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INDUCTIVE ACCELERATION OF PLANE BODIES

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A promising direction of practical application of the inductive acceleration of plane bodies is the laboratory study of processes occurring in high-velocity collisions. Unlike other methods of studying this process [1], an annular conductor accelerated by electromagnetic forces does not experience the reaction of the accelerating medium and thereby the purity of the experiment is significantly improved.

Processes of high-velocity projection of annular conductors were considered in [2, 3] where the effects of the geometric size of the accelerating system, the resistance, the self-inductance of the energy storage device, and the mass of the accelerated body on the transformation of energy in the accelerator were studied. In [4] analytical expressions and operating curves were obtained, allowing one to choose the optimal regime of acceleration, taking into account the heating of the conductor by the current passing through it. However, because a nonuniform magnetic field acts on the conductor as it speeds up, it is superheated near its inner radius and it deforms and splits. Hence the direct use of a conductor as one of the colliding bodies is limited.

In the present paper we discuss the results of a mathematical model and an experimental study of high-velocity projection of annular conductors when the colliding body is accelerated by another annular conductor. This method can be used to accelerate poorly conducting materials such as steel, titanium, etc., and dielectrics. The experiment was performed for

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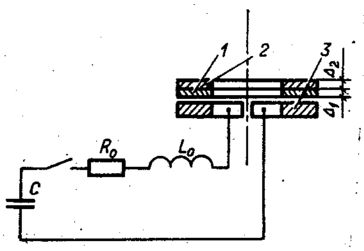

Fig. 1

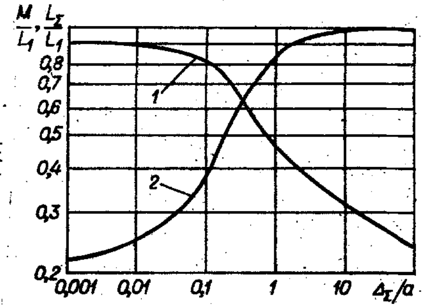

Fig. 2

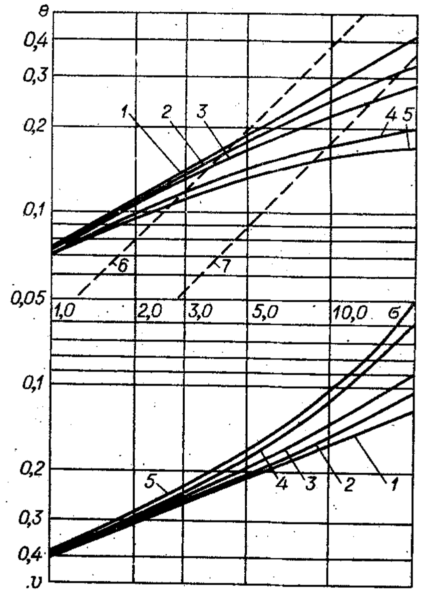

Fig. 3

various values of the parameters of the accelerator and the annular conductor characteristic in high-velocity collision processes.

1. An inductive electromagnetic accelerator of annular conductors (Fig. 1, where 1 is the accelerating conductor, 2 is the accelerated body, and 3 is the inductor) is characterized by the electrical parameters of the capacitive energy storage device, the inductor, the accelerating conductor, and the accelerated body, which can be either a conductor of a dielectric.

In the approximation used in electrical engineering, the acceleration process is described by a system of differential equations. In relative units these equations have the form

$$(\lambda_0+\lambda_1)\frac{dI_1}{d\tau}+\mu\frac{dI_2}{d\tau}+I_2\frac{d\mu}{d\varepsilon}+(\rho_0+\rho_1)I_1=\varphi_c,$$

$$\lambda_2\frac{dI_2}{d\tau}+\rho_2 I_2+\mu\frac{dI_1}{d\tau}+I_1\frac{d\mu}{d\tau}=0,\quad \frac{d\varphi_c}{d\tau}=-I_1,$$

$$\sigma\frac{dv}{d\tau}=I_1 I_2\frac{d\mu}{d\tau},$$

where

$$\varepsilon=x/(2R);\ \lambda_{0,1,2}=L_{0,1,2}/L_1;\ \mu=M/L_1;$$

$$\rho_{0,1,2}=R_{0,1,2}/\sqrt{L_1/C};\ I_{1,2}=i_{1,2}/(U_0\sqrt{C/L_1});$$

$$\varphi_c=U_c/U_0;\ \tau=t/\sqrt{L_1C};\ v=V\sqrt{L_1C}/(2R);$$

$$\sigma=4(m_1+m_2)R^2/(L_1C^2U_0^2);$$

R is the average radius of the inductor, m_1 and m_2 are the masses of the accelerating conductor and the accelerated body, $i_{1,2}$ are the currents in the capacitive energy storage device and the accelerating conductor, U_c is the voltage on the capacitor, U_0 is the charge voltage, C is the capacitance, $L_{0,1,2}$ and $R_{0,1,2}$ are the inductances and resistances of the storage device, the inductor, and the accelerating conductor, respectively. Finally, M is the mutual inductance between the inductor and the accelerating conductor, t is the time, and x is the displacement.

Assuming that the resistance of the accelerating conductor depends linearly on the input energy, we find (in relative units)

$$\rho_2=\rho_{20}\exp(\nu\theta), \tag{1.1}$$

where ρ_{20} is the initial value of the resistance ρ_2, $\nu=kU_0^2C^{3/2}/(\gamma_1S^2\sqrt{L_1})$, $\theta=\int_0^\tau I_2^2d\tau$, k is a coefficient characterizing the material making up the conductor [6], and γ_1 and S are the density and cross-sectional area of the conductor. The parameters M, L_1, L_2, S, R_1, R_{20}

depend on the electromagnetic field and are determined by transient processes and by heating of the inductor and conductor. Using the model of the electromagnetic field described in [7], it is found that in the case of high-velocity projection and when the thickness of the aluminum accelerating conductor is $\Delta_1 \leqslant 1$ mm, the current density can be assumed to be uniform over the cross section. But for a single-coil inductor made of copper or a copper alloy there is a sharply defined surface effect. Hence $S = a\Delta_1$, where $a = (D_1 - D_2)/2$, and D_1 and D_2 are the outer and inner diameters of the annular conductor. The mutual inductance and the equivalent inductance of the inductor—ring system L_Σ are shown in Fig. 2 as functions of the equivalent gap Δ_Σ between the inductor and the ring used in the calculation given below; curve 1 shows M/L_1 and curve 2 shows L_Σ/L_1. The introduction of an equivalent gap means that in the calculation of the inductances one can replace the magnetic field of the real system with that of current layers separated from each other by the distance Δ_Σ. Therefore

$$\Delta_\Sigma = \Delta_0 + \Delta' + \Delta'',$$

where Δ_0 is the geometric gap, and Δ' and Δ'' take into account the magnetic field in the inductor and the accelerating ring; these are calculated from the equality of the magnetic field energy in the equivalent gaps and in the inductor and accelerating ring (in analogy with the calculation of the "magnetic flux skin layer thickness" given in [8]).

We note that the value of Δ' will increase during the acceleration process because of the decrease of the discharge frequency of the energy storage device (due to the increase of L_Σ; see Fig. 2) and also because of the decrease of the conductivity in the presence of Joule heating. However this increase of Δ' weakly (0.5 to 1%) affects the acceleration process because of the rapid increase of the geometric gap such that $\Delta_0 \gg \Delta'$.

The system of differential equations was solved numerically for the initial conditions $\tau = 0,\ I_1 = I_2 = 0,\ \varepsilon = 0,\ v = 0,\ \varphi_c = 1$.

The dependence of the relative velocity and the parameter θ on the relative total mass is shown in Fig. 3 (curve 1: $\nu = 0$, curve 2: $\nu = 5$, curve 3: $\nu = 10$, curve 4: $\nu = 20$, curve 5: $\nu = 25$; $\rho_0 + \rho_1 = \rho_{20} = 0.05$).

The resistances ρ_0 and ρ_1 of the primary electric circuit cause an increase in energy loss and the resistance ρ_2, in addition to increasing the energy loss, also leads to a phase shift between the currents in the inductor and the accelerating conductor. The velocity decreases because of all of these factors.

We choose the condition $\theta \leqslant [\theta]$ as a condition for allowable heating, where $[\theta]$ is given by the limiting value $[\ln(\rho_2/\rho_{20})]$.

It follows from (1.1) that

$$[\theta] = [\ln(\rho_2/\rho_{20})]/\nu.$$

The relation between the allowable heating and the relative total mass has the form

$$[\theta] = \sigma\left[\ln\frac{\rho_2}{\rho_{20}}\right]\frac{L_1^{3/2} a \sqrt{C}}{kl4R^2}\Delta_1\varkappa,$$

where $\varkappa = m_1/(m_1 + m_2)$; and $l = 2\pi R$.

The value of $[\ln(\rho_2/\rho_{20})]$ at which an aluminium accelerating conductor begins to vaporize can be chosen as two [5].

The dependence of $[\theta]$ on the parameter σ (see Fig. 3, curve 6: $\Delta_1\varkappa = 0.263$ mm and curve 7: $\Delta_1\varkappa = 0.117$ mm) can be used to determine the heating-limited velocity and to find the minimum thickness of the accelerating conductor Δ_1^*. The Δ_1^* isolines using $\Delta_2\gamma_2/\gamma_0$ and U_0 as coordinates are shown in Fig. 4 (curve 1: $\Delta_1^* = 0.8$, curve 2: $\Delta_1^* = 0.7$, curve 3: $\Delta_1^* = 0.6$, curve 4: $\Delta_1^* = 0.5$ mm). These curves can be used to choose the optimal (from the point of view of attaining the highest velocity) acceleration regime. Calculations are presented for the parameters ($C = 162$ µF, $L_0 = 16$ nH, $L_1 = 32$ nH, $D_1 = 37$ mm, $D_2 = 23$ mm, $\gamma_1 = \gamma_0 = 2.7$ g/cm^3) corresponding to the experimental unit described below.

2. In order to test the relations obtained above and to study the dynamics of the acceleration, we studied experimentally the acceleration of titanium rings of thickness 1 mm by aluminium accelerating conductors of thickness 0.5 and 0.8 mm. An energy storage device of trimodular design with an energy capacity 202.5 kJ and characteristic frequency 130 kHz was constructed from IR-50-3 capacitors joined by plane leads. The switching of each module

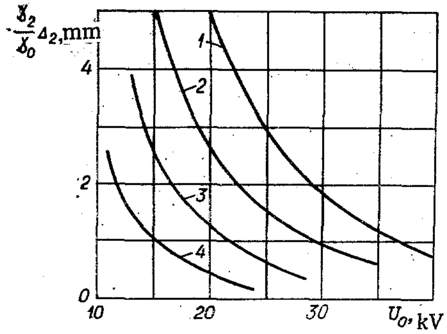

Fig. 4

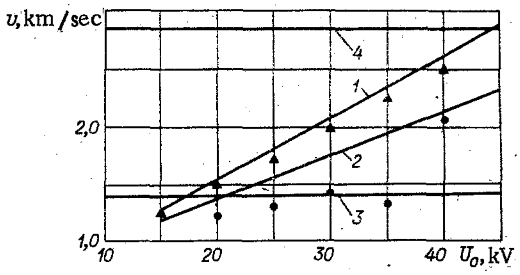

Fig. 5

was done by a solid-state bichannel discharger. The velocity of the body was determined by two methods: by the shadow method (rapid photodetection of the acceleration) and by an oscillogram of the signal using a contact transducer. The distance between the initial position of the accelerated ring and the transducer was chosen to be an order of magnitude larger than the extent of the acceleration region in order to ensure that the error in the measurement of the velocity would not exceed 5%.

The experimental results and the calculated curves are shown in Fig. 5 (curves 1 and 2: calculation with Δ_1 = 0.8 and 0.5 mm, curves 3 and 4: heating-limited velocity with Δ_1 = 0.5 and 0.8 mm, ▲, ● show the experimental results with Δ_1 = 0.8 and 0.5 mm, respectively). A decrease in the thickness of the accelerating conductor leads to an increase in the resistance and decreases the calculated velocity. The experimental velocities for $U_0 \geqslant 30$ kV were less than the calculated values by about 5 to 10%. The principal cause of this difference is plastic deformation of the brass inductor due to the combined effects of heating and electromagnetic pressure which was confirmed by performing a specially designed experiment at reduced energies of the storage device. When there is deformation the mutual inductance between the inductor and the accelerating ring decreases, which leads to a decrease in the velocities attainable experimentally. In addition to the electrodynamic regime, acceleration of the body can occur due to plasma and metal vapor formed by an electrical explosion of the accelerating conductor. In this case a velocity somewhat above the heating-limited value can be attained. This regime occurs in the accelerating of a titanium ring by an accelerating conductor of thickness 0.5 mm with a voltage of 40 kV on the capacitive storage device (see Fig. 5). A velocity increase of 0.6 km/sec above the heating-limited value was detected.

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