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MODELING OF THE PROCESS OF ELECTRIC-DISCHARGE SINTERING OF METAL POWDERS

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Consideration has been given to the process of electric-discharge sintering (EDS) of a powder fill in passing an electric current through it. The dependences for calculation of the heat release, the efficiency of an EDS unit, the resistance of a powder fill, and the temperature in the contact zone have been obtained. An algorithm for calculation of the technological parameters of the process of EDS has been given.

Introduction. Electric-discharge (electric-pulse) sintering of a powder fill placed in a dielectric matrix and compacted by punch electrodes is based on passing a high-power short-duration electric-current pulse of duration 10^{-5}–10^{-3} sec through it; the density of the current can attain 10^5–10^6 kA/m^2. Simultaneously with the electric discharge a variable magnetic field that causes radial compression of the powder fill (pinch-effect) is induced in it perpendicularly to the direction of motion of the current. This results in the local heating of powder-fill particles in the zone of contact and their sintering [1, 2]. Capacitive energy storages that represent a high-voltage (1–10 kV) bank of capacitors have gained wide acceptance as pulse current generators in EDS units. The EDS method is efficient for sintering of the powders of refractory and difficult-to-shape metals; porous powder materials produced from them find use in different branches of mechanical engineering and instrument making and in medicine [3, 4]. Therefore, investigation of the process of EDS is a topical problem of powder metallurgy. The mechanism of contact formation between powder particles in EDS has been studied in [5–8]; the influence of the discharge voltage and the compaction pressure on it has been shown. It has been established that the formation of a porous powder material occurs during the first period of discharge. At this instant, a current pulse has the form of damped harmonic oscillations. However, the dependence reflecting the relationship between the process of heat release, the capacity of the bank of capacitors, the inductance of the conductors of the discharge circuit of an EDS unit, the resistance of a powder fill, and the discharge time has not been established in [1–8]. This makes it impossible to evaluate the efficiency of the unit, which is determined by the ratio of the thermal energy released in the powder fill over the interval equal to the period of discharge time to the value of the electric energy stored by the bank of capacitors.

The dependence reflecting the relationship between the initial discharge voltage and the temperature in the zone of contact of powder-fill particles in EDS is also not given in [1–8], which makes it impossible to calculate the technological parameters ensuring the sintering of a powder fill and production of a porous powder material from it by modeling the process of EDS.

This work seeks to theoretically investigate the process of EDS and to determine:

(1) the criterion in the case of whose fulfillment most of the thermal energy (no less than 95% of the energy stored by the bank of capacitors) will be released in the discharge circuit over the first period of oscillation of the voltage;

(2) the analytical dependence reflecting the relationship between the physicomechanical properties of a powder fill and the compressive force of punch electrodes;

(3) the analytical dependence reflecting the relationship between the discharge voltage and the temperature of heating of powder particles.

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Influence of the Electrical Parameters of the High-Voltage Discharge Circuit on the Process of Heat Release in EDS. The process of change of the voltage in the electric circuit of the discharge of a high-voltage bank of capacitors through a powder fill in EDS is described by the equation [9]

$$\frac{d^2U}{dt^2} + \frac{R}{L}\frac{dU}{dt} + \frac{U}{LC} = 0 \,, \quad R = R_1 + R_2 \,. \tag{1}$$

In the case of damped harmonic oscillations, it is necessary to satisfy the condition [10]

$$\beta^2 < \omega^2 \,, \tag{2}$$

where

$$\beta = R/(2L) \,; \tag{3}$$

$$\omega = \sqrt{\frac{1}{LC} - \beta^2} \,. \tag{4}$$

The solutions of (1) are

$$U(t) = U_0 \exp(-\beta t)\cos(\omega t + \varphi_0) \,, \tag{5}$$

$$I(t) = \frac{I_0}{\cos(\varphi_0)} \exp(-\beta t)\sin(\omega t + \varphi_0) = \frac{U_0}{R\cos(\varphi_0)} \exp(-\beta t)\sin(\omega t + \varphi_0) \,. \tag{6}$$

The electromagnetic energy in the electric discharge circuit is described by the equation

$$W(t) = \frac{CU^2(t)}{2} + \frac{LI^2(t)}{2} \,. \tag{7}$$

Change in this energy leads to a release of the thermal energy $Q(t)$ in the powder fill; the thermal energy, with account for (3)–(7), is determined by the expression

$$Q(t) = -\Delta W(t) = \frac{CU_0^2}{2}\left[1 - \exp(-\beta t)\left(\cos^2(\omega t + \varphi_0) + \frac{L}{CR^2}\sin(\omega t + \varphi_0)\right)\right]. \tag{8}$$

Equation (8) describes the process of heat release in EDS. The heat-release time depends on the decrement of damped oscillations δ, the value of which, with account for (5) and [10], is computed as

$$\delta = \frac{U\left(\frac{2\pi}{\omega}\right)}{U_0} = \exp\left(-\beta\frac{2\pi}{\omega}\right). \tag{9}$$

The efficiency of the EDS unit is calculated in the form

$$\eta = (1 - \delta)\frac{R_1}{Z} = (1 - \delta)\frac{R_1}{\sqrt{R^2 + \left(\frac{1}{\omega C} - \omega L\right)^2}} \,. \tag{10}$$

For no less than 95% of the thermal energy to be released in EDS during the first period of the discharge, we must prescribe $\delta \le 0.05$. If this is satisfied, the time of the process of EDS is calculated with the use of (3) and (4).

Let δ be equal to 0.05; on the basis of (4) and (9), we express the resistance of the powder fill by the parameters L, C, and δ:

$$R = \sqrt{\frac{L}{C}\frac{4\ln^2(\delta)}{4\pi^2 - 1}} . \tag{11}$$

From relations (2), (5), and (11), we can determine the criterion for which most of the thermal energy will be released on the EDS unit over the first period of the discharge:

$$\sqrt{\frac{L}{C}} \le R < \sqrt{\frac{2L}{C}} . \tag{12}$$

If the resistance of the powder fill is known, dependences (8), (10), and (12) enable us to select, by modeling, such values of R, L, and C for which the efficiency of the EDS unit will be maximum.

Electrical Resistance of the Powder Fill. To obtain the analytical dependence for calculation of the electrical resistance of the powder fill with allowance for the analysis of [11–16] we introduce the following assumptions.

1. Powder particles have a spherical shape.
2. The dimension of the zone of contact between powder particles is small as compared to its diameter.
3. Deformation of a powder particle, produced by the compressive force of the punch electrodes, is elastic; it is determined by the relations

$$d = \left(\frac{3F_0D_0}{E}(1-\nu^2)(1-\sigma)\right)^{1/3} = D_0\left(\frac{3\pi p}{E}(1-\nu^2)(1-\sigma)\right)^{1/3} , \tag{13}$$

$$y = \left(\left[\frac{3F_0(1-\nu^2)(1-\sigma)}{E}\right]^2 \frac{1}{D_0}\right)^{1/3} = D_0\left(\frac{3\pi p}{E}(1-\nu^2)(1-\sigma)\right)^{2/3} . \tag{14}$$

The average diameter of a powder particle is computed from the Anderson formula

$$D_0 = D_1D_2\sqrt{\frac{2}{D_1^2 + D_2^2}} . \tag{15}$$

With account for (13)–(15), the relationship between the diameter of the contact zone and the value of the linear deformation is equal to

$$d = y\left[\frac{ED_0^2}{3F_0(1-\nu^2)(1-\sigma)}\right]^{1/3} = y\left[\frac{E}{3\pi p(1-\nu^2)(1-\sigma)}\right]^{1/3} . \tag{16}$$

Since the surfaces of two powder particles are separated by a nonconducting layer whose thickness is made up of oxide films, for the electric current to flow through a powder particle, it is required (according to [14, 15]) that the compressive force of the punch electrodes produce a linear deformation of the powder particle under which the condition $y > 2l_0$ would be satisfied.

Let the quantities l_0 and x be related by the ratio

$$\varepsilon = l_0/y , \tag{17}$$

then (16) with account for (17) is transformed as

$$d = (y - 2l_0)\left[\frac{ED_0^2}{3F_0(1-\nu^2)(1-\sigma)}\right]^{1/3} = y(1-2\varepsilon)\left[\frac{E}{3\pi p(1-\nu^2)(1-\sigma)}\right]^{1/3} . \qquad (18)$$

4. The number of contacts per particle $N_{\text{c.p}}$ depends on the porosity of the powder fill Π and is determined from the Eremeev formula

$$N_{\text{c.p}} = \frac{\Pi + 3 + \sqrt{\Pi^2 - 10\Pi + 9}}{2\Pi} . \qquad (19)$$

5. The distribution of the released energy among powder particles in EDS is uniform.

With account for (15) and (19), the number of contacts and their volume concentration in the powder fill are computed as

$$N_{\text{c.powd.f}} = N_0 N_{\text{c.p}} , \qquad (20)$$

$$N_0 = \frac{6(1-\Pi)V}{\pi D_0^3} , \qquad (21)$$

$$n_V = \frac{N_{\text{c.powd.f}}}{V} = \frac{6N_{\text{c.p}}(1-\Pi)}{\pi D_0^3} . \qquad (22)$$

Expressions (21) and (22) yield that the linear and surface concentrations of powder particles are found in the following manner:

$$n_L = n_V^{1/3} , \qquad (23)$$

$$n_S = n_V^{2/3} . \qquad (24)$$

6. The porosity of the powder fill after its compaction by the punch electrodes is determined in the form

$$\Pi = \Pi_{\text{fr.f}} - \Delta\Pi . \qquad (25)$$

7. In compaction of the powder fill, the area of its cross section remains constant; therefore, we have

$$\Delta\Pi = \frac{h_0 y n_L}{h_{\text{fr.f}}(h_{\text{fr.f}} - y n_L)} \approx \frac{h_0}{h_{\text{fr.f}}^2}\left(\frac{9Fn_V}{D_0 E N_{\text{c.p}}}(1-\nu^2)(1-\sigma)\right)^{1/3} . \qquad (26)$$

With account for the assumptions 1–7 made above and for (18), (23), and (24), we obtain the equation for calculation of the specific resistance of the powder fill:

$$\rho_{\text{powd.f}} = \rho\,\frac{4D_0}{\pi(1-2\varepsilon)^2 n_V^{1/3}}\left(\frac{E}{3FD_0(1-\nu^2)(1-\sigma)}\right)^{2/3} . \qquad (27)$$

Knowing the height of the powder fill after its compaction h and the cross-sectional area S, we can determine with (27) the resistance of the powder fill:

$$R = \rho \frac{4D_0}{\pi (1-2\varepsilon)^2 n_V^{1/3}} \left(\frac{E}{3FD_0 (1-\nu^2)(1-\sigma)} \right)^{2/3} \frac{h}{S} . \tag{28}$$

In EDS, under the action of the pinch-effect, a radially directed force develops in the powder fill; this force produces a radial pressure whose average value is equal to [17]

$$p_r = \frac{\mu_0 I^2}{4\xi\pi^2 r^2_{\text{powd.f}}} \int_0^{r_{\text{powd.f}}} \frac{J_0^2 (\alpha \mathbf{r} \sqrt{-i}) - J_1^2 (\alpha \mathbf{r} \sqrt{i})}{J_1^2 (\alpha \mathbf{r} \sqrt{-i})} \mathbf{r} d\mathbf{r} , \quad \alpha = \sqrt{\frac{\omega\mu_0}{\rho}} , \quad i^2 = -1 . \tag{29}$$

The action of this pressure can produce a nonuniform pore distribution in the porous powder material. If the condition

$$p_h = \frac{F}{S_h} \ge p_r \tag{30}$$

is observed, this will not take place. In the case of satisfaction of the condition $p_h = p_r$ the force of friction of the powder against the lateral wall of the matrix will be equal to zero.

Using (10), (28), and (29), criterion (12), and condition (30), we can calculate the optimum value of the resistance of the powder fill in EDS by varying the parameters D_0, h, S, and p.

Relationship Between the Discharge Voltage and the Temperature of Heating of a Powder Particle. Let us introduce the following model assumptions:

(a) heat in the contact zones of all powder particles is released uniformly; the processes of heat exchange in them are independent of each other;

(b) in view of the rapidity of the process of EDS, there is virtually no heat exchange with the ambient medium;

(c) heating of a powder particle is carried out owing to the heat sources that are the contact zones;

(d) the zone of contact represents a hemisphere whose diameter is determined by Eq. (13);

(e) the specific energy in the zone of contact expended in heating the particle is determined by the ratio

$$q = \frac{CU_0^2}{4N_{\text{c.powd.f}}} ; \tag{31}$$

(f) propagation of heat inside the particle itself is by the scheme of Fig. 1, according to which the first half of the heat released in the contact zone goes to heat one powder particle whereas the second half goes to heat the other particle;

(g) heat exchange between the internal particle layers is determined by the Fourier law

$$q = -\lambda \frac{\Delta T}{\Delta x} \Delta S \Delta t . \tag{32}$$

Assumptions (a)–(g) given above, Eq. (31), and criterion (12) yield the following:

(1) the value of the specific thermal power P_0 of the contact zone of a powder particle over one period in EDS is

$$P_0 = \frac{2\pi q}{\omega} , \tag{33}$$

where ω is computed from (4);

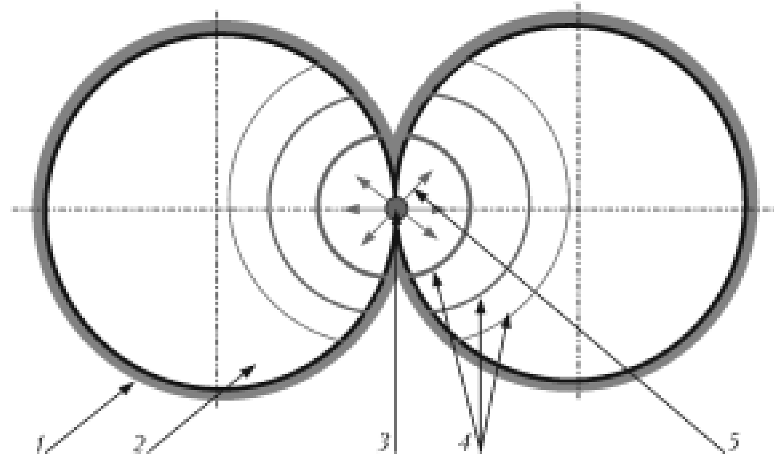


Fig. 1. Scheme of heat exchange between the heated layers of a powder particle: 1) oxide film; 2) powder particle; 3) contact zone; 4) isotherms; 5) direction of propagation of heat.

(2) based on the area of a spherical segment through which the heat flux into the particle goes and which is at a certain distance x from the contact zone, the change in the temperature between the thickness element of the heated layer dx and the contact zone is determined with account for (31)–(33) as

$$dT = -\frac{P_0}{\lambda\pi}\frac{dx}{x\,(x + \sqrt{D_0^2 - x^2} - D_0)}\,; \tag{34}$$

(3) when the heat release in the contact zones of a powder particle in EDS is uniform, a temperature field is formed in it in such a manner that a point with a minimum value of the temperature is at the geometric center of the particle. This imposes the following constraints on the depth of heating of the elementary layers:

$$d/2 \le x < D_0/2\,. \tag{35}$$

With account for (35), expression (34) is reduced [18] to

$$dT \approx -\frac{P_0}{\lambda\pi}\frac{dx}{x^2\left(1 + \dfrac{x}{D_0}\right)}\,. \tag{36}$$

If we assume that the thermal conductivity of the powder-particle material remains constant in EDS, expression (36) yields

$$\Delta T = -\frac{P_0}{\lambda\pi}\left[\frac{1}{D_0^2}\ln\left(\frac{D_0 + x}{x}\right) - \frac{1}{xD_0}\right]\Bigg|_{d/2}^{x}\,. \tag{37}$$

Then, using (33) and (37), we determine the relationship between the initial value of the discharge voltage and the temperature change as

$$\Delta T = -\frac{CU_0^2}{\lambda\omega}\left[\frac{1}{D_0^2}\ln\left(\frac{D_0 + x}{x}\right) - \frac{1}{xD_0}\right]\Bigg|_{d/2}^{x}\,. \tag{38}$$

TABLE 1. Physical Properties of VT1-00 Powder and Compact Titanium

Properties of the VT1-00-titanium powder fill				Properties of the compact titanium material							
$\gamma_{fr.f}$	D_1	D_2	l_0	γ	λ	c	ρ	E	ν	T_{fsn}	Q_{μ}
2700	–400	315	1	4540	21.9	25.0	0.42	95	0.3	1941	14.6

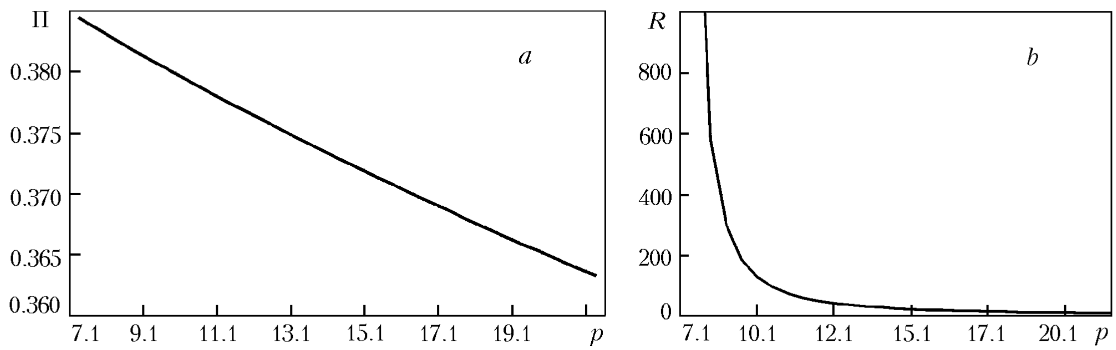


Fig. 2. Porosity (a) and resistance (b) of a powder fill vs. compaction pressure.

If we assume that the thermal conductivity in EDS is a function of the temperature $\lambda = \lambda(T)$, we find with (36) the temperature field of a powder particle from the expression

$$\int_{T_x}^{T_q} \lambda(T)\, dT = -\frac{P_0}{\pi}\left[\frac{1}{D_0^2}\ln\left(\frac{D_0 + x}{x}\right) - \frac{1}{xD_0}\right]\Bigg|_{d/2}^{x} . \tag{39}$$

Here T_q is the temperature in the zone of contact, which is calculated with account for (32) as

$$T_q = \frac{3q - 2.25b\gamma\pi d^3}{4(c_1 + c_2)\gamma\pi d^3} . \tag{40}$$

In the calculations with the use of dependences (37) and (38), T_q is the maximum temperature.

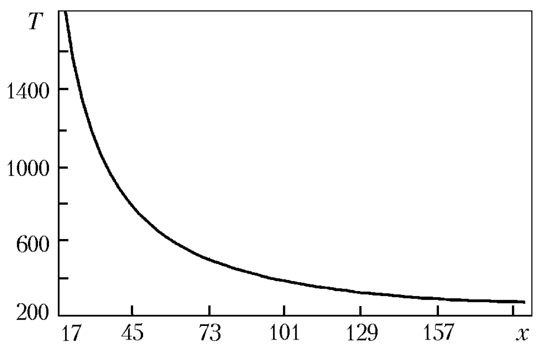
Dependences (31)–(38) establish the relationship between the initial discharge voltage and the temperature of heating of a powder particle and enable us to calculate the initial (optimum for EDS) discharge voltage of a high-voltage bank of capacitors.

Calculation of the Technological Parameters of the Process of EDS and Analysis of the Results Obtained. Let us consider the algorithm of calculation of the physical parameters of the process of EDS to produce a cylindrical billet with overall dimensions D = 5 mm and h_0 = 10 mm and porosity Π = 0.35. The starting material will be a powder fill consisting of VT1-00-titanium spherical powder.

1. Employing the initial data of Table 1, we determine with the use of (12)–(27) the manner in which the porosity of the powder fill (Fig. 2a) and its resistance (Fig. 2b) change with compaction pressure.

2. With account for criterion (12), the resistance of the powder fill will be R_1 = 0.01 Ω for the following parameters of the electric-discharge circuit of the EDS unit: (a) period of the discharge $T \simeq 70$ μsec; b) capacity of the high-voltage bank of capacitors C = 900 μF; c) inductance in the discharge circuit L = 0.15 μH. Based on this fact (see Fig. 2a and (27) and (30)), it follows that the compressive force of the punch electrodes must be F = 200 H.

3. Using dependences (31)–(39) we determine the initial value of the discharge voltage of the bank of capacitors. When U_0 = 1500 V the temperature distribution inside a powder particle is characterized by the dependence given in Fig. 3 after the discharge of the high-voltage bank of the EDS unit. Heat release in the powder fill and change in the voltage in the discharge circuit will represent processes described by Eqs. (8) and (5). The dependences obtained with the use of them are given in Figs. 4 and 5.



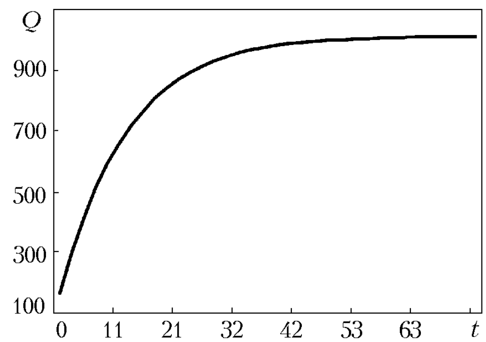
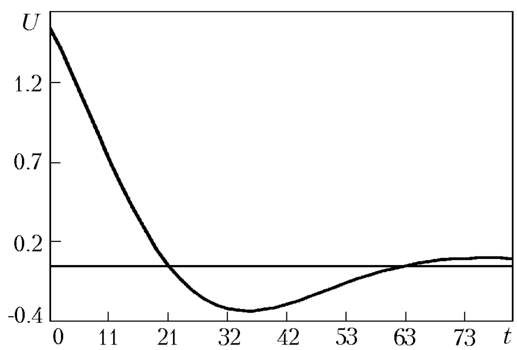


Fig. 3. Change in the temperature as a function of the coordinate into the powder particle. T, K; x, μm.

Fig. 4. Thermal-energy release vs. discharge time.



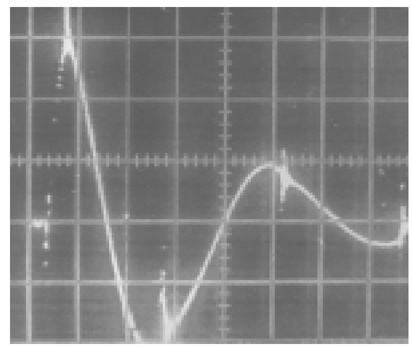


Fig. 5. Change in the voltage on the bank of capacitors as a function of the discharge time in EDS.

Fig. 6. Change in the voltage in the discharge circuit of the EDS unit in sintering of a powder fill.

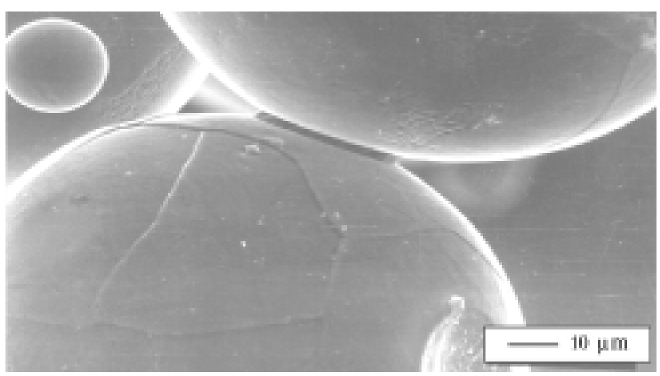


Fig. 7. Contact zone between two particles of a powder fill after EDS.

The technological parameters calculated with the use of dependences (12)–(27) and (30)–(39) and given above in items 2 and 3 were specified on an Impulse-BM EDS unit. The electric-pulse shape obtained in EDS is presented in Fig. 6.

It is clear (Figs. 5 and 6) that the graphic curve of change of the voltage in the electric-discharge circuit, calculated with the use of Eqs. (5) and (11), and the oscillogram obtained in EDS coincide in shape. The contact between two particles of the sintered spherical powder (Fig. 7) confirms the legitimacy of the employment of the model assumptions given in this work. The cylindrical billets had overall dimensions D = (5 ± 0.05) mm and h_0 = (10 ± 0.1) mm and porosity Π = 0.35 ± 0.01.

CONCLUSIONS

1. By theoretical investigation of the process of EDS of powders, we have determined:

(a) the criterion in the case of whose fulfillment most (no less than 95% of the energy stored by the bank of capacitors) of the thermal energy will be released in the discharge circuit over the first period of voltage oscillations;

(b) the analytical dependence reflecting the relationship between the electrical resistance of a powder fill and its physicomechanical properties and the compressive force of the electrodes;

(c) the analytical dependence reflecting the relationship between the discharge voltage and the temperature of heating of powder particles.

2. The dependences obtained in the work enable one to model the process of EDS of powders and to calculate its optimum technological parameters for spherical metal powders.

NOTATION

b, specific heat of fusion, J/g; C, capacity of the bank of capacitors, μF; c, c_1 and c_2, specific heat, specific heat of the solid and liquid states of the material of a powder particle, J/(kg·K); D, diameter of the powder fill, mm; D_0, D_1, and D_2, average diameter and minimum and maximum size of a powder particle, μm; d, diameter of the contact zone, μm; E, Young modulus, MPa; h, $h_{fr.f}$, and h_0, height of the fill, the free fill, and the compact material, mm; F and F_0, compressive force of the electrode and force acting on a powder particle, N; I and I_0, electric discharge current and maximum value of the current in the circuit, kA; J_0 and J_1, Bessel functions of the first kind; L, inductance of the circuit, μH; l_0, thickness of the oxide film, μm; $N_{c.p}$, number of contacts per powder particle; N_0, number of powder particles in the fill; $N_{c.powd.f}$, number of contacts in the powder fill; n_V, volume concentration of contacts of the particles in the powder fill, mm^{-3}; n_L, linear concentration of contacts of the particles in the powder fill, mm^{-1}; n_S, surface concentration of contacts of the particles in the powder fill, mm^{-2}; P_0, value of the specific thermal power released on a powder particle in the powder fill, W; p, p_r, and p_h, compaction pressure, radial pressure, and pressure on the lateral side, MPa; Q, heat, J; Q_μ, molar heat of fusion, J/mole; q, specific discharge energy, mC/mm^{-3}; R, R_1, and R_2, electrical resistance, electrical resistances of the powder fill and the current leads of the electric-discharge unit, Ω; $r_{powd.f}$, radius of a cylindrically shaped powder fill, mm; $\mathbf{r}$, radius vector connecting the center of the powder-fill cross section and its arbitrary point, μm; S and S_h, cross-sectional areas of the powder fill and its lateral surface, mm^2; ΔS, area of the surface through which the heat flux passes, μm^{-2}; T, T_x and T_q, T_{fsn}, temperature, temperature at the considered point of a powder particle and in the zone of contact, fusion temperature, K; t, time, μsec; U and U_0, electric discharge voltage and initial value of the voltage on the bank of capacitors, kV; V, volume of the powder fill, mm^3; W, energy of the discharge circuit of the EDS unit, J; x, distance between the contact zone and the considered internal layer of a powder particle, μm; y, value of the linear deformation of a powder particle, μm; Z, electric-circuit impedance, Ω; β, damping factor, sec^{-1}; γ and $\gamma_{fr.f}$, density of the material of a powder particle and the free fill of the powder material, kg/m^{-3}; ΔT, temperature change, K; Δt, time change, μsec; ΔW, change in the energy in the discharge circuit of the EDS unit, J; Δx, thickness of the heated layer, μm; ΔΠ, porosity change; δ, decrement of damped oscillations; ε, ratio of the thickness of the nonconducting layer to the value of the linear deformation; σ, coefficient of sliding friction; η, efficiency; λ, thermal conductivity, W/(m·K); μ_0, permeability of free space, H/m; ν, Poisson coefficient; ξ, coefficient of lateral pressure in the rigid mold; Π and $\Pi_{fr.f}$, porosity and porosity of the free fill; $\rho_{powd.f}$, specific resistance of the powder fill of a particle, μΩ·m; ρ, specific resistance of the material of a powder particle, μΩ·m; φ_0, angle of the initial phase of oscillations, rad; ω, damped-oscillation frequency, rad/sec. Subscripts: 0, 1, and 2, order of numeration; h, L, r, S, and V, height, length, radius, area, and volume variables; q, in the zone of contact; x, at the point in question; μ, in the mole of a substance; c.powd.f, contacts of the powder fill; c.p, contacts of particles; powd.f, powder fill; fr.f, free fill; fsn, fusion.

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