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Improvement of Plasma Coatings Used in Medicine

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A technology for production of implants with porous coatings is suggested. The coatings provide prolonged release of medicinal substance from the coating to the surrounding tissue. The physical, technological, and design features of the process of coating application to the implant surface are reviewed with special emphasis on the biological compatibility of the coatings.

Materials of medical use, such as intra-tissue implants, should meet specific interrelated requirements for their biological, physical, mechanical, and technological character [1]. Development of biocompatible materials is enhanced by nanotechnology and plasma technologies [2, 3]. In particular, such technologies can be applied for creation of special porous coatings on the surface of intra-tissue implants Porous coatings of this type can be used to release drugs into surrounding tissue for a prolonged time [2].

An improved technology of plasma-mediated coating is suggested in this work to provide more homogeneous distribution of coating parameters (dispersity, particle and thermal flux distribution), thereby increasing the coating strength. The suggested technology is based on a systematic analysis of the physicochemical and constructive properties of plasma coatings and can be used to regulate coating properties such as porosity and adhesion (Table 1).

Let us consider the physicotechnological substantiation of introducing new technological methods to conventional coating procedures. The first technological innovation is to improve the kinematic scheme of the plasmatron by providing it with additional mobility (sweep) in the direction perpendicular to its main motion. Such sweep improves the coating parameters at the application spot. The geometric scheme of coating concerning the plasmatron sweep is shown in Fig. 1.

Increase in the distribution homogeneity relative to plasmatron sweep can be explained theoretically. Let the kinematic scheme of the plasmatron sweep be described using the random distribution law [4]:

$$z = x + y, \qquad (1)$$

where z is random powder particle dispersity at the application spot depending on plasmatron sweep mobility; x is random powder dispersity at the application spot in the absence of plasmatron sweep mobility; y is random powder particle dispersity at an arbitrary point of the application spot due only to the plasmatron sweep.

Based on [3], let the distribution of random value x be assumed to be normal and the distribution of random value y be equiprobabilistic (Fig. 2).

TABLE 1. Technology of Production of Powder Plasma Coatings with Controlled Parameters

Notation	Technology
y_1	Improvement of plasmatron kinematic scheme
y_2	Addition of gas discharge for activation of particles coated on the surface
y_3	Formation of dynamic vacuum for regulation of heating and mobility of particles
y_4	Improvement of gas discharge power sources for combined coating technology
y_5	Development of vacuum chambers with floodgates
y_6	Development of adaptive control system for regulation of plasma coating of powder materials based on computer technology

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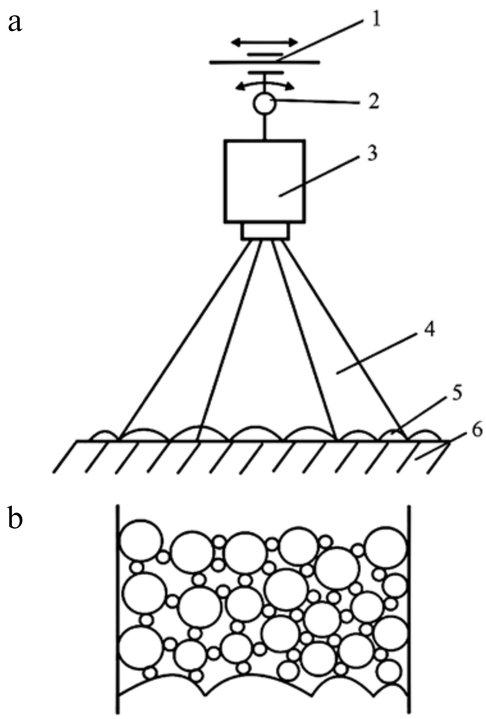

Fig. 1. Scheme of coating concerning plasmatron sweep: 1) kinematic unit for progressive mobility of the plasmatron; 2) kinematic unit for plasmatron sweep mobility; 3) plasmatron; 4) plasma jet; 5) coating spot; 6) coating surface (substrate); a) kinematic scheme of plasmatron mobility; b) powder dispersity structure at the application spot.

If the distribution density of x and y are $\varphi(x)$ and $\varphi(y)$, respectively, the distribution density of the sum $x + y$ is an integral [4, 5]:

$$\varphi(z) = \int_0^\infty \varphi(x)\varphi(z-x)dx = \int_0^\infty \varphi(y)\varphi(z-y)dy. \quad (2)$$

If the equiprobabilistic distribution of y is from a to b, the distribution density is:

$$\varphi(y) = \varphi(z-x) = 1/(b-a). \quad (3)$$

For normal distribution of x, this value is:

$$\varphi(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\bar{x})^2}{2\sigma^2}} = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(z-y-\bar{x})^2}{2\sigma^2}}, \quad (4)$$

where $\bar{x}$ is the mathematical expectation of x; σ is the mean square ratio $x/\bar{x}$.

The probability density is:

$$\varphi(z) = \int_a^b \varphi(y)\varphi(z-y)dy = \frac{1}{b-a}\cdot\frac{1}{\sigma\sqrt{2\pi}}\int_b^a e^{-\frac{(z-y-\bar{x})^2}{2\sigma^2}}dy. \quad (5)$$

The integral is calculated from a to b because it is non zero in the interval $a < y < b$.

The expression for $\varphi(z)$ was derived in [4]:

$$\varphi(z) = \frac{1}{b-a}\left[\Phi\left(\frac{b-z+\bar{x}}{\sigma}\right) - \Phi\left(\frac{a-z+\bar{x}}{\sigma}\right)\right], \quad (6)$$

where

$$\Phi\left(\frac{b-z+\bar{x}}{\sigma}\right) - \Phi\left(\frac{a-z+\bar{x}}{\sigma}\right)$$

is the normalized Laplacian.

The distribution curves according to the composition law are shown in Fig. 3 for both normal and equiprobabilistic distributions.

The parameter λ is:

$$\lambda = (b-a)/b\sigma_x. \quad (7)$$

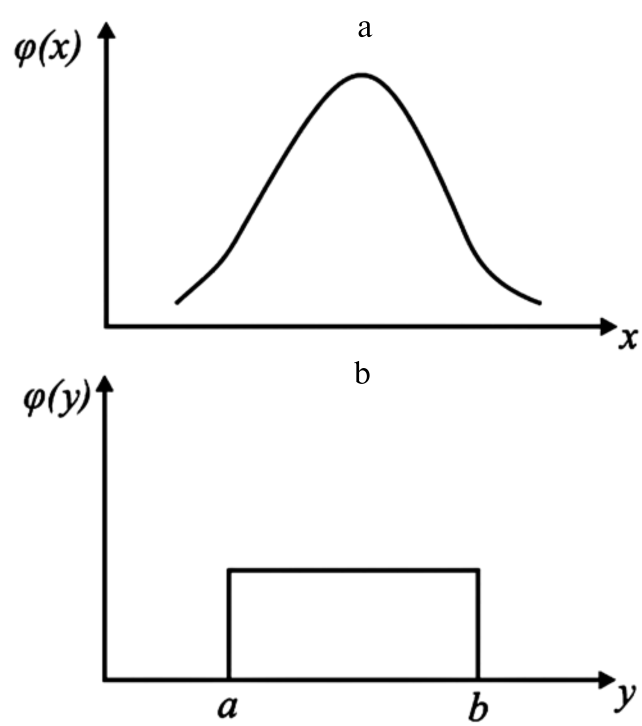

Fig. 2. Powder dispersity according to probability laws: a) normal distribution; b) equiprobabilistic distribution.

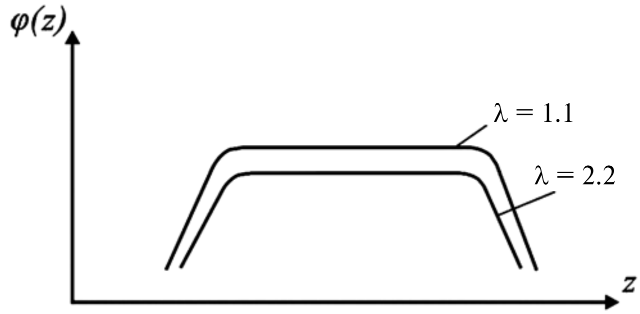

Fig. 3. Composition of distribution laws.

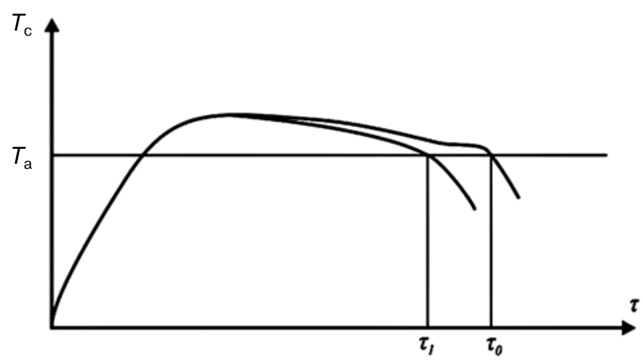

Fig. 4. Thermal activation scheme: T_c – contact zone temperature; T_a – activation temperature; τ_1 to τ_0 – time, within which $T_c > T_a$.

The curves in Fig. 3 are consistent with the suggestion that the plasmatron sweep improves distribution of powder at the application spot.

The coating strength can be increased by gas discharge and surface activation. Chemical activation of the surface in the plasma jet can be due to various processes. In particular, thermal activation at the zone of contact is necessary to increase the coating strength. The thermal activation scheme at the contact zone is shown in Fig. 4.

To provide strong coating, the contact temperature T_c within time τ_0 should be less than the activation temperature T_a. If $T_c < T_a$ within time τ_0, the probability of interaction between atoms in the contact zone decreases, thereby decreasing the coating strength.

A protective gas medium provides an additional increase in the plasma coating strength. An electrically neutral gas medium is able to modify chemical properties of interacting molecules. In addition to the protective function, such a medium is also able to provide thermal activation of the coating surface. The processes of thermal activation and evaporation are simultaneous, which allows for their optimization in a rarefied gas medium.

The substrate can be activated in a rarefied gas medium using an arc discharge. The arc discharge in the rarefied gas medium is implemented in many microscopic spots moving along the cathode surface. The current density in the microscopic spots is 10^3-10^6 A/cm^2. The mean lifetime in spots ~0.1 mm in diameter is 10^{-3}-10^{-5} sec. Thus, each cathode spot is an intensive source of heating. Microscopic spots are generated at the cathode areas providing better conditions for thermoelectron emission. Temperature increase, destruction of oxide film, and modification of the material at the sites of contact between particles and substrate provide conditions necessary for the electron emission. Therefore, the microscopic spot moves to the site of evaporation. It is safe to suggest that such processes induce a local increase in the substrate temperature.

The problem of calculation of the heat conditions at the cathode microscopic spot was solved using boundary thermal conductance theory in a cylindrical frame of reference. The heated surface was represented as a semi-limited body with uniform source of power:

$$\begin{cases} \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial x^2} - \frac{1}{a}\frac{\partial T}{\partial r} = 0; \\ -\lambda\frac{\partial T}{\partial x}(r, 0, t) = \begin{cases} g, & \text{for } r \le r_0; \\ 0, & \text{for } r > r_0; \end{cases} \\ T(\infty, \infty, 0) = 0. \end{cases} \tag{8}$$

The solution of the problem in for $x = 0$ is [2]:

$$T(r,\tau) = \frac{gr_0}{\lambda} \times \\ \times \sqrt{\frac{a\tau}{rr_0}} \sum_{n=0}^{\infty} \left\{ 2ierfc\left[(2n+1)\left(\frac{r_c}{r_0} - 1\right) - \frac{\left(\frac{r_c}{r_0} - \frac{r}{r_0}\right)}{\sqrt{a\frac{r}{r_0^2}}} \right] + \right. \\ \left. + 2ierfc\left[(2n+1)\left(\frac{r_c}{r_0} - 1\right) + \frac{\left(\frac{r_c}{r_0} - \frac{r}{r_0}\right)}{\sqrt{a\frac{r}{r_0^2}}} \right] \right\}, \tag{9}$$

where r_0 is radius of the source; r_c is radius of semi-limited cylinder with thermal source; g and r are thermal activation zone radii; a and λ are substrate material thermophysical coefficients; τ is time.

Thermal activation temperature $T_{t.a}$ is calculated from the equation derived in [3]:

$$T_{t.a} = \frac{E(B_p + B_s)}{kB_s(Int + 30)} - \frac{B_p}{B_s}T_m, \qquad (10)$$

where E is activation energy of chemical bonds; k is the Boltzmann constant; B_p and B_s are thermal coefficients of particle and substrate; T_m is melting temperature of the particle material.

The results of the calculation demonstrated that Eq. (7) was valid within the area $(1.25\text{-}1.75)r_0$. The diameter of the area is 12.5-27.5 μm.

Thus, the method suggested in this work allows plasma-mediated coatings with required porosity and strength to be formed. Such coatings can be used in intratissue implants for increasing their biological compatibility.

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REFERENCES

1. A. V. Liasnikova, A. V. Lepilin, N. V. Bekrenev, and D. S. Dmitrienko, Dental Implants: Research, Development, Manufacture, and Clinical Use [in Russian], SGTU, Saratov (2006).
2. A. V. Liasnikova and T. G. Dmitrienko, Biocompatible Materials and Coatings of New Generation: Specific Features of Manufacture, Nanostructuring, Properties, and Perspectives of Clinical Use [in Russian], Nauchnaya Kniga, Saratov (2011).
3. S. M. Lisovskii, V. M. Taran, and A. V. Liasnikova, Devolopment of Electroplasma Technologies and Automated Equipment [in Russian], MGTU, Moscow (2005).
4. V. V. Kudinov, P. Yu. Pekshev, and V. E. Beleshchenko, Plasma Coating Application [in Russian], Nauka, Moscow (1990).
5. I. S. Solonin, Mathematical Statistics in Machine Industry Technology [in Russian], Mashinostroenie, Moscow (1972).