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Energy release properties of amorphous boron and boron-based propellant primary combustion products

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ABSTRACT

The microstructure of amorphous boron and the primary combustion products of boron-based fuel-rich propellant (hereafter referred to as primary combustion products) was analyzed by scanning electron microscope. Composition analysis of the primary combustion products was carried out by X-ray diffraction and X-ray photoelectron spectroscopy. The energy release properties of amorphous boron and the primary combustion products were comparatively studied by laser ignition experimental system and thermogravimetry–differential scanning calorimetry. The primary combustion products contain B, C, Mg, Al, B_4C, $B_{13}C_2$, BN, B_2O_3, NH_4Cl, H_2O, and so on. The energy release properties of primary combustion products are different from amorphous boron, significantly. The full-time spectral intensity of primary combustion products at a wavelength of 580 nm is ~2% lower than that of amorphous boron. The maximum spectral intensity of the former at full wave is ~5% higher than that of the latter. The ignition delay time of primary combustion products is ~150 ms shorter than that of amorphous boron, and the self-sustaining combustion time of the former is ~200 ms longer than that of the latter. The thermal oxidation process of amorphous boron involves water evaporation (weight loss) and boron oxidation (weight gain). The thermal oxidation process of primary combustion products involves two additional steps: NH_4Cl decomposition (weight loss) and carbon oxidation (weight loss). CL-20 shows better combustion-supporting effect than $KClO_4$ in both the laser ignition experiments and the thermal oxidation experiments.

1. Introduction

A boron-based fuel-rich propellant is an ideal fuel for solid ducted rocket. Specifically, the boron contained in this propellant has high gravimetric calorific value (58.74 kJ g^{-1}, 2.3 times that of magnesium and 1.9 times that of aluminum) [1]. However, boron has high melting and boiling points, is difficult to ignite (high oxygen demand), and its products can agglomerate during combustion, thus causing low combustion efficiency in practical applications. Therefore, to give full play to the excellent performance of boron is difficult [2–4]. As a result, the combustion characteristics and modification methods of boron-based propellants have always been a significant issue to scholars.

The primary combustion of a boron-based propellant (hereafter referred to as primary combustion products) takes place in the solid propellant gas generator. The

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primary combustion products are then injected into the afterburning chamber for secondary combustion. The combustion degree of primary combustion products is low because of the low temperature and low oxygen content in the gas generator. The excellent performance of boron-based fuel-rich propellants mainly plays out during the secondary combustion in the afterburning chamber. Given that the physical and chemical properties of primary combustion products are different from those of amorphous boron, a study on primary combustion products and their secondary combustion can provide direct guidance for improving the combustion efficiency of boron-based propellants. In recent years, scholars have begun to focus on the combustion characteristics of primary combustion products.

The combustion characteristics of boron particles and boron-based propellants have been studied over the past decades. Foelsche et al. [5,6] studied the ignition and combustion characteristics of crystalline boron under different pressures, temperatures, and oxygen concentrations. Obuchi et al. [7]studied the effects of magnesium metal additives to the ignition delay time of amorphous boron and found that the ignition delay time of boron and magnesium mixture can be divided into two areas in low temperature. The addition of magnesium can effectively reduce the ignition temperature of boron particle. Xi et al. [8]indicated that Bi_2O_3 is the most active catalyst for boron oxidation among Bi_2O_3, Fe_2O_3, SnO_2, MgO, Al_2O_3, CeO_2, and CuO. They also proposed a two-solvent method for coating boron particles because of the shortcoming of the recrystallization method [9]. Yeh et al. [10] established a comparatively perfect ignition and combustion model of boron. They considered that polymer $(BO)_n$ produces during the combustion of boron, and it then diffuses from the inside to the outside in the oxide layer. Schadow et al. [11] used a color photography to observe the reaction characteristics of boron powder and gaseous propellants in the afterburning chamber. They considered the need to burn additional gaseous fuel in the afterburning chamber to heat up and ignite boron particles. Zhou et al. [12] indicated that the effect of B_4C (one constituent of primary combustion products) on the ignition and combustion of boron particles changes with temperature. Hu, et al. [13,14] established a one-dimensional model to investigate the ignition process of boron particles in boron-based propellants, while considering the Stefan flow effects. They also established a two-phase reacting flow model in the secondary combustor of a ducted rocket. They used the eddy break up model and a well-established boron particle ignition and combustion model to simulate the gas and particle-phase combustion, respectively. Mellor et al. [15] used the liquid nitrogen cooling method to collect primary combustion products. They also analyzed the chemical composition and size distribution of the primary combustion products. They found substantial changes in the chemical composition, but the particle size was almost unchanged. Liu et al. [16] used the minimum free energy method to calculate the formulation of primary combustion products and found that their method was feasible.

At present, studies on boron particle and boron-based fuel-rich propellants are comprehensive. However, studies focused directly on primary combustion products and their secondary combustion are lacking. The composition of primary combustion products is complicated, and different ingredients may react and influence one another. Therefore, a study on primary combustion products requires various methods.

In the present study, the microstructure of amorphous boron and primary combustion products was analyzed by scanning electron microscope (SEM). The composition of primary combustion products was analyzed by energy dispersive spectrometry (EDS), X-ray diffraction (XRD), and X-ray photoelectron spectroscopy (XPS). The ignition and combustion characteristics of amorphous boron and primary combustion products were comparatively studied by a laser ignition experimental system. The thermal oxidation characteristics of amorphous boron and primary combustion products were comparatively studied by thermogravimetry–differential scanning calorimetry (TG–DSC).

2. Experimental section

2.1. Materials

The amorphous boron sample used in this study was obtained from Baoding Zhongpuruituo Technology Co., Ltd., China. The sample is brown at room temperature (Fig. 1 (a)) and has a nominal purity of 99%.

Along with studies of boron samples, a test of B/KCl mixture was also conducted as described in Section 3.2.

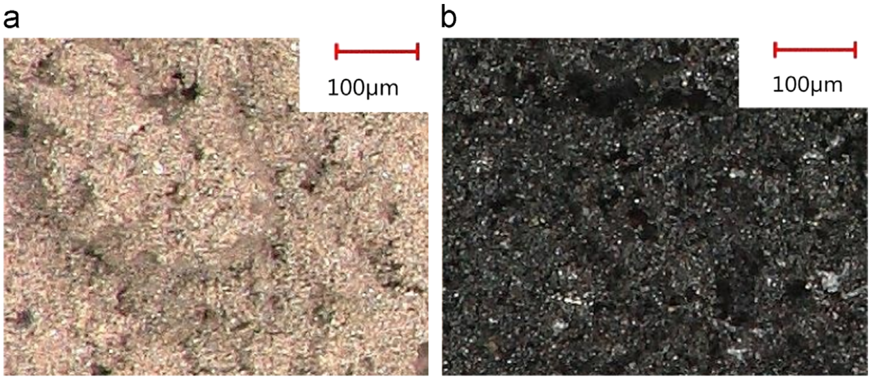

Fig. 1. Optical micrograph of samples (200 ×) (a) Amorphous boron and (b) primary combustion products (1).