of oxidation temperature, the bending strength and elasticity modulus of the composite without coated carbon fiber decrease gradually. When the temperature is over 800 °C, the bending properties of the composite decrease sharply because most carbon fibers lose efficacy during the secondary oxidation of phenolic resin. The carbon fibers can no longer play a role in strengthening the overall mechanical properties of the composites. However, the carbon fiber with two kinds of anti-oxidation coating still has considerable bending properties after oxidation treatment under 800 °C for 10 min.

When the composites with coated fibers are oxidized under 1400 °C for 10 min, the bending properties of the carbon fiber reinforced composite with SiC/SiO$_2$ coating decreased rapidly. The SiO$_2$ glass layer can be formed on the surface of the composite around 1200 °C, which effectively prevents the further reaction of

| Temperature (°C) | Uncoated CF/PR | Standard deviation | SiC/SiO$_2$ coated CF/PR | Standard deviation | SiC-ZrO$_2$-MoSi$_2$/Ni coated CF/PR | Standard deviation |
|------------------|----------------|--------------------|--------------------------|--------------------|-------------------------------------|--------------------|
| 600              | 78.2%          | 0.013              | 84.7%                    | 0.014              | 89.7%                               | 0.015              |
| 800              | 64.9%          | 0.009              | 76.5%                    | 0.020              | 85.9%                               | 0.010              |
| 1000             | 52.8%          | 0.011              | 65.2%                    | 0.013              | 78.4%                               | 0.012              |
| 1200             | 39.3%          | 0.015              | 51.00%                   | 0.017              | 73.0%                               | 0.019              |
| 1400             | 24.9%          | 0.013              | 31.3%                    | 0.019              | 65.1%                               | 0.012              |
| 1600             | 8.8%           | 0.007              | 11.0%                    | 0.009              | 53.7%                               | 0.011              |

Figure 2. The bending strength of uncoated/coated CF reinforced phenolic resin composites with different oxidation temperature treatment.
oxygen with carbon fiber and phenolic resin. However, CO₂ gas destroys the integrity of coating. What’s more, the different CTE between SiC/SiO₂ coating and carbon fiber can lead to the separation of them, resulting in poor interface bonding between the carbon fiber and the substrate materials [25, 26]. As the coating peels off from the substrate, the composites oxide rapidly and the mechanical properties also decreased obviously.

The oxidation resistance of carbon fiber reinforced composite with SiC–ZrO₂–MoSi₂/Ni coating is better. The main effective reactions which contributes to the improvement of the anti-oxidation performance of composites are as below.

\[
\begin{align*}
\text{SiC} + 2\text{O}_2 &\rightarrow \text{SiO}_2 + \text{CO}_2(g) \\
\text{SiC} + \text{O}_2 &\rightarrow \text{SiO}_2 + \text{CO}(g) \\
\text{MoSi}_2 + 7\text{O}_2 &\rightarrow 1/5\text{Mo}_5\text{Si}_3 + 7/5\text{SiO}_2 \\
\text{MoSi}_2 + \text{O}_2 &\rightarrow \text{Mo} + \text{SiO}_2 \\
\text{MoSi}_2 + 3\text{O}_2 &\rightarrow \text{MoO}_2 + 2\text{SiO}_2 \\
\text{MoSi}_2 + 7/2\text{O}_2 &\rightarrow \text{MoO}_3 + 2\text{SiO}_2 \\
\text{ZrO}_2 + \text{SiO}_2 &\rightarrow \text{ZrSiO}_4 \\
2\text{Ni} + \text{O}_2 &\rightarrow 2\text{NiO}
\end{align*}
\]

On the one hand, the coating is prepared by composite electroplating that has higher interface bonding strength with carbon fiber [27], and the differences of CTE among coating, fiber and base material are much smaller, which keep the integrity of composite materials. On the other hand, the ductility of such coating is better. After the oxidation of phenolic resin at the surface, the anti-oxidation coating of the carbon fiber becomes the surface material to prevent further contact among oxygen, the fiber and the substrate. The nano-particles in the coating can reduce the coating stress caused by the formation of NiO. What’s more, the intermediate product ZrSiO₄ generates during the coating can fill up the creep and the cracks cause by MoSi₂ [28–30]. These three nano-particles work together to improve the overall oxidation resistance of the composite greatly. After oxidation treatment at 1600 °C for 10 min, the bending strength and elasticity modulus of the composite reach a reasonable range, which are 43.97 MPa and 3.6 GPa respectively.

### 3.3. Fracture mechanism analysis

The SEM images of original carbon fiber cloth, removed protective film carbon fibers, and carbon fiber with phenolic resin coating are shown in the figure 4. From the results, it can be deduced that the protective film on the surface of carbon fiber has been removed. The ravine is obvious and it can improve the bonding strength between coating and fiber. Figure 4(c) presents that the carbon fiber can be well compounded with phenolic resin.

Figure 5 shows the surface morphology of composites with SiC–ZrO₂–MoSi₂/Ni coating after 10 min oxidation treatment under 600 °C, 800 °C, 1200 °C and 1600 °C.

When the oxidation temperature is lower than 800 °C, the structure of carbon fiber is basically intact, and only the resin on the surface is partially oxidized. However, when the oxidation temperature is over 1200 °C, the phenolic resin is seriously oxidized with cracks and holes. Inside, the fibers maintain their shape and can be
identified clearly. It can be deduced that although the high temperature did partial destruction of the substrate, the composites still stay usable due to the existence of coated carbon fibers. The whole system is oxidized layer by layer instead of oxidized instantly. Firstly, the phenolic resin of the composite is oxidized and partially ablated, which physically peels off the surface of the sample. Such a phenomenon will become obvious after 10 min 800 °C treatment. It means that the oxidation of external resin happens when the temperature is 800 °C–1200 °C. Then, with the increase of the temperature, the coating starts to be oxidized and becomes major components to prevent further oxidation. Combine with figures 3 and 4, when the temperature ranges between 1200 °C to 1600 °C, the mechanical properties and the shape of composites are in an acceptable range. It proves that the
anti-oxidation coating of carbon fibers indeed protects the whole composite system. When the temperature is 1600 °C or even higher, the composites are burned into powder. Then SEM image shows that the fiber is damaged hardly so the overall mechanical properties of materials are also reduced rapidly.

Figure 6 presents the SEM image of the cross-section of SiC–ZrO2–MoSi2/Ni coated carbon fiber reinforced composites with 10 min, 800 °C oxidation treatment. Figure 6(a) shows that the carbon fiber with anti-oxidation coatings prepared by composite electroplating is very compact. Only part of the phenolic resin is ablated at the surface of the composite. No through crack or hole is found on the coating, and the separated fibers can extend intendedly after being destroyed by external force. From figure 6(b), it can be found that the composite maintains its structure after heat treatment as such composite is prepared by molding method. The sandwich structure effectively improves the overall high-temperature resistance and mechanical properties of the system.

4. Conclusions

The paper proposes two kinds of new anti-oxidation carbon fiber reinforced composites. By using the molding processing method, SiC/SiO2 coated carbon fibers and SiC–ZrO2–MoSi2/Ni coated carbon fibers are used to improve the mechanical properties of CFRP under high-temperature air environment. The results show that both coatings can increase the oxidation resistance of CFRP without decreasing the mechanical properties of composites. Without coating, the CFRP can be quickly oxidized around 800 °C, and CFRP with SiC/SiO2 coating can maintain its mechanical properties around 800 °C–1200 °C while SiC–ZrO2–MoSi2/Ni coating is 1200 °C–1600 °C. Such CFRP can extend the application areas of carbon fibers, including aerospace engineering. However, there is still a lot of room for improvement, such as simplifying the production process or discovering more suitable anti-oxidation coatings for a different substrate.

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References

[1] Souto F, Calado V and Pereira N Jr 2018 Lignin-based carbon fiber: a current overview Mater. Res. Express 5 072001
[2] Bowman S, Jiang Q and Memon H 2018 Effects of styrene-acrylic sizing on the mechanical properties of carbon fiber thermoplastic towpregs and their composites Molecules 23 547
[3] Arai Y et al 2019 Carbon fiber reinforced ultra-high temperature ceramic matrix composites: a review Ceram. Int. 45
[4] Kubota Y et al 2019 Oxidation and recession of plain weave carbon fiber reinforced ZrB2–SiC–ZrC in oxygen–hydrogen torch environment J. Eur. Ceram. Soc. 39 2812–23
[5] Sheehan JE 1989 Oxidation protection for carbon fiber composites Carbon 27 709–15
[6] Tang S and Hu C 2017 Design, preparation and properties of carbon fiber reinforced ultra-high temperature ceramic composites for aerospace applications: a review Journal of Materials Science & Technology 33 117–30
[7] Xiong X et al 2019 Resistance welded composite joints strengthened by carbon fiber felt: mechanical properties, failure modes and mechanism Mater. Res. Express 6 085323
[8] Aamir M et al 2019 Recent advances in drilling of carbon fiber–reinforced polymers for aerospace applications: a review Mater. Res. Express 105 2289–308
[9] Fu J et al 2019 Layer–by–Layer electrostatic self-assembly silica/graphene oxide onto carbon fiber surface for enhance interfacial strength of epoxy composites Mater. Lett. 236 69–72
[10] Zhao X et al 2020 Precursor infiltration and pyrolysis cycle-dependent microwave absorption and mechanical properties of lightweight and antioxidant carbon fiber felts reinforced silicon oxy carbide composites J. Colloid Interface Sci. 568 106–16
[11] Xu L et al 2019 Improvement of high-temperature resistance on carbon fiber felt/Portland cement composite friction material by Al2O3 sol–gel coating J. Sol-Gel Sci. Technol. 91 471–84
[12] Su X et al 2017 Microstructural characteristics and formation mechanism of laser cladding of titanium alloys on carbon fiber reinforced thermoplastics Mater. Lett. 195 228–31
[13] Liu Y et al 2018 Laser welding of carbon nanotube networks on carbon fibers from ultrasonic-directed assembly Mater. Lett. 236 244–7
[14] He H et al 2019 Effect of crystallinity of PAN–based carbon fiber surfaces on the formation characteristics of silicon carbide coating Mater. Res. Express 6 085603
[15] Bard S et al 2019 Copper and nickel coating of carbon fiber for thermally and electrically conductive fiber reinforced composites Polymers 11 823
[16] Wang X et al 2019 Fibrous porous ceramics with degradable phenolic resin reinforcing layer Ceram. Int. 45 5413–7
[17] Li S et al 2016 Structure and improved thermal stability of phenolic resin containing silicon and boron elements Polym. Degrad. Stab. 133 321–9
[18] Deng P et al 2018 Solidifying process and flame retardancy of epoxy resin cured with boron-containing phenolic resin Appl. Surf. Sci. 427 894–904
[19] Li H et al 2013 Anti-oxidation and ablation properties of carbon/carbon composites infiltrated by hafnium boride Carbon 52 (Complete) 418–29
[20] Yang W et al 2019 Preparation and properties of adhesives based on phenolic resin containing lignin micro and nanoparticles: a comparative study Mater. Des. 161 55–63
[21] Tamboli S et al 2019 Performance evaluation of cracked aluminum alloy repaired with carbon fiber reinforced polymer for aerospace application Mater. Res. Express 6 115326
[22] Yan Q et al 2012 The studying of ablation and heat insulation properties of ceramicable phenolic composite Fiber Reinforced Plastics/ Composites. 52–5 http://en.cnki.com.cn/Article_en/CJFDTotal-BLGF2012S1016.htm?len=1
[23] Yang G et al 2019 Factors affecting SiC–ZrO2–MoSi2/Ni antioxidation coating made by composite plating on carbon fibres Advances in Applied Ceramics 118 387–94
[24] Yang G et al 2018 Fabrication and anti-oxidation ability of SiC–SiO2 coated carbon fibers using sol-gel method Materials 11 350
[25] Dong C et al 2018 Evaluation of thermal expansion coefficient of carbon fiber reinforced composites using electronic speckle interferometry Opt. Express 26 531
[26] Huang X 2009 Fabrication and properties of carbon fibers Materials 2 2369–403
[27] Guo H 2007 Composite Plating Technology. 2007–1 (Beijing: Chemical Industry) 521–49
[28] Fu Q et al 2013 SiC–MoSi2/ZrO2–MoSi2 coating to protect C/C composites against oxidation Transactions of Nonferrous Metals Society of China 23 2113–7
[29] Pourasad J et al 2017 Preparation of a nanostructured SiC–ZrO2 coating to improve the oxidation resistance of graphite Surf. Coat. Technol. 323 58–64
[30] Wang P et al 2016 Oxidation protective ZrB2–SiC coatings with ferrocene addition on SiC coated graphite Ceram. Int. 42 2654–61