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Ultrasonic effect on electric spark forming and development in electroacoustic spraying [*]

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Влияние ультразвука на процессы формирования и развития электрической искры при электроакустическом напылении [***]

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Introduction. The electroacoustic application of wear-resistance coatings is studied. The work objective is to obtain a mathematical model of the ultrasonic effect on the formation and development of an electric spark occurring in the process of the electroacoustic sputtering.
Materials and Methods. The effect of ultrasonic vibrations on the processes occurring during the formation and development of a spark discharge is analyzed; the equations of continuity, energy motion and transfer, with the ultrasonic field contribution are considered. Factors affecting the thermal conductivity and electrical conductivity of strongly ionized gas are studied.
Research Results. When obtaining the model, it was assumed that the heat removal from the channel is carried out by a “clear emitter”. Then, for the channel region, a self-similar solution is made: pressure, temperature and density are constant over the cross-section, and velocity is proportional to the radius. A mathematical model that describes the processes occurring in the spark channel with the ultrasonic field energy effect is obtained.
Discussion and Conclusions. On the basis of the developed model, it is specified that under the ultrasonic radiation effect, the radius and temperature of the spark channel increase, and conditions of the double ionization under high ultrasonic energy are created.

Введение. Статья посвящена изучению процесса электроакустического нанесения износостойких покрытий. Целью работы является получение математической модели влияния ультразвука на процессы формирования и развития электрической искры, происходящей в процессе электроакустического напыления.
Материалы и методы. В основе анализа влияния ультразвуковых колебаний на процессы, протекающие при формировании и развитии искрового разряда, рассмотрены уравнения непрерывности, движения и переноса энергии с учетом вклада ультразвукового поля. Учтены факторы, влияющие на теплопроводность и электропроводность сильно ионизованного газа.
Результаты исследования. При получении модели были сделаны предположения, что отвод тепла из канала осуществляется «прозрачным излучателем». Тогда для области канала было принято автомодельное решение: давление, температура и плотность постоянны по сечению, а скорость пропорциональна радиусу. Получена математическая модель, описывающая процессы, протекающие в искровом канале с учетом влияния энергии ультразвукового поля.
Обсуждение и заключения. На основании построенной модели установлено, что под действием ультразвука увеличивается радиус и температура искрового канала, а также создаются условия двукратной ионизации при высоких энергиях ультразвука.

Keywords: electroacoustic spraying, hardening, hardening coatings, highly concentrated energy flows, ultrasound, electric spark, mathematical model, conductive channel, thermodynamics, ionization.

Ключевые слова: электроакустическое напыление, упрочнение, упрочняющие покрытия, высококонцентрированные потоки энергий, ультразвук, электрическая искра, математическая модель, токопроводящий канал, термодинамика, ионизация.

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Introduction. When applying wear-resistant coatings by electroacoustic spraying, a relatively narrow conductive channel with high temperature and ionization is formed, in which Joule heat is released, which leads to an increase in pressure and expansion of the channel. The expanding channel acts like a piston on the rest of the gas, and, since the expansion occurs at supersonic speed, it causes a shock wave, which propagates in front of this kind of piston. The temperature in the shock wave region is much higher than in the undisturbed gas, and the temperature in the channel itself is many times higher than in the shock wave. Accordingly, the density of the gas in the channel is very small; the vast majority of the mass of the moving gas is displaced from it, which makes it possible to consider the channel boundary as a piston [1].

The very fact of the formation of a narrow channel can be understood as follows: under the ultrasound action, as well as after the gas breakdown and the appearance of conductivity in the places of the current flow, Joule heat is released. The electrical conductivity of the gas is known to increase strongly with temperature. Thus, at a high degree of ionization, when the collision of electrons with ions is significant, the electrical conductivity is proportional to $T^{3/2}$. With small ionization, this dependence is sharper, since with the growth of *T,* the degree of ionization rapidly increases, and, consequently, there is a tendency to the current concentration in a relatively narrow channel. In places where the temperature is higher, the conductivity of the current is greater, so there is more current flowing, and more heat is released. This leads to even more heating and so on [2].

Physical processes determining the width of the channel and the limit of current concentration is heat transfer from the channel and the extension of the heated area under the action of pressure. The channel can be considered to be the area to the point where the temperature and the degree of ionization decreases significantly. In the channel, the inertia of the gas can be neglected, but it is necessary to take into account the release and transfer of heat. In the shock wave region, inertia must be taken into account, but electrical and thermal conductivity can be neglected. These two areas are separated by a transition layer – the "shell" of the channel. Heating and ionization of the gas entering the channel occurs in the shell [3, 4].

Materials and Methods. The main equations are the equations of continuity, motion and energy transfer taking into account the action of the ultrasonic field. They have the form of [5, 6]

$$\frac{\partial \rho}{\partial t} = V\frac{\partial \rho}{\partial r} + \rho\frac{\partial (rV)}{r\partial r} = 0 \quad (1)$$

$$\rho\left(\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial r}\right) + \frac{\partial p}{\partial r} = 0 \quad (2)$$

$$\frac{\partial}{\partial t}\left(\rho\varepsilon + \frac{\rho V^2}{2}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left\{r\rho V\left(\varepsilon + \frac{p}{\rho} + \frac{V^2}{2}\right)\right\} + \frac{\partial (rq)}{r\partial r} = jE + U \quad (3)$$

where ρ is density, V is velocity, p is pressure, ε is internal energy per unit mass of gas, q is heat flux, j is current density, E is electric field, U is contribution to the ultrasonic field.

The equation of state has the form

$$p = (n_e + n_i)T = \rho T(z+1)/m_a \quad (4)$$

where m_a is the average mass of an atom; n_e, n_i is the number of electrons and ions per unit volume; z is the average charge of an ion; $n_e = zn_i$. Temperature is expressed in energy units.

We assume that the ionization in the channel can be calculated by Saha ionization equation. The internal energy of the gas is

$$\varepsilon = \frac{3}{2}\frac{p}{\rho} + \frac{I}{m_a} = \frac{p}{\rho}\left[\frac{3}{2} + \frac{I}{(z+1)T}\right] \quad (5)$$

where I is the total ionization energy plus the dissociation energy per atom. The formula (5) is convenient to use in the case of full ionization; with incomplete ionization with increasing *T,* the value of *I* also increases. At the same time, as follows from Saha ionization equation, $I/T \approx const$, so for ε, the following formula is more convenient:

$$\varepsilon = \frac{1}{\gamma - 1}\frac{p}{\rho} \quad (6)$$

where γ is the effective adiabatic index; for air γ=1.22.

Electrical conductivity σ and thermal conductivity χ of highly ionized gas are equal to

$$\sigma = \sigma_1(T)T^{3/2} = 3\sigma'(z)T^{3/2}\Big/\left(4e^2\sqrt{2\pi m}\lambda\right)$$
$$\chi = \chi_1(z)T^{5/2} \tag{7}$$

Here, *e, m* is the charge and mass of an electron, $\lambda = \ln\left(3T^{3/2}\Big/\left(ze^3\sqrt{4\pi n_e}\right)\right)$, *σ′(z)* is the dimensionless coefficient. For *z*=1, the value is *σ′*= 1.95. The value $\chi\, e^2/\sigma T$, under the Wiedemann–Franz law, of the 1st order. For *λ*=5 *σ1(1)*=3,4.1013sec—1*eV-3/2*,

χ_1(1)=3,9.1020 cm-1 sec-1*eV-5/2.*

Research Results. Let us suppose that the time dependence of the channel radius, the boundary of which plays the role of the piston displacing the gas, has the form of *a(t)=Atk*; the motion in the shock wave region is determined by two dimensional parameters *A,ρ*.

In the equations (4)–(6), we introduce dimensionless notation (a_c — the radius of the wave front)

$$x = r/a_c(t),\ \rho'(x) = \rho/\rho_0,\ V'(x) = V/a_c,\ p'(x) = p/\rho_0 a_c^2 \tag{8}$$

Neglecting heat release and transfer, let us write the system (1)–(3) in the form

$$\begin{gathered}(V'-x)\frac{dp'}{dx} + \rho'\frac{dxV'}{xdx} = 0\\ \left(1-\frac{1}{k}\right)V' + (V'-x)\frac{dV'}{dx} + \frac{1}{\rho'}\frac{dp'}{dx} = 0\\ 2\left(1-\frac{1}{k}\right)p' + (V'-x)\frac{dp'}{dx} + \gamma\, p'\frac{dxV'}{xdx} = 0\end{gathered} \tag{9}$$

with boundary conditions at *x*=1

$$\rho' = (\gamma+1)/(\gamma-1),\ V' = 2/(\gamma-1),\ p' = 2(\gamma-1) \tag{10}$$

The position of the piston is determined by the point where *V′*=*x*. The pressure on p_k piston can be expressed through the piston speed.

$$p_k = K_p\rho_0 a^2, \tag{11}$$

where “resistance coefficient” K_p≈0,9 *(K_p=p′(a)a2/a2$_c$)* is deduced from the numerical solution of the system (9).

We neglect the radiation and assume that

$$q = -\chi\frac{dT}{dr} \tag{12}$$

Let the temperature *T* in the channel be much greater than that required for the complete ionization, therefore, on the edge, *T* is much less than in the center. Let us suppose that *T*=0 at *r*=*a*. We introduce dimensionless notations

$$s = \frac{r^2}{a^2(t)},\ \theta(s) = \frac{T}{T_0},\ u = \frac{1}{\theta}\frac{r}{2a}\left(\frac{r}{a}-\frac{V}{a}\right),\ y = \frac{r}{2a}\left\{\frac{q}{pa} + \frac{5}{2}\left(\frac{V}{a}-\frac{r}{a}\right)\right\}, \tag{13}$$

where T_0 is the temperature on the axis. We consider the pressure to be constant along the channel cross-section.

If the heat is removed from the channel by a “clear emitter”, a simple self-similar solution can be specified for the channel area: pressure, temperature and density are constant over the cross section, and the speed is proportional to the radius. The temperature drop is concentrated in the shell. In the same place, the radiation is absorbed and the ionization of the gas entering the channel takes place. Considering the shell to be thin, it is possible to obtain a system of equations for the main parameters of the channel. In general, you can use these equations to estimate them as a mathematical model that describes, although roughly, the main processes in the channel. This takes into account the approximate action of ultrasound and thermal conductivity [7].

The energy balance equations for the channel and the shell have the form

$$\frac{dW}{dt} = p\frac{d\pi\, a^2}{dt} = Q_j + Q_U, \tag{14}$$

$$\left(\varepsilon + \frac{p}{\rho}\right)\frac{dM}{dt} = Q_t + Q_R, \tag{15}$$

where *M, W* is the mass and energy of the gas in the channel. The equation (15) is obtained by integrating (3) over the cross section of the channel (including the shell) without assuming the form of distribution of values over the cross section. For a homogeneous model, let us suppose

$$W = M \cdot \varepsilon, \; M = \pi \cdot a^2 \rho .$$

The equations (14), (15) are the consequence of the law of energy conservation. The expressions for the release of heat Q_j due to the electric field and heat Q_U due to the ultrasonic field, as well as for the heat removal by radiation Q_R and thermal conductivity Q_T, can be taken as

$$Q_j = j^2 / \pi a^2 \sigma, \quad Q_U = \eta\omega \tag{16}$$

$$Q_R = \pi a^2 Q'_R(p,T), \quad Q_T = 1{,}3 \cdot 2\pi\chi \, T \tag{17}$$

where ω is the frequency of ultrasonic vibrations, η is the dimensional coefficient.

Comparing (14) and (15), we obtain that

$$Q_T + Q_R = \mu \left(Q_j + Q_U \right) , \tag{18}$$

where μ is a coefficient of the 1st order. If T is independent of t, then

$$\mu = \gamma \left[1 + (\gamma - 1) 2a^2 \left(\frac{d^2 a^2}{dt^2} \right)^{-1} \right]^{-1} \tag{19}$$

Let us consider the channel in air with the conductivity of σ=2·10^{14}sec^{-1}; *Kp*=0.9; γ=1.2; $j \sim t$; hence ξ=4.5. For the radius of the channel, we get the expression

$$a = 0{,}93 (1+\theta)^{1/6} \rho^{-1/6} j^{1/3} t^{1/2} \tag{20}$$

Here, a is measured in mm, j – in kA, t – in µs; ρ_0 =1.29·10^{-3} g / cm^3 under the atmospheric pressure. If the shock wave is weak, the radius is similarly deduced from (19).

Table 1 gives values of the radius calculated by the formula (20), with different values of θ and t (µs) at the discharge voltage V=30 V, and the battery capacity c=0.15 µF, and inductance of circuit L=4 nH (corresponding to $j=V/L$=7.5 10^9 A/sec).

Table 1

The channel radius for different values of θ, t

T / θ	0.3	0.5	1
0	0.65	1.00	1.62
1	0.73	1.12	1.82
2	0.78	1.20	1.95
3	0.82	1.26	2.04

Let us estimate the temperature in the channel. We believe that $\mu \sim 1$, for the same discharge as above at the time t=1 µs at L=4 nH we have that $Q_j + Q_U = (1+\theta) 1{,}7 \cdot 10^{13}$ erg / cm sec. If we assume that all heat is transferred by the electronic thermal conductivity, and the radiation is neglected, we obtain that
$T \approx 4(1+\theta)$eV. Taking T=4eV we find that the number of ions per unit volume in this case is n_j =9.1017, which in order corresponds to the experimental values.

Discussion and Conclusions. Based on the constructed approximate model, the following conclusions can be made about the effect of ultrasound on the development of the spark channel.

1. The radius of the channel increases by (1+θ)1/6 times in comparison with the case when there is no ultrasound, where θ is the ratio of the energies of the electric and ultrasonic fields.

2. The temperature in the channel increases proportionally (1+θ) under the assumption that the outflow of heat is carried out by the electronic thermal conductivity.

3. Already at the moment of the shock wave formation, almost complete ionization occurs in the channel, and conditions for double ionization at high ultrasound energies can be created.

References

1. Zhdanov, G.S. Fizika tverdogo tela. [Solid-state physics.] Moscow: MSU, 1962, 500 p. (in Russian).

2. Gadalov, V.N., Emel'yanov, S.G., Safonov, S.V., Vornacheva, I.V., Filonovich, A.V. Electroacoustic coating application to improve the performance of composites based on heat-resistant nickel alloys. M: Allerton Press, Inc. Russian Engineering Research, 2017, vol. 37, iss. 9, pp. 751–753.

3. Gurevich, A.G. Fizika tverdogo tela. [Solid-state physics.] St.Petersburg: BKhV-Peterburg, 2004, 320 p. (in Russian).

4. Kushner, V.S., et al. Materialovedenie. [Material science.] Omsk: OmGTU, 2008, 232 p. (in Russian).

5. Kudryashev, S.B. Razrabotka dinamiki prodol'no-krutil'nykh volnovodov primenitel'no k protsessu elektroakusticheskogo napyleniya pri uprochnenii rezhushchego instrumenta: avtoref. dis. … kand. tekhn. nauk. [Development of the dynamics of lengthwise-torsion waveguides by electroacoustic sputtering under hardening of cutting tools: Cand.Sci. (Eng.) diss., author's abstract.] Rostov-on-Don, 1998, 22 p. (in Russian).

6. Lozanskiy, E.D., Firsov, O.B. Teoriya iskry. [Theory of spark.] Moscow: Atomizdat, 1975, 272 p. (in Russian).

7. Maleev, D.N., Minakov, V.S. Elektroakusticheskoe napylenie uprochnyayushchikh pokrytiy. [Electroacoustic spraying of hardening coatings.] Rostov-on-Don: DSTU, 2014, 136 p. (in Russian).

8. Maleev, D.N., Al-Tibbi, W.H., Chilikin, D.A. Optimizatsiya protsessa elektroakusticheskogo napyleniya po kriteriyu mikrotverdosti. [Optimization of the electro-acoustic sputtering process by the microhardness criterion.] Vestnik of DSTU, 2010, vol. 10, no. 3(46), pp. 339–344 (in Russian).

9. Gadalov, V.N., Vornacheva, I.V., Makarova, I.A. Nekotorye svedeniya o sostoyanii sovremennykh uprochnyayushchikh tekhnologiy s aktsentom na elektroiskrovoe legirovanie. [On the state of modern hardening technologies with focus on electric spark alloying.] Auditorium, 2017, no. 4 (16) Available at: https://cyberleninka.ru/article/v/nekotorye-svedeniya-o-sostoyanii-sovremennyh-uprochnyayuschih-tehnologiy-s-aktsentom-na-elektroiskrovoe-legirovanie (accessed: 24.04.2018) (in Russian).

10. Belotskiy, A.V. Ul'trazvukovoe uprochnenie metallov. [Ultrasound hardening of metals.] Kiev: Tekhnika, 1989, 168 p. (in Russian).

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