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Experimental Study on Laser Ablation of C/C Composites

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Abstract. Aiming at the application of C/C composite in nozzle throat lining of solid rocket motor, the thermochemical ablation of C/C composites under CO2 or N2 different confining pressures is studied by using a continuous laser ablation test device, and some useful conclusions are obtained. In CO2 confining pressure environment, with the increase of pressure, the heat absorption effect of thermochemical reaction becomes more obvious, and the surface temperature of the sample decreases. The temperature at 1MPa and 2MPa decreases by 12% and 23% respectively, compared with the maximum temperature in N2 environment because there is no chemical reaction between N2 and C/C composites. The sample surface is carbonized after endothermic, and forms a large number of holes.

1. Introduction

The heat transfer and ablation of ablation resistant materials is a complex physical and chemical change process. Its heat transfer and ablation characteristics will be affected by many factors. C/C composite is widely used as throat lining material of rocket nozzle because of its good ablation resistance. The thermal environment of the nozzle throat is bad during the working process of the rocket motor. Due to the pyrolysis reaction of C/C composite at high temperature, it absorbs heat and produces pyrolysis gas. Then the size of its inner surface will change, which will affect the internal ballistic performance of the rocket motor[1].

In 2011 and 2013, K.Z. Li and B.L. Zha studied the actual ablative behavior of C/C composite material in solid rocket engine through ground ignition experiment, and the results showed that the fiber head was conical in high fiber density area, and the fiber was stripped in low fiber density area, and the surrounding matrix was ablated in shell shape. The oxidation of C/C composites results in the loss of the matrix material between the conical fiber and the shell and the formation of a large number of holes on the surface of the material[2,3]. F. Huang et al. used the DSMC method to reveal the ablation mechanism of C/C composites in air by studying the diffusion behavior of oxygen molecules in the ablation gap and the collision law with the wall at the micron level[4].

In 2015, J.Y. Zhi explained the thermal conductivity mechanism of C/C composites and the influence of graphitization degree, graphite scale and other factors on thermal conductivity from the micro scale. The results show that there is a linear relationship between the thermal conductivity of carbon matrix around the carbon fiber reinforcement and the thermal conductivity of C/C composites along the fiber direction[5].

In 2017, J. Lachaud et al. described the ablative mechanism of 3D C/C composites from the microscopic level. Based on the calculation of different ablative rates of carbon fiber and carbon matrix, the microscopic ablative morphology of the materials was obtained, which was consistent with the experimental results, proving the reliability of the simulation algorithm[6]. Y.Liu et al. studied the ablation characteristics of a 4D carbon/carbon composite under a high flux of combustion products with a high content of particulate alumina in a solid rocket motor[7] .

In 2018, J.M. Su et al. explored the factors affecting the ablative rate of C/C composite throat lining through several ground ignition experiments, and the results showed that pressure is the first factor affecting the ablative rate, the concentration of oxidizing components of propellant is the second factor affecting the ablative rate, and the combustion temperature of propellant has no obvious effect on the ablative rate[8].

Based on the fact that most of the previous scholars used numerical simulation analysis to study C/C composites, even if the ground ignition test of solid rocket motor was used which has a high cost. In this paper, the laser ignition test is proposed to study the ablation characteristics of C/C composites. It is more economical and convenient to operate.

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2. Test Equipment and Sample Preparation

During the working process of solid rocket motor, the C/C composite in the nozzle reacts with CO_2 and H_2O in the fuel gas. This chemical reaction results in the change of the inner surface of the nozzle. In the commonly used reaction model, similar heterogeneous reaction control equations are used for the reaction rates of C+CO_2 and C+H_2O. In this paper, the thermochemical ablation of C/C composites in CO_2 atmosphere at different pressures is studied by using a continuous laser ablation experimental device.

The continuous laser ablation experimental device generates laser from CO_2 laser with wavelength of 10.6 μm. The maximum power is 300W. The power and ablation time are controlled by the controller card. The sample is placed in a closed square cavity with a size of 110mm×120mm×260mm. In the experiment, different CO_2 atmosphere gas pressure conditions are realized by connecting the gas tank. After the experiment, the gas is discharged through the exhaust valve. In order to make the laser hit directly above the sample, a lens is set on the upper part of the square cavity, the focal length of the lens is 127mm, and finally the diameter of the light spot on the sample is 3mm. The experimental system is shown in Fig. 1. Calibrate the laser power to make the heat flux density of the heating surface of the sample the same before each experiment. The sample size of C/C composite is ϕ 5mm × 6mm cylindrical sample. The test sample is made by water cutting.

In the experiment, the infrared thermometer is used to measure the temperature of the heated surface. The model of the infrared thermometer is Ircon Modline 5. Its temperature measurement range is from 1000 ℃ to 3000 ℃. The sample under ablation is shown in Fig. 2.

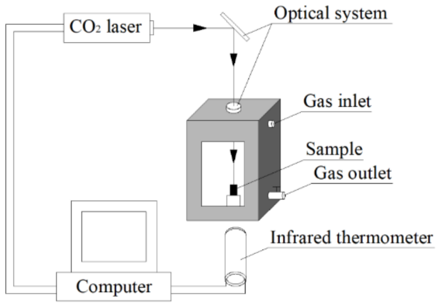

Figure 1. Schematic diagram of laser ablation experimental system

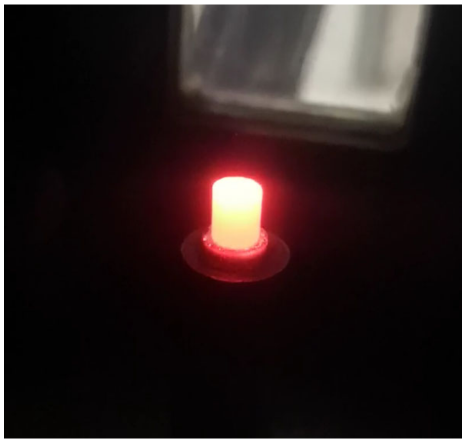

Figure 2. Sample during ablation

3. Experimental Results and Analysis

In the experiment, CO_2 or N_2 atmosphere gas with different pressure is introduced into the metal square cavity. The pressure is 0.1MPa, 1MPa, 2MPa and 3MPa respectively. The loading laser power are 120W for 60s continuously. The temperature of heating surface under different atmosphere gas conditions is measured by infrared thermometer, as shown in Fig. 3. The surface temperature is below 1273.15K, which cannot be measured due to the limitation of equipment range.

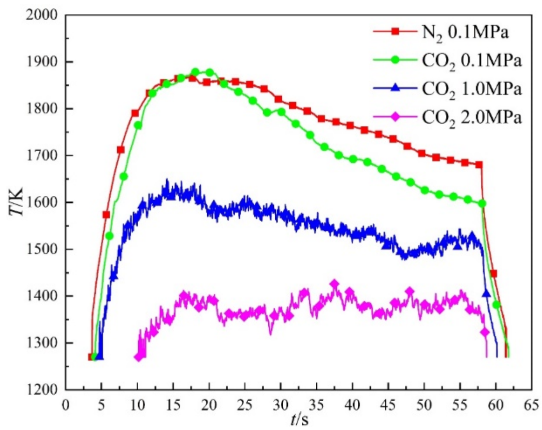

Figure 3. Variation of temperature on the heated surface of the sample with time

In N_2 environment the sample temperature is higher, which results in reducing the surface heat flux of the sample due to the pore gas expansion flue gas to escape. And it affects the light path of infrared thermometer, so the temperature declines over time. Under the same 0.1 MPa CO2 gas environment, because of the thermal chemical ablation reaction of the sample, the temperature is slightly lower than the surface temperature in N_2,as shown in Fig. 3.

With the increase of pressure, the heat absorption effect of thermochemical reaction becomes more obvious in the CO_2 environment. The temperature at 1MPa and 2MPa decreases by 12% and 23% respectively, compared with the maximum temperature in N_2 environment. The temperature at 3MPa cannot be measured because it is lower than 1273.15K. But it can be inferred that the temperature decreases by more than 30%. The output temperature data of the infrared thermometer is the maximum temperature at the test area. Due to the uneven distribution of reaction rate on the surface, the temperature fluctuation is relatively large at 1MPa and 2MPa.

The morphology of C/C composites sample after the test was obtained by Hitachi SU3500 scanning electron microscope shown in Fig. 4. Sample heated surface microstructure is as shown in Fig. 5. Due to the thermal conductivity of carbon fiber higher than that of the pyrolytic graphite substrate, so the quantity of heat to the internal transfer faster through carbon fiber. It makes carbon fiber and CO2 react faster than the pyrolytic graphite substrates, so it forms a large amount of holes in the original position of carbon fiber after the experiment shown in Fig. 5.

Figure 4. Scanning electron microscope(SEM)

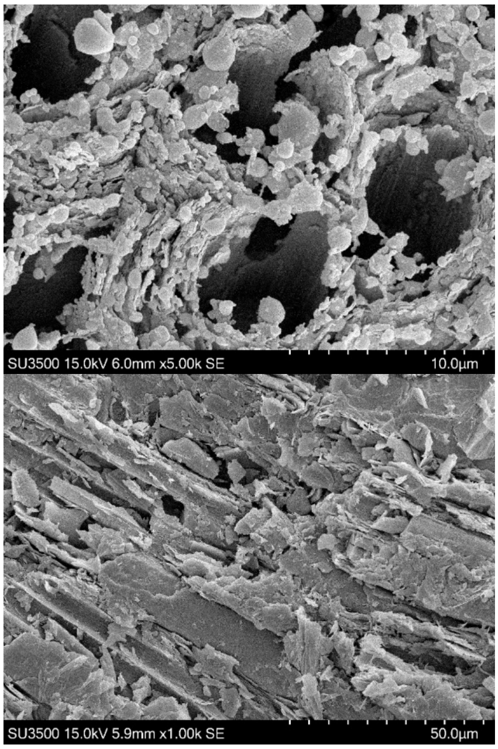

Figure 5. Microstructure of sample after ablation

4. Conclusion

In this paper, the thermochemical ablation of C/C composites under different CO_2 pressures is studied by using a continuous laser ablation test device, and the following conclusions are drawn.

(1) In CO_2 confining pressure environment, with the increase of pressure, the heat absorption effect of thermochemical reaction becomes more obvious, and the surface temperature of the sample decreases. The sample surface is carbonized after endothermic, forming a large number of holes.

(2) In N_2 confining pressure environment, the surface temperature of the sample is higher than that of CO_2 environment because there is no chemical reaction between N_2 and C/C composites.

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