Study on C/C Composites Ablated in Plasma jet

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Abstract. In order to solve thermal protection problems under atmospheric reentry conditions, some tests on the earth have been done to study antiablative properties of C/C composites in thermal plasma jet. The flow fields and the thermodynamics parameters of thermal plasma have been researched, the parabola distribution of the plasma jet has been found. Furthermore, metals melting point method was used to survey the temperature of the plasma jet fields. Calculating the ablation ratios, spectrum analysis tested the ablation productions, scaning the ablation area, and combining the plasma characters, the ablating mechanisms of C/C composites has been found. Oxidation and nitrification are dominating factor when there is no Al_2O_3 particle in the flame, and the productions include CN,C_2,C_1,CO and little CO_2.The fibres are bare, whose shape are pyramidal in the breakpoint and netlike in the bottom. Whereas mechanical erosion is dominating factor when Al_2O_3 particle is appended in the flame, and the productions are mostly CO and CN. The boundary is neatly, and the bottom is smoothly. What's more, the ablation properties of C/C composites are little different from different angle flames.

Introduction

The conditions of reentry vehicle are extremely. The thermoresistant materials are served in high heat fluxes, high enthalpy, high pressure, and perhaps high velocity particle erosion. The ablative properties of the materials are significant. Carbon/carbon (C/C) composites get over the shortages of graphite. C/C composites are leading structural materials capable of applications in ultra-high temperature environment, such as solid rocket motor (SRM), nose tips, leading edges and other thermal protection systems for space vehicles. C/C composites use carbon fibers as enhance structures and pyrolytic carbon as matrix. Carbon will sublime in high temperature environment and absorb heat. What's more, it is a high emissivity which can take away much heat energy when it is in high velocity particle erosion.

Thermal plasma is a gaseous plasma, which consist of a mixture of electrons, ions, and neutral particles. The temperature of electrons(T_e) and weighty particle(T_h) are all about 10^4K. In this paper, the ablation property of C/C composites was investigated by plasma jet test, and the result was analyzed.

Experimental

Method. Ablation behavior of C/C composites was evaluated using a 50kW plasma jet. In order to simulate the atmospheric particle, which consists of ice, snow and water, some Al_2O_3 particles has been appended in the flow. Using the shrink-expand spray pipe, the plasma has been accelerated to be ultrasonic. In the process, the plasma jet test conditions as follows:

Table 1. Plasma jet test parameters

	Q_{Ar} (SLM)	Q_{H2} (SLM)	Arc current (A)	Arc voltage (V)	Carry air (SLM)	particle Quantity (g/min)
Exp. 1	45	4.4	700	72	0	0
Exp. 2	45	6.1	700	72	3.6	35
Exp. 3	45	4.4	700	72	0	0
Exp. 4	45	6.1	700	72	3.6	35

Parameters. The specimens are three-dimensional(3D) and four-directional carbon fiber reinforce network and obtained by chemical vapor infiltration processes, their densities are all 1.95g/cm^3. The size of Al_2O_3 particles is 37.5~75um. The others were presented in table 1.

TABLE 2. THE PARAMETERS OF SPECIMENS

	Primary Thickness (mm)	Primary Mass (g)	Ablated Time (s)	Ablated Angle (^{0})	Water quantity (m^3/h)	Elevatory water temperature ΔT (k)
Exp. 1	9.56	140.302	30	0	0.95	24
Exp. 2	10.21	149.682	30	0	0.95	24.2
Exp. 3	10.20	148.319	30	60	0.95	23.9
Exp. 4	10.65	151.428	30	60	0.95	24.4

Temperature field and velocity field

In the test, average temperature of the plasma is about 11400K in the exit and average velocity in the exit is approximately 760m/s.In the midline of the plasma, the temperature is about 21050K, the velocity is about 1810 m/s, and the Al_2O_3 particles' is about 600m/s. The flow comes into being turbulent flow when it sprays into the air. Its parameters are not even in its cross section. The parameters are parabola distribution from center to edge. For the sake of research, the axile parameters are used to represent the flame's characters. The axile velocity can be calculated from the Eq.1.

$$\frac{V_g}{V_e}=\frac{0.96r_e}{ax}\sqrt{\frac{1+0.535(q-1)\frac{V_g}{V_e}}{q}}. \qquad (1)$$

where V_g is the plasma velocity, V_e is the plasma exit velocity, r_e is the exit radius, x is axile distance, α is expand angle, and θ is the ratio of plasma temperature to air's.

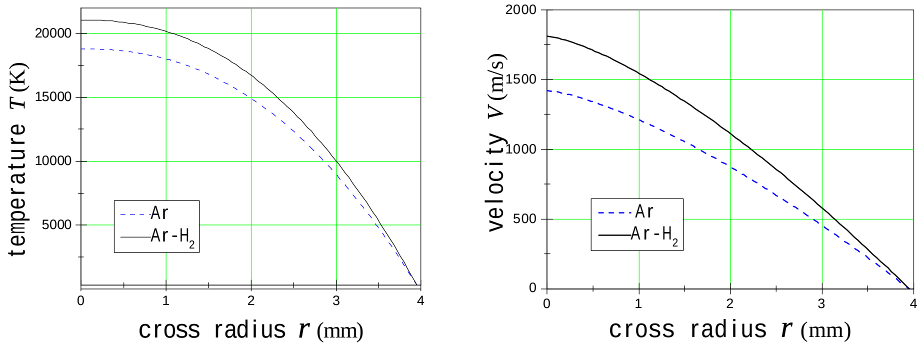
$$q=\frac{T_e}{T_a}. \qquad (2)$$

Therein, T_e and T_α respectively signify the plasma exit temperature and air temperature. The plasma axile temperature can be calculated from the Eq.3.

$$\frac{\Delta T_g}{\Delta T_e}=\frac{0.70r_e}{ax}\sqrt{\frac{1+0.735(q-1)\frac{\Delta T_g}{\Delta T_e}}{q}}. \qquad (3)$$

Therein, $\Delta T_g = T_g - T_\alpha$, $\Delta T_e = T_e - T_\alpha$; T_g denotes the plasma temperature.

The velocity and temperature of plasma are respectively 1800m/s and 21000K, the expand angle is 60°. The air temperature is assumed 303K. The results of axile velocity and temperature are presented in the fig.1.



(a)temperature (b)velocity

Fig.1. plasma axile velocity and temperature in ideal state

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In order to validate the result, metals melting point method was used to survey the temperature of the plasma jet fields. Some metal threads were put in the plasma jet. For example, the melting point of mulybdenum thread is 2890K.Finding the place where the thread melted, which is equal to the temperature of the plasma jet.

Results and discussion

The main component of C/C composites is carbon. The potential heat of carbon is 59450kj/kg, and its sublimation temperature is almost 3300K. In this test, the ablation distance between the specimens and the spray exit is 20mm, then, the plasma temperature on the surface of the specimens is almost 13900K. The velocity of airflow is about 1200m/s and the particale's is about 350m/s. Spectrum analysis shows the productions include CN,C_2,C_1,CO and little CO_2.The possible reactions are as follows:

$$2C + O_2 \longrightarrow 2CO \quad (4)$$

$$2C + N_2 \longrightarrow 2CN \quad (5)$$

$$2CO + O_2 \longrightarrow 2CO_2 \quad (6)$$

$$iC \longrightarrow Ci(g), i = 1,2,...,5 \quad (7)$$

TABLE 3. ABLATION RATIOS

	Rest thickness (mm)	Rest mass (g)	linear loss rate (mm/s)	mass loss rate (g/s)
Exp. 1	8.63	139.378	0.031	0.0308
Exp. 2	8.95	148.629	0.042	0.0351
Exp. 3	9.21	138.839	0.033	0.0316
Exp. 4	9.42	150.348	0.041	0.0360

The reaction mechanisms of C/C composites are complicated. it is different in different areas.

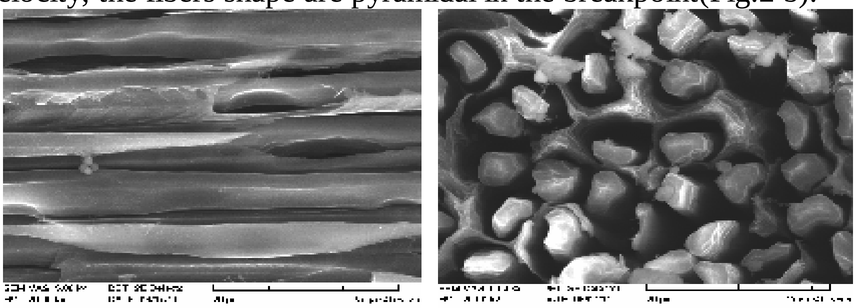
When the temperature is about to 400℃, oxygen which is in the material surface hole begins to combustion. Because of abundant oxygen in the air, the reaction near the ablation edge is oxygen rich. The reaction equations are as follows: $2C + O_2 \longrightarrow 2CO$, $2CO + O_2 \longrightarrow 2CO_2$.The productions are carbon monoxide and carbon dioxide.

In the center of the ablation, the temperature is about 13900K. Besides oxidation reaction, the reaction include $2C + N_2 \longrightarrow 2CN$, $C + N_2 \longrightarrow CN_2$ and $iC \longrightarrow Ci(g), i = 1,2,...,5$. The productions are CN, C2, C1, CO and little CO2. Thus the reaction rate is faster in the center area.

From the ablation edge to the center, chemical reaction transfer gradually from oxidation to oxidation and nitrification with the temperature increase.

When some Al2O3 particle appended in the flame, the C/C composites is consumed mostly by mechanical erosion. The reactions are uncompleted. The productions are mostly CO and CN.

In the 1st experiment, there is no Al2O3 particle in the flame. The airflow and the ablation surface is a right angle. As matrix density is lower than carbon fiber, matrix consumes faster than carbon fiber. Fibers protuberate in the surface after ablation. In the center of ablation area, fibers are barely as meshwork(Fig.2 a). In the ablation edge, chemical reaction decrease acutely for great grads of temperature and velocity, the fibers shape are pyramidal in the breakpoint(Fig.2 b).



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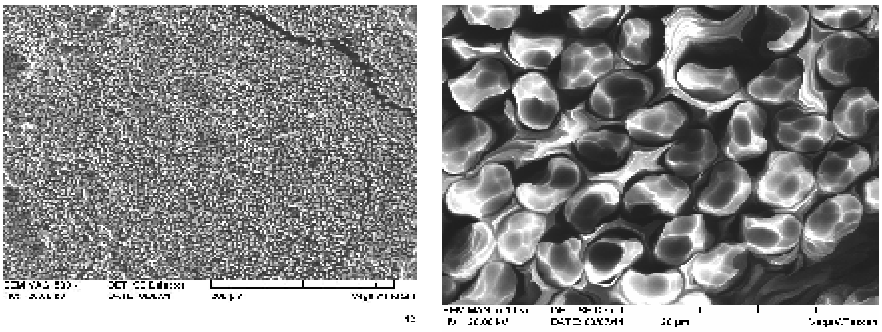
(a) (b)

Fig 2. SEM micrographs of experiment 1st in vertical ablation without particles

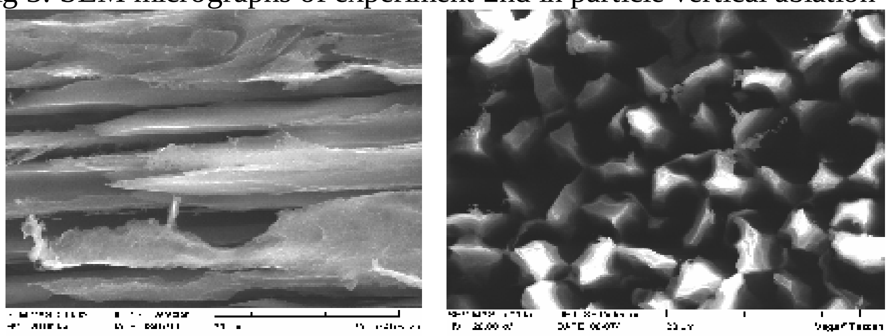
In the 2nd experiment, some Al_2O_3 particle is appended in the plasma jet (In the SEM, some Al_2O_3 particle can be found like snow). In order to elevate the enthalpy of the plasma jet, the quantity of H_2 was increased. The flow and the ablation surface is a right angle. Ablation is a combination of chemical reaction (oxidation mainly), thermal–physical process and mechanical erosion. The specimens were exfoliated, and ablation ratios increase acutely. The surface is smoothly in the center of ablation area (Fig.3 a), and the faultage is neat in the ablation edge. The specimens exfoliate in snow (Fig.3 b). The mass loss rate and the linear loss rate are respectively 0.0351g/s and 0.042mm/s(Table 2). The mass loss rate is 1.14 times to the no particles', and the linear loss rate is 1.35 times to the no particles'. Therefore, mechanical erosion is dominating factors when Al_2O_3 particle appended in the flow.

In the 3rd experiment, there is no Al_2O_3 particle in the flow. The flow is 60° to the ablated surface (Fig.4). The mass loss rate is 0.0316g/s, which is 1.02 times to the vertical's, and the linear loss rate is 0.029 mm/s, which is 1.06 times to the vertical's.



(a) (b)

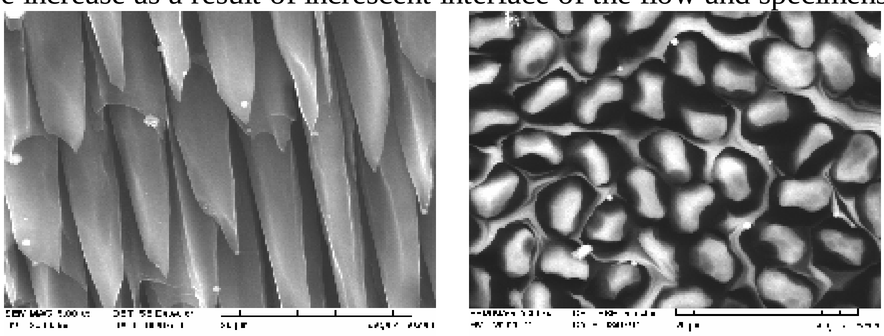
Fig 3: SEM micrographs of experiment 2nd in particle vertical ablation



(a) (b)

Fig 4. SEM micrographs of experiment 3rd 60° without particle ablation

In the 4th experiment, some Al_2O_3 particle is appended in the flow and the quantity of H_2 was increased. The flow is 60° to the ablated surface (Fig.5). The mass loss rate is 0.0360 g/s, which is 1.02 times to the vertical's, and the linear loss rate is 0.041 mm/s, which is 0.976 times to the vertical's. Owing to the acute angle ablation, the temperature and velocity in cross direction is lower than the vertical ablation, so thermal–stress and mechanical erosion became lower, therefore the linear loss rate is lower in vertical direction, whereas the specimens are four direction, ablated angle does not dominate. The mass loss rate increase as a result of increscent interface of the flow and specimens.



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(a) (b)

Fig 5. SEM micrographs of experiment 4th 60° with particle ablation

Conclusions

1) The antiablation of c/c composites is rather different in different place. In the plasma ablation experiments, oxidation and nitrification are dominating factors when there is no Al_2O_3 particle in the flame, and the productions are CN, C2, C1, CO and little CO_2. The fibres are bare, whose shape are pyramidal in the breakpoint and netlike in the bottom. Whereas mechanical erosion is dominating factors when Al_2O_3 particle is appended in the flame, the reaction is incomplete and the production are mostly CO and CN. The boundary is neatly, and the bottom is smoothly.

2) Influences on antiablative properties is little for the three-dimensional and four-direction c/c composites

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