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Aluminum Droplet Combustion in Normal and Low-gravity Environment

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Abstract: A study of aluminum droplet ignition and combustion through an advanced experimental technique in normal and low-gravity environment is presented. It was found that the gravity level greatly influences dynamics of aluminum droplet combustion and morphology of combustion products. In addition, the content and pressure of oxidizing environment also influence sizes, size-distribution, shape of combustion products.

Key words: aluminum droplet; combustion characteristic; gravity
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1 Introduction

Aluminum combustion is an important unresolved problem of the droplet-combustion science. A distinctive feature of aluminum (as some other high energetic metals) combustion is the formation of condensed products. Despite of great significance of this process for many applications (interior ballistics, pyrotecnics, ceramic technology) there is no theoretical model of the process[1] accepted commonly. It is due to the difficulties of experimental investigation. Some difficulties are associated with high values of temperature and concentrated gradients around burning particle that restricts application of the standard methods for diagnostics of chemical reactions. Other difficulties are associated with free, complicated streamline flow around the burning particle. To overcome these problems, an advanced experimental technique was used in this study which allows one to determine the thermal structure of reaction zones and the product morphology at the various moments of particle's ignition and combustion. This technique uses the laboratory-scale installation for multi-parameter study of single droplet combustion in low gravity environment[2,3]. There are two main reasons to investigate Al-droplet combustion in low- or micro- gravity environment. First, the microgravity gives a unique opportunity to avoid non-regular disturbances introduced in the combustion process by free convection. Such conditions, assumed in many theories[1], could provide a correct comparison of theoretical and experimental data. Second, preliminary experiments[3] have shown that morphology of condensed phase of combustion products significantly depends on gravity level and other characteristics of oxidizing gas-mixture. That is why the emphasis in this paper is on morphology of condensed phase of combustion products (c-phase) and their dependence on combustion conditions (in normal and low gravity environment).

The morphology characteristics have been determined by using the scanning and transmission electron microscopy. Peculiar clusters and longitudinal macro-aggregates of spherical microparticles have been found in the products of low-gravity combustion under high pressure. Geometrical characteristics of these aggregates and distribution of microparticles correlate with pressure of oxidizing environment.

2 Experimental set-up

The installation includes a dropping platform equipped for optical and thermal registration of droplet ignition and combustion (see Fig. 1). The dropping platform provides decreasing of gravity level to 0.01 g. Maximum duration of low gravity conditions is equal to 0.65 s that is enough to study ignition and combustion of the small droplets. A high-pressure combustion chamber and equipment for high-speed photo and cinema filming are placed on the dropping platform. The chamber keeps pressure up to 5.88 MPa.

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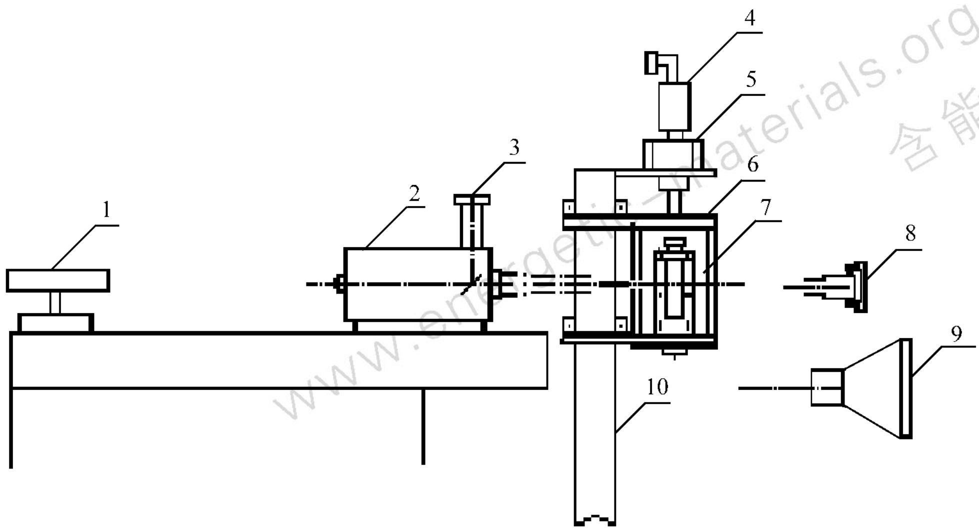


Fig. 1　Schematic diagram of the experimental set-up

1—alignment laser; 2—ruby laser; 3—radiation energy meter; 4—electromagnetic launching device; 5—lock; 6—dropping platform; 7—combustion chamber; 8—reflector; 9—control camera; 10—rail.

The particle ignition is executed by using the ruby-laser GOR-300 (the wavelength is 0.69 μm, the laser-pulse duration is 6 ~ 7 ms).

The combustion chamber, in Fig. 2, has a set of micro-thermocouples ((W + 5% Re)/(W + 20% Re), diameter 10 ~ 20 μm). The purpose of this set is to record the temperature distribution around the burning particle during its slow drift through the set in low-gravity conditions. A special unit is used in some experiments to fix a metallic droplet on micro-thermocouple during ignition and subsequent combustion. The thickness of that wolfram-rhenium thermocouple is equal to 10 μm. The droplet temperature was recorded during the lifetime of droplet.

The effect of gravity level on the c-phase formation is tested by use of the catching of burning particle on metallic plate at different instants of combustion process. The condensed product morphology is investigated by using scanning and transmission electron microscopy. The Philips microscopes SEM 515 and EM-430ST (operated at 200 kV) have been used for this purpose.

The ignition and subsequent combustion of aluminum particles from 0.2 to 0.8 mm have been studied in the oxygen mixtures: 20% oxygen and 80% argon (or helium, nitrogen, CO_2), under pressures from 98 kPa to 5.88 MPa in normal and low-gravity environment.

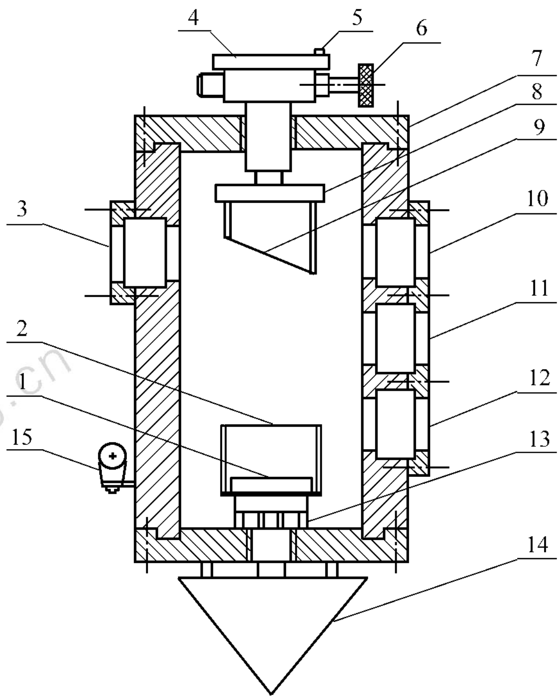


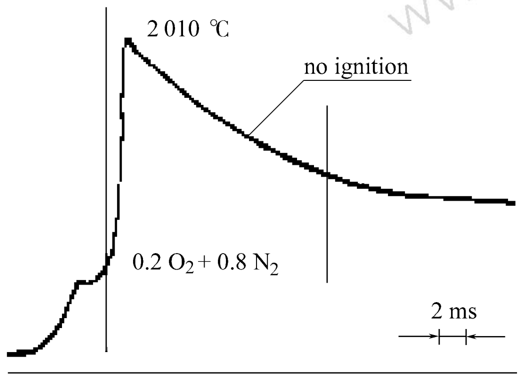
Fig. 2　Schematic diagram of the combustion chamber

1—plate for catching hold of condensed products of droplet combustion; 2—micro-thermocouples; 3—window for laser-beam irradiation; 4—unit to attach the chamber to electromagnetic lock; 5—contact sensor; 6—valve; 7—upper cap; 8—unit for particle fixing; 9—tested particle; 10, 11, 12—windows; 13—millwright unit for attachment of thermocouples set; 14—unit for chamber attachment to dropping platform; 15—reference lamp.

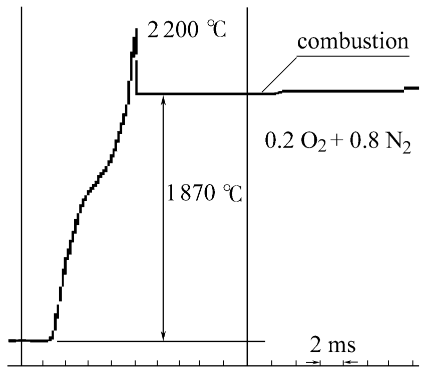
3 Results and discussion

3.1 Thermal characteristics of droplet ignition and combustion

Figure 3 presents two typical temperature-time curves of the droplet under pulse irradiation. The $T(t)$-curves indicate that temperature at the ignition moment is about 2 300 K ± 100 K. This fact correlates with melting temperature of Al_2O_3 (2 320 K) which coats the tested particles. The droplet temperature during combustion in 20% O_2 + 80% Ar environment is 2 390 K ± 50 K, which is lower than boiling temperature of aluminum (2 790 K) or its alloy Al + Al_2O_3 (< 3 250 K). The droplet temperature during the combustion in 20% O_2 + 80% N_2 environment under 98 kPa is 2 240 K ± 50 K, which is close to the ignition temperature of aluminum droplet: 2 300 K ± 100 K, but lower than aluminum boiling temperature.



(a)



(b)

Fig. 3 Temperature-time curves of aluminum particle under laser-pulse irradiation (droplet diameter is 0.4 mm)
(a) sub-critical irradiation; (b) super-critical irradiation.

The ignition and combustion temperatures of particle do not significantly depend on the gravity level. Meanwhile, in low-gravity environment (in contrast to the normal gravity) the temperature distribution around the particle is characterized by wide spatial scale. In addition, there are observed pulsations of the thermal radiation of particle during combustion. It is much expressed if gas pressure is higher than a critical one (0.49 MPa for 20% O_2 + 80% N_2). These clearly defined pulsations are (most probably) associated with the thermal hysteresis[4] of heterogeneous oxidation of aluminum.

3.2 Microparticles aggregates in combustion products

Reduction of gravity level influences most significantly the morphology of combustion products. Fig. 4 ~ 7 illustrate the products of Al-droplet-combustion in normal and low gravity environment. The scanning electron microscopy have shown that c-phase in low-gravity conditions consists of aggregates of spherical microparticles (sizes from 10 nm to 3 μm), and these microparticles form chains (10 μm in length) which look like fine fibers at low magnification (see Fig. 4). Aggregates of such fibers can form peculiar space-structures around a large nuclear particle of the products (about 3 μm). Such a structure (5 μm in size) looks like a dandelion in one case or a cellular frame in other case. Altogether these frames form a longitudinal (snake-like) macro aggregate (1 ~ 2 cm in length) (see Fig. 5). This structure is probably due to some drift of the burning Al-droplet through its own cloud of combustion products.

The indicated space structures are not observed in normal-gravity conditions. In such a case the sediment of droplet combustion products is uniformly distributed as separate particles or small aggregates (consisting of several particles) whose size is from 0.1 μm to 1 ~ 2 μm (see Fig. 6). In these aggregates sizes of contact surfaces are comparable with those of contact microparticles. The linear aggregates are not observed.

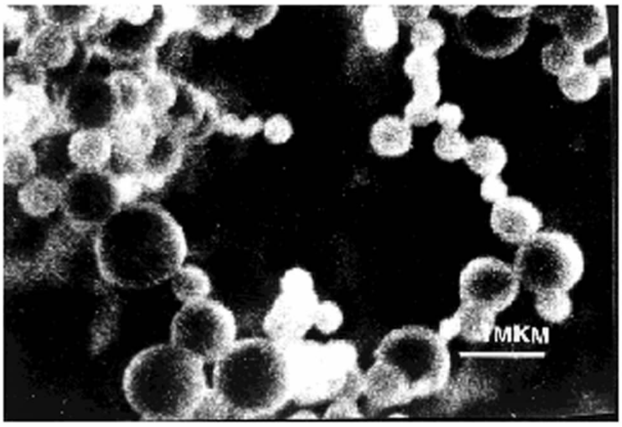


Fig. 4　The chains of microparticles
(p = 5.88 MPa, O_2 + Ar)

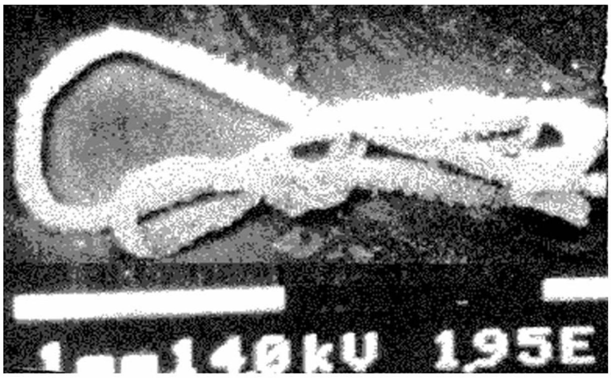


Fig. 5　Snake-like macroaggregate of microparticles
(p = 5.88 MPa, O_2 + Ar, low gravity, scale – 1 mm)

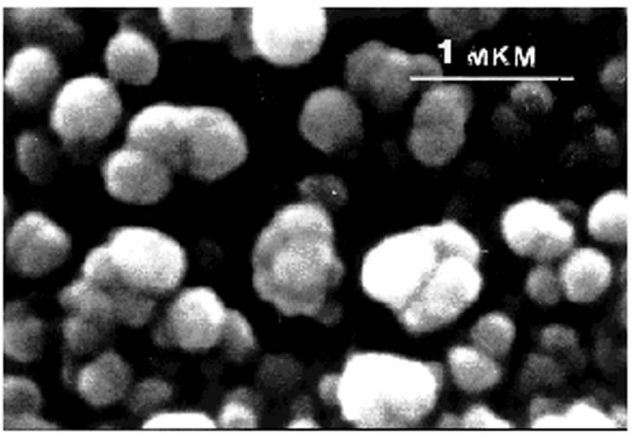
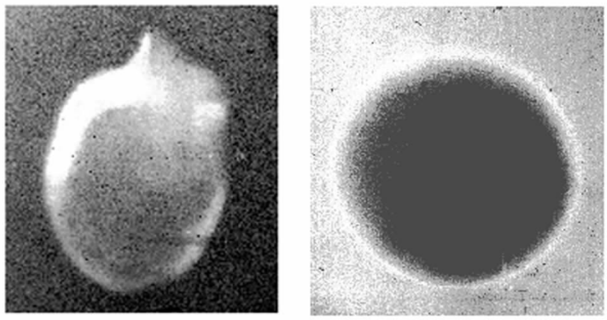


Fig. 6　Products of droplet combustion in normal gravity environment



(a)　　(b)

Fig. 7　Morphology of initial (a) and final (b) state of quasi-amorphous microparticle transformed in the TEM column: (a) dark field image of initial state of microparticle with Al_2O_3 skin layer (combustion under p = 5.88 MPa, O_2 + Ar, low gravity, particle size is 0.2 μm); (b) bright field image of final amorphous state, the particle size is 0.85 μm.

The snake-like macroaggregates are observed only in low gravity conditions if the gas pressure is high enough. It is found a correlation of geometrical characteristics of microparticles chains and aggregates with pressure of oxidizing gas. The mean size of spherical microparticles at 5.88 MPa (0.6 ~ 0.7 μm) is three times higher than that at 1.96 MPa. The size distribution of microparticles is more uniform at 5.88 MPa and 1.96 MPa than that at 3.92 MPa.

In all cases the investigated structures are quite stable against the long effect of electron beam of scanning microscope, which results, for example, in heating of tested sample. The chains of microparticles are strongly connected among themselves though the square of particles' contact is rather small (in contrast with normal gravity conditions, Fig. 6).

The analysis of diffraction patterns and images taken by transmission electron microscopy indicate that spherical microparticles can have crystallized or quasi-amorphous structure. The crystallized particles by their nature correspond to aluminum oxide, but also to pure aluminum. Typical size of such crystals formed under 5.88 MPa of 20% O_2 + 80% Ar is 0.2 ~ 0.3 μm. The quasi-amorphous particles have skin-layer of Al_2O_3 with hexagonal lattice. The dark field image of such a particle is presented in the Fig. 7 (a).

Significant difference must be noted in behavior of crystal and amorphous particles under electron beam in the TEM column. The crystal particles are quite stable against the long effect of electron beam of transmission microscope. In contrast with this, the image and diffraction pattern of quasi-amorphous particle are transformed under the electron beam. At first, the diffraction rings from the skin layer Al_2O_3 are blurred during 10 ~ 60 minutes which indicates total transformation of skin layer to amorphous statement. Then, during 5 ~ 6 hours, diameter of tested amorphous particle increases in 3 ~ 4 times, see Fig. 7 (b).

4 Conclusion

The gravity level significantly influences dynamics of aluminum droplet combustion and morphology of combustion products. Formation of chains, clusters and macro-aggregates of microparticles are observed in low-gravity environment. This phenomenon is expressed if gas pressure is high enough (1.96 ~ 5.88 MPa). The content and pressure of oxidizing environment influence sizes and shape of macro-aggregates as well as the size-distribution of spherical microparticles. These microparticles can be crystals (Al or Al_2O_3), or have quasi-amorphous structure. The state of quasi-amorphous microparicles is unstable under the electron beam of transmission microscope.

A treatment of obtained experimental data needs further development of Al combustion theory taking into account real droplet temperature during combustion process, kinetics of heterogeneous and bulk reactions, and presence of aluminum and aluminum oxide in wide region around burning droplet.

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铝液滴在常重力和失重环境下的燃烧

摘要: 通过一种先进的实验手段研究了铝液滴在常重力和失重两种不同环境下的点火及燃烧特性。结果表明,重力对铝液滴燃烧的动态特性及燃烧产物的形态结构有较大影响。此外,氧化环境的组分及压力也会影响燃烧产物的颗粒尺寸、粒度分布和形态。

关键词: 铝液滴; 燃烧特性; 重力