Chinese Journal of Aeronautics, (2017), **xxx**(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Effect of particle size and oxygen content on ignition and combustion of aluminum particles

Yu'nan ZHOU, Jianzhong LIU [*]**, Daolun LIANG, Wei SHI, Weijuan YANG, Junhu ZHOU**

State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310027, China

Received 8 November 2016; revised 22 February 2017; accepted 18 April 2017

KEYWORDS

Aluminum;
Flame;
Ignition and combustion;
Laser;
Thermal analysis

Abstract Particle size and oxygen content are two of the key factors that affect the ignition and combustion properties of aluminum particles. In this study, a laser ignition experimental system and flame test system were built to analyze the ignition and combustion characteristics and the flame morphology of aluminum particles. A thermobalance system was used to analyze the thermal oxidation characteristics. In addition, the microstructure of aluminum was analyzed by scanning electron microscopy. It was found that the oxidized products were some of the gas phase products agglomerated. Smaller particle size samples showed better combustion characteristics. The combustion intensity, self-sustaining combustion time and the burn-off rate showed a rising trend with the decrease in the particle size. Increasing the oxygen content in the atmosphere could improve the ignition and combustion characteristics of the samples. Four distinct stages were observed in the process of ignition and combustion. Small particle size samples had a larger flame height and luminance, and the self-sustaining combustion time was much longer. Three distinct stages were observed during the thermal oxidation process. The degree of oxidation for small-sized samples was significantly higher than that for the larger particle size samples. Moreover, it was observed that the higher the oxygen content, the higher the degree of oxidation was.

1. Introduction

Aluminum is an important energetic component of many solid propellants, explosives, and pyrotechnic formulations.[1–3] It is added to rocket propellants to increase the specific impulse and raise the flame temperature.[4] Thus, the research on aluminum has been an ongoing effort. Specifically, aluminum has both high gravimetric calorific value (30.96 kJ/g) and volumetric calorific value (83.59 kJ/cm^3). Furthermore, due to its wide availability, low cost, harmless formation, and non-toxic

* Corresponding author.
E-mail address: jzliu@zju.edu.cn (J. LIU).
Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2017.09.006

characteristic, aluminum is also used as a cost-effective metal fuel.[5]

In its practical applications, aluminum is mixed with the solid propellant in a certain proportion, and eventually releases the chemical energy in the form of combustion. So the study of the ignition and combustion characteristics of aluminum particles can guide the applications of aluminum based composite propellants and provide a theoretical basis for studying the mechanism of aluminized composite propellant combustion and improving the combustion efficiency of solid propellants.[6]

The ignition and combustion characteristics of aluminum and aluminum-based propellants have been studied over the past decades.[7,8] Glassman and Brzustowski[9,10] recognized that aluminum combustion would be similar to combustion of droplets of a hydrocarbon fuel for which the D^2 law (D is the aluminum particle size)is applicable for ignition and combustion, depending on the melting and boiling points of the metal and the oxide. Belyaev et al.[11] added a small amount of aluminum powder into a solid propellant and found that the burning time could be extended by increasing the aluminum particle size from 10 μm to 150 μm. Bazyn et al.[12] employed the shock tube to study the effects of atmospheric conditions on the burning time, and found that the burning time is the shortest in O_2, and the longest in H_2O, and also shows a tendency to extend with increase in the amount of oxidizer. Lynch et al.[13] obtained the same results as Bazyn et al. and found that the actual burning time was shorter than that predicted by the model of diffusion-controlled combustion. Roberts et al.[14] performed a shock experiment under low pressure conditions, and found that reducing the oxygen concentration caused extension of the ignition time.

Until now, the ignition and combustion mechanisms of a single particle have not been studied thoroughly. Thus, the research on the ignition and combustion behavior of small aluminum particles is still an ongoing process. Particle size and ambient atmosphere can significantly influence the ignition and combustion characteristics of aluminum particles. However, very few studies have focused directly on the effects of particle size and oxygen concentration. Most of the previous reports have been on micron-sized aluminum larger than 10 μm which is not applicable for practical engineering applications. It is necessary to separately study the nano-aluminum material because the physical properties of nanocrystalline metals are significantly different than those of bulk polycrystalline metals.[15]

In this study, the aluminum microstructure was analyzed using Scanning Electron Microscopy (SEM). The effects of particle size and oxygen concentration on the ignition and combustion characteristics of aluminum particles were systematically investigated using a laser ignition experimental system. Lastly, employing a thermobalance, the effects of particle size and oxygen concentration on the thermal oxidation characteristics were investigated.

2. Experimental and methods

2.1. Materials

The aluminum samples used in this study were obtained from Shanghai Shuitian Technology Co., Ltd., Shanghai, China. The nominal purity of the samples was 99%. The samples were dark grey at room temperature. The nominal size of the samples were 80 nm, 1 μm, 10 μm and 50 μm, and the mean particle size were 102 nm, 3.53 μm, 8.617 μm and 37.75 μm, respectively. As samples are of a non porous material, their specific areas are only affected by particle size.

2.2. Devices and methods

SEM images were taken by a Hitachi SU-70 field emission SEM, after gold sputtering for two minutes. Thermogravimetric (TG) analysis experiments on the samples were conducted on a TA-Q500 thermal analysis system. Approximately 2 mg of the samples was packed in Al_2O_3 crucible for each TG experiment. The samples were heated from room temperature to 1000 °C at a heating rate of 10 °C/min. The reaction gas was a mixture of nitrogen at a constant gas flow of 40 mL/min and oxygen at a flow of 10 mL/min, 27 mL/min, and 100 mL/min for different oxygen content experiments.

A laser ignition system (Fig. 1) was designed and constructed for the laser ignition experiments. This experimental setup has been widely used in metal ignition and combustion studies.[16–18] This system consisted of four parts, namely combustion diagnosis unit, laser ignition unit, gas regulation unit, and data acquisition unit. The CO_2 laser was used to heat and ignite the samples. An AvaSpec-3648 fiber optic spectrometer was used to record the characteristic speactra of the samples during the combustion stage in real time. A Redlake GE4900-T12 color high speed camera, with a maximum resolution of 1024 dpi × 768 dpi, recorded the changes of the flame during combustion. The switch gear controlled the CO_2 laser and fiber optic spectrometer at the same time. The flowmeter and gas cylinder were set to control the atmosphere and gas flow rate of the combustion chamber. In this experiment, the laser power was set to 270 W, and firing time of the laser was 1 s. Approximately 10 mg of the samples was loaded into the Tungsten crucible in the combustion chamber. The reaction gas was a mixture of oxygen and nitrogen which contained 20%, 50%, 70%, and 100% oxygen, at a constant flow of 1 L/min. The combustion products were collected and weighed. The burn-off rate was obtained by calculating the amount of reacted aluminum from the weights of the combustion products.

3. Results and discussion

3.1. Microstructure analysis

Figs. 2 and 3 show the SEM images of the aluminum sample with average particle size of 1 μm, and its primary combustion products after ignition by laser. Before ignition, the particles have a spherical shape, and the size distribution is relatively uniform, around 1 μm (Fig. 2). The particles were found to be aggregated with each other, and the surface was not completely smooth due to some protuberances and cavities. The shape of the particles after ignition is irregular. There are two distinctly different regions present in the sample (Fig. 3). One region (Section A) consists of inhomogeneous spherical particles clustered together, and the particles expanded in size because of oxidation. The other region (Section B) is a section

Please cite this article in press as: ZHOU Y et al. Effect of particle size and oxygen content on ignition and combustion of aluminum particles, *Chin J Aeronaut* (2017), https://doi.org/10.1016/j.cja.2017.09.006