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On the Role of Exothermal Chemical Reaction during Wire Explosion in Water

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Abstract—The explosion of a metal wire in water, accompanied by exothermal chemical reaction with evolution of a large amount of heat, gives rise to thermal ionization of the reaction products. As a result, a dense plasma is generated and energy on the order of or greater than that initially accumulated in the storage battery is liberated. *© 2003 MAIK "Nauka/Interperiodica".*

The electrical explosion of a wire as a result of a high-power pulse of current offers a convenient model for basic investigations of various physical phenomena involving high energy densities. On the other hand, there are many technical applications of the electrical explosion of wires: generation of high pressure pulses by the explosion in a liquid medium [1–3], synthesis of nanopowders [4], etc.

Considering the explosion of a wire in liquid as a means of creating pulsed pressure, it is necessary to evaluate the efficiency of this process. For this purpose, we have to determine what part of the energy initially stored in a capacitor bank is deposited in the discharge. To this end, we obtained oscillograms of the discharge parameters, current and voltage, and determined the deposited energy by numerically integrating these curves.

Of special interest are the cases when the explosion of a metal wire in a liquid medium involves a chemical reaction between the metal and this liquid [3, 5]. In particular, the explosion in water usually leads to the formation of metal oxides and is accompanied by evolution of a large amount of heat, because the reactions between metals and water are exothermal. In the general case, such reactions can be described by the equation

$$mM + nH_2O \longrightarrow Ox + nH_2O + Q,$$

where M is the mass of the exploded metal, Ox is the mass of the oxide products, and Q is the reaction heat.

In our experiments, wires of various metals (aluminum, titanium, tantalum, tungsten, and molybdenum) were exploded in water. The samples had various diameters and a length of 23 cm. The experiments were performed in a discharger of the trigatron type [6] with graphite electrodes. Figure 1 shows the oscillograms of current (upper curves) and voltage (lower curve) measured during the explosion of aluminum (Figs. 1a and 1b) and titanium (Fig. 1c) wires. As can be seen from these data, the passage of the initial current pulse (the first peak on the left) through a metal is accompanied by a secondary pulse (the rightmost peak) appearing with some delay, or without it, depending on the applied voltage (the storage battery voltage). The latter

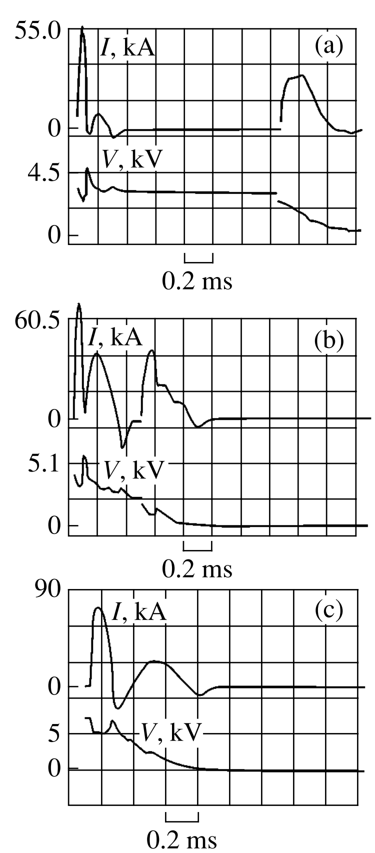

Fig. 1. The oscillograms of current and voltage measured during the explosion of (a, b) aluminum and (c) titanium wires in water at V = 4.6 (a), 5.1 (b), and 5.0 kV (c).

Table

No.	Metal	Mass, g	Capacitor bank energy E_0, kJ	System energy E_S, kJ	Reaction heat q, kJ	Integrated energy E^{Σ}, kJ	$E^{\Sigma} - E_0$, kJ	$\frac{N_i}{N}$, 10^{-2}	Temperature of reaction products T, 10^4 K
1	Al	0.31	16.2		19.20	23.36	7.17		
2	Al	0.31	19.9	19.0	19.20	30.37	10.6	<0.1	
3	Al	0.31	24.7	19.6	19.20	42.00	17.55	0.1	1.0
4	Mo	0.44	23.5	31.0	3.52	54.45	30.95	0.14	2.3
5	W	0.613	23.5	33.95	2.76	57.45	33.95	0.244	5.0
6	Ti	2.08	23.5		65.87	43.55	20.05		
7	Ti	3.25	23.5		102.9	52.0	28.5		
8	Ta	0.747	23.5	25.5	8.65	46.7	23.2	0.11	0.11
9	Ta	1.50	23.5	31.95	17.3	53.41	29.90	0.15	0.15

pulse is related to the passage of current through the chemical reaction products. It is possible to observe how this pulse shifts leftward with increasing voltage (cf. Figs. 1a and 1b). This is explained by the fact that the explosion is followed by the formation of a cylindrical region (coaxial with the exploding wire) filled with the products of reaction between water and metal. The pressure and temperature in this cylindrical region are high due to a large amount of heat liberated from the exothermal chemical reaction. The current cannot pass through the products until the pressure drops to a level at which breakdown is possible. This delay is clearly illustrated by Fig. 1a.

The results of numerical integration of the current and voltage oscillograms are presented in the table. As can be seen from these data, the value of energy E^{Σ} obtained by numerical integration of the discharge current and voltage curves exceeds the energy E_0 accumulated in the storage battery. As a result of the exothermal chemical reaction, the system acquires an energy denoted by E_S. Evolution of the large amount of heat leads to thermal ionization of the reaction products (this process is considered below), resulting in the formation of a dense plasma (with a density on the order of 10^{18} cm^{-3}). This plasma is polarized so that the capacitor bank is charged to a voltage of about 6 kV.

Thus, the value of E^{Σ} usually exceeds the energy E_0 accumulated in the storage battery. In the case of explosion of aluminum and titanium wires, the excess energy $\Delta = E^{\Sigma} - E_0$ is close to the energy of exothermal chemical reactions. For the explosion of refractory metal wires, the excess energy is greater than the values of the heat of formation of the corresponding oxides known to the author. It is not excluded that plasma chemical reactions may lead to the formation of oxides possessing higher heats of formation Q (the values of Q were taken from [7]). The values of the reaction heat q in the table were calculated for the known amount of a metal entering into the reaction.

From an analysis of the oscillograms, it is also possible to determine the number of charged particles N_i in the plasma and to estimate the temperature T and the degree of ionization N_i/N of this plasma (see table). The temperature T was calculated using the Saha equation [8].

Thus, it is necessary to emphasize the following experimental features:

(i) In the case of a titanium wire with a diameter d_0 = 2 mm, the energy stored in the capacitor bank was insufficient to explode the sample of the corresponding mass, provided that the required energy is calculated by the formula

$$Q = m[c(T_2 - T_1) + q_m + c(T_3 - T_2) + \lambda + \dots],$$

where m is the mass of the metal wire, q_m is the specific heat of melting, λ is the specific heat of vaporization, c is the heat capacity, T_1 is the initial temperature, T_2 is the melting temperature, and T_3 is the temperature of evaporation. Thus, the explosion takes place only due to a chemical reaction between the heated titanium wire and water leading to the oxide formation.

(ii) In the case of aluminum wires, the excess energy Δ increases with the initial voltage to which the capacitor bank is charged.

(iii) In the case of tantalum, tungsten, and molybdenum wires (Fig. 2), the energy excess relative to that stored in the capacitor bank cannot be explained using the values of the heat of formation of the corresponding oxides known to the author (see table). It is likely that plasmachemical reactions may lead to the formation of oxides possessing higher heats of formation.

Now let us consider the mechanism of the observed phenomenon. This analysis is well illustrated by Fig. 1a. On the oscillogram of current, the first sharp peak on the left corresponds to the current passing through the aluminum wire. The current pulse amplitude was on the order of 55 kA. This current pulse leads to melting of the metal and the development of a magnetohydrodynamic instability of the waist type [9], which results in breakage of the liquid metal column into separate parts. This is clearly seen in the photographs obtained using a high-speed photoregistrator [3]. Since the residual voltage drop across the discharge gap upon melting of the wire is insufficient to evaporate the metal, the current ceases to pass through the melted metal. At the moment of wire breakage, the electric circuit response leads to overvoltage across the discharge gap. This voltage is sufficient to initiate the arc between separate parts of the liquid metal column, which causes evaporation of the metal.

As the aluminum wire is heated, the metal enters into exothermal chemical reaction between the metal and water:

$$2Al + 3H_2O \longrightarrow Al_2O_3 + 3H_2 + Q,$$

where Q = 1672 kJ/mol is the reaction heat per mole of the metal. The reaction products are ionized by the UV radiation generated in the course of the wire explosion. Additional ionization is related to the large thermal energy liberated from the exothermal reaction, whereby the reaction products are heated to a temperature on the order of 10^4 K (see table). The plasma contacts with the wall and becomes polarized. The discharge current changes direction and charges the capacitor bank up to about 5.0 kV. At the time t = 0.4 ms, the voltage applied to the discharge gap is about 4.5 kV and the energy stored in the capacitor bank amounts to 19.0 kJ. During the time interval from t = 0.4 ms to t =1.48 ms, the current is zero and the battery voltage slightly decreases. This voltage is insufficient to cause breakdown of the plasma of reaction products occurring at a high pressure [2, 3]. The pressure decreases with time and, beginning with t = 1.48 ms, the current passes through the plasma until almost complete discharge of the capacitor bank. Numerical integration of the current and voltage oscillograms in this region (Fig. 1a) yields an energy of about 10.6 kJ, which is comparable to the energy stored in the capacitor bank (19.0 kJ).

As can be seen from the oscillograms of current and voltage measured during the explosion of refractory metal wires, the current begins to pass through the reaction products immediately after the explosion. This behavior is explained by the fact that, at the moment of metal evaporation (i.e., about t = 0.2 ms), the voltage drop across the discharge gap reaches 6 kV. This voltage is sufficient for the current to pass through the dense plasma of chemical reaction products. In all cases, a deposit formed in the system consists of metal oxides.

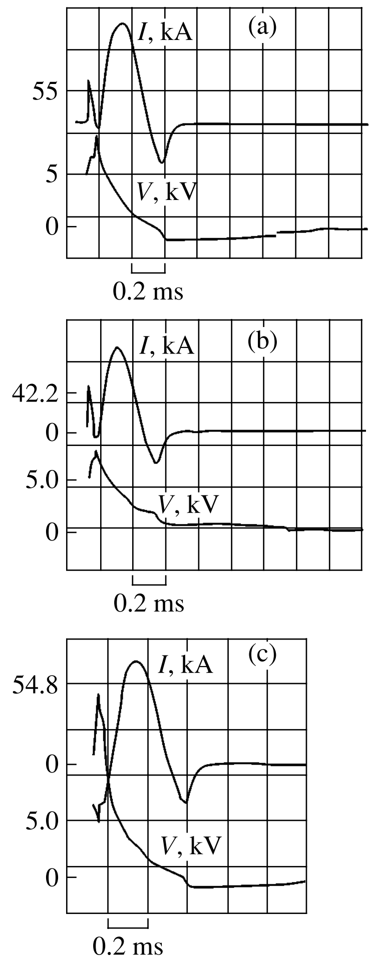

Fig. 2. The oscillograms of current and voltage measured during the explosion of (a) tantalum, (b) tungsten, and (c) molybdenum wires in water at V = 5.0 kV.

In summary, the explosion of a metal wire in water is accompanied by exothermal chemical reaction with evolution of a large amount of heat. As a result, the reaction products possess a high temperature and are subject to thermal ionization. This results in the formation of a dense plasma of the products of exothermal chemical reaction. The plasma exhibits polarization and the system acquires an energy on the order of or greater than that initially stored in the capacitor bank. Numerical integration of the current and voltage oscillograms gives values of energy comparable with those acquired by the system upon the wire explosion.

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