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Studying the mechanism of electric explosion of metal conductors

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Abstract. The article gives a description of the history of the development of research of electric explosion of metal conductors, the authors offer a modern view on the physics of the process of electric explosion. The result of such an explosion can be, in particular, the production of nanopowders, which today have found the widest application in industry, agriculture, medicine, and so on.

Key words and phrases: electrical explosion of conductors, explosion physics, exploding wires, nanopowders

1. Introduction

An electric explosion of metal conductors is usually understood to mean the explosive destruction of a conductor with a powerful current impulse passing through it. When a metal conductor is rapidly heated to a temperature above the boiling point, a metal-liquid-vapor phase transition is observed, a dense metal plasma is formed and further formation of small particles, while the explosion products expand and cool. The products of the explosion flying away at high speed quickly cool down, a fine powder is formed. Having created suitable initial conditions for this experiment, particularly, nanopowders are possible to obtain.

Today, nanopowders are widely used as raw materials for the production of ceramic, magnetic, and composite materials, as well as in the production of superconductors, solar cells, lubricant additives, and so on. The use of nanopowders in industry is also very extensive. These are diffusion welding technologies, the creation of protective and anti-friction coatings and the restoration of worn parts of mechanisms. Also, the intensity of the use of nanopowders in agriculture and the environmental protection industry increases annually in the extraction and processing of minerals, in water treatment, in cosmetology and medicine.

This phenomenon is accompanied by current interruption and generation of high-voltage pulses. In addition, the formation of high power shock waves,

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the flow of chemical reactions and the formation of bright flashes of light is possible. Due to the fact that an electric explosion is realized under very different conditions (by energy level, by type of metal, by environment, by final result), the resulting effects are also very diverse. All this contributes to a detailed study of the present phenomenon — here, the study of thermophysical properties of metals at high temperatures. An electric explosion of high-temperature plasma can be used as a source in studies of controlled thermonuclear fusion [1, 2], in studies generation of powerful soft X-ray pulses as well as in works on the creation of light sources. In addition, the explosion of wires is used in breakers, fuses in various electrophysical installations.

In connection with the above, more accurate knowledge of the mechanisms of the electrical explosion of metallic conductors is extremely important today. We want to consider the history of the development of this issue and formulate our thoughts on the mechanism of the explosion of conductors to better understand this process.

2. Background

The first theoretical publications on the explosion of conductors date back to the second half of the 18th century. One of the founders of experiments was Michael Faraday in the middle of the 19th century. When a Leyden jar was discharged through a gold wire on the inner walls of the flask, he received a thin metal film. But by the middle of the 20th century the number of publications on the explosion of conductors exceeded 800. It becomes obvious that the electrical explosion of conductors belongs to a poorly studied area of the interaction of metals with electric and magnetic fields. For example, the electrical conductivity of metals has been well studied only in the condensed state and in the ideal state plasma at a temperature of the order of 10^4 K. And such states as the vicinity of the critical point are still the subject of research.

In connection with the foregoing, the study of the mechanism for the realization of an electric explosion of metallic conductors seems to us extremely important.

Nanopowders can be obtained by electrical explosion of a conductor by passing through it a powerful current pulse with a duration of about 1 microsecond and a density from 10^4 to 10^6 A/mm^2. Such impulse heating of the metal can be carried out by discharging a charged capacitor through a thin wire. A wire with a diameter of 0.1 to 1.0 mm is used for this purpose. An electric explosion is accompanied by the generation of shock waves and creates the possibility of rapid heating of metals at a rate of more than $10^8 \div 10^{10}$ K/sec to high temperatures $T > 10^4 K$. At the initial stage of the electric explosion, the heating of the conductor is accompanied by its linear expansion at speed of about 2 m/sec. At the explosion stage, the metal overheats above the melting temperature as a result of the passage of a current pulse, the substance expands at a rate of up to $5 \cdot 10^3$ m/sec. The pressure and temperature of the shock wave front reaches 10^8 Pa [3]. As a result of condensation with the rapid expansion of steam, small particles are formed. Thus, by changing the explosion conditions, it is possible to obtain powders with particle sizes from 100 µm to 50 nm [4]. And by means of an electric

explosion in an inert atmosphere, it is possible to obtain powders of metals and alloys (oxides, nitrides and metal carbides) and fine powders of oxides, nitrides, carbides or mixtures thereof by introducing additional reagents into the reactor (air, a mixture of oxygen and an inert gas, nitrogen, distilled water, paraffin, technical oil). There are known cases of obtaining copper powders by electric explosion in an inert gas at a pressure of 200 Pa with a size of about 20 nm and aluminum powders with an average particle size of about 50 nm. Anderson in his paper [5] photographed line spectra and estimated the temperature of such a plasma $T = 2 \cdot 10^4$ K, which is close to the temperature of stellar atmospheres. There are also known attempts to use this plasma in experiments on the problem of controlled thermonuclear fusion [6].

According to the experimentally obtained data, the powders obtained by the explosion of an electric wire have a large excess energy. So, aluminum powders with an average particle size of 500 to 800 nm have an excess energy of up to 200 kJ/mole and silver powders with an average particle size of about 120 nm have an excess energy of up to 80 kJ/mole, which is several times more than the melting heat of a massive substance. We believe that excess energy cannot be caused only by surface energy. It is believed that the excess energy of fine powders obtained by electric explosion is stored in the form of surface energy, internal defects and charge. The size distribution of the powder particles lies in the range from 10 to 500 nm. The particles of metal powders obtained by electroexplosion are spherical, while the particles of nitride powders have a cut. It is worth mentioning that interest in this described phenomenon is also due to the use of "exploding wires" to obtain a dense high-temperature plasma. The first author to obtain synchronous oscillograms of current and voltage during the discharge of a charged capacitor through a copper conductor was Vrana [7], who discovered that the current in the conductor stops during discharge at current density of more than 10^6 A/sm^3 and after a while resumes, creating a secondary pulse lasting almost until the capacitor is completely discharged (figure 1). The conductor material was found lately to be in the plasma state during the period of the secondary current pulse.

Purposeful studies of the thermophysical properties of metals by the method of electric explosion of conductors were laid down by the work of Soviet scientists. For example, in the works of Lebedev [8] molybdenum, tungsten, nickel and platinum conductors with a diameter of 0.05–0.10 mm were blown up by current pulses with a density of more than 10^6 A/sm^2. Characteristic points t_1, t_2, t_3, t_4 were fixed on the oscillograms of current and voltage on the conductor (figure 1). To clarify the physical nature of the points t_1 and t_2, experiments were carried out with forced switching off of the current at a given time. With the current turned off at time t_1, the conductor remained in a solid state; with turned off at time t_2 is it falls apart into separate drops. This proves that the moments t_1 and t_2 correspond to the beginning and end of the melting of the sample. On the oscillograms for molybdenum and platinum, the energy introduced into the metal is calculated over the time $(t_2 - t_1)$. The metal goes into an anomalous state after the moment t_3, when the stress on the sample rises sharply. The resistance of liquid conductors made of tungsten, platinum, molybdenum and nickel turned out to be weakly dependent on the energy introduced into them in the range from t_2 to t_3.

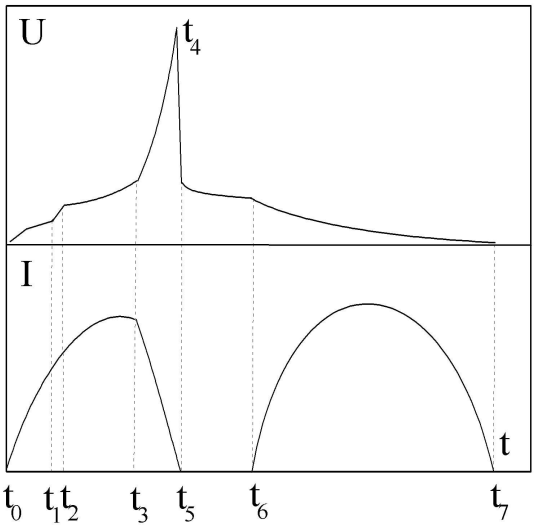

Figure 1. The oscillogram of the current I and voltage U on the conductor in case of an electrical explosion of a copper conductor

During the explosion of refractory metals in air in the range from t_2 to t_3, a violation of the oscillograms is observed. This is due to the development of a gas discharge in air along the surface of the sample and leads to heating of the metals. There are various mechanisms of destruction of the conductor: breaks, disintegration into drops, destruction with the formation constrictions, uniform expansion of the liquid conductor in the initial stage of its explosion and subsequent formation of a transverse layered structure were found to be possible by using the method of obtaining single photographs of a conductor being heated by a current pulse.

In Kvartskhava's experiments [9] the energy being introduced into a copper conductor during the first current pulse was measured. This energy in the case of microsecond pulses appeared to increase with increasing current density and can exceed the heat of metal evaporation. The resistance of the conductor after t_3 for the energy given decreases with the current density increasing. In the research of Kulgavchuk and Novoskoltseva X-ray images of an exploding copper synchronized with current and voltage oscillograms conductor were obtained.

The conductor was found to expand after the point t_3 in the case of microsecond current pulses remaining intact. Its stratification into transverse layers begins in the vicinity of the point t_4, after the density of copper in a solid conductor becomes equal to $\rho = 4.1$ g/sm^3, i.e. in similar works by foreign authors [10–13] the main attention is paid study of the process of electric explosion and shock waves. The shock wave begins to develop after the moment t_3 (figure 1), so the point t_3 can be considered the starting point of the electrical explosion. Peregud [14] studied the development process of magnetohydrodynamic and electrothermal instabilities of the shape of a metal conductor being heated by a current pulse. They also detected luminescent radiation of metals (figure 1) emitted by a liquid conductor being destroyed at the end of the first current pulse.

3. Mechanism of electrical explosion of conductors

To heat the conductor to the starting point of the electric explosion of the conductor (point t_3 on figure 1) without destroying the subsequent explosive boiling of the metal it is necessary to satisfy three basic conditions.

1. The heating of the conductor must be continuous, which requires the aperiodicity of the discharge of the capacitor. This means that the average resistance of the conductor during the heating process must satisfy the condition:

$$R \geqslant 2\left(\frac{L}{C}\right)^{\frac{1}{2}}, \tag{1}$$

where L, C are inductance and capacitance of the capacitor. If we assume that the resistance R of a liquid conductor at melting temperature $R_2 = \rho_2 l/s$, then it follows from condition (1) that the ratio of the conductor length l to its cross section s :

$$\frac{l}{s} \geqslant \frac{2}{\rho_2}\left(\frac{L}{C}\right)^{\frac{1}{2}}, \tag{2}$$

where ρ_2 is the resistivity of the liquid metal at the melting point.

2. The second condition is such that when heated, the conductor should not be destroyed under the influence of MHD perturbations of its shape and evaporation from its surface. To do this, it must be heated, observing the conditions:

$$\varepsilon \geqslant \varepsilon_m = \frac{i_m^2 \rho}{DC_p} = \frac{\mu_o C_p \left(T_3 - T_2\right)^2}{4\rho}, \tag{3}$$

where ρ, D, C_p are the average values of the resistivity, density and specific heat capacity of a liquid metal in the temperature range from T_2 to T_3. This velocity is related to the time t_3 of heating the conductor to the point T_3, for which the condition must be met:

$$t_3 \leqslant t_{3m} = \frac{T_3 - T_0}{\varepsilon_m}, \tag{4}$$

where ε_m is the greater of the values ε_m, $T_0 = 300$ K is the initial temperature of the conductor.

Let the point T_3 be reached at time t_m of maximum current in the circuit. If the discharge occurs in a way close to critical, then $t_3 = t_m = 2L/R$. Substituting in this expression instead of R the resistance of the conductor at the melting point, from (3) the second condition is obtained:

$$\frac{l}{s} = \frac{2}{\rho_2} \cdot \frac{L\varepsilon_m}{T_3 - T_0}. \tag{5}$$

3. The third condition is the sufficiency of energy charged capacitor. If this energy is sufficient not only to heat the conductor to a temperature of T_3, but also to overheat it to a temperature of T_4, then its intense

explosive boiling will occur. But will arise in constrictions in which the electrothermal instability develops after the point T_3. Assuming that at the point T_4 the specific energy of the metal is ϖ_4, then

$$0,5 \cdot C \cdot U_0^2 \geqslant \varpi_4 m, \tag{6}$$

where U_o is the initial voltage on the capacitor; m is the mass of the conductor.

Thus, the conditions (2), (5), (6) are well satisfied for conductors whose l/s ratio is large enough, provided that the discharge circuits have a low inductance and a high initial voltage across capacitor. Such conditions are easier to fulfill for metals with bigger resistivity.

The table 1 presents the results of calculating the minimum current density and the heating rate of the conductor according to the formula (3), as well as the maximum heating time t_{23m} of a liquid conductor from the point T_2 to the point T_3 for different metals, when calculating $T_3 = 0.80 \cdot T_c$ is accepted.

Table 1

Boundary conditions for the parameters of pulsed heating of metals taking into account evaporation from the surface of the conductors

	W	Mo	Pt	Cu	Pb	Cs	Hg
$i_m \cdot 10^{-6}$,A/sm^2	2.30	3.12	3.39	7.47	1.68	1.63	3.74
$\varepsilon_m \cdot 10^{-8}$, K/sec	4.10	5.22	3.53	5.93	2.80	8.67	10.2
t_{23m}, μsec	20.7	11.9	12.5	5.52	11.0	1.53	1.09

4. Out-spinodal electrical explosion and spinodal decay unstable liquid metal phase

In figure 2 a diagram of the states of titanium in the liquid-vapor phase transition region is presented. On it, C is the critical point calculated by the equation (1); for this point, according to [15], $T_c = 9040$ K, $p_c = 156$ MPa, $V_s = 71.1$ sm^3/mole. The binodal bC is determined by extrapolating the temperature dependence of the saturated vapor pressure from the normal boiling point T_2, p_2 to the critical point T_c, p_c; it is calculated by the formula

$$\ln \frac{p}{p_2} = B - \frac{A}{T}, \tag{7}$$

in which the constants A and B are equal:

$$A = \frac{\ln (p_c/p_2)}{1/T_2 - 1/T_c}, \quad B = \frac{A}{T_2}.$$

For titanium $A = 4.34 \cdot 10^4$ K, $B = 12.14$.

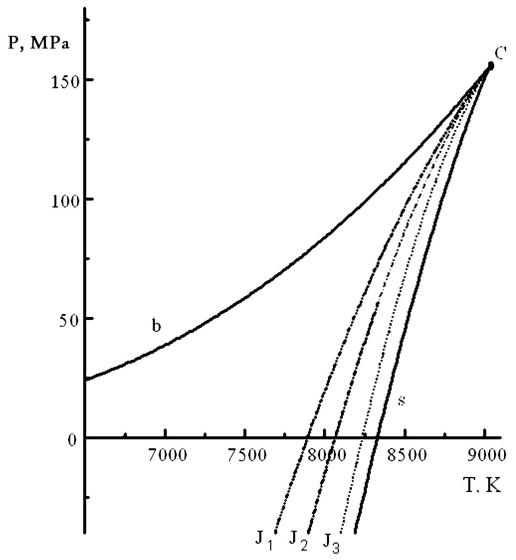

Figure 2. The diagram of the states of titanium in the liquid-vapor phase transition area

Spinodal sC of the liquid phase in figure 2 is crosses the temperature axis at the point $T_{s,p=0} = 8330$ K, then it enters the field of negative pressures [16].

The area of the metastable liquid (superheated or stretched liquid) lies between the binodal and the spinodal. In the area of positive pressures, the spinodal determines the boundary of the thermodynamic stability of the liquid. In the area of negative pressures [17], the spinodal determines the tensile strength of the liquid.

The appearance of an overheated liquid metal near the spinodal was experimentally proved when metal conductors are heated by a microsecond current pulse. In this case, the metal evaporates both through the surface of the conductor and through the surface of the vapor nuclei that appear on the finished centers. However, such evaporation is insignificant and therefore the conductor remains in the liquid state until the spinodal is reached. The calculation shows [18] that the minimum heating rate of various metals to near-spinodal states is equal to $(3 \div 10) \cdot 10^8$ K/sec, which corresponds to the density of the heating current $(2 \div 8) \cdot 10^6$ A/sm^3 and the heating time of the liquid $1 \div 10$ μsec. With pulsed heating of the conductor at atmospheric pressure the heating line is located below the binodal line bc in figure 2, since the reactive pressure of the scattering vapor acts on the surface of the conductor $p = 0.55 p_b$ [18]. Overheating of a thermodynamically stable liquid above the spinodal point is impossible, since when approaching this point, an explosive boiling mechanism is activated, caused by a high frequency of homogeneous nucleation of vapor nuclei.

Figure 2 shows lines for three different frequencies of homogeneous nucleation of vapor nuclei in superheated liquid titanium [19]:

$$J_1 = 1 \text{ sm}^{-3} \cdot \text{sec}^{-1}, \quad J_2 = 10^{20} \text{ sm}^{-3} \cdot \text{sec}^{-1}, \quad J_3 = 10^{28} \text{ sm}^{-3} \cdot \text{sec}^{-1}.$$

The values required for calculations ρ_L, ρ_v, σ are determined by empirical formulas for the thermodynamic properties of liquid metals near the critical point [20]. The frequency of homogeneous nucleation is shown by calculations

to increase by 28 orders of magnitude when approaching the spinodal along the heating line at $p = 0.55p_b$ in the temperature range $\Delta T = 230$ K $= 0.025T_c$. This ensures explosive effervescence of superheated liquid metal without reaching a spinodal phase explosion. Thus, explosive boiling up is the main factor determining the electrical explosion of conductors when heated by a microsecond current pulse.

Thus, if during pulsed heating of a liquid, its heating time satisfies the condition $\Delta t_s < \theta$, then it becomes possible to enter the region of an unstable phase (behind the spinodal), while the thermodynamic stability coefficients are negative. The elasticity and heat capacity of such a phase will also be negative. The surface tension of the unstable liquid phase is zero [21], which limits the formation of vapor nuclei. These features determine the nature of the decay of the unstable phase, known as spinodal decay [22]. With the subsequent development of the described process, a continuous formation of an heterogeneous structure occurs, consisting of small contracting and expanding regions without phase boundaries between them. It is believed that the speed of a spinodal decay is determined by heat exchange between the described areas. Since the heat capacity of the unstable phase is negative, its thermal conductivity is $a = \lambda/\rho \cdot C_p$ also negative (λ is the thermal conductivity coefficient). The temperature differences arising in the locally unstable phase increase exponentially until the system leaves the zone of instability. The process of spinodal decomposition is replaced by the formation and growth of nuclei of a new phase.

The possibility of realizing unstable states of liquid metals is evidenced by experiments with an "anomalous" electric explosion of conductors at a heating rate more than $5 \cdot 10^{10}$ K/sec and heating time to the peak voltage point $t_4 < 0.1$ μsec.

Under these conditions, the heating time of the liquid metal Δt_S in the vicinity of the spinodal will be less than the time development of the process of homogeneous nucleation of vapor nuclei, which determines the possibility of reaching spinodal [23]. The energy was shown to be W_4 introduced into the metal with this heating mode by the time t_4 is several times higher than the heat of its evaporation Λ_{b0} at the normal boiling point. For example, with an abnormal explosion of gold conductors at a current density of $i = 3.3 \cdot 10^8$ A/sm^2 the ratio of $W_4/\Lambda_{b0} = 10$. At the same time the volume of metal is shown by method of high-speed photography to exceed the initial volume by no more than 4 times in the vicinity of the point t_4. A large energy density was shown by these experiments that are carried out in an unstable liquid phase for a short time (several nanoseconds). This ensures high attenuation intensity and high local temperatures at individual points.

The existence of such local "hot spots" during the electrical explosion of conductors is confirmed by the release of multiply charged ions from the explosion zone; for example, charge states of atoms were found: Cu^{+27}, Ag^{+37}, Au^{+51}. In [24] during an out-spinodal explosion of aluminum, the release of X-ray quantum with the energy 1–20 keV was detected. The output of short-wave X-ray quantum with a wavelength $0.15 \div 0.28$ nm during an electric explosion of titanium and iron was also detected in the work [25]. The rate of expansion of a substance during an out-spinodal electric explosion can be estimated using the formula [26]:

$$v = 2 \cdot \left(\frac{\gamma \varpi_4}{\gamma - 1} \right)^{1/2}, \tag{8}$$

where γ is adiabatic index; ϖ_4 is excess specific energy introduced into the metal during its overheating from the normal boiling point to the point t_4 (figure 1). With $\gamma = 1.2$ [26] and the values of ϖ_4 obtained in experiments with an "anomalous" electric explosion of conductors made of copper, silver, gold and tin [18], $v = (15 - 20)$ km/sec. The so-called "anomalous" electric explosion is of great interest. At a sufficiently high heating rate, energy, being several times higher than the heat metals sublimation, enters the metal. In the process of such an "anomalous" electrical explosion, an emission of X-rays and multiply charged ions was detected. X-ray radiation ejected from an exploding conductor during its expansion in 10 nsec was showed by the photographs and observed with a high-speed video camera. This is explained as follows. In the process of spinodal decomposition of the liquid metal phase, regions with local elevation points appear. This leads to thermal excitation of atoms and electronic transitions generating X-ray quantum.

5. Conclusions

To summarize, we analyzed the literature on the history of the formation and development of studies of the explosion of metal conductors and offered an understanding of the mechanism of this process.

References

[1] M. M. Martynyuk and N. Y. Kravchenko, "Nuclear fusion reaction in metaphase substance in the process of electrical explosion [Reaktsiya yadernogo sinteza v mezofaznom veshchestve v protsesse elektricheskogo vzryva]," *Applied Physics*, no. 1, p. 79, 2003, in Russian.

[2] M. M. Martynyuk and N. Y. Kravchenko, "Impact-cluster nuclear fusion. Conditions of excitation of the process [Udarno-klasternyy yadernyy sintez. Usloviya vozbuzhdeniye protsessa]," *Bulletin of Peoples' Friendship University of Russia. Series: Mathematics, Informatics, Physics*, no. 1, pp. 118–128, 2005, in Russian.

[3] N. Y. Kravchenko, "The numerical solution of the Rayleigh–Plisset equation for spark cavitation and calculation of the maximum temperature and pressure in a cavity," *Journal of Mechanics of Continua and Mathematical Sciences*, no. Special Issue-1, pp. 465–473, Mar. 2019. DOI: 10.26782/jmcms.2019.03.00046.

[4] N. Y. Kravchenko and M. M. Martynyuk, "Dynamics of homogeneous cavitation bubbles in water under large amplitude pressure oscillations [Dinamika zarodyshey gomogennoy kavitatsii v vode pod deystviyem davleniya bol'shoy amplitudy]," *Bulletin of Peoples' Friendship University of Russia. Series: Mathematics, Informatics, Physics*, vol. 8, pp. 118–121, 2000, in Russian.

[5] J. A. Anderson and S. Smith, "General charcteristics of electrically exploded wires," *The Astrophysical Journal*, vol. 64, no. 5, pp. 295–314, 1926.

[6] L. A. Artsimovich, *Controlled thermonuclear reactions [Upravlyayemyye termoyadernyye reaktsii]. Ed. 2nd.* M.: Fizmatgiz, 1963, in Russian.

[7] J. Wrana, "Vorghnge beim Schmeilzen and Verdampfen von Drghten mit sehr hochen Stromdichten," German, *Archiv für Electrotechnik*, vol. 33, no. 10, pp. 656–672, 1939.

[8] S. V. Lebedev, "Explosion of a metal by an electric current," *Journal of Experimental and Theoretical Physics*, vol. 32, no. 2, p. 199, 1957.

[9] I. F. Kvartskhava, A. A. Plyutto, A. A. Chernov, and V. V. Bondarenko, "Electrical explosion of metal wires," *Journal of Experimental and Theoretical Physics*, no. 1, p. 40, 1956.

[10] A. A. Rukhadze, Ed., *Exploding wires [Vzryvayushchiyesya provolochki].* 1963, in Russian.

[11] A. A. Rukhadze and I. S. Spiegel, Eds., *Electric explosion of conductors [Elektricheskiy vzryv provodnikov].* M.: Mir, 1965, in Russian.

[12] W. G. Chace and H. K. Moore, Eds., *Exploding wires.* N.Y.: Plenum Press, 1964, vol. 3.

[13] W. G. Chace and H. K. Moore, Eds., *Exploding wires.* N.Y.: Plenum Press, 1968, vol. 4.

[14] K. B. Abramova, N. A. Zlatin, and B. P. Peregud, "Magnetohydrodynamic instability of liquid and solid conductors. Destruction of conductors by an electric current," *Journal of Experimental and Theoretical Physics*, vol. 6, no. 12, p. 2007, 1975.

[15] P. A. Tamanga, M. M. Martynyuk, and N. Y. Kravchenko, "Spinodal of liquid phase on basis of generalized Berthelo's equation [Spinodal' zhidkoy fazy po obobshchennomu uravneniyu Bertelo]," *Bulletin of Peoples' Friendship University of Russia. Series: Mathematics, Informatics, Physics*, no. 9, pp. 56–58, 2001, in Russian.

[16] M. M. Martynyuk and N. Y. Kravchenko, "Limit of thermodynamic stability of a liquid phase in the field of negative pressure [Granitsa termodinamicheskoy ustoychivosti zhidkoy fazy v oblasti otritsatel'nykh davleniy]," *Journal of Physical Chemistry*, vol. 72, no. 6, pp. 998–1001, 1998, in Russian.

[17] M. M. Martynyuk and N. Y. Kravchenko, "Boundary of liquid phase thermodynamic stability at negative pressure," *Russian Journal of Physical Chemistry*, vol. 72, no. 6, pp. 885–887, 1998.

[18] M. M. Martynyuk, *Phase transitions during pulsed heating [Fazovyye perekhody pri impul'snom nagreve].* Moscow: RUDN, 1999, in Russian.

[19] M. M. Martynyuk, P. A. Tamanga, and N. Y. Kravchenko, "The titanium phase diagram at the phase transition region liquid-vapor [Fazovaya diagramma titana v oblasti fazovogo perekhoda zhidkost'-par]," *Bulletin of Peoples' Friendship University of Russia. Series: Mathematics, Informatics, Physics*, no. 10, pp. 121–125, 2002, in Russian.

[20] M. M. Martynyuk, *Parameters of the critical point of metals [Parametry kriticheskoy tochki metallov]*. M.: RUDN, 1989, in Russian.

[21] M. M. Martynyuk and N. Y. Kravchenko, "Conditions for excitation of spinodal decomposition of an unstable liquid phase in the process of pulsed heating of metals," *Bulletin of the PFUR. Series Mathematics, Informatics, Physics*, no. 1, pp. 92–99, 2008, in Russian.

[22] V. P. Skripov and A. V. Skripov, "Spinodal decomposition (phase transitions via unstable states)," *Sov. Phys. Usp.*, vol. 22, pp. 389–410, 1979. DOI: 10.1070/PU1979v022n06ABEH005571.

[23] N. Y. Kravchenko and M. M. Martynyuk, "Dynamics of homogeneous cavitation nuclei in water under high-amplitude sinusoidal pressure fluctuations [Dinamika odnorodnykh yader kavitatsii v vode pri vysokoamplitudnykh sinusoidal'nykh pul'satsiyakh davleniya]," *Bulletin of PFUR. Series Physics*, no. 8 (1), pp. 118–121, 2000, in Russian.

[24] I. M. Vitkovitsky, "X-ray emission from exploding wires," *Physics of Fluids*, vol. 7, no. 4, p. 612, 1964. DOI: 10.1063/1.1711249.

[25] P. Burkhalter, J. Davis, J. Rauch, and W. Clark, "X-ray line spectra from exploded-wire arrays," *Applied Physics*, vol. 50, no. 2, p. 705, 1979. DOI: 10.1063/1.326034.

[26] Y. B. Zeldovich and Y. P. Raizer, *Physics of shock waves and high-temperature hydrodynamic phenomena [Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavleniy]*. M.: Nauka, 1966, in Russian.

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Изучение механизма электрического взрыва металлических проводников

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Аннотация. В статье представлено описание истории развития исследований электровзрыва металлических проводников, предложен современный взгляд на физику процесса электровзрыва. Результатом такого взрыва может стать, в частности, производство нанопорошков, которые сегодня нашли самое широкое применение в промышленности, сельском хозяйстве, медицине и так далее.

Ключевые слова: электрический взрыв проводников, физика взрыва, взрывающиеся провода, нанопорошки