ABLATION OF THE CARBON/CARBON COMPOSITE NOZZLE-THROAT IN A SMALL SOLID ROCKET MOTOR

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Introduction

Carbon/carbon (C/C) composites own unique properties such as low density, high specific strength and modulus, low coefficient of thermal expansion, good ablation and thermal shock resistance [1]. The application of such composite components in aerospace propulsion system can increase payload, simplify the overall nozzle, improve the reliability of system. The excellent properties of C/C components (integral throat and entrance, etc.) have been evidently demonstrated on Ariane 5 solid rocket motor (SRM) [2]. Researchers [3-6] have carried out lots of work on formulating a comprehensive model to predict recession rate of C/C nozzles by computer simulation. However, these models were based on carbon materials thermochemical erosion, which are not completely accordant with practical ablation. So, it is necessary to study the ablation mechanism of C/C nozzle materials in the practical SRM environment.

In this study, integral nozzle samples were exposed to the SRM hot-fire testing environment to investigate the ablation of C/C composites themselves. The microstructure and ablation morphology and mechanism of C/C composites were studied.

Experimental

The integrated needled carbon fiber felts (about 0.20 g/cm^3) were employed as the reinforcements for C/C composites. Densification of porous carbon felts was carried out by a thermal gradient chemical vapor infiltration (CVI) process with methane in the range of 1173-1473 K. After the thermal gradient CVI, the densified C/C composites were graphitized in an argon atmosphere.

The apparent density of the as-prepared composites was about 1.80 g/cm^3. Two kinds of nozzles were designed and they have the same geometry parameters except the throat diameter. A small SRM hot-fire testing system was employed (Fig. 1) to investigate the ablation of C/C composites. The metalized Ammonium perchlorate/hydroxyl-terminated polybutadiene (AP/HTPB) composite propellant with 17 wt.% Aluminum (Al) was used for the test. The theoretical temperature of the combustion gases produced from the metalized AP/HTPB/Al was about 3400K. Reduced-scale nozzles (The throat diameter of Nozzle 1 was less than that of Nozzle 2) were used for the hot-fire tests. Each nozzle was exposed to the combustion gases in 3-4 s. The chamber pressure was monitored by a pressure gauge.

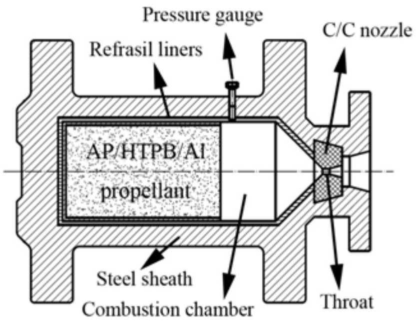

Fig. 1 Schematic of the small SRM hot-fire testing system.

Results and Discussion

Table 1. Calculated chemical composition of the equilibrium combustion products at the nozzle throat.

Species	Mole fractions (mol %)	
	Nozzle 1	Nozzle 2
H_2	33.001	32.684
CO	25.471	25.367
HCl	13.549	13.443
H_2O	9.116	9.085
Al_2O_3(L)	7.653	7.611
N_2	7.435	7.407
H	1.531	1.957
CO_2	0. 910	0.919
Cl	0.421	0.540
AlCl	0.281	0.335
OH	0.171	0.216
AlOH	0.166	0.198

The equilibrium compositions of propellant combustion products were calculated by the Chemical Equilibrium with Applications code from NASA [7]. The maximum chamber pressures (15.2 MPa for Nozzle 1 and 7.7 MPa for Nozzle 2) were used for the chemical equilibrium calculation. The results showed in Table 1. H_2O, OH and CO_2 were considered to be primary oxidizing species for chemical attack to carbon materials [3-6], which consumed the carbon of throat surface to form CO because of the heterogeneous reactions of the species with carbon

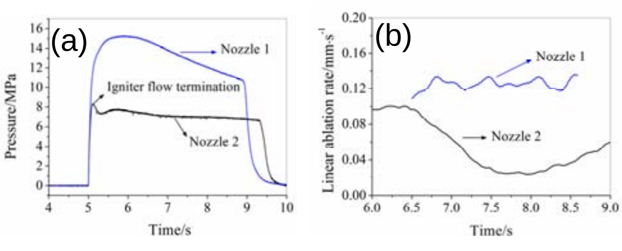

Fig. 2 (a) Recorded pressure-time traces, (b) linear ablation rate of nozzle throat.

Fig. 2 shows the resulting pressure-time traces and linear ablation rate. With the ablation going on, the combustor pressure decreased almost linearly until the propellant eventually burnt out. The linear ablation rate remained periodic fluctuation in the range of 0.11-0.13 mm/s for high combustor pressures because of the fiber fracture, but at low pressures, it had the maximum value (remained almost constant at 0.10 mm/s) at the beginning, followed a linear decrease, remained almost a constant level for 0.5 s (reached the minimum value), and finally almost increased linearly.

Conclusions

The ablation was controlled by heterogeneous reactions together with mechanical breakage. The mechanical breakage rate increased at high pressures. The fibers were oxidized into cone shapes in the area of high fiber density, but those in the area of few fibers peeled off the matrix by the aerodynamic stress because of their weak strength after oxidation. Meanwhile, the matrix around the fiber bundles was oxidized into a shell shape and that among the cone-shaped fibers was blown away by the combustion gases.

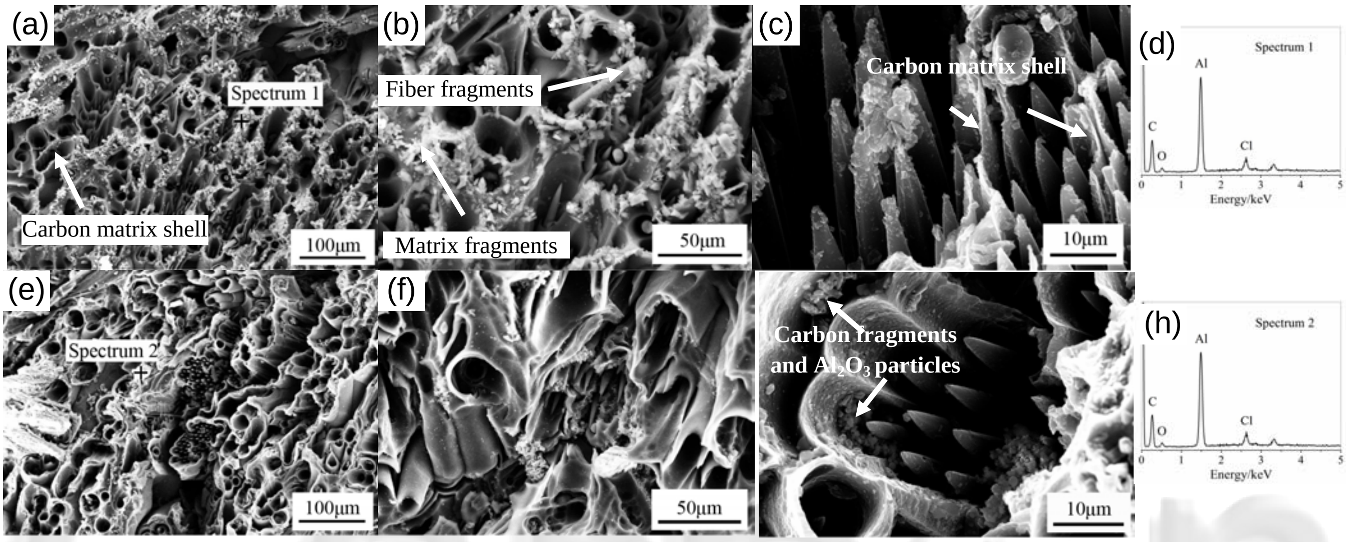

Fig. 3 Morphology and EDS patterns of C/C composite throat: (a-d) Nozzle 1, (e-h) Nozzle 2.

Fig. 3 shows morphology and EDS patterns of C/C throat after hot-fire tests. The fibers were ablated into cone shapes in the area of high fiber density, but those in the area of few fibers peeled off the matrix by the aerodynamic stress because of their weak strength after oxidation. Meanwhile, the matrix around the fiber bundles was ablated into a shell shape and that among the cone-shaped fibers was blown away by the combustion gases. The formed cone-shaped fibers, the matrix among the cone-shaped fibers blown away by the combustion gases, and shell-shape matrix resulted from the oxidation (heterogeneous reaction). The fractured carbon fiber and matrix fragments were caused by the mechanical breakage. The ablated fibers and matrix were ruptured into carbon fragments when the strength of the ablated fibers and matrix could not withstand the aerodynamic stress of the high-temperature and high-pressure combustion gases. The ablation surfaces of throats for Nozzles 1 and 2 also presented some obvious differences. As far as Nozzle 1, a large number of carbon fragments appeared on the ablation surface and no obvious Al_2O_3 particles were found as shown in Fig. 3a-c. While for Nozzle 2, lots of Al_2O_3 particles (Fig. 3e-g) deposited on the ablation surface and only a few carbon fragments appeared on the wall of carbon shell (Fig. 3g). It indicated that the carbon fibers/matrices breakage rate increased for high combustor pressures.

Acknowledgement. This work has been supported by the National Natural Science Foundation of China under Grant No. 50902111, 50972120 and Foundation of State Key Laboratory of Solidification Processing under Grant No. G8QT0222.

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