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A novel external thermal protection coating for aerospace vehicles

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Abstract

An external thermal protection coating was developed for the aerospace vehicle with high-mach number speed and long flight time. The effects of functional fillers including silicates, fibers and hollow microspheres on the forming process and the ablation resistance of the coating were studied. Meanwhile, the performance of thermal protection coating was investigated by wind tunnel tests under different heat flow conditions. When the coating thickness was 3~5 mm and the maximum heat flow of wind tunnel was 1460 kW/m^2, the interfacial temperature between the composite sample and the coating varied between 64℃ and 72℃.

1. Introduction

The external thermal protection coating is the key material for design and development of aerospace vehicles. Its performance is an important factor in determining the advancement and reliability of new aerospace vehicles. For the long-duration aerospace vehicles, the external thermal protection coating needs not only the ablative performance to withstand the high Mach number hot air erosion, also the thermal insulation performance to withstand thousands of high temperature resulting from aerodynamic heat. It is essential to study the external thermal protection coating with the thermal insulation and ablation performances which could meet the requirements of the aerospace vehicles.

In the present work, the external thermal protection coating material chose silicone rubber as the base polymer. The heat insulation fillers were ablative fillers, reinforcing fillers. The coating material displayed excellent ablative resistance and heat insulation. We also studied the thermal protection, ablation and processing performances of the obtained coating material.

2. Experimental

2.1 Coating preparation

The thermal protection coating material was made of the silicone and fillers mixture (Component A), curing agent (Component B), and diluents (Component C). The coating material was prepared by uniformly mixing component A and component B in proportion. The viscosity was regulated with component C. The coating material was formed by spraying. W-77 spray gun was used to spray (caliber: 2 mm, air compressor pressure: 0.4~0.8 MPa). Environment humidity was less than 85%, and the temperature was higher than 15℃. The cure condition was curing for 7d at room temperature.

2.2 Performance analysis of the thermal protection coating

The wind tunnel test was carried out to validate the thermal protection performance of the coating when the aerospace vehicle undergone the aerodynamic heating and gas etching environment during flight. The carbon fiber reinforced epoxy resin composite (100 mm×100 mm×2 mm) was utilized as the sample substrate, and it was sprayed with 3~5 mm thickness thermal protection coating. Two temperature measuring points were arranged for measuring the interfacial temperature of the wind tunnel test sample. The wind tunnel test time was 117 s, and the maximum heat flux was about 1460 kW/m^2. Thermogravimetric analysis (TGA) was performed with a METTLER-TOLEDO instrument under a 20 mL/min N_2 at the heating rate of 20℃/min. The performance requirement and test method of the thermal protection coating were listed in **Table 1**.

Table 1: Performance requirements and test methods of the thermal protection coating

Items	**Performance requirements**	**Test requirements**	**Test methods**
Tensile strength (MPa)	≥2.0	20℃	GB/T528-09
Elongation at break (%)	≥20%		
Tear strength between the composite and the coating (MPa)	≥2.0		HG4-852-81
Shear strength between the composite and the coating (MPa)	≥2.0		GB/T 7124-1986
Density (g/cm^3)	≤0.93		GB/T 14838-2009
Thermal conductivity (W/(m·K))	≤0.2		GB/T22588-2008
Specific heat capacity (kJ/(kg·K))	≥1.1		
Shore hardness (HA)	≥85		GB/T 531.1-2008
The interfacial temperature between the composite and the coating (℃)	＜120	/	/
Linear ablation rate (mm/s)	≤0.3	15s	GJB 323A-1996
Char yield at 800℃ (%)	＞50%	/	TGA
Processing performance	Curing time at room temperature ≤7d		/

3. Results and discussion

3.1 Basic performances of the coating

The basic performances of the external thermal protection coating were summarized in **Table 2**. The forming and curing processes were carried out according to Section 2.1. The tests of the coatings were determined according to the standard in Section 2.2. From **Table 2**, the tensile strength of the external thermal protection coating was more than 3.0 MPa. The thermal conductivity was lower than 0.2 W/(m·K) and the char yield of the coating was 57% at 800 ℃. All the results indicated that the prepared external thermal protection coating possessed excellent mechanical, heat insulating performances and high char yield. The performances of the thermal protection coating could meet the index requirements.

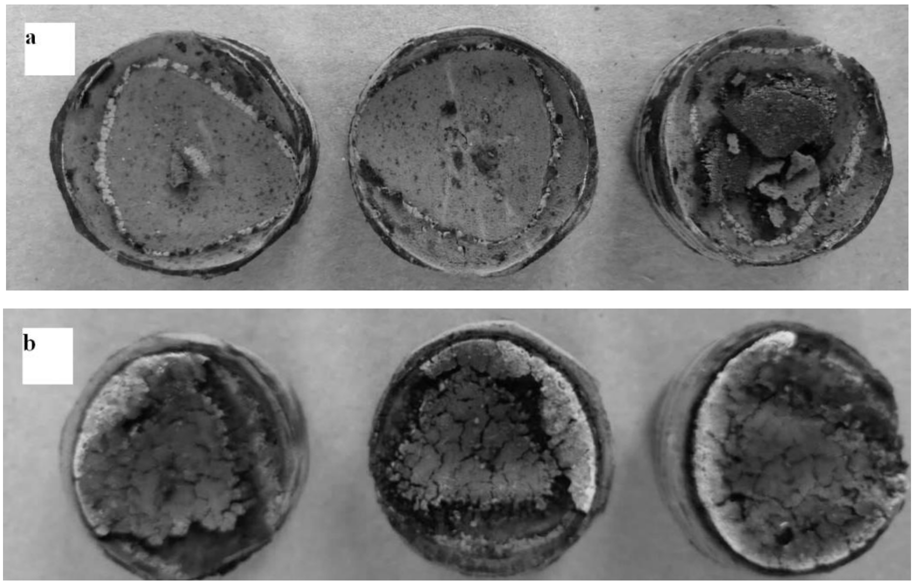
Table 2： Summary of the basic performances of the coating

Items	**Performances of the coating (20℃)**
Density (g/cm^3)	0.80~0.90
Tensile strength (MPa)	3.0~4.0
Elongation at break (%)	20%~30%
Tear strength between the composite and the coating (MPa)	1.5~2.0
Shear strength between the composite and the coating (MPa)	1.5~2.0
Shore hardness (HA)	85~90
Thermal conductivity (W/(m·K))	0.15~0.2
Specific heat capacity (kJ/(kg·K))	1.1~1.5
Char yield at 800℃ (%)	57

3.2 Study of the thermal ablation and process performance

3.2.1 Effect of silicate fillers

The external thermal protection coating was based on the two-component addition type room temperature vulcanized silicone rubber. The thermal ablation performance was enhanced with the addition of silicate fillers. The montmorillonite and mica with the mass ratio of 1:1 was chosen. The thermal ablation resistance was evaluated utilizing the oxy-acetylene ablation test. The images of the samples after oxy-acetylene ablation test were exhibited in **Figure 1**. The results of the influences of the addition content of the silicate fillers on the oxy-acetylene ablation test were summarized in **Table 3**. It could be seen that when the content of the silicate fillers was between 3.0~5.0 wt%, the char behavior of the coatings was outstanding. Moreover, the sample after oxy-acetylene ablation test showed high charring hardness, low linear ablation rate and consecutive charring structure.



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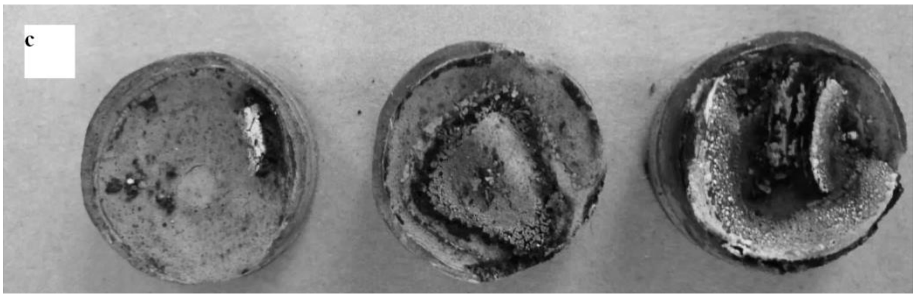

Figure 1: Images of thermal protection coatings after the oxygen-acetylene ablation test (The amount of silicate filler, a: 1~3%, b: 3~5%; c: 5~8%)

Table 3: The data of thermal protection coatings after oxygen-acetylene ablation test

Number	**Amount of silicate filler (%)**	**The pattern after ablation**	**Line ablation rate (mm/s)**	**Carbon layer hardness after ablation (HA)**
a	1~3	Carbon layer shedded	0.259	90
b	3~5	Continuous carbon layer formed	0.230	95
c	5~8	Carbon layer shedded	0.265	85

3.2.2 Effect of the fiber dosage

1.0~2.0 mm chopped fiber was used to enhance the scour resistance of the coatings. Spray forming process was adopted for thermal protection coatings. Therefore, if the amount of chopped fiber was too much, it might affect the forming process of coating materials. The research of fiber amount was necessary. **Table 4** showed the effect of fiber amount to the spray forming process of thermal protection coatings. Through the results of spray forming in **Table 4**, it could be found that spray gun was blocked as the amount of fiber was beyond 5%. Considering to the scour resistance and forming process comprehensively, the fiber dosage in thermal protection coatings was set as 3%~5%.

Table 4: The effect of fiber dosage to the spray forming process

Amount of fiber（%）	**Performance of coating spray process**
0.5~1	Continuous spraying
1~3	Continuous spraying
3~5	Continuous spraying
5~7	Spray gun was blocked during spray process

3.2.3 Effect of the addition amount of hollow microspheres

The capacity of heat insulation was needed for thermal protection coatings when they were facing to the applications. In this research, in order to increase the heat insulation capacity, hollow microspheres were added into the coatings. Because of low density, hollow microspheres tend to float in the coating. It affected the dispersion stability of coatings greatly. **Table 5** showed the dispersion condition and molding quality of the coatings after addition of

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different amounts of hollow microspheres. It could be seen that when the amount of hollow microspheres was beyond 20%, the microspheres started to float in the coatings, and layering also occurred in the formed coatings.

Table 5: The effect of hollow microsphere amount to the dispersed state and forming quality of the coatings

Hollow microsphere amount (%)	**Dispersed state**	**Appearance**
5~10	Well dispersed	Homogeneous and smooth
10~15	Well dispersed	Homogeneous and smooth
15~20	Well dispersed	Homogeneous and smooth
20~25	Floating slightly	Layering

3.3 Thermal protection performances of the coating

By simulating the flight environment of an aircraft, the test of arc wind tunnel for external thermal protection coating was carried out. The experiment data and results were listed in **Table 6**. The photos before and after arc wind tunnel test were showed in **Figure 2** and **3**. After the test, the interface temperature of the coatings maintained between 64~72℃. It was lower than 120℃ and met the target requirement. There were slight erosion marks on the surface of the coating. Mass ablation rate was lower than 1.5%. The results of arc wind tunnel test proved that the coatings had certain ablation resistance and thermal insulation. They could protect the base material well, which met the requirements of aircraft structural parts.

Table 6: The experiment data and results of arc wind tunnel test

Number	**Interface temperature/℃**	**Mass ablation rate of the coatings/%**	**Appearance of coating surface**
a	64/66.1	0.36	Smooth surface, slight erosion marks
b	70/72	1.3	
c	66.9/70.2	0.75	

Figure 2: Photograph of thermal protection coatings before wind tunnel test

Thermal protection coating was sprayed on a composite structural component of an aerospace vehicle to confirm the spraying process, curing process and process adaptability. The composite structural component with the thermal protection coating had passed a flight test.

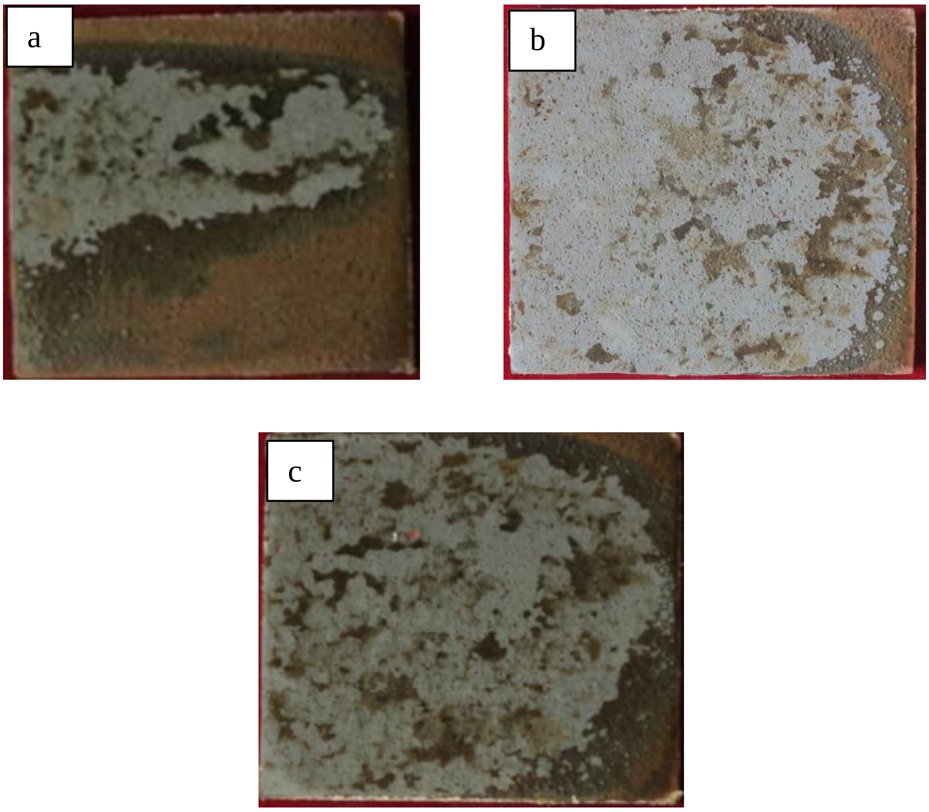

Figure 3: Photographs of thermal protection coatings after wind tunnel test

3.4 The thermal protection mechanism of the coating

Thermal protection coating technology belonged to the ablation mode. Its effectiveness essentially depended on the pyrolysis process. The process was related to material characteristics and aerodynamic conditions. When they match with each other well, an excellent thermal protection coating was obtained.

The thermal protection coating undergone material pyrolysis, material carbonization, carbon layers reaction and surface carbon layer expansion at high temperature. The decomposition heat of external thermal protection material, the thermal radiation of dense carbon shell, the combustion heat of residual carbon, and the thermal insulation of low density zone were all contribute to thermal protection performance of coating.

Conclusions

In this work, a kind of thermal protection coating was developed on the basis of a two-component addition type room temperature vulcanized silicone rubber. The coating showed excellent thermal insulation and ablation resistance. The dosages of fibre and hollow microspheres affected the spraying process and the forming quality. The use level of layered silicates affected the ablation resistance performance. The results of the dynamic arc-heated tunnel test showed that the surface temperature of aerospace vehicle structural component could be reduced to 64 ℃ by using a 3-5 mm thickness coating. In addition, the coating could provide a reliable thermal protection for the shell structural component and had both fine heat insulation and ablation resistance performance. The scale-up forming process indicated that the usable life and curing time of the coating were also satisfied the operating requirements of the aerospace vehicle. Hopefully, the developed thermal protection coating will provide efficient new materials and easily industrialized methods for the aerospace vehicle.

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