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POSSIBILITY OF GENERATING STRONG MAGNETIC FIELDS IN CONDUCTING MATERIALS BY THE ACTION OF HIGH-VELOCITY PENETRATORS

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The possibility of increasing the intensity of a magnetic field produced previously in a conducting medium moving under the action of a high-velocity penetrating body is analyzed. A simplified model of the interaction of an impactor and a conducting target with a transverse magnetic field is constructed within the framework of a one-dimensional scheme. It is shown that the degree of increase in the field intensity is determined by the relation between the magnetic-field compressibility and diffusion factors, and the corresponding dimensionless determining parameter is determined. Magnetic-field compression is estimated for a perfectly conducting medium and media with real conductivity. The significance of the thermal and mechanical effects accompanying the penetration of an impactor into a target with a transverse magnetic field is assessed.

The generation of ultrahigh magnetic fields (with induction of about hundreds of tesla) leads to the occurrence of extreme conditions for materials and strong mechanical, thermal, and electromagnetic effects of scientific and practical interest.

Magnetic fields of extremely high intensities are generated in a pulsed mode using the principle of energy cumulation during compression of an initial, relatively weak, field. The initial field is produced in the cavity of a conducting liner or in a dielectric material that can be transferred to a conducting state by strong compression. In the first case, compression and increase in the intensity of magnetic fields are ensured by fast compression of the liner, as a rule, by detonation products of an explosive charge. In the second case, this is performed by producing a convergent shock wave in a dielectric material. Both methods of magnetic-field amplification have been studied extensively and widely used in experiments [1]. In the present paper, we consider a different method of increasing the magnetic-field intensity, in which a magnetic field is produced directly in a conducting medium. In this case, magnetic-field compression leading to an increase in the intensity occurs for a particular pattern of motion of the conducting medium.

Let us consider the physical principles of increase in the magnetic-field intensity in a moving conducting medium. The evolution of the magnetic field is described by the equation

$$\frac{d}{dt}\Big(\frac{\boldsymbol{B}}{\rho}\Big) = \frac{\boldsymbol{B}}{\rho}\,\nabla \boldsymbol{v} + \frac{\eta}{\mu_0\rho}\,\Delta \boldsymbol{B}, \tag{1}$$

where $\boldsymbol{B}$ is the magnetic-field induction vector, $\boldsymbol{v}$ is the material particle velocity vector, ρ is the density of the medium, η is the resistivity of the medium, and $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the permeability of vacuum [2]. According to this equation, the time dependence of the magnetic-field induction at any particle of the medium is determined by the following two factors: the deformations and rotary motion of the material particles occurring during motion of the medium [the first term on the right side of (1)] and diffusion of the magnetic field in the material, leading to gradual equalization of the field nonuniformity if it exists.

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The first of the indicated factors governing the variation in the magnetic-field induction in material particles is related to the effect of so-called "freezing" of a magnetic field in a material, which is most pronounced for a perfectly conducting medium ($\eta = 0$). As is known, the essence of this effect is that in a moving conducting medium, the magnetic-induction vector lines $\boldsymbol{B}$ tend to move together with material fibers of the medium that initially coincide with the vector lines. In this case, a change in the length of the component material segments of the material fiber determines a proportional change in the value of B/ρ in the particles located in these segments, which is proportional to it. Under the assumption of low compressibility of the medium ($\rho \approx$ const), the absolute value of the magnetic induction in the medium varies accordingly. Therefore, with elongation of the material fibers of a perfectly conducting medium, the magnetic-field induction in its particles should increase. In this case, there is, in essence, compression of the magnetic field in the particles of the medium, i.e., compression of the magnetic flux in the direction perpendicular to the direction of the stretched material fibers.

The magnetic-field "freezing-in" effect can be used to produce strong magnetic fields in conducting materials. The possibility of amplifying a magnetic field produced previously in such a material arises if the motion of the material is accompanied by large high-rate tensile strains of material fibers that are initially oriented in the direction of the field. Obviously, the increase in the field intensity in the stretched particles is more considerable when the diffusion of the field is manifested to a lesser degree, i.e., when the resistivity of the material η is lower and its deformation is faster. At rather high strain rate, the magnetic-field "freezing-in" effect and amplification can also be achieved for materials with real conductivity.

Conditions for the magnetic-field "freezing-in" effect and amplification are produced by penetration of high-velocity impactors into a target. In this case, particles of the target that are initially perpendicular to the direction of penetration and are located, during penetration, near the boundary of contact with the head part of the impactor are subjected to extremely large tensile strains [3]. Therefore, if the target is high-conducting, preliminary generation in it of a magnetic field that is transverse to the direction of penetration (Fig. 1a) produces conditions for further "pumping" of the field in a thin layer adjacent to the impactor (Fig. 1b). Such "pumping" can be accompanied by physical phenomena (thermal, mechanical) that can have a significant effect on the penetration of the impactor into the target.

Justification of the possibility of magnetic-field amplification during high-velocity penetration into a target and insight into the features of this process are provided by the following simplified model. We consider the interaction of an impactor and a conducting target with a transverse magnetic field within the framework of a planar scheme, assuming that the impactor moves perpendicular to the free surface of the target. We keep track of the evolution of the magnetic field only in the target particles located in the plane of symmetry of the penetrating body. The velocity of a point of the target in the plane of symmetry on the boundary with the impactor (the penetration velocity) is considered constant and equal to u_c. The rate of motion of particles in the depth of the target is assumed to decrease under a linear law to zero with variation in the coordinate reckoned from the boundary of contact with the impactor. The distance from the boundary of contact to the point at which the velocity of the target particles vanishes is denoted by l_0. The value of l_0 should apparently be of the order of the thickness of the impactor.

We assume that at the initial time, in the target material there is a uniform magnetic field with induction B_0 that is perpendicular to the direction of motion of the impactor. Obviously, in the subsequent evolution during the penetration process, this field for the target particles in the plane of symmetry will also have a single transverse component. The target material is considered an incompressible conducting medium with resistivity η. We also assume that in the plane of symmetry, the degree of nonunformity of the magnetic field during penetration is determined primarily by the nonuniformity in the longitudinal direction, and transverse diffusion of the field is ignored. We assume that the interface between the target and the impactor is perfectly conducting, thus ruling out diffusion of the field into the impactor.

Under the assumptions made above, using a moving frame of reference attached to the interface between the target and the impactor, we arrive at the following one-dimensional problem (Fig. 2). A plane flow of

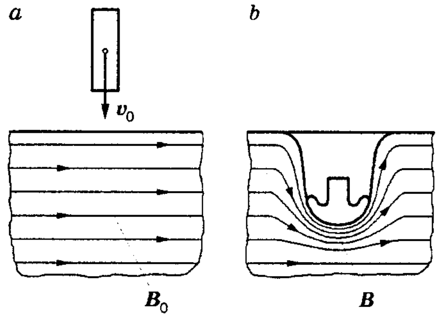

Fig. 1

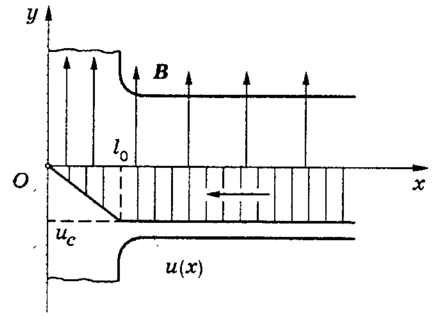

Fig. 2

an incompressible conducting material which at infinity has velocity u_c directed opposite to the x axis is decelerated on a perfectly conducting rigid, fixed wall, and in the deceleration region of width l_0, its velocity changes under the law $u = u_c x/l_0$. In the flow material there is a magnetic field transverse with respect to the direction of flow (directed along the y axis), whose induction at infinity is equal to B_0.

Under the adopted assumptions, Eq. (1), which describes the evolution of the magnetic field, has the form

$$\frac{\partial B}{\partial t} + v_x \frac{\partial B}{\partial x} = B \frac{\partial v_y}{\partial y} + \frac{\eta}{\mu_0} \frac{\partial^2 B}{\partial x^2}.$$

Since $v_x = -u$ and the continuity equation for an incompressible medium leads to $\partial v_y/\partial y = -\partial v_x/\partial x$, we rewrite this equation as

$$\frac{\partial B}{\partial t} = u \frac{\partial B}{\partial x} + B \frac{\partial u}{\partial x} + \frac{\eta}{\mu_0} \frac{\partial^2 B}{\partial x^2}.$$

Reducing the obtained equation to dimensionless form using the adopted relation $u(x)$, for the definition of the magnetic-field induction in the moving material, we obtain the differential relations

$$\frac{\partial B'}{\partial t'} = \begin{cases} x' \dfrac{\partial B'}{\partial x'} + B' + æ \dfrac{\partial^2 B'}{\partial (x')^2}, & 0 \leqslant x' \leqslant 1, \\ \dfrac{\partial B'}{\partial x'} + æ \dfrac{\partial^2 B'}{\partial (x')^2}, & x' > 1. \end{cases} \tag{2}$$

Here $x' = x/l_0$, $t' = t\,u_c/l_0$, $B' = B/B_0$, and

$$æ = \frac{\eta}{\mu_0 u_c l_0}. \tag{3}$$

The quantity $\tau_e = l_0/u_c$, which is the time scale and determines the time of penetration at depth l_0, will be called the characteristic time of deformation of the target. We also note that the dimensionless time t' has the meaning of the current penetration depth expressed in the thicknesses of the deformed layer of the target l_0.

As follows from Eqs. (2), the character of variation in the magnetic field in the target material during penetration depends on the dimensionless parameter æ defined by relation (3). It is not difficult to establish that this parameter characterizes the relation between magnetic-field compression and diffusion factors chosen from an analysis of the right side of Eq. (1). In other words, it is the ratio of the characteristic time of deformation of the target τ_e to the characteristic time of magnetic-field diffusion $\tau_d = \mu_0 l_0^2/\eta$ [2] for a conducting layer of thickness l_0:

$$æ = \frac{\tau_e}{\tau_d}.$$

Thus, the value of the parameter æ provides information on the extent to which the increase in the field intensity in the compression region is affected by diffusion processes. From this point of view, magnetic-field

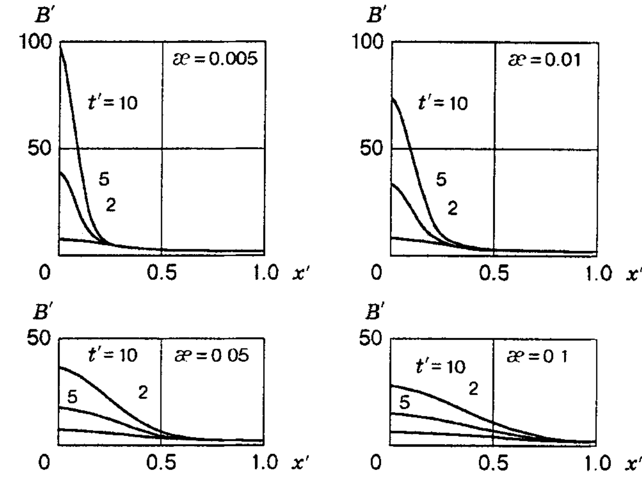

Fig. 3

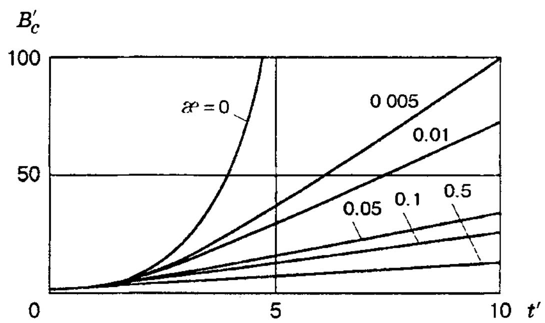

Fig. 4

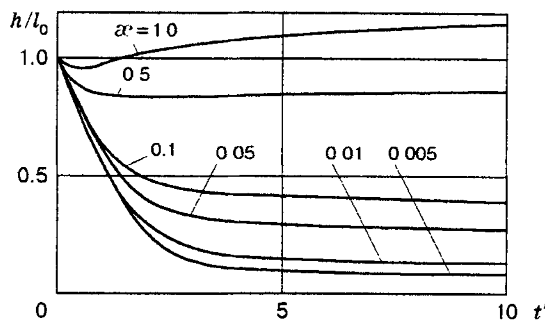

Fig. 5

compression in the limiting case, i.e., for a perfectly conducting target ($\eta = 0$ and $æ = 0$) is of great interest. According to the first relation of (2), the variation in the magnetic-field induction B'_c in such a target on the boundary of contact with the impactor $x' = 0$ (Fig. 2) is described by the equation

$$\frac{dB'_c}{dt'} = B'_c,$$

whose solution subject to the initial condition $B'_c(0) = 1$ yields an exponential increase in the field intensity in the target particles adjacent to the impactor with increase in the penetration depth:

$$B_c = B_0 \exp(t') = B_0 \exp(u_c t / l_0).$$

For media with real conductivity ($æ \neq 0$), features of magnetic-field compression taking into account diffusion processes were determined by numerical integration of relation (2). On the interface between the target and the impactor, we used the condition $\partial B'/\partial x' = 0$, which follows from the adopted assumption of perfect conductivity of this interface.

Some results of calculations performed for various values of the parameter $æ$ are shown in Figs. 3–5. We note that a value of $æ \approx 0.01$ corresponds to impactors with a cross-sectional dimension of about 1 mm that penetrate into a copper or aluminum target with velocities of about several kilometers per second. Figure 3 gives the distributions of the magnetic-field induction across the thickness of the target at various times, and Fig. 4 shows the change in the field intensity B'_c on the interface between the target and the impactor. From the curves presented in Fig. 5, it is possible to determine how the value of $æ$ affects the change in the thickness h of the target layer in which there is a considerable increase in the magnetic-field induction (we shall call it the "magnetic layer"). As the thickness of the "magnetic layer," we took the dimension of the zone on whose boundary the increment of the magnetic-field induction $\Delta B = B - B_0$ decreased by not more than a factor of two compared to the increment in the field intensity on the boundary with the impactor $\Delta B_c = B_c - B_0$.

As follows from the results obtained, the magnetic-field diffusion weakens its compression considerably. The rate of compression in the narrow boundary layer of the target material is decelerated as the rate of diffusion processes (the parameter æ) becomes higher. Simultaneously, the thickness of the "magnetic layer" increases. At $t' = 4$–5 [which corresponds to a penetration depth of the impactor of (4–5)l_0], a practically linear increase in the field intensity is established on the boundary with the impactor (see Fig. 4), and the thickness of the "magnetic layer" remains unchanged (see Fig. 5). In particular, for $æ = 0.01$, which is adopted as the basis, intense "pumping" of the field (by about a factor of 70 at $t' = 10$) occurs in a region with dimension of about 10% of the thicknesses of the deformed target layer. Thus, when the parameter æ is small, it is possible to speak of a magnetic skin layer that forms on the interface between the target and the impactor. For rather large values of æ ($æ > 1$), diffusion of the field leads to the "magnetic layer" propagating beyond the deformed layer of the target ($h > l_0$), but the field intensity increases insignificantly in this case.

As follows from relation (3), during amplification of the magnetic field in the target, the scale effect should be manifested, and the efficiency of compression should increase with increase in the dimensions of the impactor (hence, with decrease in æ).

Thus, using the proposed model of the process, it is shown that the deformation of the target in the region of contact with the head part of the impactor produces conditions for increase in the field intensity.

Under real conditions, as noted above, the increase in the magnetic-field intensity in the target should be accompanied by strong thermal and mechanical effects. The possibility of these effects is due to eddy induction currents occurring in the compression region, where the field becomes strongly nonuniform. The bulk density of the currents can be evaluated by $j \approx B_c/(\mu_0 h)$. Thus, the rate of increase in temperature in the target material layer adjacent to the impactor is given by the expression

$$\frac{\Delta T}{\Delta t} \approx \frac{\eta}{\rho c \mu_0^2} \frac{B_c^2}{h^2},$$

where c is the specific heat of the target material. According to this relation, during "pumping" of a magnetic field in a metallic target to 100 T in a layer 1 mm thick, the temperature of this layer can increase at a rate of up to 1000 K/μsec. At this heating rate, the material in the compression region can enter not only to the liquid but also to the vapor state with thermal explosion of the magnetic skin layer. Simultaneously, considerable ponderomotive forces should act during interaction of the induction currents with the compressed magnetic field in the "magnetic layer." For a field intensity of about hundreds of tesla, the action of these forces is equivalent to a value of about 10 GPa for the magnetic pressure $p_m = B_c^2/(2\mu_0)$ stretching the skin layer, which is comparable to the pressure produced by detonation of explosives [4].

Obviously, such powerful thermal and force factors should affect the mechanism of the penetration process by producing prerequisites for a decrease in the penetration capability of impactors during interaction with "magnetized" conducting targets.

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