IMPACT INTERACTION OF PROJECTILE WITH CONDUCTING WALL AT THE PRESENCE OF ELECTRIC CURRENT

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Abstract. The paper introduces with schemes of possible electromagnetic armor augmentation. The interaction of projectile with a main wall of target after penetration across the pre-defense layer is of interest here. The same problem is of interest for the current-carrying elements of electric guns. The theoretical analysis is done in the paper for the impact when the kinetic energy of projectile is enough to create the liquid layer in the crater of the wall's metal. Spherical head of projectile and right angle of inclination have been taken for consideration. The solution of problem for the liquid layer of metal around the projectile head has resulted a reduction of the resistant properties of wall material under current influence, in view of electromagnetic pressure appearance, what is directed towards the wall likely the projectile velocity vector.

INTRODUCTION

The physics of penetration at the presence of electric current has not only peculiarities caused by an additional Joule heating, a current is able also to change the energy distribution onto summands. Without touch of the micro aspects of this problem, authors have considered the question about macroscopic effect of electrodynamic forces stipulated by the geometrical peculiarities of current passage along the surface of target, on the process of projectile penetration.

THE OBJECT UNDER CONSIDERATION

This paper consideration can be of interest for two applications of the pulsed power, as rail gun and electromagnetic armor augmentation. There is supposed that in both cases the electric current in the wall of target can be excited by the corresponding pulsed power supply.

Schemes of electrical augmentation of armor

At least two hypothetical schemes of electrical augmentation of armor are known. The first one is based on the "railgun effect" and has a goal to increase a square of impact by some displacement of leading part of projectile in a transversal direction due to appearance of electromagnetic forces \( F \) as a projectile 2 will close the electric voltage of pulsed power supply \( C \) applied between main wall 3 and additional defense layer 1 (Fig.1). In the second scheme it is supposed to use the compression of magnetic field confined in the local volume between main wall 3 and additional defense layer 1 after the instant of projectile 2 coming (Fig.2). In this scheme that is necessary to provide the commutation of pulsed power supply \( C \) just before impact. In the both schemes vector \( F \) shows the electromagnetic force direction. Let evaluate the second scheme on its principal ability to reduce a destructive action of
projectile. If the current is switched at instant of projectile touching of pre-defender \(I\) (Fig.2), the further deformation of layer \(I\) is going with a closed contour of current in the internal surfaces of layer \(I\) and wall of target \(3\). Let layer \(I\) is ideally flexible conductor with very low inertia and will suppose the flat (one-dimensional) band of layer. Up to a time of wall touch by layer a cross section of free cavity between them reduces twice. Initial magnetic field \(B_0\) increases there twice in result of the flux compression, if the flux losses are neglected. Magnetic energy in the cavity increases in a second degree on the field, but in view of reduction of the field volume in two time the final magnetic energy is only \(W_m = 2 P_m V_0\), where \(P_m = B_0^2 / 2\mu_0\) is an initial magnetic pressure in the cavity, \(V_0\) is an initial volume of field. Note, that at two-dimensional deformation of defender a volume of the field would be reduced only in 30%, however the field increase would be less then twice. Thus, in the most optimistic estimation the increment of magnetic energy in the cavity at the field compression by projectile cannot exceed its initial value. Taking out of consideration all additional kinds of projectile work, increment of kinetic energy of projectile is \(\Delta W_k = k_s W_m\), where \(k_s\) is a coefficient of magnetic energy losses. The average braking electromagnetic force along a displacement of projectile is \(F = \Delta W_k / h = k_s \cdot 2P_m S_i\), here \(h\) is displacement of projectile in a normal direction up to closing of cavity, \(S_i\) is a square of current-carrying surface of defender layer as acceptor of magnetic pressure. Braking force is more than total force of an initial magnetic pressure in view of the field increase at the compression. The known expression for an inductance of two parallel plates with opposite currents [1] can be rewrite as \(L = 0.5\mu_0 S_c / b\), where \(S_c\) is a square of cross section of cavity confined by the sides of plates, \(b\) is a width of current strip (or, the same, each plate). It gives a possibility to estimate a current needed for opposition to projectile with kinetic energy 10 MJ, with its reduction on 10% due to electromagnetic defense. It would be in general view

\[
i = [\Delta W_k \cdot 2b / k_s \mu_0 S_c]^{1/2},
\]

and numerically, at \(b = 0.05m\), \(S_c = 0.07m \times 0.2m\), \(\Delta W_k = 1\) MJ, \(k_s = 0.7\), the needed current is \(i = 2.84\) MA. Technically that is not simple to provide this magnitude of current. Nevertheless the considered scheme is not looking more difficult for realization, than scheme in the Fig.1.

**Electromagnetic energy influence on the mechanical properties of conductor**

Electromagnetic energy is able to change the strength ability of metals not only by addition of source heat losses and electromagnetic forces but also due to influence on the thermodynamic parameters of matter. Correlation between parameters that correspond to different kinds of energy is looking relatively simple at the elastic non-isothermal deformation of material. In a problem of definition for limit state of material the linear concept of accumulation of each kind energy extreme values is not true. That is more correct to use thermodynamic criterion of strength in view of correlation\( (Y_2(\lim) / Y_1(\lim)) \Delta V = Const\), where \(Y_2(\lim)\) is summarized mechanical work on deformation up to destruction, \(Y_1(\lim)\) is total energy expend on the heating of metal up to melting point in result of different actions, \(\Delta V\) is relative change of metal volume in result of thermal action, including Joule’s losses. That yields to set of interconnection correlations in the form

\[
\Delta \sigma_{0.2} / E = f(\alpha T, \xi_e \Psi), \quad \Delta \sigma_b / E = f(\alpha T, \xi_e \Psi),
\]

\[
\Delta \varphi = f(\alpha T, \xi_e \Psi),
\]
where $\Delta \sigma_{0.2}$ is deviation of yield point at the action of electric current, $\Delta \sigma_b$ is deviation of ultimate strength, $\Delta \psi$ is deviation of deformation limits under action of electric current, $E$ is Young's modulus, $a$ is a coefficient of thermal expansion, $\xi_e$ is electrostriction coefficient, $T$ is temperature and $\Psi$ is electric potential. Interpretation of these functional dependencies for specific range of loading (current density, temperature, initial mechanic loads) is the important problem in the evaluation of conductors destruction limits. In application to problem of projectile penetration into metal target the specific factors must be taken into attention in addition to above told ones. Using the theory of similarity, the task about depth of penetration $L$ can be formulated in the form of criterion dependence (1).

$$L = \xi \left( \frac{\sigma_{0.2}}{E} \frac{\sigma_b}{E} \alpha \frac{\psi}{T \rho \rho_1} \frac{p}{\psi_{cldT}} \right) \left( \frac{Q_{pl}}{T_{pl}} \mu U I \Delta m E \frac{E}{\rho_0 \sigma_1^2} \frac{1}{\rho_0 \rho_1} \frac{d_0}{d_f} \right) \left( \frac{V_0}{\rho_1} \frac{\rho_0 \rho_1^2 \alpha}{H_2} \frac{H_1}{H_1} \frac{X}{\alpha T \rho_1} \right) \left( \frac{1}{2 \rho_0} \frac{c_p}{\alpha E} \frac{j B t}{\sigma_1 E^2} \frac{\mu \sigma_1 \alpha T}{\rho_0 V} \right)$$

(1)

Arguments in brackets include the criteria of static loading as $\sigma_{0.2}/E$, $\sigma_b/E$, $\alpha$, where $\alpha$ is a transversal contraction at the break, also the correlation between mechanical and thermal processes, as well as between heat energy and energy of phase transition. The second group of criteria gives the relative time characteristic of impact, connection between impact velocity $V_0$ and elastic waves speed, relative loss of mass $\Delta m$ in target at the impact, ratio of coefficients for thermal and electromagnetic diffusion in a target. Other values has been used in (1): $P$ is a force of resistance to impact, $S$ is square of impact, $c_p$ is a specific thermal capacity, $Q_{pl}$ is heat of melting, $T_{pl}$ is a melting point, $\mu$ is a magnetic permeability of target, $U$ and $I$ are electric field and current, $r$ is a characteristic dimension of target, $\alpha_T$ is a coefficient of temperature conduction, $\sigma_e$ is an electrical conductivity of target, $\gamma$ is temperature coefficient of electric resistance, $\rho_0$ is a target material density, $j$ and $B$ are a current density and field in a contact zone of target, respectively, $t$ is a time duration of impact, $H_1$ and $H_2$ are the static hardness for target and projectile head respectively, $X$ is a form-factor for the projectile head, $l_0$ is length of projectile, $d_0$ is a diameter of projectile. In general, at the temperature rise under action of electric current material has lowering of strength, the increase of strength can be recognized at very high speed of deformation and at the presence of effective covering. With using of theory of similarity experimental data about material durability can be generalized in the view

$$\sigma = \left[ 1.822 + Ei^\gamma(-0.1-k_e e) \right]^{n_r+n_j+n_e} \times \left( 1 - \frac{T}{T_{n_3}} \right)^{m_r} \left( \frac{1}{j_{max}} \right)^{m_j} \left( 1 + \frac{\dot{e}}{\dot{e}_{max}} \right)^{m_e},$$

where $Ei^\gamma$ (arg) is the integral exponential function, $k_e$, $n_r$, $n_j$, $n_e$, $m_r$, $m_j$, $m_e$ are empirical coefficients for the corresponding factors of influence, $j_{max}$ and $\dot{e}_{max}$ are the maximal testing values of electric current density and speed of deformation. Coefficients can be defined from curves of deformation. For orientation, in the conducting materials of electrical engineering there are the magnitudes: $k_e \approx 60...110$, $n_r = 0...-0.15$, $n_j = 0...-0.1$, $n_e = 0...0.3$, $m_r = 0.55...0.85$, $m_j = 1...1.15$, $m_e = 1...2$. The accuracy of approximation for curves of deformation using above expression is going to 5%.

**ANALYSIS OF PROJECTILE PENETRATION**

The impact velocity of projectile can be enough to create the liquid crater (bath) around a top of head under condition $\rho_c V^2/Y_d = 10^3$, here $\rho_c$ is a density of projectile material, $Y_d$ is a dynamic yield point. Energy expand on the melting of metal is $W_q \equiv (mV^2/2)(1-e^{-2})$, where $e$ is a coefficient of impact rebound. Using significance of $e$ from [2], it is possible to get the radius of melted zone around top of projectile: $r_e \equiv \left( \frac{\rho_c}{\alpha} + (3W_d / 2\pi L p) \right)^{1/3}$,
$r_i$ is radius of projectile head. In assumption of a presence of the liquid metal layer around the top of head when has a form of hemi-sphere the electromagnetic pressure can be calculated for the target with passage one-directional electric current along its surface. The acting forces have been considered in the equation of motion neglecting the viscosity force. Current density distribution in the neighborhood of a projectile top in the cylindrical co-ordinates $(r, \theta)$ is obtained by the solution of electrodynamic task:

$$J_e = J_0 \left(1 - \frac{\Lambda^3 \eta^3}{r^3}ight) \cos \theta \phi - J_0 \left(1 + \frac{\Lambda^3 \eta^3}{2r^3}ight) \sin \theta \phi$$

with a parameter $\Lambda = \left(\frac{2(\sigma_\phi - \sigma_i)}{2\sigma_\phi + \sigma_i}\right)^{1/3}$, that includes the electrical conductivity of target $\sigma_\phi$ and projectile $\sigma_i$. $J_0$ is undisturbed value of current density on some distance of impact zone. With a proper approximation for the field, a magnetic pressure on the projectile top surface can be found by integration of equation of the forces equilibrium and is given in expression (2), where $p_0$ is a basic value of pressure:

$$p \left(\eta, \theta\right)_{\eta \to \eta} = p_0 - \frac{\mu_0 J_0^2 \eta^2}{4} \left(1 - \Lambda^3\right)^2 \sin^2 \theta, \quad (2)$$

Total force on the projectile head (electromagnetic in sum with hydrostatic one) is respectively

$$F = F_{st} - 6 \mu_0 J_0^2 \frac{\eta^2}{\theta} \cdot f(\sigma_R),$$

where $\sigma_R = \sigma_1 / \sigma_e$, $f(\sigma_R) = \sigma_R^2 / (2 + \sigma_R)^2$. The function $f(\sigma_R)$ is shown in the Fig.4. The additional electromagnetic force in a liquid metal is directed towards the target, reducing the resulting mechanical resistivity of metal with respect to impact of projectile. In the Fig.4 it is seen that an electromagnetic force is going to a stable level at a growth of ratio $\sigma_R$ up to $\infty$. If head of projectile doesn’t conduct a current ($\sigma_R \to 0$), a total force of resistance is defined by a hydrostatic pressure only: $F_{st} = \pi \eta^2 p_0$.

**CONCLUSION**

In a macroscopic consideration the analysis of influence for a current flowing along the surface of target has resulted a decrease of mechanical strength of metal wall of target in view of electromagnetic force appearance directed toward a target. Some useful criteria for the impact penetration can be obtained by using the theory of similarity.

**REFERENCES**