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ORIGINAL ARTICLE

Aluminum micro-particles combustion ignited by underwater electrical wire explosion

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Abstract The results of experiments on the ignition of aluminum micro-particles' combustion by underwater electrical wire explosion (UEWE) are reported. A compact sub-microsecond timescale duration high-current (240 kA) pulsed power generator was used to explode copper and aluminum wires electrically in different aluminum powder suspensions. The combustion of the aluminum micro-particles was characterized by a target time-of-flight method and optical measurements of the exploding wire and aluminum suspension light emission. It was shown that, by using a proper solution and type of aluminum powder, this method allows aluminum micro-particle combustion in the estimated range of 32–79 % efficiency.

Keywords Electrical wire explosion · Aluminum combustion · Water · Aluminum powder · Shock waves

1 Introduction

Many papers and reviews were devoted to the subject of the reliable ignition and combustion of aluminum powders dispersed in water [1–11]. It is well known that when Al_2O_3 is formed as a product of the combustion of pure aluminum with oxidizers, a large amount of energy is released as a result of exothermic reaction. For the suspension of aluminum micro-particles in water one obtains the following exothermic chemical reaction [12]:

$$2\text{Al (solid)} + 3\text{H}_2\text{O (liquid)} = \text{Al}_2\text{O}_3\text{ (solid)} + 3\text{H}_2\text{ (gas)} + \text{Q (15kJ/g)}, \quad (1)$$

The ignition of the combustion can be achieved by the heating process produced by shock waves (SW), strong radiation, or by another body that provides a temperature that is sufficiently high, which is close to the aluminum boiling point of 2,467 °C. Thus, the first requirement for successful ignition of the aluminum powder is to achieve and sustain a high temperature at the surface of the aluminum micro-particles. In earlier papers by Belyayev et al. [2], one can already find the experimental dependencies of aluminum micro-particles' ignition and combustion times on temperature, pressure, concentration of oxygen in the background medium, and the aluminum micro-particle size. For instance, the authors state that inside a high-temperature ($T > 2{,}000$ K) flux consisting of H_2O and CO_2 the combustion time t_c of aluminum particles does not depend on the temperature and pressure (for $P > 2 \times 10^6$ Pa), but does depend strongly on the diameter of the particles as: $t_c(\text{ms}) = 0.67[d^{1.5}(\mu\text{m})/a_c^{0.9}]$, where d is the diameter of the aluminum micro-particle and a_c is the oxygen concentration. For the ignition time, the empirical expression $t_{ign}(\mu\text{s}) = 3.6d^2(\mu\text{m}) \times \exp[32{,}000/(RT)]$, where R is the gas constant and T is the temperature, was suggested. Gurevich et al. [3] suggested an experimental dependence for the threshold temperature $T_{cr} = T_m - 0.6 - C_k^{0.3}\lambda^{-1} d \times \exp(-0.85d^{1/2})$ for the beginning of the aluminum particles combustion in air. Here $T_m = 2{,}300$ K is the melting temperature of Al_2O_3, C_k is the relative concentration of the oxygen in the background media, $d(\mu\text{m})$ is the diameter of the particle, and λ [Cal/(cm s deg)] is the coefficient of thermal conductivity of the background medium at $T = 0.5T_{cr} + 0.5(T_0 + T_m)$, where $T_0 = 293$ K. In Ref. [9], it is stated that 3–10 kJ/g is required to ignite the combustion of aluminum micro-particles. In their studies, Fedorov

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et al. [13,14] showed that the time delay t_{ign} of the aluminum micro-particles ignition depends on the value of T of the ambient medium and the dimensions of the micro-particle. The obtained dependence of $t_{ign} = f(T)$ for aluminum micro-particles with a typical size of 7 μm can be approximated as $T = 1{,}784 + 125.8 \times \exp[-(t_{ign} - 1.5)/0.0775]$, resulting in $t_{ign} \leq 10^{-7}$s at $T \geq 2{,}600$ K. In addition, it was shown that for T = const the smaller the particle dimensions are, the smaller is the value of t_{ign}. Another important finding was that when aluminum powder (5–20 μm) is ignited by SW, the velocity of the latter should be $V_{SW} > 3.4c_0$ and the energy density of the SW should be >10 J/cm^2. Here c_0 is the sound velocity of the medium. The time required to combust completely an aluminum particle can be estimated roughly using the maximum oxidation rate (reactivity) R_{oxid} of the Al. For instance, at $T \approx 2{,}000$ K, the highest reactivity is 0.5 mg/min, which results in a time of ∼120 ns for the combustion of a 1 μm-radius aluminum micro-particle. Thus, one can conclude that by choosing the aluminum micro-particles' concentration, size, water temperature, and pressure properly, one can achieve reliable control of the process of ignition and combustion of Al.

The studies cited above, which were carried out in the $10^{-3} - 10^{-5}$ s timescale, showed that ignition of aluminum particles can be achieved also in the range of $10^{-6} - 10^{-7}$s if sufficient energy is delivered to these particles of several microns' size. Thus, one can consider applying underwater electrical wire explosion (UEWE) to achieve fast ignition of aluminum powder combustion. Indeed, UEWE is characterized by fast phase transitions of the exploding wire resulting in formation of a wire plasma with a temperature of several eV, pressure up to 5×10^8 Pa, and SW with pressure at the front up to 5×10^9 Pa [15].

In our preliminary research, a planar wire array was exploded electrically under water to verify the combustion of the aluminum wires. The purpose of these experiments was to compare the mechanical energy acquired by a target placed a few mm above the exploding array. This target was accelerated by the water flow generated by the underwater electrical explosion of either a copper or aluminum planar array. These experiments were carried out using a high-current generator (stored energy of ∼4 kJ at 28 kV charging voltage) producing a current pulse with an amplitude of ∼350 kA and rise time of ∼1,000 ns at short-circuit load [16]. A 40 mm-long wire array was made of 40 wires of either copper (100 μm in diameter) or aluminum (127 μm in diameter). Explosion of these wire arrays led to an aperiodic discharge, with ∼70 % of the stored energy being deposited into the array within ∼500 ns.

Typical waveforms of the discharge voltage, current, delivered power, and energy in the case of copper and aluminum wire array electrical explosions are shown in Fig. 1. One can

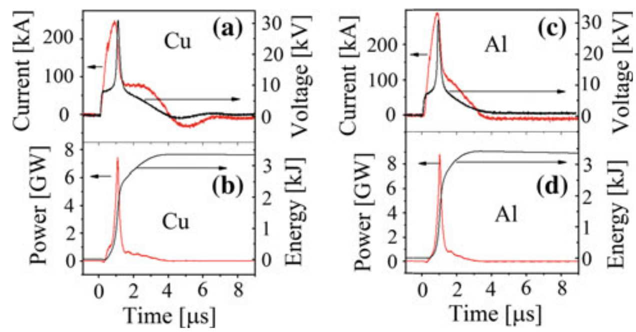

Fig. 1 Typical waveforms of the discharge current and discharge voltage for (**a**) copper wires and (**c**) aluminum wires. Deposited power and energy for (**b**) copper wires and (**d**) aluminum wires

see almost the same discharge parameters in both copper and aluminum wire array explosions.

The water flow generated by the wire array pushes a target constituting either a stainless steel rod with a diameter of 8 mm or an aluminum disk with a diameter of 29 mm. The target was immersed in the water and placed above the array at a distance of 10 and 8 mm in the case of the stainless steel rod and the aluminum disc, respectively. The kinetic energy of the target accelerated by the SW was measured using two methods, in the first of which the time-of-flight (TOF) of the rod was observed using a multi-frame fast 4Quik05A camera (frame duration of 1 μs, time interval between frames of 0.3 ms) in the experimental setup shown in Fig. 2.

Typical multi-exposure frames of the rod during its TOF are shown in Fig. 3. One can see significantly faster rod propagation in the case of the aluminum than in the case of the copper wire array explosion. The TOF data were used to calculate the target velocity showing a ∼38 % increase in the velocity of the rod in the case of aluminum wire explosion, which corresponds to a 1.9-fold increase in the rod's kinetic energy.

In the second method of measuring the target kinetic energy [15], a series of thin current-carrying wires were used

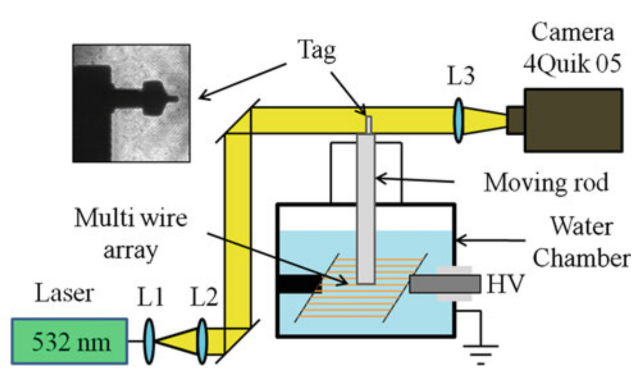

Fig. 2 Experimental setup. L1, L2 are the lenses for the laser beam extension. L3 is the imaging lens. M1, M2 are the mirrors

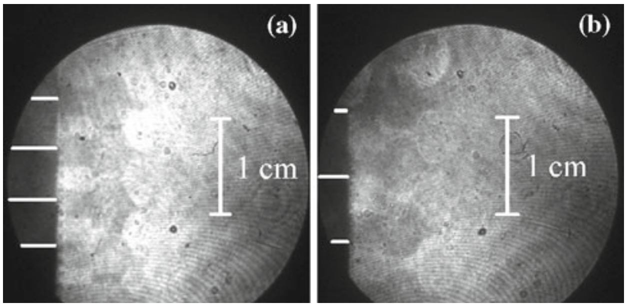

Fig. 3 Overlaid image of the target positions after the copper (**a**) and aluminum (**b**) wire array explosion. Time delay between frames is 0.3 ms, frame duration is 1 µs

that disconnected a part of an external electrical circuit each time a wire was destroyed by the moving target. Thus, the time delays between the current interruptions in the wires were used to obtain the target TOF. This method showed similar results for the increase in the kinetic energy of the target [16]. The latter can be explained only by an increase in the energy delivered to the water flow due to the aluminum combustion process. Similar results were obtained for a rod with an increased cross-sectional area and for a rod placed at larger distances (up to 30 mm) from the exploding wire array.

However, the question related to the ignition of the aluminum micro-particles and water solution using sub-microsecond UEWE remained unanswered. In the present paper, results of successful sub-microsecond ignition and combustion of aluminum micro-particles water suspension using UEWE are presented.

2 Experimental setup

Experimental research of aluminum micro-particle ignition using UEWE was carried out using the same setup as in earlier research with a high-current generator (see Sect. 1). The discharge current and voltage were measured using a self-integrated Rogowski coil and a Tektronix high-voltage divider, respectively. The resistive voltage was calculated by subtracting the inductive voltage, taking the constant inductance of the wire array into account. In the experiments, two types of single wire were used: aluminum and copper. The length and diameter of the wires were optimized to obtain an aperiodic discharge when maximal power release is achieved and when almost all the energy stored in the generator is transferred to the exploding wires [17]. The parameters of the wires are listed in Table 1, and the scheme of the experimental setup is shown in Fig. 4.

The ignition process was tested using three types of aluminum powders: powder P01 produced by "ALEX Ltd" (Russia) with an average micro-particle size of 0.1 µm (measured density $\rho = 0.21$ g/cm^3); powder P11a purchased from Alfa Aesar with an average micro-particle size of 11 µm ($\rho = 1.27$ g/cm^3); and STREM Chemicals, Inc. powder P11b with an average micro-particle size of 11µm ($\rho = 1.59$ g/cm^3). In the present experiments, different concentrations of aluminum powder-water suspension were tested: 1/1, 1/6, and 1/9. Let us note that, according to the stoichiometry [see (1)], the optimal mass ratio between the water and aluminum powder is 1/1, with a maximum energy release of ∼15 kJ/g, depending on the aluminum powder properties. The prepared aluminum powder-water suspension was used to fill a dielectric tube with a diameter of 6 mm, and a copper or aluminum wire placed at the tube axis between the high-voltage and grounded electrodes (see Fig. 4).

Table 1 Wire parameters

Wire parameters	Cu	Al
Wire diameter, mm	0.6	0.8
Length of wires, mm	40	40
Initial resistance of the wire, mΩ	2.4	2.2
Initial mass of the wire, g	0.1	0.05
Energy of sublimation, J	580	650

In order to determine the effect of the aluminum powder combustion, a stainless steel rod with a diameter of 8 mm, length of 30 cm, and weight of 190 g was placed on a movable grounded electrode. The time-dependent position of the rod was measured by a continuous-wave (CW) laser beam (532 nm) and a Hamamatsu photo-multiplier tube (PMT) R7400-U-0.4 (see PMT1 in Fig. 4). The laser beam passes through a vertical slit located in front of the rod. A blade knife was connected on the upper surface of the rod in such a way that it partially blocked the laser beam when the rod was moving. A decrease in the laser beam intensity was registered by PMT1. The velocity of the rod was determined by the rate in the change of the PMT1 voltage. Prior to each experiment, the response of PMT1 to the laser beam intensity was measured at different rod positions at steps of 1 ± 0.01 mm using a thumbscrew connected to the rod. The total path of the rod used for the measurements was 8 mm. After the calibration had been completed, the thumbscrew was disconnected from the rod. Finally the rod's velocity was determined as $V_{\mathrm{r}} = \left[\mathrm{d}\,(\mathrm{PMTsignal})/\mathrm{d}t\right]/\left[\mathrm{d}\,(\mathrm{PMTsignal})/\mathrm{d}h\right]$, where $\mathrm{d}\,(\mathrm{PMTsignal})/\mathrm{d}h$ was calculated using the dependence of the laser beam intensity on the rod position h, which was obtained during the calibration procedure. Lenses L1 and L2 and the pinhole P with a diameter of 10 µm (see Fig. 4) were used as a beam expander and a spatial filter, respectively. Lens L3 was used to collect the transmitted laser beam and to focus it on the PMT photocathode. To avoid ambient light, a 532 ± 1.5 nm laser interference filter was placed at the PMT entrance. During the calibration

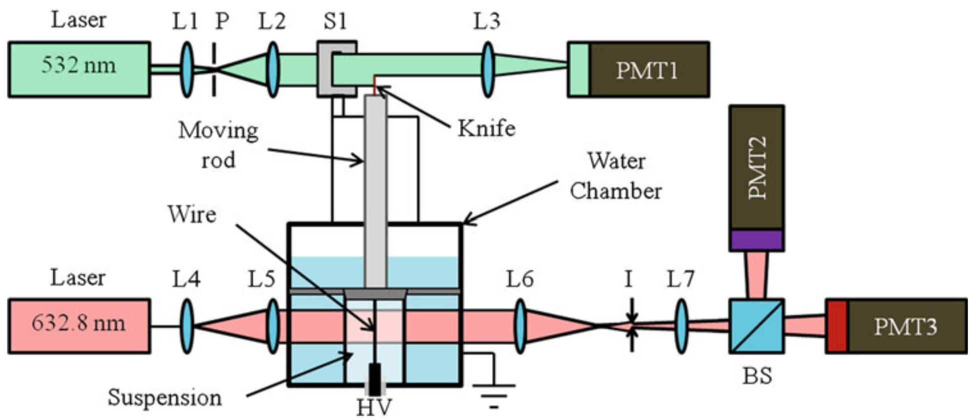

Fig. 4 Experimental setup with single UEWE and aluminum powders suspension

procedure, the CW laser beam was modulated by a series of pulses with a duration of ∼1 ms using a vent as a shutter.

In addition, the intensity of the light emitted from the exploding wire and aluminum suspension was measured using two PMTs coupled to interference filters of 410 ± 5 and 656 ± 5 nm in order to determine the Planck temperature. This optical system was aligned using a 632.8 nm CW laser without filters in front of the PMTs. Lenses L4 and L5 were used to expand the laser beam and parallelize it. Lens L6 was used to image the area close to the exploded wire without magnification. An iris diaphragm, I, was placed at the image plane to determine an observation region, 3 mm in diameter, around the exploded wire. When the dielectric tube was filled with an optically opaque aluminum suspension, the observation region could be considered as the outer border of the suspension. Lenses L6 and L7 collected and transferred the light emission that passed through the iris to two PMTs using a cube beam splitter (see BS in Fig. 4). This optical setup, including optical windows, water, lenses, and the PMTs, was calibrated using an etalon Oriel QTH200 lamp. In this system, a vent was also used to ensure the linear mode of the PMTs' operation during the calibration prior to the generator shots. In experiments with the aluminum suspension, the calibration of the PMTs was not possible because of the opacity of the suspension. Thus, this calibration was carried out only when the wires were exploded in de-ionized water. Narrow pass band interference filters F2 (410 ± 5 nm) and F3 (656 ± 5 nm) were placed in front of PMT2 and PMT3, which were supplied by a dc voltage of 500 V.

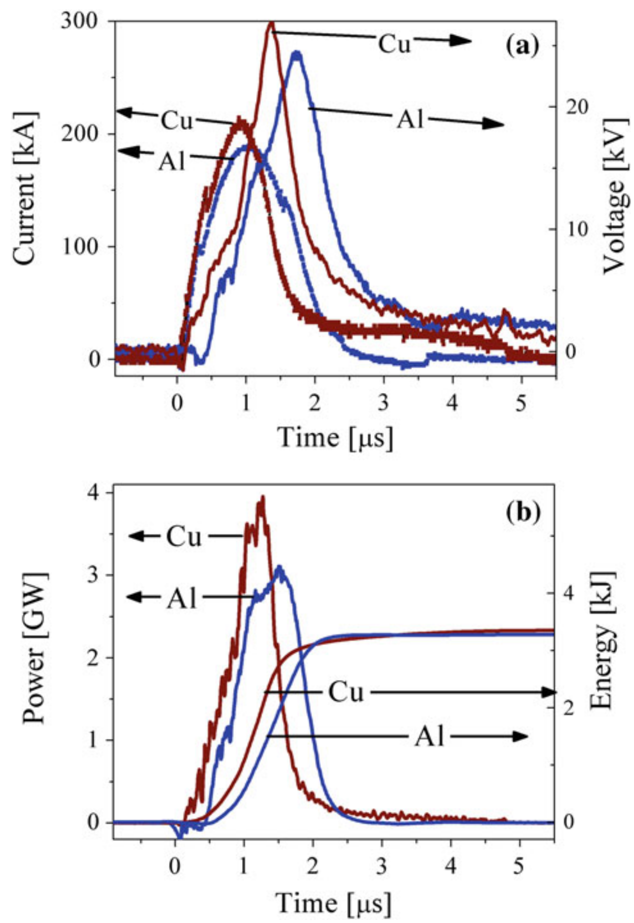

Fig. 5 Typical waveforms of (**a**) the discharge current and resistive voltage and (**b**) the power and deposited energy in the cases of copper and aluminum wire explosions

3 Experimental results

Typical waveforms of the discharge current and voltage and the temporal behavior of deposited power and energy in the cases of copper and aluminum wires explosions in deionized water are shown in Fig. 5.

The same data were obtained for copper and aluminum wire explosions in aluminum powder suspensions. This indicates the absence of a shunting plasma channel whose formation in aluminum suspension could be expected. Typical waveforms obtained by PMT1 that show a decrease in the laser light intensity because of the light screening by the rod motion are presented in Fig. 6.

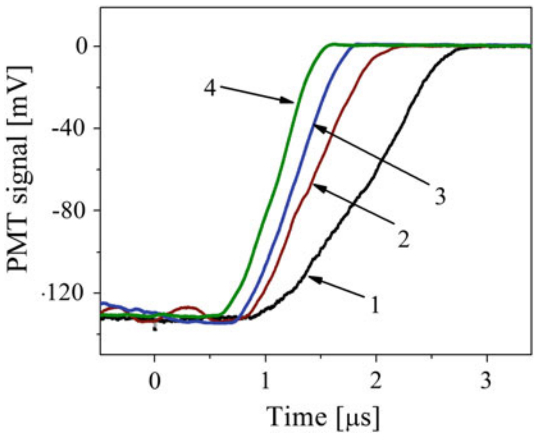

Fig. 6 Typical waveforms of the laser intensity recorded by PMT1. *1* Copper wire explosion in de-ionized water; *2* aluminum wire explosion in de-ionized water; *3* copper wire explosion in aluminum/water suspension (composition aluminum powder P11b/water: 1/1), *4* aluminum wire explosion in aluminum/water suspension (composition aluminum powder P11b/water: 1/1)

The velocity of the rod was used to calculate the kinetic energy E_{kin} transferred to the rod. The results of the experiments with different wire explosions in de-ionized water and in different aluminum powder suspensions are summarized in Table 2. One can see that the best result, i.e., the largest velocity acquired by the rod, was obtained in the experiments with an aluminum wire electrical explosion in a P11b/water suspension ratio of 1/1. Indeed, one can see that the velocity of the rod obtained in the experiment with the P11b/water suspension ratio of 1/1 is ~2.1 times larger than the velocity of the rod in experiments with copper wire explosion in pure water, and 1.5 times larger than in experiments with aluminum wire explosion in de-ionized water. In the latter case, one can expect aluminum wire combustion as well. These data indicate successful aluminum powder ignition and combustion. Let us note that in the experiment with aluminum wire electrical explosion in a P11b/water suspension ratio of 1/1, the greatest damage to the experimental setup was obtained, which indirectly indicates the release of additional energy during this shot. Here, m_{Al} is the mass of aluminum powder used in each shot; $I_{\max}$ is the maximum amplitude of the discharge current; $P_{\max}$ and E are the power and energy deposited into the wire; and V_{r} and E_{kin} are the rod average velocity and kinetic energy, respectively.

Typical waveforms of light emission from exploding copper and aluminum wires in water without the aluminum powder suspension are shown in Fig. 7. One can see that in the copper wire explosion the radiation begins near the maximum of the discharge current and the duration of that radiation pulse at the full width at half maximum (FWHM) is ≤ 0.6 μs. In the aluminum wire explosion, the first intense pulse of radiation is followed by a second long (up to ~80 μs) duration light emission. This long-duration light emission can be related to aluminum wire combustion and agrees well with earlier results [18].

The typical light emission observed in the experiment with copper wire and a powder P11b suspension explosion (concentration water/power of 1/1) is shown in Fig. 8. A rather strong second radiation pulse with an FWHM of ~50 μs that begins with a time delay of ~30 μs with respect to the termination of the first radiation pulse can be seen. The latter appears when the copper wire explosion begins. It is possible that the delay in the second radiation pulse appearance is related to the suspension opacity. Namely, it is reasonable to assume that the aluminum powder ignition and combustion start in the vicinity of the exploding wire with an intensity significantly smaller than the intensity of the radiation emitted by the exploding wire. Only when the combustion process proceeds outward to larger radii can one expect to obtain radiation resulting from the aluminum combustion. The ratio of light intensities at wavelengths of 410 and 656 nm were used to estimate the temperature of the light emission source assuming black body radiation. These estimates showed that this temperature is in the range 4,000–5,000 K. This temperature is significantly larger than that required for

Table 2 The results of experiments with copper and aluminum wires explosions in de-ionized water and in different aluminum powders suspension

Experiment	m_{Al}, g	$I_{\max}$, kA	$P_{\max}$, GW	E, kJ	V_{r}, m/s	E_{kin}, J
Cu wire + water	–	210	3.5	2.5	5	2.4
Al wire + water	0.054	190	2.3	2.7	6.9	4.5
Cu wire + P01/water suspense ratio 1/9	0.04	200	3.7	2.9	4.1	1.6
Cu wire + P01/water suspense ratio 1/6	0.06	200	3.2	2.7	5	2.4
Cu wire + P11a/water suspense ratio 1/6	0.13	190	3.3	2.7	5.2	2.6
Cu wire + P11a/water suspense ratio 1/1	0.47	200	3.0	2.4	6.7	4.3
Cu wire + P11b/water suspense ratio 1/6	0.17	200	4.0	2.7	6.9	4.5
Cu wire + P11b/water suspense ratio 1/1	0.59	200	2.5	2.7	9.2	8.0
Al wire + P11b/water suspense ratio 1/1	0.64	220	–	–	10.4	10.3

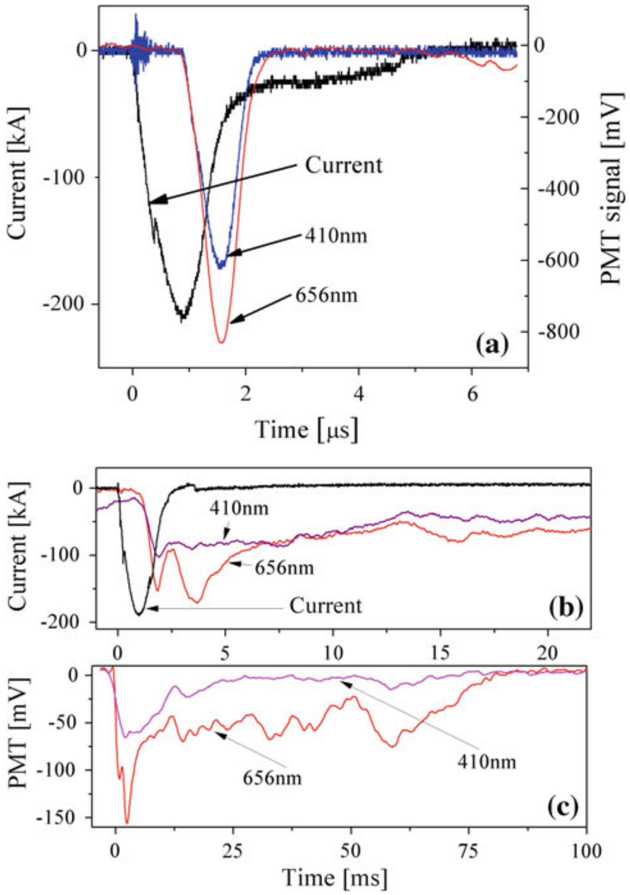

Fig. 7 **a** Typical discharge current and PMTs waveforms of light emission for copper wire electrical explosion in water. Typical discharge current and PMTs waveforms for aluminum wire explosion in water: short (**b**) and long (**c**) timescales

aluminum micro-particles ignition and combustion, namely, 500–2,300 K, depending on the ambient pressure and size of the aluminum particle. Nevertheless, numerical simulations [19] showed that one can obtain a significantly higher combustion temperature, namely, up to 4,500 K, which can be even higher when the ambient pressure is increased.

Here let us note that experiments with copper wire and different suspension concentrations of aluminum powder P01 having the smallest (≤ 0.1 μm) micro-particle sizes did not show any evidence of ignition of the suspension. Indeed, the intensity of the light emission observed in these experiments was negligibly small, indicating the absence of aluminum powder combustion. These results agree with the absence of a difference in the rod velocities obtained in copper wire explosions in de-ionized water and in powder P01 suspension. In addition, experiments with the powder P01 suspension with ratios of 1/6 and 1/1 were carried out with explosion of a copper wire having a diameter of 50 μm. In this case, an approximately periodical discharge with a period of ~ 4 μs was realized because the wire explosion was followed by a fast breakdown of the discharge channel and formation of highly conductive plasma. Nevertheless, also these experiments showed negative results for aluminum powder P01 combustion. That is, neither a long duration radiation pulse nor an increase in rod velocity was obtained. In fact, the results obtained with powder P01 contradict semi-empirical estimates, showing that at the same values of P and T the smaller the size of the micro-particle, the shorter the time required for ignition of this micro-particle. These results are not yet clearly understood, and they necessitate additional research.

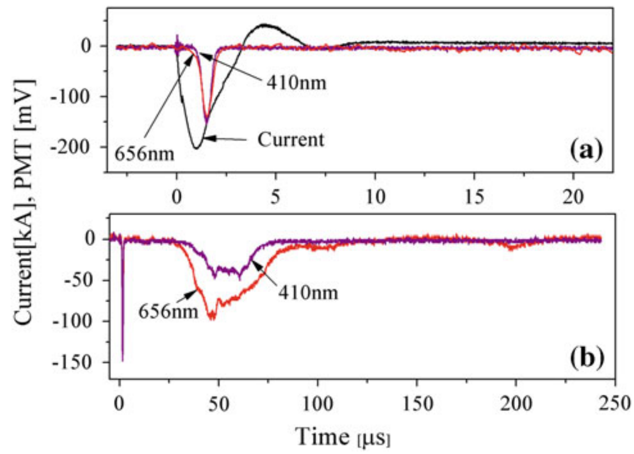

Fig. 8 **a** Typical discharge current and light emission intensity at wavelengths of 410 and 656 nm in the case of copper wire. **b** PMT waveforms of light emission for P11b/water suspension for ratio 1/1

Finally, studies of copper wire explosions in suspension with aluminum powder P11a showed intense and long-duration (up to 70 μs) light emission only when an aluminum powder/water ratio of 1/1 was used. The latter indicates intense combustion of the aluminum powders and agrees qualitatively with the rod velocity measurements.

4 Discussion

The results (light emission and rod velocity measurements) of experiments using aluminum powder P11b/water suspension allow one to state that the application of sub-microsecond timescale underwater electrical wire explosion leads to the ignition of aluminum powders water suspension.

Let us estimate the amount of the additional energy deposited into the water due to aluminum combustion, considering a cylindrical volume of the suspension with an average pressure P_{Al} that pushes a piston with a mass of $m \approx 0.2$ kg. This case will be assumed as comparable to that of a copper wire explosion in water; that is, we assume that the process of the rod acceleration and the dielectric tube destruction are similar for a single wire explosion in deionized water and in aluminum powder water suspension. Indeed, the generated SW with a pressure of $\sim 10^9$ Pa propagates toward the cylindrical wall at an average velocity of $\sim 3 \times 10^5$ cm/s. This SW reaches the wall within $\sim 1\ \mu$s. Partial reflection of the SW and its propagation toward the axis together with the following reflection back also takes a few microseconds. Therefore, within $\sim 10\ \mu$s one obtains a uniform pressure distribution in a cylindrical volume with a radius of 3 mm and a height of 40 mm assuming that there is no damage to the dielectric tube.

First, let us calculate the distance that the rod propagates during its acceleration, considering that the exploding wire energy is transferred to the mechanical energy of water at a ~ 20 % efficiency rate [20,21]. When ~ 3 kJ of the energy is deposited into the copper wire, one obtains $E_{\mathrm{W}} = 600$ J of mechanical energy transferred in the water volume $\mathrm{V_{tot}} = 2 \times 10^{-6}\,\mathrm{m}^3$ inside the dielectric tube. The pressure that accelerates the rod can then be calculated as $P = E_{\mathrm{W}}/\mathrm{V_{tot}} = 3 \times 10^8$ Pa. Thus, in the case of a copper wire explosion in de-ionized water the distance required for the rod to accelerate to a velocity of 5 m/s ($E_{\mathrm{kin1}} = 2.4$ J) is $h_1 = E_{\mathrm{kin1}}/(\mathrm{PS}) = 0.16$ mm, where $S = 5 \times 10^{-5}\,\mathrm{m}^2$ is the rod's cross-sectional area. The time of the rod's acceleration to velocity $V_{\mathrm{r}} = 5$ m/s can be estimated as $\tau = m_{\mathrm{r}} V_{\mathrm{r}}/(\mathrm{PS}) \approx 64\ \mu$s.

Let us now estimate the additional energy deposited in the water volume $\mathrm{V_{tot}}$ in the case of a copper wire explosion in aluminum powder suspension due to the combustion of the aluminum micro-particles. Let us note that the damage to the dielectric tube leads to a fast (microsecond timescale) decrease in pressure inside the water volume. Thus, we assume that the time duration of the additional pressure coincides with the time of the light emission $t_{\mathrm{comb}} \approx 60\ \mu$s obtained in experiments with P11b/water suspension (see Fig. 8b). In this case, the rod's velocity $V_{\mathrm{r}} = 9.2$ m/s is acquired over a distance of $h_{\mathrm{Cu+susp}} = 0.5 V_{\mathrm{r}} \times t_{\mathrm{comb}} = 0.27$ mm. Considering an average pressure distribution inside the dielectric tube during the aluminum powder combustion, the pressure P_{Al} can be estimated as $P_{\mathrm{Al}} = E_{\mathrm{kin2}}/(\mathrm{S} \times h_{\mathrm{Cu+susp}}) \approx 5.9 \times 10^8$ Pa, where $E_{\mathrm{kin2}} = 8$ J (see Table 2). This pressure allows the mechanical energy of water $E_{\mathrm{Cu+susp}} = P_{\mathrm{Al}} \times V_{\mathrm{tot}} = 1.17$ kJ that is distributed inside the tube volume to be estimated. Now, assuming that the conversion efficiency of the thermal energy resulting from the combustion of the aluminum powder to the water's mechanical energy is the same, i.e., 20 %, as in the case of a single wire explosion, one obtains the total released thermal energy $E_{\mathrm{th}} = 5.85$ kJ, of which ~ 3 kJ is contributed by the wire explosion. Thus, the energy gain due to the combustion of the aluminum powder is ~ 2.85 kJ. In this experiment, 0.59 g of aluminum powder was used, which results in ~ 4.8 kJ/g of energy being released during aluminum powder combustion, i.e., a ~ 32 % efficiency rate of the aluminum powder combustion for Q = 15 kJ/g (see (1)).

An additional method of estimating the efficiency of the combustion of the aluminum powder and the additional energy delivered was applied. Here, we also use the assumption that the rod's acceleration due to thermal energy release inside the dielectric tube during wire explosion is similar in the de-ionized water and in the aluminum powder suspension. The results of experiments with copper wire explosion in de-ionized water when $E_0 \approx 3$ kJ was delivered to the exploding wire showed that the energy acquired by the rod is $E_{\mathrm{kin1}} \approx 2.4$ J. In the case of a copper wire explosion with aluminum powder suspension, one can estimate the energy E_{kin2} that should be released into the water when the rod acquires energy $E_{\mathrm{kin2}} \approx 8.0$J as $E_{\mathrm{Cu+susp}} \approx E_{\mathrm{kin2}} \times E_0/E_{\mathrm{kin1}} \approx 10$ kJ. Thus, the additional energy that one can expect to obtain due to the combustion of the aluminum powder is ~ 7 kJ. This results in the rate of the efficiency of the aluminum powder combustion being ~ 79 %.

Now, let us consider the time delay in the appearance of the light emission resulting from the combustion of the aluminum powder, and the duration of this light emission. Aluminum powder ignition cannot be considered to be due to the generated SW; otherwise one should obtain combustion light emission within several microseconds of the beginning of the wire explosion from the entire volume of the water solution. In addition, the thermal conductivity mechanism can be excluded as an explanation for the aluminum powder ignition because of the rather long time it requires (second timescale for water and millisecond timescale for aluminum material). One can, however, consider that the aluminum powder is ignited by the intense radiation flux that is emitted by the exploding wire and absorbed by the aluminum micro-particles that occupy a volume in the vicinity of the wire. Assuming black body radiation with intensity ε_0, one can estimate the time t_{ign} required for the ignition of a micro-particle with radius $r = 5\ \mu$m and density $\rho = 2.7$ g/cm^3 by the radiation of the exploding wire with surface temperature [22] $T \approx 10^4$ K:

$$t_{\mathrm{ign}} = \frac{2.35 \times 10^7 r \rho c_{\mathrm{p}} \Delta T}{T^4} \approx 14\ \mu s \tag{2}$$

Here $c_{\mathrm{p}} = 0.88 \times 10^3$ J/(kg · deg), $\Delta T = 500$ K is the temperature necessary for ignition, and $T = 10^4$ K is the wire temperature. This estimate agrees fairly well with experimental results, showing a time delay in the appearance of the second light emission of $\sim 20\ \mu$s.

The measured time duration of the light emission related to the aluminum powder combustion is around $\leq 100\ \mu$s. Taking a micro-particle radius of $r = 5\ \mu$m, one can estimate the time of combustion as [19]:19 $t_{\mathrm{comb}} \approx 0.012 r^2 \simeq 300$ ms, which is significantly larger than the obtained light emission. This discrepancy could be related to the pressure of $\sim 10^9$ Pa, which can decrease significantly the combustion time of the aluminum micro-particles.

5 Conclusion

The results of experiments in which a compact sub-microsecond timescale high-current generator was used for copper wires underwater electrical explosions in different aluminum powders suspensions were reported. In the experiments, target time-of-flight diagnostics and optical measurements of the light emission by PMTs with different interference filters were used. It was shown that using a proper solution and type of aluminum powders allows one to ignite the combustion of aluminum micro-particles. Estimates showed that this method allows an efficiency of aluminum micro-particles combustion in the range (32–79) % to be achieved.

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