Journal of Applied Mechanics and Technical Physics, Vol. 40, No. 2, 1999

ANALYSIS OF THE ULTIMATE KINEMATIC CHARACTERISTICS OF RAILGUN ACCELERATORS OF SOLIDS

S. V. Stankevich and G. A. Shvetsov

UDC 583.4 + 533.95

A comparative analysis of the dependences of the ultimate (under heating conditions) velocity on the dimensions and thermal properties of the projectile and on the length of the railgun is performed on the basis of a numerical solution of two-dimensional unsteady equations of magnetic-field diffusion and heat transfer. Homogeneous and multilayer projectiles and homogeneous rails and rails with a resistive coating are considered. It is shown that the ultimate kinematic characteristics of railgun accelerators of solids can be considerably increased by changing the structure and thermal properties of the materials of the projectile and the electrodes.

Introduction. One factor that hinders attainment of high velocities in the acceleration of conducting solids in railguns is the loss of metal contact between the projectile (armature) and the rails (electrodes) and transition to the electric-arc regime of short circuit. Results of numerical simulation of the electrothermal state of the armature show that the temperature of the armature is nonuniform across its section and is maximum in the regions of contact between the rear side of the armature and the rail surface, where there is concentration of current due to the velocity skin effect (VSE) [1–4]. The velocity of the projectile at which it begins to melt near the contact boundary between the rails and the armature is commonly called the critical or ultimate velocity, i.e., the velocity at which metal contact is still retained. For traditional materials, the ultimate velocity is usually about 1 km/sec, which currently limits the use of conducting solids in railguns. A considerable number of recent papers deal with the search for methods of increasing the critical (ultimate) velocity, or, in other words, decreasing the current concentration due to the VSE. Multilayer bodies with orthotropic electric conductivity, bimetallic rails whose contact side is coated with a layer of a material with high electric resistance, and other approaches (see, for example, [1, 3–7]) were studied. It should be noted that the potentials of composite materials for increasing the ultimate velocity have not been completely clarified. Sometimes, authors draw opposite conclusions. In particular, the statement of Dreizin [5] that a high-ohmic coating is efficient at increasing the ultimate velocity is in conflict with the conclusion of Long and Weldon [3] that such coatings are not recommended for use in railguns of solids. This can be due to the fact that different physical phenomena are considered in the analysis of the heating rate of the armature, and coating materials with different electrothermal properties are used (Mo and C).

In the present work, we perform a comparative analysis of the influence of resistive coatings with different electrothermal properties on the ultimate kinematic characteristics of homogeneous and multilayer armatures in the nonarc regime of acceleration. The nonarc regime occurs when the armature does not melt during acceleration. Two physical processes that affect the variation in the temperature of the armature are taken into account: Joule heating and heat transfer. Ignoring the other phenomena responsible for heating of the armature and decrease in the effectiveness of acceleration, in particular friction, we obtain the upper bound for the ultimate velocity in the nonarc acceleration regime. The difference between the results obtained

---

Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 40, No. 2, pp. 156–162, March–April, 1999. Original article submitted June 29, 1998.

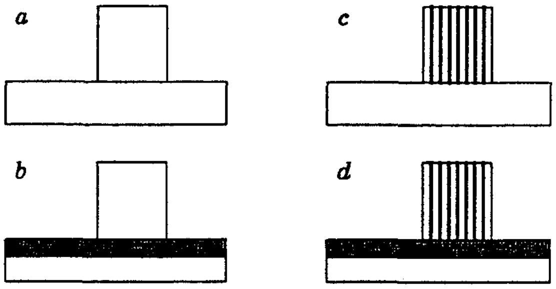

Fig. 1

and those published in [3, 5] is that the ultimate velocity is calculated under two conditions: there is no melting of the armature and the length of the railgun is specified.

Formulation of the Problem. We consider the acceleration of homogeneous and multilayer conducting solids of rectangular cross section with dimensions $h \times l$ (h is the spacing between the rails and l is the length of the armature) in electromagnetic launchers with homogeneous rails and rails whose contact side is coated with a material with high specific electric resistance. The configuration of the calculation regions, which are half the longitudinal sections of railguns, is shown in Fig. 1 for a homogeneous armature and rails (a), a homogeneous armature and rails with a resistive layer (b), a multilayer armature and homogeneous rails (c), and a multilayer armature and rails with a resistive coating (d).

The time-dependent distributions of the magnetic field and the temperature of the armature and rails were determined by numerical solution of a system of unsteady equations of magnetic-field diffusion and heat transfer in a two-dimensional formulation [6]. It was assumed that the electrothermal properties of the materials do not depend on temperature and there is ideal electric and thermal contact on the boundaries between the armature and the rails and the resistive coating and the support, i.e., at the boundary, the conditions of continuity of the magnetic field, temperature, tangential component of the electric field, and the normal components of the current density and heat flow are satisfied. The magnetic field in the channel of the railgun $H_0(t)$ in the two-dimensional formulation was assumed to be known and equal to the linear density of the current through the armature.

Studies of the ultimate kinematic characteristics of a metal armature showed that the ultimate velocity depends only slightly on the form of variation in the accelerating magnetic field with time [4, 6]. Therefore, in the present work, we used the particular form of the functional dependence of the accelerating magnetic field on time $H_0(t) = H_n t^{n/2}$ (n is a positive integer). This simplifies the calculations considerably since it allows one, by selecting just one parameter H_n, to satisfy the following condition: melting must begin when the armature travels a specified distance L. The calculations were conducted for $n = 1$–5, but it was established that the ultimate velocity depended weakly on n in the cases considered. The maximum relative change in the ultimate velocity for the indicated range of n does not exceed 5%. Below, we present the results obtained for $n = 1$. Instead of the magnetic permeability of vacuum $\mu_0 = 1.26$ μH/m, the inductance per unit length $\lambda = 0.45$ μH/m was used as the coefficient of proportionality between the magnetic-pressure force and the square of the amplitude of the magnetic field in the channel.

Homogeneous Armature and Resistive Layer. The influence of a resistive layer on the ultimate kinematic characteristics of a homogeneous armature was studied in a series of calculations for three materials of the layer with considerably different conductivities: titanium ($\sigma = 1.8 \cdot 10^6$ $\Omega \cdot$m), Copel ($\sigma = 0.21 \cdot 10^6$ $\Omega \cdot$m), and graphite ($\sigma = 0.04 \cdot 10^6$ $\Omega \cdot$ m). The width of the layer was varied from 0 to 1.2 mm. Armatures made of aluminum, copper, and tungsten were examined.

Use of a resistive layer has an ambiguous effect on the rate of change in the maximum temperature of the armature, and hence, and the ultimate velocity V. The ultimate velocity can both increase and decrease, depending on the width d and conductivity of the layer, the electrohermal properties and dimensions of the

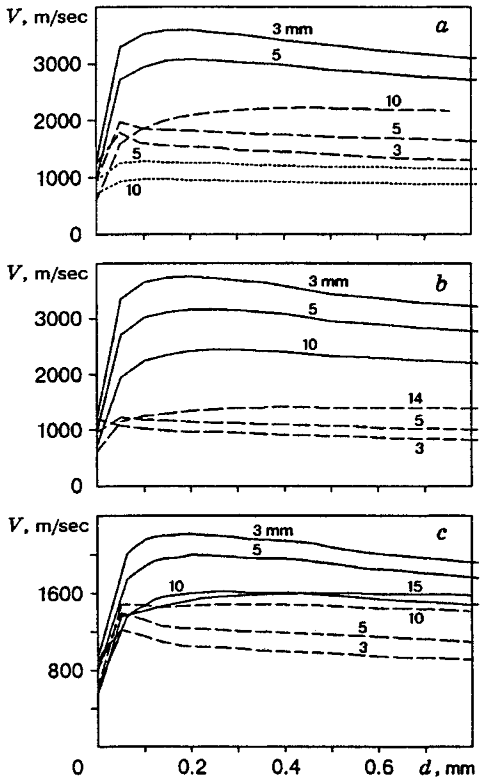

Fig. 2

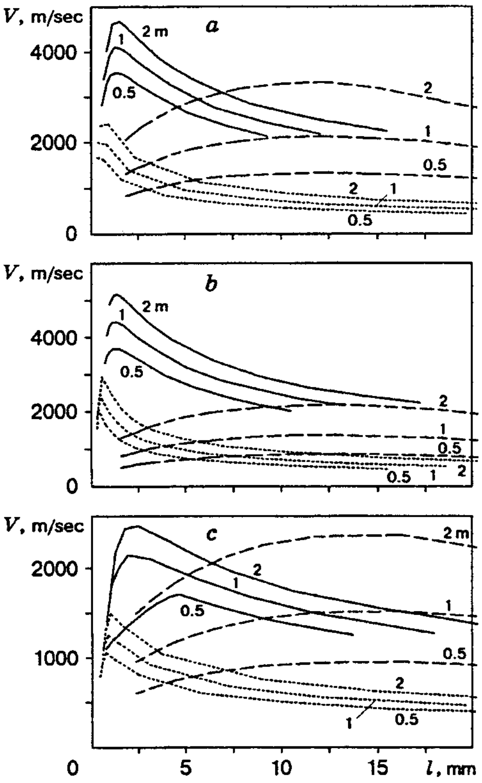

Fig. 3

armature, and the specified acceleration distance. The armature can be heated in two regimes. In the first, the variation in the armature temperature is determined mainly by the current flowing in it and the armature is heated mainly as a result of the increase in the temperature of the contact boundaries due to Joule heating of the resistive layer. An increase in the width or resistivity of the resistive layer lowers the current concentration on the rear parts of the contact boundaries between the armature and the rails, and, as a result, the rate of Joule heating of the armature decreases. In this case, however, there is an increase in the temperature of the resistive layer on the contact surface, both due to the growth of ohmic losses in this layer and decrease in the heat removal from the contact boundary into the depth of the rails.

The rise in the armature temperature caused by Joule heating of the resistive layer is maximal in the initial stage of acceleration. As the armature is accelerated, the heating and temperature of the resistive layer decrease, and, hence the maximum temperature of the armature also decreases. With further increase in the armature velocity, the Joule heating of the armature caused by the current concentration due to the VSE becomes more intense, and the temperature of the armature begins to grow again.

Figure 2 shows the ultimate velocity versus the width of the resistive layer for armatures of different length (indicated in millimeters on the curves) made of aluminum (a), copper (b), and tungsten (c) and for various materials of coatings on a copper support. All curves are obtained for an acceleration distance of 1 m. The dashed curves refer to a resistive graphite coating, the dotted curves refer to a titanium coating, and the solid curve to a Copel coating.

For all the examined armature materials, resistive coatings of titanium and Copel increase the ultimate velocity compared to the case of rails without a coating ($d = 0$). A titanium layer ensures a slight increase in the ultimate velocity (15–20%) for acceleration of an Al armature (Fig. 2a). For W and Cu armatures on rails with a titanium coating, the same relative increase in the ultimate velocity was obtained. A Copel layer increases the ultimate velocity by 2 or 3 times.

As shown in Fig. 2, the ultimate velocity decreases with increase in the length of the armature. This

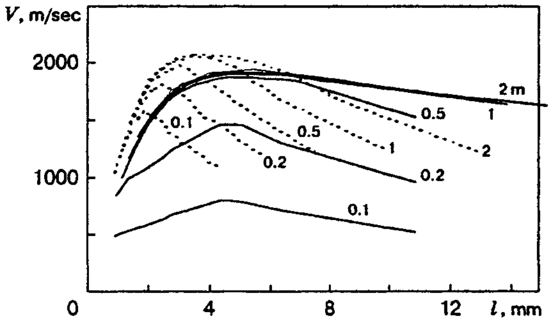

Fig. 4

is typical of cases with predominant Joule heating of the armature, whose rate is determined by the current concentration due to the VSE. A graphite coating increases the ultimate velocity for W and Al armatures with $l > 2$ mm and for a copper armature with $l > 5$ mm. The maximum ultimate velocity for a graphite coating is reached in transition from the armature heating regime determined by the heating of the resistive layer (small l) to the heating regime determined by the VSE.

In all the cases illustrated in Fig. 2, the ultimate velocity of the armature grows rapidly as the width of the resistive layer d increases from zero to a certain value d_{opt}. With further increase in d, it decreases slowly. The optimal width of the resistive layer is different for all the coating materials examined: it is minimal for a Ti coating (about 50 μm) and maximal for graphite (about 400 μm). The calculations show that d_{opt} depends weakly on the length of the armature and the acceleration distance. The value of d_{opt} decreases with increase in the armature length and increases with increase in the acceleration distance. We note that, in all cases, the relative changes in the velocity do not exceed 5% when the layer width varies from $0.5d_{\text{opt}}$ to $2d_{\text{opt}}$. The maximum increase in the ultimate velocity is obtained for a resistive graphite coating. Below, we present the results obtained for resistive coatings 250 μm wide; this width, as shown in Fig. 2, ensures an almost maximum increase in the ultimate velocity.

Figure 3 shows the curves of the ultimate velocity versus the armature length calculated for acceleration distances $L = 0.5$, 1, and 2 m for homogeneous armatures made of aluminum (a), copper (b), and tungsten (c). The solid curves refer to a resistive Copel layer, and the dashed curves refer to a graphite coating. The dotted curves are obtained for copper rails without a resistive layer. The figures on the curves indicate the acceleration distances in meters. In all the curves, the ultimate velocity increases with increase in the acceleration distance, and the maximum ultimate velocity in this case is shifted toward smaller lengths of the armature. With increase in L, the relative increase in the ultimate velocity is found to be more rapid for a graphite coating than for a Copel coating and for rails without a coating.

Of the materials considered, a Copel coating yields the highest ultimate velocity, and the linear dimensions of the armature are small in this case (about 2–4 mm for $L = 1$–2 m). For a graphite coating the maximum ultimate velocity is lower than for a Copel coating, but it is reached for greater lengths of the armature. In this case, the kinetic energy of the armature per unit cross-sectional area of the accelerator channel is much higher compared to the case of a Copel coating.

Multilayer Armature and Resistive Layer. In railguns with homogeneous rails, the ultimate velocities of armatures consisting of alternating conducting and nonconducting layers (see Fig. 1c) far exceed the ultimate velocities of homogeneous armatures (see Fig. 1a) [7]. In addition, for armatures with orthotropic conductivity, the maximum ultimate velocity is reached for greater armature lengths compared to homogeneous armatures.

It was of interest to verify whether the maximum ultimate velocity of an orthotropic armature could be shifted toward larger values of l by using rails with a resistive coatings (see Fig. 1d). The curves of the ultimate velocities of a tungsten armature versus its length calculated for acceleration distances of 0.1, 0.2, 0.5, 1, and 2 m are given in Fig. 4. The dotted curves show the calculation results for a multilayer armature

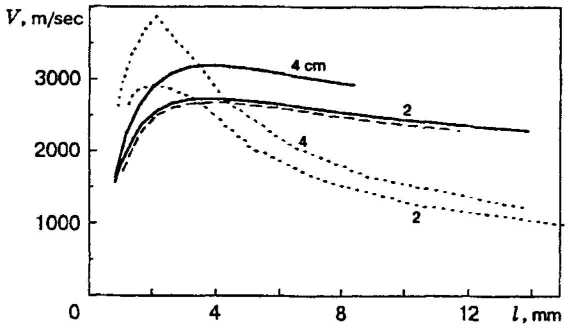

Fig. 5

and rails without a coating (see Fig. 1c), and the solid curves show the results for the same armature and rails with a resistive Copel coating (see Fig. 1d). The figures on the curves indicate the acceleration distances in meters. It is evident that, indeed, there is a shift of the maximum ultimate velocity toward larger values of l, and this maxima is rather flat.

Although the maximum ultimate velocity of a multilayer armature is lower than that of a homogeneous armature on rails with a resistive coating, the ratio of the velocities is reversed with increase in the values of l. It is important that, in this case, the ultimate velocity does not depend on the acceleration distance for $L > 0.5$ m. The above is true for Al and Cu armatures with orthotropic conductivity, and for $L \geqslant 0.5$ m, the ultimate velocity for these armatures does not depend on the acceleration distance. This indicates that the dimensions of the region of the contact boundary through which the current passes are determined mainly by the properties and dimensions of the resistive coating (in this case, Copel).

For acceleration distances less than 1 m, a multilayer armature with $l >$ 5–7 cm on rails with a Copel coating ensures a greater increase in the ultimate velocity compared to homogeneous rails. In this case, the characteristic dimension of the region of the contact boundary through which the current passes increases somewhat as a result of field diffusion along the insulating layers.

The calculations did not reveal a significant difference in the ultimate velocity between a multilayer armature on rails with a graphite coating and a homogeneous armature on the same rails (see Fig. 3c; dashed curves).

Analysis shows that the degree of current concentration in a multilayer armature with orthotropic electric conductivity is inversely proportional to the height of the railgun channel. Figure 5 gives the curves of the ultimate velocity versus the armature length calculated for a multilayer armature on rails without a coating (dotted curves) and with a resistive Copel layer (solid curves) for $L = 1$ m and $h = 2$ and 4 cm. The figures on the curves indicate the values of h (in centimeters).

An increase in the ultimate velocity with growth in h is noted, although it is less considerable than in the case of rails without a resistive layer. This is due to the fact than the region of current concentration on the contact boundary is largely determined by the dimensions and conductivity of the resistive coating.

For rails with a Copel coating and a specified acceleration distance, the curves of the ultimate velocity versus the armature dimensions are almost the same for multilayer armatures of copper and aluminum and for a multilayer tungsten armature. As an example, Fig. 5 shows the curve for a copper multilayer armature (dashed curve).

Conclusion. The results obtained indicate that a resistive coating can be used to advantage to decrease the current concentration in the armature due to the velocity skin effect. This considerably decelerates the heating of the armature near the contact boundaries. As a result, the ultimate velocity to which the armature can be accelerated in a channel of a specified length with retention of solid metal contact with the rails can be increased by 2–4 times and the kinetic energy of the armature can be increased by 4–16 times compared to the case of rails without a coating. With further decrease in the conductivity of the resistive layer, the current concentration in the armature decreases, but, in this case, overheating and failure of the resistive layer can take place.

Use of a multilayer armature with orthotropic electric conductivity combined with a resistive coating on the contact side of the rails provides for high velocity and energy characteristics of the armature at short acceleration distances.

It should be noted that the use of a resistive coating has a number of features that can considerably lower the attainable velocities. First, the velocity of magnetic-field diffusion along a resistive layer is higher than the diffusion velocity in the armature. As a result, the armature current flows along the contact boundary in the opposite direction to the rail current. Interaction of these currents gives rise to a magnetic pressure force that repels the contact surfaces. If special precautions are not taken, this can lead to loss of metal contact between the projectile and the rails. Since, the repelling force decreases as the magnetic field penetrates into the armature and the armature velocity increases, one method of overcoming this problem is to use a resistive layer with conductivity decreasing by a particular law in the direction of motion. Second, the resistive layer fails under the considerable thermal stresses caused by sharp temperature variations on the boundaries of the resistive layer. These stresses can be reduced by using a resistive material with high thermal conductivity, melting point, and mechanical strength. In this connection, resistive coatings of composite materials (in particular, obtained by the method of explosive compaction of powders) appear to be promising.

REFERENCES

1. F. J. Young and W. F. Hughes, "Rail and armature current distribution in electromagnetic launchers," *IEEE Trans. Magn.*, **18**, No. 1, 33–41 (1982).
2. L. D. Thornhill, J. D. Batteh, and J. L. Brown, "Armature options for hypervelocity railguns," *IEEE Trans. Magn.*, **25**, No. 1, 552–557 (1989).
3. G. C. Long and W. F. Weldon, "Limits to the velocity of solid armature in railgun," *ibid.*, pp. 347–352.
4. G. A. Shvetsov and S. V. Stankevich, "Ultimate velocities of plates accelerated by magnetic field," in: *Proc. 6th Int. Conf. on Megagauss Magnetic Field Generation and Related Topics* (Albuquerque, U.S.A., Nov. 8–11, 1992), Nova Sci. Publ., New York (1994), pp. 385–397.
5. Yu. A. Dreizin, "Solid armature characteristics with resistive Rails," *IEEE Trans. Magn.*, **29**, No. 1, 798–803 (1993).
6. G. A. Shvetsov and S. V. Stankevich, "Ultimate velocities of multilayer projectiles in induction and railgun accelerators," in: Proc. 5th Europ. Symp. on EML Technology (Toulouse, France, Apr. 10–13, 1995) (1995), p. 53.
7. G. A. Shvetsov and S. V. Stankevich, "Ultimate kinematic characteristics of armatures with orthotropic and anisotropic electroconductivity," *IEEE Trans. Magn.*, **33**, No. 1, 266–271 (1977).