Ignition and Combustion of Individual Aluminum Particles below 10μm at Different Laser Heating Rates

Hou Fengting[1], Li Shengji[2], Wang Yue[1], Huang Xuefeng[1,*]

[1] Institute of Energy, Department of Physics, Hangzhou Dianzi University, Hangzhou, 310018, China

[2] College of Materials and Environmental Engineering, Hangzhou Dianzi University, Hangzhou, 310018, China

Abstract

The ignition and combustion characteristics of individual aluminum particles below 10μm were investigated. A specific experimental setup and corresponding diagnosis method were presented to directly observe the ignition and combustion behaviors. Individual aluminum particles heated by laser at different power density undergo similar several stages, including thermal expansion, alumina shell rupture, molten aluminum core overflow, shell melt and aluminum evaporation, ignition and combustion of aluminum vapor. This work will be beneficial to further extend the investigation of submicron individual metal particles and reveal their combustion mechanism by direct observation.

1 Introduction

Aluminum has been widely used as an additional metal additive in solid rocket propellants. The combustion characteristics of aluminum varies greatly with different sizes and operational conditions. Friedman et al.[1,2] studied how the ambient gas temperature and oxygen content influence the ignition and subsequent combustion of aluminum particles ranging from 15 to 67μm. Roberts et al.[3] demonstrated that 20μm particles were ignited in oxygen using the reflected shock in a single-pulse shock tube near the end wall. The contribution of heterogeneous reaction to heat particles was significant at lower temperature, while may be neglected at gas temperature above 3000K. Maček et al.[4] observed the ignition and combustion characteristics of individual aluminum particles of 32-49μm diameter in a gas environment of known composition and temperature. Davis[5] used high-speed cinematography to observe the burning process of aluminum particles with initial diameters ranging 53-103μm.

The results obtained by different experimental methods are not consistent. There is no unified authoritative conclusion about the oxidation and combustion mechanism of aluminum, so the research on individual aluminum particle needs to be extended. At present, there are many experimental methods to unveil the combustion of individual aluminum particle, mainly including laser ignition[6], electric heating wire[7-8], flat flame burner [1-2], shock tube [9-10], stroboscopic lamp [11], hot air heating [12], etc. Legrand et al.[13] showed that the surface exothermic process plays a leading role in the aluminum combustion by an electric levitation and laser ignition system. Zhu et al.[7] used a high frequency induction heating wire to ignite a solid aluminum cylinder placed in the stagnation region of the oxygen/nitrogen mixture stream and recorded the ignition temperature. Friedman et al.[1-2] utilized two methods to obtain experimental data, one was to inject aluminum particles into the hot gas stream produced by the flat flame burner, and the other was to burn the particles in the combustion products of the ammonium perchlorate flame. The burning time of 10~100μm aluminum follows an exponential relationship to the diameter: t-$D^{1.2\text{-}1.5}$. Bazyn et al.[9] used the shock tube to study the flame radiation intensity and peak burning temperature of the aluminum with the size of 80nm ~ 40μm. Ohkura et al.[11] ignited nano-aluminum powder for the first time with a strobe light and provided direct experimental evidence to show that the oxidation follows melting dispersion mechanism. Derevyaga et al.[12] investigated combustion of aluminum in an inductor and in a stream of hot gas blown through a tubular electric furnace.

We found that the various methods and experimental devices have some defects: First, the various heating power is not convenient for immediate regulation, which leads to the inability to accurately control the heating rate. Second, the combustion process is difficult to control and record for individual aluminum particles whose size are below 10μm. This motivates us to conduct this work. In this study, an experimental setup was designed and built to make the laser accurately act on individual aluminum particles for heating. The laser power was varied by tuning the modulated current magnitude. The high-speed camera was used to record the ignition and combustion process. Digit image processing was utilized to obtain the parameters such as ignition delay time, ignition mode, flame propagation speed and flame characteristics of individual aluminum particles. The effect of heating rate on the ignition and combustion process of individual aluminum particles below 10μm is to provide a reference for exploring the ignition and combustion mechanism of aluminum and the application of submicron to 10μm in solid rocket propellants.

2 Materials and methods

The micron-sized aluminum was purchased from Changsha Tianjiu Corporation. Its purity reaches 99.8%, containing impurities of Fe, Si, Cu, O, etc. The schematic of experimental setup is shown in Fig.1. The laser is split into two beams. The dominant beam is again shaped by beam expander, dichroic and objective to focus on individual aluminum particle and ignite it. The other beam directly reaches the power meter to measure the ignition power. The high-speed camera was used to record the ignition and combustion of aluminum at 11, 000 fps. Lamp and condenser were utilized for clear imaging. Aluminum samples were placed into an open burner with atmospheric pressure and temperature. By evaluation, the burner wall has a negative impact on the ignition since its temperature rise around aluminum particle is below 2 ℃ in a short ignition period.

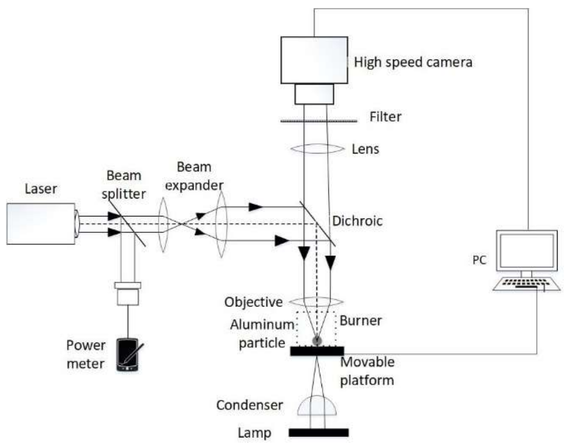

Fig.1 Schematic of experimental setup

3 Results and discussion

Figure 2 shows ignition and combustion process of an individual aluminum particle in a diameter of 6.82μm at low laser power density of $5.88 \times 10^5 W/cm^2$. The pictures obtained by digit imaging treatment are shown in Fig.3. The single aluminum particle looks like black and has high circularity (see Fig.2(a)). After heated by laser, the aluminum particle thermally expanded. The particle size significantly increased, and the particle was slightly depressed right above, as shown in Fig.2 (b). It indicates that the thermal expansion of aluminum is heterogeneous. As the aluminum particle was continuously heated by laser, the depression right above the particle bulged and the particle returned to a more complete circle. It suggests that the aluminum particle started to melt (see Fig.2(c)). During the period of Fig.2 (d) and (e), the particle edge became unsmooth. It might be inferred that the cracks occurred and resulted in the alumina thin film rupture. During the period Fig.2 (f)-(g), significant deformation right above the particle can be obviously observed, at which point the heated aluminum core melted into liquid aluminum and overflowed from the ruptured Al_2O_3 shell. At that moment of Fig.2 (h), more liquid aluminum overflowed, and the particle shape became irregular. In Fig.2 (i)-(k), the particle area increased again, at which time the aluminum particle almost melted to evaporate. Fig.2 (l)-(p) show a weak flare stood on the surface of aluminum particle and then extinguished. It can be inferred that the heat absorbed by the aluminum particle at this time is close to the ignition energy threshold under the condition. The individual aluminum particle was heterogeneously ignited.

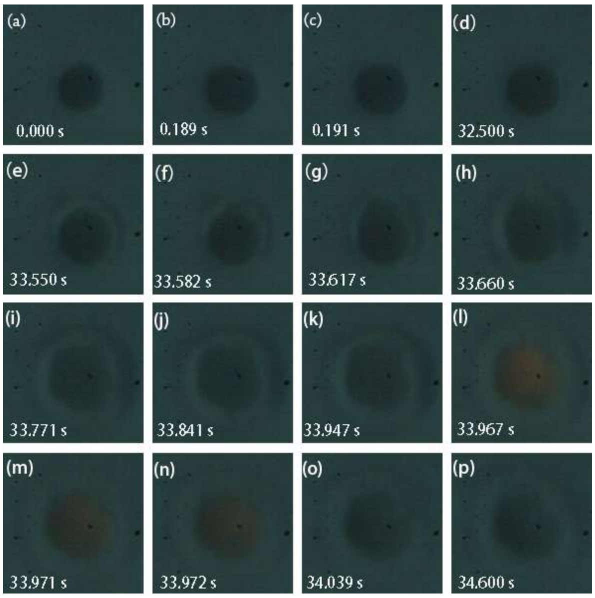

Fig. 2 Burning sequence of single aluminum particle

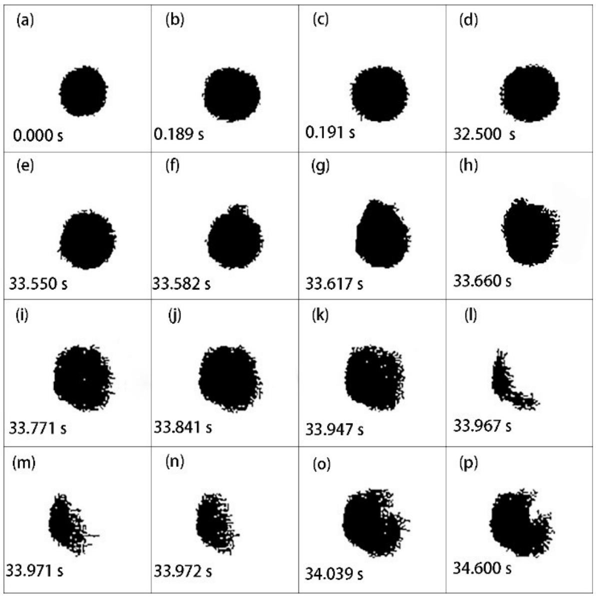

Fig. 3 The pictures after digit imaging treatment

In Fig. 3, it can be clearly seen that the whole process of the individual aluminum particle deformation. Due to the appearance of flame, covering the particle profile, the processed particle images might be irregular like crescent (see Fig.3 (l)-(n)). Figs.4 and 5 demonstrate another two cases as laser power density enhanced till 7.56 and $8.81 \times 10^5 W/cm^2$. The diameters of two aluminum particles are 6.67 and 6.25μm, respectively. It can be observed that individual aluminum particles have similar deformation like Fig.3 during ignition and combustion. The variation of particle size and circularity of individual aliminum particles with the heating time were summarized in Fig. 6. According to Figs. 2-6, the changes in particle size, shape and phase, aluminum particle undergoes several stages after being heated by laser: thermal expansion, alumina shell rupture, molten aluminum core overflow, shell melt and aluminum evaporation, ignition and combustion of aluminum vapor. Trunov[14] developed a simplified ignition model and assumed that ignition occurs when the particle's temperature exceeds the alumina melting point. It is consistent with the experimental observation shown in Figs.2-5. Rai et al.[15] demonstrated that prior to melting of aluminum, slow oxidation occurs due to the diffusion of oxygen through the aluminum oxide shell.

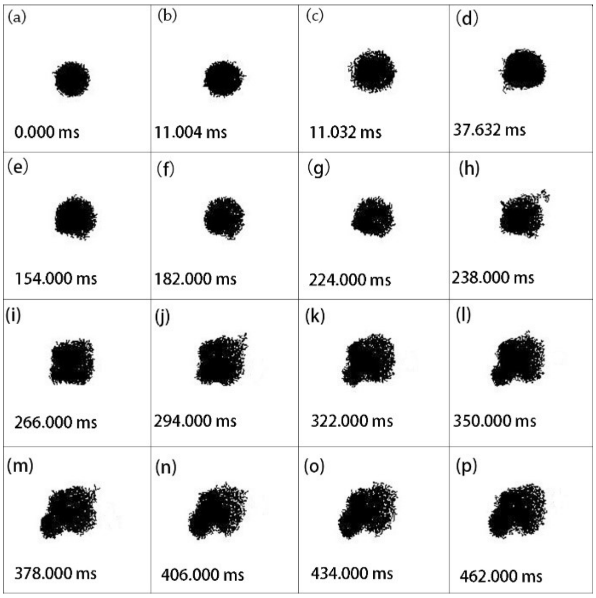

Fig. 4 Digit pictures for aluminum of 6.67μm

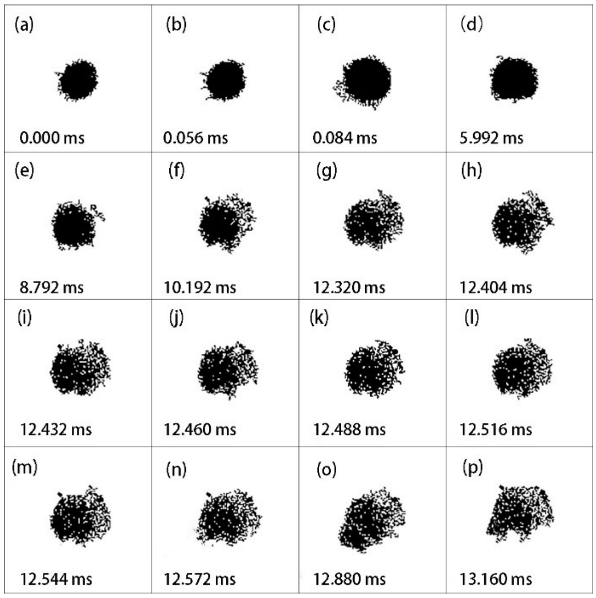

Fig. 5 Digit pictures for aluminum of 6.25μm

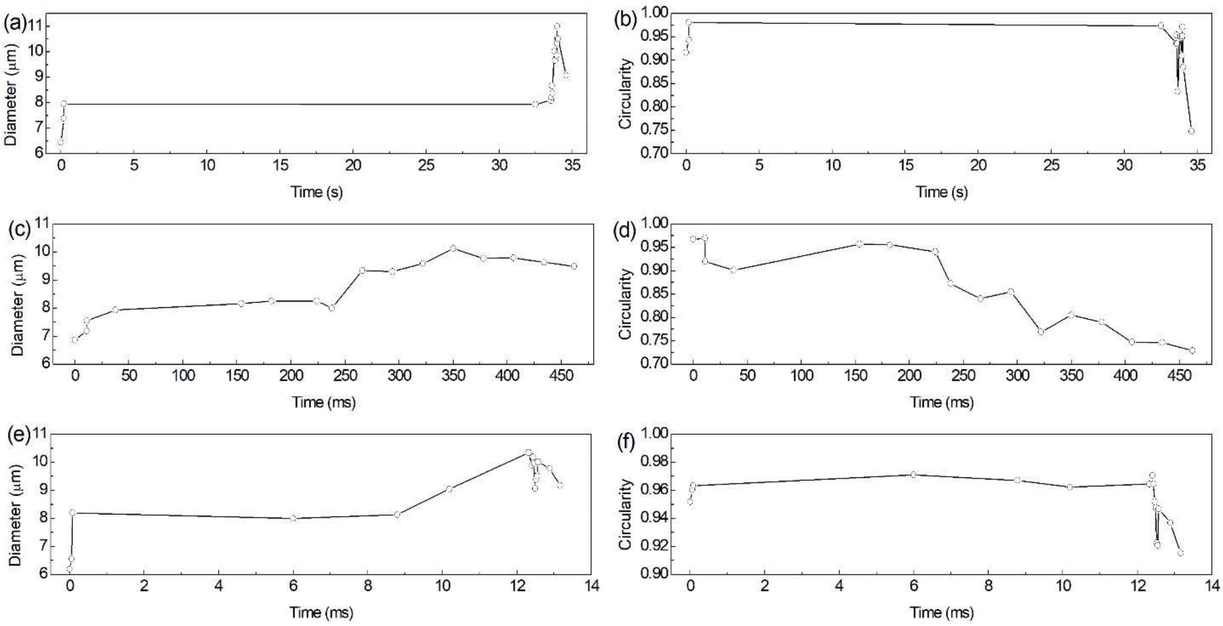

Fig.6 The variation of particle size and circularity of individual aliminum particles

The initial sizes of individual aluminum particles slightly decrease, 6.82μm - 6.25μm, however the heating power density of laser were gradually enhanced. Therefore, the temperature rise became more quickly for cases 1-3. The results show that the heating time required for the particle's equivalent size expanded to 150%

of the original one was shortened, 34s, 0.34s and 0.0125s, respectively. It indicates that the heating rate significantly affects the oxidation and combustion process of aluminum particles.

Figure 7 shows a typical photograph sequence of ignition and combustion of individual aluminum particle. When the laser power is 0.28 W and the ignition power density is 9.49×10^5 W/cm^2, the individual aluminum with a particle size of 10.4 μm will be ignited after 0.273ms (see Fig.7(b)). The flame appeared weak yellow at 1.909ms, and there was a bright yellow flame in the lower left corner of particle. This phenomenon is related to the metal ignition quasi-steady-state combustion model established by Woongsup [16]. At 2.546 ms, the aluminum particle was completely covered by yellow flame, indicating that convective heat transfer effects and surface heterogeneous reactions promote ignition, and the molten aluminum core is gradually exposed to the oxidant to cause it to enter the steady state combustion stage (see Fig.7(d)). At 3.091ms, the aluminum particle burned with severe flame and gas evolution (see Fig.7(e)); At 3.818ms, the combustion peaked, at which point the flame front was the largest and the brightness was the highest. The projected area of flame front was calculated according to the appearance of flame from Fig.7 (c) to the peak (f), and thus the flame diffusion rate reached 20.524mm/s. After the combustion reached its peak, the flame front gradually shrank (see Fig.7(g) and (h)), and the flame shrinkage rate was 10.556mm/s. At 5.0ms, the combustion extinguished.

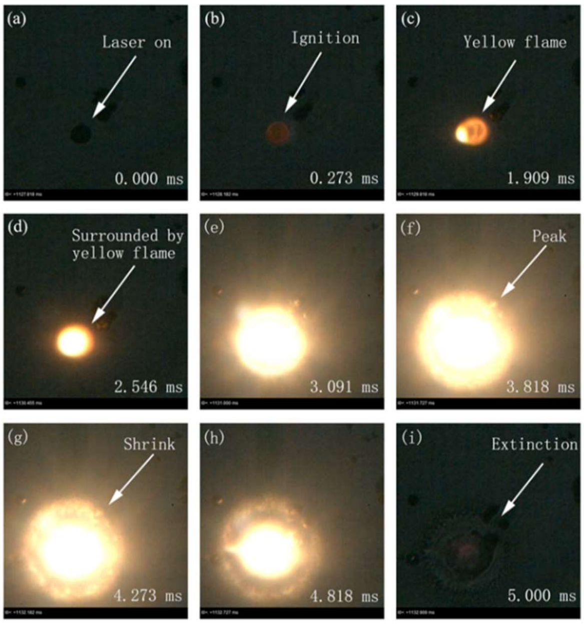

Fig.7 Photograph sequence of ignition and combustion of individual aluminum particle

4 Conclusions

Through laser ignition and combustion experiments on individual aluminum particles, the following conclusions can be drawn: (1) The experimental device and diagnosis method provide direct observation for investigating the ignition and combustion behaviors of individual aluminum below 10μm. (2) The thermal expansion and ignition of individual aluminum particles are heterogeneous. (3) Heating rates have a significant effect on the deformation, ignition and combustion of individual aluminum particles, while aluminum particles experience similar process to ignite through thermal expansion, shell rupture, melt, overflow and evporation etc..

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