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THERMAL LIMITATION ON THE VELOCITY OF RING CONDUCTORS IN THE CASE OF INDUCTION AXIAL ACCELERATION

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UDC 538.54.001

The possibility of obtaining velocities of 1-5 km/sec with plane ring conductors in electromagnetic accelerators was demonstrated experimentally in [1, 2]. One of the main limitations in achieving high velocities when conductors are thrown into a magnetic field is the heating of the conductor and its transition from the solid state into a liquid or gaseous form. Nevertheless, in the practical utilization of high-velocity accelerators of macroparticles, the problem arises of determining the physical and mechanical properties and physical state of the thrown impactors. It is extremely difficult to solve this problem experimentally due to the short duration of the acceleration process and the high velocities of the impactors. In [3], by means of an approximate analysis, a relation is obtained which establishes the connection between the heating and the electromagnetic acceleration of the conductor, which holds over a range from the boiling point of nitrogen to the melting point of the corresponding metal, and in [4, 5] expressions are obtained for the limiting velocity of plane metal macroparticles in the ideal case of their acceleration in a uniform magnetic field.

In the present paper we consider the heating which occurs when a plane metal ring is accelerated in a two-dimensional pulsed magnetic field of a single-turn inductor.

The basic acceleration arrangement is shown in Fig. 1. The system of integrodifferential equations which describe the electromagnetic and electromechanical transients in this device has the form [6]

$$\tilde{\delta}(Q, t) + \frac{\mu_0 \gamma(Q, t)}{2\pi} \frac{d}{dt} \sum_{i=1}^{2} \int_{S_i} \tilde{\delta}(M, t) K(Q, M)\, ds_i = \begin{cases} \dfrac{\gamma(Q, t)}{2\pi \sqrt{r_Q}} \varphi[i_1(t)] & \text{for} \quad i = 1, \\ 0 & \text{for} \quad i = 2; \end{cases} \tag{1}$$

$$m \frac{dv}{dt} = \mu_0 \int_{s_2} \tilde{\delta}(Q, t) \sum_{i=1}^{2} \int_{s_1} \tilde{\delta}(M, t) \frac{z_Q - z_M}{\sqrt{(z_Q - z_M)^2 + (r_Q + r_M)^2}} \frac{1}{\sqrt{r_M r_Q}} \left[-K + \frac{(z_Q - z_M)^2 + r_Q^2 + r_M^2}{(r_Q - r_M)^2 + (z_Q - z_M)^2} E \right] ds_i ds_2; \tag{2}$$

$$dz/dt = v, \tag{3}$$

where

$$\varphi[i_1(t)] = U_0 - R_0 i_1 - L_0 \frac{di_1}{dt} - \frac{1}{C} \int_0^t i_1 dt; \quad i_1 = \int_{s_1} \frac{\tilde{\delta}(M, t)}{\sqrt{r_M}} ds_1;$$

Istra. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 23, No. 6, pp. 46-51, December, 1982. Original article submitted October 22, 1981.

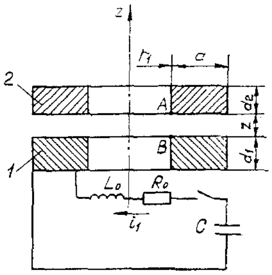

Fig. 1

TABLE 1

Metal	Melting point		Boiling point	
	solid state	liquid	liquid	vapor
	γ^*_{sm}	γ^*_{lm}	γ^*_{lb}	γ^*_{vb}
Al	0,154	0,096	0,032	0,0017
Cu	0,121	0,084	0,053	0,010

$\tilde{\delta}(Q, t) = \delta(Q, t)\sqrt{r_Q}$; S_i is the meridian section of the conductors of the inductor (i = 1) and the accelerated ring (i = 2), v is the velocity of the ring, z is the distance between the inductor and the ring, L_0 and R_0 are the internal inductance and resistance of the capacitive energy store, Q and M are arbitrary points in the meridian section of the conductors s_i, $K(Q, M) = (2/k - k)K(k) - (2/k)E(k)$; $k = 2\sqrt{r_M r_Q}/\sqrt{(r_Q + r_M)^2 + (z_Q - z_M)^2}$ is the modulus of the complete elliptic integrals of the first kind K(k) and the second kind E(k) [7].

Taking into account the change in the electrical conductivity of the conductor due to Joule heating by the current of density δ, following [4], we will neglect the contribution of the thermal conductivity while the internal energy of the conductor is changing, effects due to the compressibility of the materials, and phase changes, and we will assume that the thermal equation has the form

$$\partial W(Q, t)/\partial t = (\delta^2(Q, t)/\gamma(Q, t_0))[1 + \beta W(Q, t)], \tag{4}$$

where β is the thermal coefficient, and W(Q, t) is the increase in the heat content with respect to the state at 0°C.

The system of equations (1)-(4) was solved numerically as in [6]. Comparison of the calculated values of the terminal velocity of the ring with experimental data (a description of the experiment is given in [1, 2]), shows that they are in good agreement (the disagreement does not exceed the experimental error).

The mathematical model enables us to calculate the temperature and the electrical conductivity of the metal of the accelerated ring and inductor at any instant of time. To determine the relative electrical conductivity of the metal $\gamma^* = \gamma/\gamma_0$, corresponding to the phase transition (Table 1), we used the values of the current integral given in [4], which were found from experiments on the explosion of conductors. In Fig. 2 we show the results of a calculation of the heating process when an aluminum conductor is accelerated in the magnetic field of a copper inductor when a capacitive energy store is discharged through it (C = 120 μF, L_0 = nH, Y_0 = 40 kV, R_0 = 3 MΩ, d_1 = 1.4 mm, d_2 = 1 mm, r_1 = 13 mm, $a_1 = a_2$ = 6 mm, z_0 = 0.2 mm, a — b:t = 1.9, 3.8, 6.8 μsec, v = 1.37, 2.78, and 3.2 km/sec, and z = 1.1, 5.3, and 14.7 mm respectively).

We deposited on the cross section of the conductors, lines of the same conductivity at different instants of time, which enables us to follow the heating process and the motion of the boundary of the liquid metal. In view of the nonuniformity of the current distribution over the cross section of the ring and the inductor, melting began at the most heated points of the cross section (points A and B, see Fig. 1).

We determined by calculation the limiting permissible velocity of the accelerated ring v_l, for which the most heated region of the ring cross section reaches the melting point ($\gamma^*_{Al} = 0.154$ and $\gamma^*_{Cu} = 0.121$), but the material of the conductor was in the solid state.

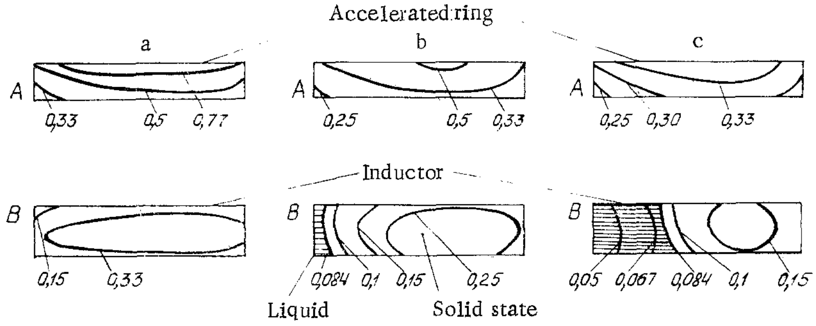

Fig. 2

TABLE 2

Ring thickness	Limit velocity		
d_2, mm	v_l, km/sec	v'_l km/sec [4]	v''_l km/sec [3, 5]
1,0	5,15	7,42	13,1
0,8	3,98	5,94	10,5
0,6	3,60	4,46	7,8
0,4	2,27	2,97	5,2

As an example, we show in Table 2 the results of a calculation of v_l for induction acceleration of aluminum conductors of different thickness ($C = 120\ \mu F$, $L_0 = 90$ nH, $U_0 = 100$ kV, $R_0 = 3\ M\Omega$, $r_1 = 13$ mm, $a_1 = a_2 = 6$ mm, $d_1 = 1.4$ mm, and $z_0 = 0.2$ mm).

For clarity and greater generality of the results in this example the energy store was chosen to be greater than that necessary to reach the velocity v_l, so that after reaching v_l the ring continues to obtain energy, which can lead to its complete melting and even evaporation. It is seen from Table 2 that v_l, when ring conductors are accelerated, is less than v_l', calculated from the equations for determining the limiting velocity of displacement of a thin plate [4], and less than v_l'', calculated from the equations given in [3, 5] when a plane electromagnetic wave acts on the accelerated conductor. Hence, when determining v_l it is necessary to take into account the geometry of the accelerated conductor and inductor.

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