PARTICLE PRODUCTION BY ELECTRICAL EXPLOSION OF A CONDUCTOR

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In electric explosion of conductors upon passage of a high power current pulse the wire material is destroyed, as a result of which particles of extremely small size are formed. Measurements of the size of such particles and a study of their properties were carried out in [1-5]. It has been found experimentally that the mean particle diameter depends upon the initial wire diameter, the counter-pressure of the surrounding medium, and the energy density introduced into the wire. Moreover for energy levels in the wire of the order of magnitude of the sublimation energy the powder contains two fractions of differing size. The coarser have a characteristic size of 1 μm, while the finer range from 0.01 to 0.1 μm. It has been proposed that the particles from the portion of the wire which does not evaporate upon explosion break up as they fly away, finally producing the coarse fraction, while during their rapid expansion the metal vapors condense into the drops of very small diameter [2]. The goal of the present study is to construct a theory which will permit numerical modeling of condensation processes in electrical size in the powder formed.

Physical Formulation of the Problem. We will make the following simplifications: we will not consider the process of conductor heating during current passage, and take as the beginning of dispersion the time when the wire has already failed, so that no current flows, and its section has increased to 10 times its initial value. We will consider the problem in a one-dimensional axisymmetric formulation. The surrounding medium is an inert gas (argon) so that chemical reactions between the explosion products and the external gas will not be considered. The drops are considered electrically neutral. We neglect the viscosity of the vapor and surrounding gas. We assume that energy liberation takes place uniformly over the entire wire volume, and the dispersion velocity is proportional to the distance from the wire axis (at the initial moment). The fraction of liquid and vapor phase in the expanding medium depends on the energy introduced, but it is difficult to determine precise relationships between them because of the significant disequilibrium of the processes occurring. For definiteness we will assume that the energy liberated is expended in heating, fusion, further heating, evaporation of a portion of the wire to the point where the vapors reach saturation corresponding to the temperature of the heated metal. This uniquely defines a ratio between the evaporated and nonevaporated portions of the substance. At high energy levels all the material evaporates and a portion of the energy is expended in ionizing the vapor. Thus, two types of initial conditions are possible.

In the first case we have a cylinder of radius R_{01}, filled by a plasma with concentrations of neutral atoms n_0 and singly charged ions n_1 ($n_0 + n_1 = n_{01}$), in which particles n_4 with radius r_4 are uniformly distributed. Outside the cylinder we have the inert gas n_3 at rest. We will not consider the volume boiling mechanism itself, whether homogeneous or heterogeneous (on grain boundaries, impurities, inhomogeneous inclusions), so in our model the choice of initial drop size r_4 is quite arbitrary and will be taken equal to 1/100 of the wire diameter independent of energy liberation. Numerical calculations showed that variation of the initial drop size (from 0.03 to 0.003 times the wire diameter) does not affect the final particle size due to fractionation of the drops during expansion.

In the second case initially there are no particles, but generation of "fine" drops upon super-cooling of the expanding vapor is possible.

In the model to be used the energy balance equation has the form

$$me = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 + Q_7 + Q_8,$$

where e is the specific energy supplied to the conductor; m is the total mass of the wire; $Q_1 = mC_T(T_f - T_i)$ is the heating of the wire before fusion; $Q_2 = m\lambda$ is the heat of fusion; $Q_3 = mC_\ell(T_{boil} - T_f)$ is the heat expended before boiling; $Q_4 = \chi \cdot$

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mq represents evaporation of a fraction χ of the wire material ($0 \le \chi \le 1$); $Q_5 = \sigma(4\pi r_4^2 n_4)$ is the surface tension energy of the liquid drops formed upon wire breakup; $Q_6 = \chi$ Ip ym/m_0 represents ionization of evaporated metal vapor (y is the degree of ionization); Ip is the ionization potential; m_0 is the mass of the vapor molecule; $Q_7 = \chi(3/2)\, kT_e ym/m_0$ is the thermal energy of the electrons (k is Boltzmann's constant); $Q_8 = e_{kg} + e_{kd}$ (e_{kg}, e_{kd} are kinetic energies of gas and drops). In choosing the initial conditions we assume that y is determined by the temperature and density of the material [6].

In addition we assume that heat-mass transport occurs between the vapor and liquid drops in accord with the expressions presented in [7].

Having specified the initial energy liberation, we determine the system temperature, fraction of material evaporated, degree of ionization, and initial concentration of the drops, if such exist. Naturally with increase in energy liberation n_4 decreases and the mean distance between drops increases.

Mathematical Formulation. In cylindrical geometry the system of hydrodynamics equations considering the metal plasma, inert gas, and condensed particles can be written in divergent form (aside from the electron temperature equation) in the following manner:

$$\frac{\partial n_0}{\partial t} + \frac{\partial (n_0 u_0)}{\partial R} + \frac{n_0 u_0}{R} = I_0^{(n)} - \text{Ion}; \tag{1}$$

$$\frac{\partial n_1}{\partial t} + \frac{\partial (n_1 u_1)}{\partial R} + \frac{n_1 u_1}{R} = I_1^{(n)} + \text{Ion}; \tag{2}$$

$$\frac{\partial n_3}{\partial t} + \frac{\partial (n_3 u_3)}{\partial R} + \frac{n_3 u_3}{R} = 0; \tag{3}$$

$$\frac{\partial (\sum_i n_i m_i u_i)}{\partial t} + \frac{\partial (\sum_i m_i n_i (u_i^2 + kT_i/m_i) + P_e)}{\partial R} + \frac{\sum_i m_i n_i u_i^2}{R} = \sum I_i^{(mnu)}, \quad i = 0, 1, 3; \tag{4}$$

$$\frac{\partial (\sum_i n_i m_i^2 (u_i/2 + (3/2)\, kT_i/m_i) + (3/2)\, n_e kT_e)}{\partial t} + \frac{\partial (\sum_i u_i n_i m_i ((u_i^2/2 + (3/2)\, kT_i/m_i) + kT_i/m_i) + ((3/2)\, n_e kT_e + P_e)\, u_1 + Q_e)}{\partial R} + \tag{5}$$

$$+ \frac{\sum_i u_i n_i m_i ((u_i^2/2 + (3/2)\, kT_i/m_i) + kT_i/m_i) + ((3/2)\, n_e kT_e + P_e)\, u_1 + Q_e}{R} = \sum_i I_i^{(mnE)} - \left(\frac{kT_e}{2} + \text{Ip}\right) \text{Ion}, \quad i = 0, 1, 3;$$

$$n_e \frac{\partial kT_e}{\partial t} + n_e u_1 \frac{\partial kT_e}{\partial R} + \frac{2}{3} P_e \frac{\partial u_1}{\partial R} + \frac{2}{3} \frac{\partial Q_e}{\partial R} + \frac{(2/3)\, (P_e u_1 + Q_e)}{R} = -\frac{2}{3} (\text{Ip} + 2kT_e)\, \text{Ion} - \text{Ch}. \tag{6}$$

In Eqs. (1)-(6)

$$I_i^{(n)} = (\dot{n}_{4i} - \dot{n}_{i4}) \quad (i = 0, 1, 3);$$

$\dot{n}_{i4} = \eta_i n_i 4\pi r_4^2 n_4 \mid V_{i4} \mid$ is the number of vapor molecules ($i = 0$) or ions ($i = 1$), condensed on type 4 particles per unit volume per unit time, $i = 0, 1, 3$ ($\eta_3 = 0$, therefore $\dot{n}_{j3} = \dot{n}_{3j} = 0$); $\dot{n}_{4i} = 4\pi r_4^2 n_4 n_\ell v_s \exp(-q_i/T_4)$ is the number of molecules ($i = 0$) or ions ($i = 1$), evaporating from type 4 drops; q_i is the heat of evaporation of component i; n_1, v_s are the concentration and speed of sound in the liquid metal; $\mid V_{i4} \mid = \sqrt{8kT_i/(\pi m_i) + (u_i - u_4)^2}$; m_i is the mass of a metal plasma

molecule or ion at $i = 0$, 1 or the mass of an inert gas atom at $i = 3$; η_i is the accommodation coefficient ($0 < \eta_0 < 1$ and $\eta_3 = 0$, and we also assume $\eta_1 = \eta_0$);

$$I_i^{(mnu)} = -F_i + m_i\dot{n}_{4i}u_4 - m_i\dot{n}_{i4}u_i;$$
$$F_i = \pi m_i n_i (1 - \eta_i) r_4^2 (u_i - u_4) |V_{i4}| n_4$$

is the resistance force of the moving particles in the metallic plasma or inert gas;

$$I_i^{(mnE)} = -F_i u_4 + m_i (\dot{n}_{4i}u_4^2/2 - \dot{n}_{i4}u_i^2/2) + (3/2)(\dot{n}_{4i}kT_4 - \dot{n}_{i4}kT_i).$$

Here n_0 is the concentration of neutral metal atoms; n_1 is the ion concentration; n_3 is the inert gas concentration; the subscript 4 refers to drops; the plasma is assumed quasineutral, therefore $n_{ion} = n_e$ at any point; the drift velocities of ions, electrons, and neutral metal atoms, and the inert gas are assumed identical because of the high friction between these components. Moreover, it is assumed that $T_0 = T_1 = T_3$. Further, $P_e = n_e kT_e$ is the electron pressure; $Q_e = -(5/2)(n_e kT_e \tau_e/m_e)\,\mathrm{grad}(kT_e) + n_e kT_e u_1$ is the electron thermal flux; Ion $= n_e(\alpha n_0 - \beta n_e^2)$ is the rate of electron generation per unit volume; Ch $= 2m_e/m_1 k n_e(T_e - T_1)/\tau_e$ is the intensity of heat exchange between electron and the heavy plasma components; Ip is the ionization potential, for copper equal to 7.724 eV; $\alpha = CkT_e\sqrt{8kT_e/\pi m_e}(ip/kT_e + 2)\exp(-Ip/kT_e)$ is the ionization rate; $\beta = 1.1 \times 10^{-14}\,C\,(Ip/kT_e + 2)$ is the recombination rate; C is a constant;

$$\frac{1}{\tau_e} = \frac{1}{\tau_{ei}} + \frac{1}{\tau_{e0}} = n_e\bar{v}_e\sigma_1 + (n_0 + n_3)\bar{v}_e\sigma_2; \qquad \bar{v}_e = \sqrt{\frac{8kT_e}{\pi m_e}}; \quad \sigma_1 = \frac{6\cdot 10^{-6}}{(T^0)^2}; \quad \sigma_2 = \pi r_b^2.$$

The expressions for α and β were taken from [8], while that for the electron thermal flux Q_e is from [9]. It is assumed that the energy liberated due to recombination of electrons with ions, is expended in heating the electron component, but by means of collisions of electrons with atoms and ions can be transferred to the latter.

The equations for the drops are written in the following manner:

$$\frac{\partial m_4 n_4}{\partial t} + \frac{\partial (m_4 n_4 u_4)}{\partial R} + \frac{m_4 n_4 u_4}{R} = I_4^{(mn)}; \tag{7}$$

$$\frac{\partial m_4 n_4 u_4}{\partial t} + \frac{\partial m_4 n_4 u_4^2}{\partial R} + \frac{m_4 n_4 u_4^2}{R} = \sum_i (m_i\dot{n}_{i4}u_i - m_i\dot{n}_{4i}u_4 + F_i); \tag{8}$$

$$\frac{\partial m_4 n_4 C_\ell T_4}{\partial t} + \frac{\partial m_4 n_4 C_\ell T_4 u_4}{\partial R} + \frac{m_4 n_4 C_\ell T_4 u_4}{R} =$$
$$= \sum_i \left(\dot{n}_{i4}\left(q_i + m_i\frac{(u_i - u_4)^2}{2} + \frac{3}{2}kT_i\right) - \dot{n}_{4i}(q_i + kT_4)\right), \quad i = 0, 1, 3. \tag{9}$$

In Eqs. (7)-(9)

$$I_4^{(mn)} = \sum_i I_{i4}^{(mn)} = \sum_i (\dot{n}_{i4} - \dot{n}_{4i})\, m_i \quad (i = 0, 1, 3);$$

$m_4 = (4/3)\pi r_4^3\rho_4$ is the mass of a liquid metal drop; C_ℓ is the heat capacity of the metal drop.

Breakup of Original "Large" Drops. As is well known, at a level of heat introduced into the wire of the order of the sublimation energy a significant fraction of the expanding material is in the from of liquid drops from the very beginning. Upon expansion liquefaction of vapor occurs so rapidly that a heat exchange exists between the gas and particles, the drops cooling more slowly than the gas. If a vapor nucleus develops within a drop, the pressure therein will be determined by the external pressure plus a contribution from surface tension forces:

$$P_{nuc} = P_{ex} + 2\sigma/r_d + 2\sigma/r_{nuc} \tag{10}$$

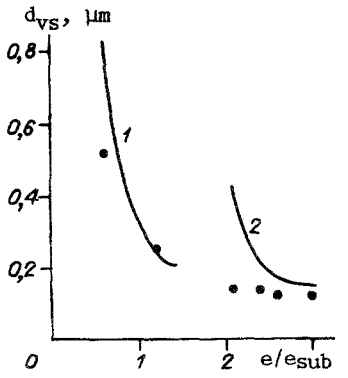

Fig. 1

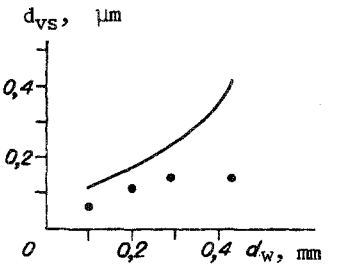

Fig. 2

The pressure in the vapor bubble depends exponentially on the drop temperature (denoted here by T_4):

$$P_{nuc} = A \exp(-B/T_4), \tag{11}$$

and if this value exceeds the right side of Eq. (10) the gas nucleus begins to grow. The drop explodes due to superheating. Equations (10) and (11) can be found in [7]. For an estimate we will take $r_{nuc} = r_d$, take the temperature dependence of σ from [10], and constants A and B of the copper vapor elasticity curve (here and below we will consider explosion of a copper wire) as presented in [11]. We write the condition for drop explosion in the form

$$A \exp(-B/T_4) > (n_0 + n_1 + n_3)\, kT_1 + 4\sigma/r_d \tag{12}$$

The initial drop size was taken as quite large (1/100 of wire diameter), and as numerical modeling shows, even in the initial stage of expansion the temperature difference between vapor and drops becomes marked, and Eq. (12) is satisfied. We assume that the drops break into several pieces and the size of the newly formed particles is on the average two times smaller than the original ones. This is only a coarse approximation, while in fact the process of explosive decomposition is very complex, and the particles produced have some spectrum over radius. As the numerical study showed, if we pick various breakup mechanisms (into 2, 3, 4, 5, 8 droplets), the final results may differ by 10%. Breakup continues as long as Eq. (12) is satisfied.

Generation of "Fine" Drops in the Metal Vapor. At high energy levels, twice or more the sublimation energy, the fraction of liquid phase is initially small, but vapor ionization is marked. Here the problem reduces to expansion of a plasma cylinder into a medium with resistance. Our model provides for simultaneous examination of the kinetics of interaction between the charged and neutral plasma components (ionization and recombination) upon expansion into the inert gas. Rapid cooling of the plasma upon expansion leads to "quenching" of the ionic component of the mixture and its supercooling. The presence of ions then significantly increases the rate at which condensed phase nuclei appear. The number of liquid phase nuclei or condensation centers appearing per unit volume, as well as their size, depend on the degree of supercooling achieved, the density of the vapor, and the rate of expansion at the given moment. As follows from our calculations, repeating [12], in general form (without reference to the geometry of the expansion) for the volume element of expanding vapor the maximum supercooling as a function of saturated state parameters and constants of the material can be determined from the transcendental equation

$$\frac{1}{I(\theta_{max})}\frac{d(\ln(\rho))}{dt} = D\frac{q}{T_1}\left\{\frac{1{,}5\theta_{max}^3}{b}\left(1 - \exp\left(-\frac{q\theta_{max}}{T_1}\right)\right)\frac{1}{\tau\left|\frac{d(\ln(\rho))}{dt}\right|}\right\}^3, \tag{13}$$

where $\rho = (n_0 + n_1)\, m_0$ is the gas density; T_1 is the gas temperature; q is the specific heat of evaporation; D is a numerical constant equal to $4.253 \cdot 10^{-3}$; θ_{max} is the degree of vapor supercooling ($\theta = (T_p - T_1)/T_p$); T_p is the saturation temperature for the given vapor density; $1/\tau = 4\pi d^2 n_0 \bar{u}$ is a quantity of the order of magnitude of the probability of gas kinetic collisions of vapor molecules at the moment of saturation; d is the molecular radius; $\bar{u}$ is the thermal velocity of the molecules; $b = 16\pi\sigma^3\omega^2/3k^3q^2T_1$; σ is the surface tension coefficient of the fused metal; ω is the specific volume of a single molecule in the liquid state; $I(\theta_{max}) = C_1(\exp(-\beta_0) + y\exp(-\beta_e))$ is the rate of formation of condensation centers per molecule;

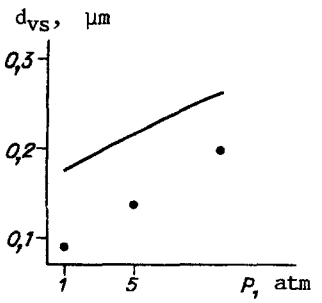

Fig. 3

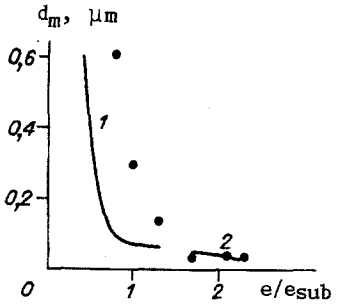

Fig. 4

$$\beta_0 = b/\theta^2; \quad C_1 = 2\omega n_0 \bar{u} \sqrt{\sigma/kT_1}; \quad \beta_e = \beta_0 (1 + 8a^3/r_c^3 - 6a^3/(dr_c^2));$$

$a = (z_1^2/16\pi\sigma)^{1/3}$ (z_1 is the charge of the electron); r_e is determined from the equation $\theta = (2\sigma\omega/kqr_e)(1 - a^3/r_e^3)$.

All the condensation centers are generated over the course of a short time interval, when the supercooling is close to the maximum value θ_{max}. Due to heat liberation supercooling then decreases, and the drops begin to grow. The total number of centers (calculated per molecule) is

$$\nu = \int_0^\infty I(\theta(t'))\, dt' = I(\theta_{max})\, \Delta t_m = (3\pi/8)\, I(\theta_{max})\, \frac{\theta^3}{b}\, \frac{1}{\left|\frac{d(\ln(\rho))}{dt}\right|} \tag{14}$$

(Δt_m is the effective duration of the supercooling maximum). Note that we have obtained Eqs. (13) and (14) by repeating the calculations of [12] with more general assumptions. Modeling of the plasma expansion with consideration of Eqs. (13) and (14) permits determining the time and place at which condensation begins and its further development, as well as estimating the total quantity of drops produced.

The first nuclei appear on the periphery of the plasma region near the contact boundary with the argon. Then with continued expansion the condensation front moves toward the center of the explosion, reaching it at the time when the cloud diameter is 20-25 times greater than the initial wire diameter (for an energy level $e/e_{sub} = 2$). Having obtained the total quantity of condensation centers and knowing the mass of the wire, we can evaluate the final particle size. It follows from Eq. (14) that the larger the superheating θ_{max} achieved and the lower the vapor density, the more condensation centers appear per unit mass of material. As numerical experiment showed, the greater the energy introduced into the wire, the later supercooling sets in, the lower the vapor density at the moment of nucleus formation, the greater θ_{max}, and consequently the more the number of condensation centers produced. The final mean particle size then decreases. On the other hand, with increase in counter-pressure or growth initial conductor diameter the mean diameter of the particles produced will increase.

Results. In comparing the results of numerical calculations with experimental data it must be remembered that in reality there exists some distribution of particles over size and the characteristic drop diameter will depend on the method used for calculation. In the model described above for low energy levels ($e/e_{sub} < 1.5$, breakup of original drops) as well as high ones ($e/e_{sub} > 2$, drop generation on ions) the total quantity of particles obtained in the explosion chamber N can be determined. We then determine the mean cubical diameter with the expression

$$d_{mc} = \sqrt[3]{\frac{6V}{\pi N}},$$

where V is the initial volume of the conductor.

Experimenters often use other expressions to find characteristic particle size, for example, the so-called volume-surface diameter, by the expression $d_{vs} = 6V/S$ (S is the total surface of all particles), or the mean numerical particle diameter, defined as $d_m = \Sigma d_i/N$ (d_i is the diameter of particle i). In the general case all the characteristic dimensions presented above may not coincide with each other. Thus, for a logarithmic normal distribution (most characteristic of ultradispersed powders) $d_{mc} = 1.62\, d_m = 0.62\, d_{vs}$ [13].

In Figs. 1-3 (data from [3] for explosion of copper in argon) for particle size we use the volume-surface diameter, while in Fig. 4 (data of [2] for explosion of copper in air) mean numerical is to be understood.

The lines of Fig. 1 show the calculated dependence of volume-surface diameter d_{vs} of copper particles upon the energy density introduced into the conductor (for a pressure in the surrounding medium of 5 atm and initial wire diameter of 0.43

mm), while the points are particle sizes found experimentally under the same conditions [3]. Figure 2 illustrates the dependence of characteristic particle size on diameter of the wire exploded (external gas pressure 5 atm, specific energy $e/e_{sub} = 2.1$), the line being the theoretically predicted curve, and the points experimental values. It turns out that the size of the particles produced depends only weakly on external pressure. This fact is reflected in Fig. 3 (initial wire diameter 0.43 mm, $e/e_{sub} = 2.4$).

For explosion of a copper wire in air the surface of the particles produced is coated by oxide [2], and our model does not consider chemical reactions. Nevertheless, assuming that the oxide film coating the particle does not greatly affect its size, we decided to compare data on a copper explosion with our calculations. And in this case too, the theoretical curves shown in Fig. 4 characterize the dependence of particle size produced by copper explosion in air upon energy introduced in a qualitatively correct manner. In Figs. 1 and 4 curve 1 is calculated assuming breakup of original drops while curve 2 is for metal vapor condensation on ions.

It should be noted that the model chosen here for expansion of explosion products does not always correspond satisfactorily to the experimental conditions of [2, 3]. This is related not only to the possibility of chemical reactions, vapor viscosity, etc., but primarily, in our opinion, to inhomogeneity of the explosion over the length of the wire. Therefore in those cases where stratification is more clearly expressed (large wire diameter or decreased energy input) the correspondence between calculation and experiment is degraded (Figs. 1, 2).

It has been shown experimentally [2] that in the intermediate energy range $e/e_{sub} = 1\text{-}2$ aside from breakup of original drops there also occurs within the expanding plasma condensation on ions, and in the final outcome a bimodal particle distribution over size is obtained. The mechanism for forming new condensation centers in the expanding vapor containing a significant quantity of "coarse" particles is more complex and will require further theoretical study.

In conclusion we note that the proposed model for expansion of the products of electrical explosion of a conductor, including the possibility of breakup of original "large" drops into finer ones (at energy levels not greater than the sublimation energy) and allowing tracing of liquid phase nuclei formation (at energy levels twice and three times the sublimation energy) produces a qualitatively correct prediction of size of the ultradispersed particles produced by the electrical explosion method. However, unfortunately it does not provide an answer to the question of two characteristic particle sizes upon introduction into the wire of an amount of heat greater than, but less than twice than the sublimation energy.

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