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Monitoring of Aluminum Nanopowder Combustion Ignited by Laser Radiation

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Abstract—The paper presents the results of observing, in a real time, the process of combustion in air of aluminum nanopowder ignited by laser radiation. The obtained results convincingly evidence the possibility and perspective of visualization of ignition process by means of laser monitor. The video images allow observing the main stages of the combustion process including starting of combustion in the place of laser radiation focusing, spreading of the heat wave and appearance of the second combustion wave. For quantitative analysis of the combustion process, we suggest to analyze the average intensity of images registered by laser monitor.

1. INTRODUCTION

Nowadays the keen interest of scientists is concentrated in nanoparticle industry. Particularly, aluminum-based materials offer a number of interesting and potentially high impact commercial opportunities [1–5]. Ceramic materials on AlN basis are among the most promising materials used as heat-removing dielectric substrates in microelectronics and optoelectronics [3]. A phenomenon of self-heating of aluminum nanoparticles and the resulting hydrogen is an interesting solution for pure hydrogen production. At the same time, AlN is an undesirable product in the combustion of solid propellants, thermites and explosives [1].

One of the methods of nanopowder combustion ignition is application of laser radiation [6, 7]. This method allows dispensing laser energy transfer to find optimal conditions for laser ignition. High temperatures (2200–2400°C) attained during aluminum nanopowder combustion and high reaction rate are the problems that complicate the study of the process. Observation of the combustion process in its own light is possible using camera and neutral filter in front of it. However, this method gives only a part of information about the process. Firstly, the temperature of the second combustion stage is much higher than the temperature of the first stage. Usage of a darker filter to observe the second stage does not allow us to observe the first stage properly, and vice versa. Secondly, using conventional video equipment, we observe an overview of a large surface, while it is interesting to get microscopic images of the surface during combustion. Therefore, there is a need to develop new research methods and techniques for visual control of nanopowder combustion.

Gaseous metal vapor active media have unique characteristics such as narrow natural bandwidth of amplification, high single pass gain, high pulse repetition frequency, operation in the visible spectral region, high average power and ability to control laser radiation parameters [8–11], which make these media appropriate for use as brightness amplifiers in laser projection microscopes and laser monitors [11–15]. The laser monitor combines a microscopic scheme, an illuminator and a narrow-band brightness amplifier. Thus, laser monitors allow investigation of the object surface through the flame or plasma and visualization of the processes shielded by intensive background lighting. In particular, they can be used to perform diagnosis of the substance surface burning with high intensity of light emission during

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the combustion process [15]. The presented earlier results of observing, in a real time, the process of aluminum nanopowder combustion in air proved that observation of microstructure formation processes by means of a laser monitor is quite accessible.

The present work is continuing of the work [15]. It presents the results about aluminum nanopowder combustion ignited by laser radiation.

2. EXPERIMENTAL DETAILS

During the experiments, the aluminum nanopowder in the form of a sample of rectangular elongated shape was placed on an aluminum substrate of 4 mm thickness. We used a similar nanopowder to that in [15]. The sample weight was more than 3 g, to provide the combustion duration enough for visual diagnostics.

The combustion process, including ignition, is accompanied by intensive background lighting. In this work, a compact laser monitor was used for real time monitoring of nanopowder combustion in the air. The laser monitor was built based on the laboratory-made copper bromide brightness amplifier. The gas-discharge tube had an aperture of 1.5 cm and a length of the active area of 50 cm. The tube generated 20 μJ pulse amplified spontaneous emission at 510.6 and 578.2 nm wavelengths operating at 20 kHz pulse repetition rate.

Ignition of the combustion process of aluminum nanopowder provided by 532 nm continues wave radiation of DPSS laser. The laser beam with an average output power 200 mW was focused on the sample in the area controlled by the laser monitor and aside. Fig. 1 shows the scheme of the experimental setup.

Recording of images was carried out using high-speed CMOS camera HiSpec Fastec 1 with the possibility of external synchronization. Video recording was enabled with an external trigger simultaneously with the opening of shutter.

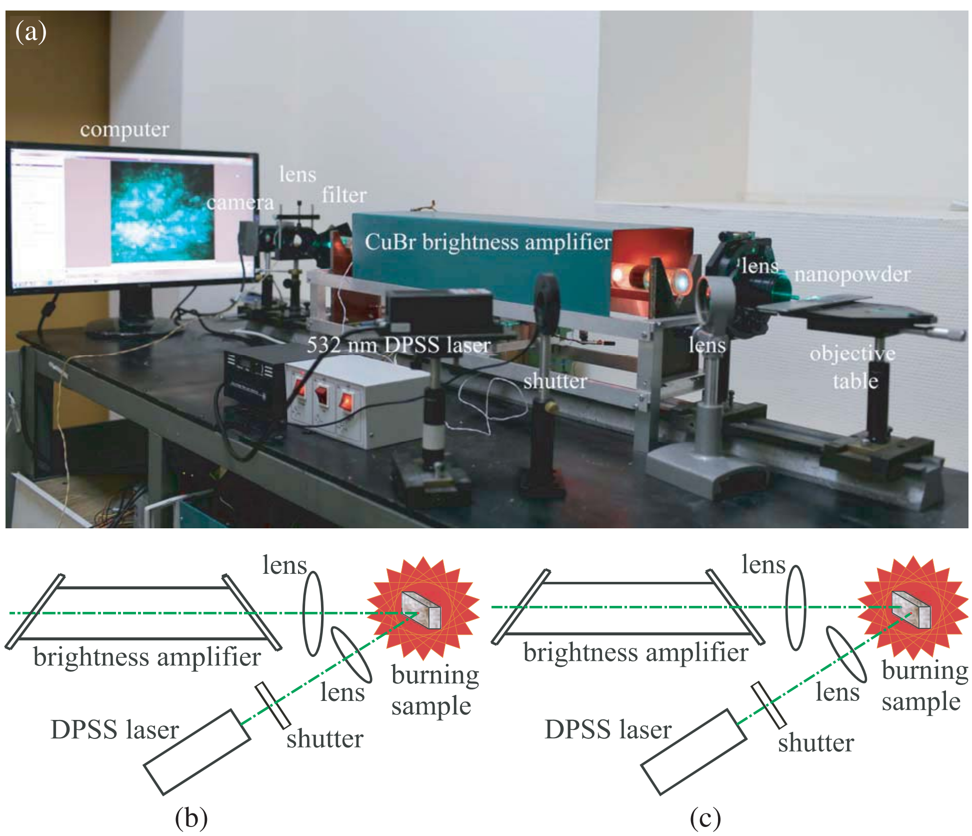

Figure 1. (a) Photo of the experimental set-up and (b) schemes of ignition in the point of observation and (c) aside.

3. RESULTS

Figure 2 shows frames of the high-speed imaging of the combustion process in its own light. The recording of the combustion in its own light (without laser monitor) was realized only by means of the high-speed camera with the Navitar DO-5095 lens (50 mm with manual focus) mounted directly on it. To prevent the camera saturation the low-pass filter was used. On the frames of high-speed recording, we can observe ignition of the low-temperature stage of combustion, its spreading, starting of the second high-temperature stage of combustion, and cooling. Evidently, the initiation of the combustion process takes place in the region of interaction of the laser radiation with the aluminum nanopowder. Then, the combustion front propagates along the sample until the edges of the sample are reached. At the edges of the sample, a large contact area of the burning substance with air is provided. Thus, the second combustion wave begins at the edges of the sample, and the origin of the second wave is not definite. The second wave can begin in several regions of the sample at the same time.

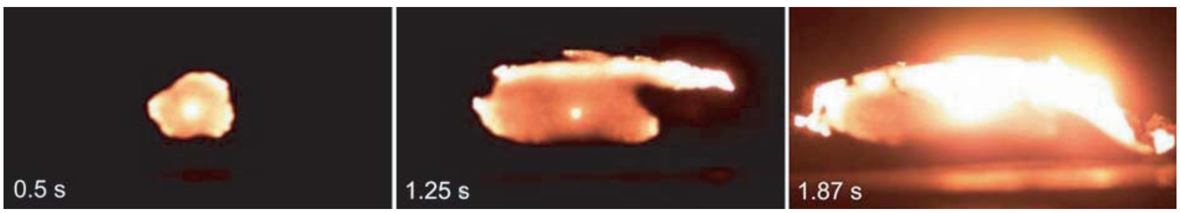

Figure 2. Frames of high-speed imaging of Al nanopowder combustion in its own light at different moments of time, relative to the ignition moment.

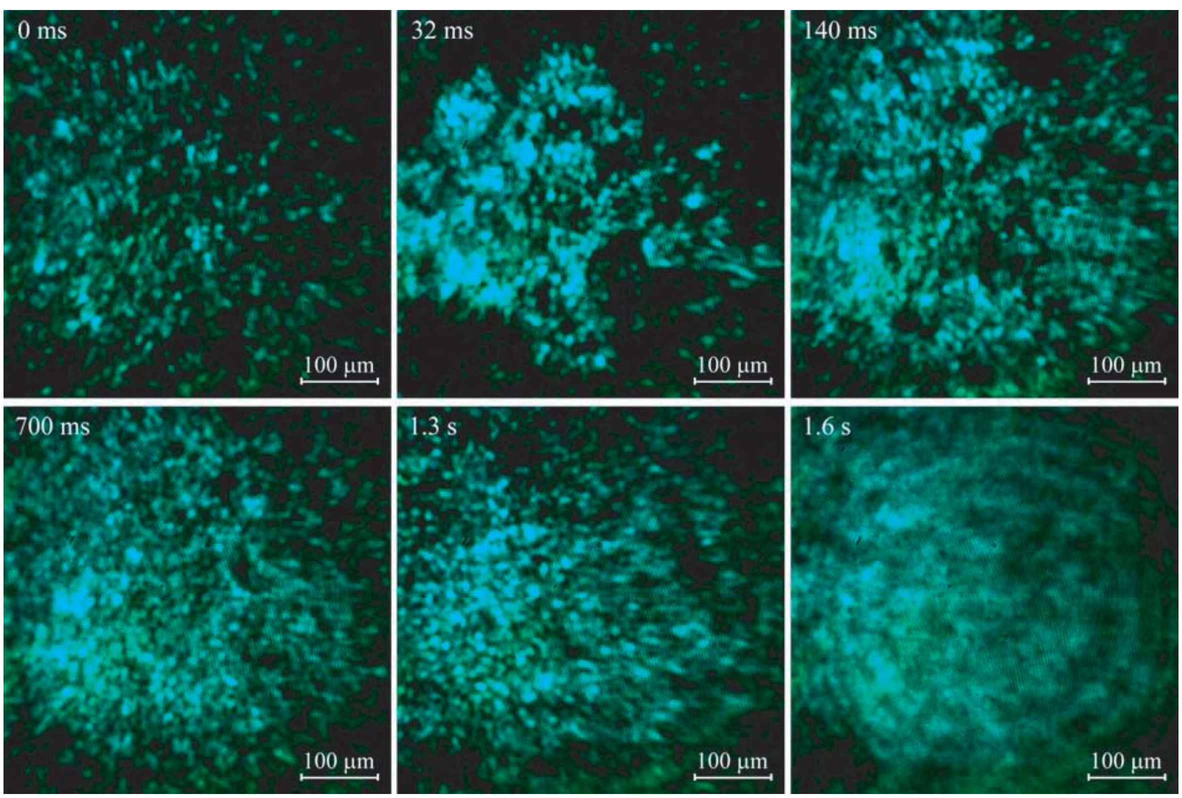

Figure 3. Frames of high-speed imaging of Al nanopowder combustion obtained by the laser monitor in the point of laser ignition at different moments of time. The first image corresponds to starting of laser ignition.

Thus, observing in its own light, we can qualitatively evaluate the nature of combustion, while the exact location of the source of ignition is not possible to estimate.

Figures 3 and 4 show some key frames of the high-speed recordings obtained by the laser monitor when ignition is in the area of view of the laser monitor (scheme in Fig. 1(b)) and aside (scheme in Fig. 1(c)). The objective lens with the focal length of 80 mm was used as an image-forming lens. The area under observation was about $0.5\,mm^2$. To ensure good quality of the observation of combustion waves and accuracy in estimation of their propagation velocities, the use of high magnification is not reasonable. Dimensions of the laser monitor field of view should be more than the width of the combustion wave at least by an order.

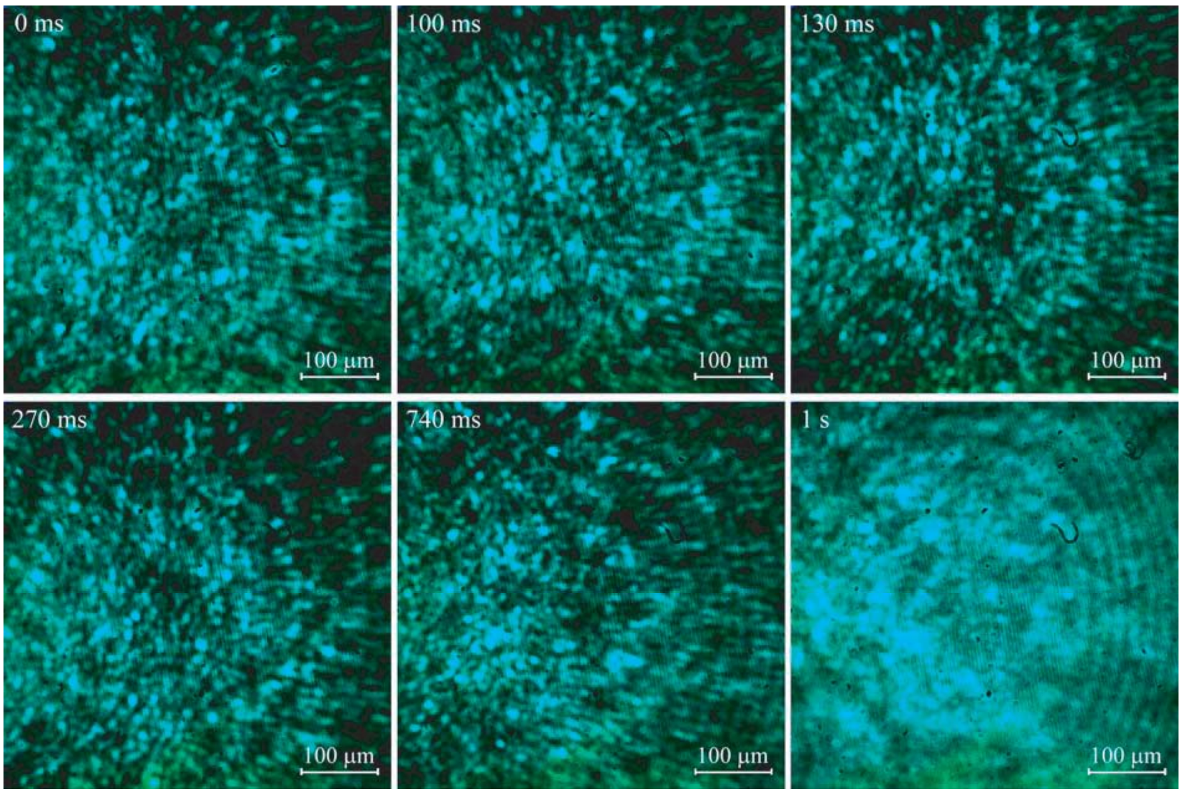

Figure 4. Frames of high-speed imaging of Al nanopowder combustion obtained by the laser monitor at different moments of time. The first image is the moment just before the visible modification of surface.

The main stages of the combustion process and their time parameters can be estimated visually using the image sequence recorded by the high-speed camera. The recording time of 2 seconds is enough to monitor the ignition and low-temperature stage of combustion, the transition to a high-temperature stage, and approximately 0.5 seconds of the high-temperature stage.

According to the principle of laser monitor operation, the change in the intensity of the laser monitor output signal, i.e., the total brightness of the image, correlates with the change in the reflection coefficient of the object under observation. As noticed in [15], the surface reflectance is changing during the combustion stages. In this connection, for the quantitative analysis of the combustion process, we suggest to analyze the average intensity of images registered by laser monitor.

Figure 5 presents the time-dependences of average intensity of images of the high-speed recordings corresponding to Figs. 3 and 4. As shown in Fig. 5, we can clearly identify the stages of combustion in the area of observation. Moreover, we can notice the difference in reflectance changing in the laser interaction area and outside. When monitoring in the area of ignition, the first low-temperature stage starts just after igniting laser switching on (Fig. 5(a)). The wave front propagation is accompanied by

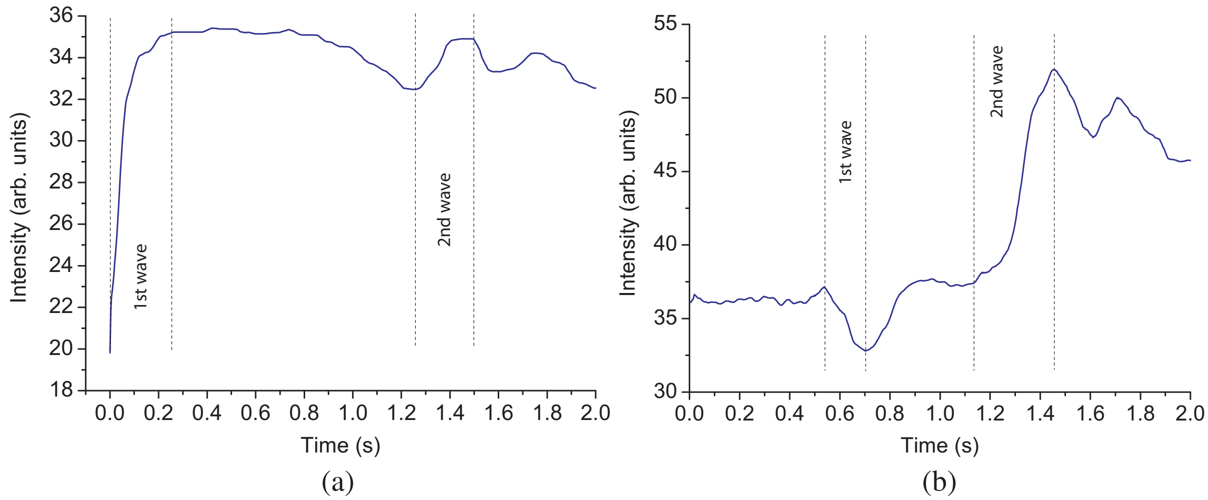

Figure 5. Average image intensity of high-speed recordings. (a) Monitoring in the area of laser ignition (scheme in Fig. 1(b)); (b) monitoring in the central area with ignition at the end of the sample (scheme in Fig. 1(c)).

increasing of reflection. After that the intensity is stable for some time, and then it starts to decline due to the powder moving. The next intensity growth signalizes the beginning of the second wave. When monitoring not in the area of ignition, the first wave needs some time to reach the area of observation (Fig. 5(b)). We can see the first wave front as declining of intensity. Between the first and second combustion waves, the powder can move changing the intensity. Rapid increase in intensity signals the starting of the second combustion wave.

4. CONCLUSION

The obtained results convincingly evidence the possibility and perspective of visualization of ignition process by means of the laser monitor. The video images allow monitoring the main stages of the combustion process including starting of combustion in the place of the laser radiation focusing, spreading of the heat wave and appearance of the second combustion wave.

Intensity of images registered by laser monitor is changing during the combustion process. Plotting the intensity graph, we can track the sample surface changing. This makes it possible to automate the measurements. Knowing the characteristic variations of intensity during the combustion process, it is possible to identify the corresponding stages of combustion. Using this method, it is possible to more accurately determine the temporal parameters of the processes in comparison with visual observation or video recording.

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