THEORY OF ELECTROMAGNETIC EFFECTS ACCOMPANYING DYNAMIC DEFORMATION OF METALS

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A number of studies [1-6] have presented data on electromagnetic effects accompanying dynamic loading of metals. In [1-5] the development of electrical signals was related to the electron-inertial effects (see, for example, [7]).

The present study will derive an equation which relates the electric field intensity to the current density in a metal undergoing dynamic deformation. This equation is then used to analyze electromagnetic effects and evaluate such effects numerically for the case of shock loading of metal bars.

To describe the dynamics of the metal's electron gas in the deformation wave we use linearized hydrodynamic equations. This approximation is valid under conditions with dominating collisions where local equilibrium exists [8], which can be expressed by the inequalities

$$\omega\tau \ll s/v_F; \quad (1)$$

$$\omega\tau_\varepsilon \ll 1, \quad (2)$$

where $\omega$ is the deformation wave harmonic frequency; $\tau$ is the electron momentum relaxation time; s, deformation wave velocity; $v_F$, Fermi electron velocity; $\tau_\varepsilon$, electron energy relaxation time.

For metals, condition (1) is usually the more severe one. In as much as for typical metals $s \sim 5\cdot10^5$ cm/sec, $v_F \sim 10^8$ cm/sec, $\tau \sim 10^{-13}$ sec, it follows from Eq. (1) that $\omega \ll 5\cdot10^{10}$ sec$^{-1}$.

Because of the linerity of the equations used, this same condition extends to the electromagnetic field frequency. It is thus obvious that the approximation being used encompasses practically the entire radio spectrum.

The ionic lattice deformation wave is assumed to be a known function of coordinate and time.

We write the equation of conservation of electron gas momentum density in a coordinate system fixed to the lattice:

$$m\frac{d(n_e\mathbf{u}')}{dt} = -en_e\mathbf{E} - \frac{2\varepsilon_F}{3}\operatorname{grad} n_e - \frac{mn_e\mathbf{u}'}{\tau} - m_0\frac{d(n_e\mathbf{V})}{dt}, \quad (3)$$

where m is the effective electron mass; $n_e$, electron concentration; $\mathbf{u}'$, mass velocity of electron gas in the coordinate system fixed to the lattice; $-e$, charge on an electron; $\mathbf{E}$, intensity vector of the electric field produced by separation of charges in the deformation wave (if necessary this quantity can also consider an external electric field); $\varepsilon_F$, Fermi energy; $m_0$, mass of the free electron; $\mathbf{V}$, mass velocity of ions.

It is well known that the noninertial nature of a reference frame is equivalent to the presence of some gravitational field. The gravitational mass of a metal electron, in contrast to its inert effective mass, is equal to the mass of a free electron. The last term on the right side of Eq. (3) considers "gravitational" forces produced by the noninertial nature of the reference frame chosen (see, for example, [9]).

The term inversely proportional to relaxation time considers dissipative forces. Forces proportional to the concentration gradient are generated by the dependence of chemical potential on electron gas density (piezogalvanic effect [10]).

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It is obvious that if necessary the right side of Eq. (3) can consider forces produced by a magnetic field, temperature gradient, high-frequency phonon flux, etc.

Transforming Eq. (3) to the laboratory reference frame, in the linear approximation we obtain

$$\frac{\partial \mathbf{u}}{\partial t}=-\frac{\mathbf{u}-\mathbf{V}}{\tau}-\frac{e}{m}\mathbf{E}-\frac{2\varepsilon_F}{3n_0}\operatorname{grad} n_e+\left(1-\frac{m_0}{m}\right)\frac{\partial \mathbf{V}}{\partial t}, \quad (4)$$

where $\mathbf{u} = \mathbf{u}' + \mathbf{V}$ is the mass velocity of the electron gas in the laboratory reference frame; $n_0$ is the unperturbed ion and electron density.

Expressing the mass velocity in terms of the current density and using Maxwell's equations, after various transformations we obtain from Eq. (4) to the accuracy of terms of order $\omega\tau v_F/s \ll 1$ the desired equation

$$\left(\frac{\partial}{\partial t}-\frac{\tau v_F^2}{3}\operatorname{grad}\operatorname{div}\right)\mathbf{j}=\sigma\frac{\partial}{\partial t}(\mathbf{E}+\mathbf{E}_0), \quad (5)$$

where $\mathbf{E}_0=\frac{m_0}{e}\frac{\partial \mathbf{V}}{\partial t}+\frac{2\varepsilon_F}{3en_0}\operatorname{grad} n_I$ are lateral forces produced by the deformation wave, with the first term corresponding to the electron-inertial effect and the second to the piezogalvanic; $\sigma$ is the conductivity of the metal; $n_I$ is the ion density.

We note that at $\omega \ll \frac{3}{\tau}\frac{s^2}{v_F^2} \sim 7\cdot 10^8$ $\sec^{-1}$ Eq. (5) reduces to Ohm's law with consideration of lateral forces: $j = \sigma(E + E_0)$.

In the case of the experimental conditions of Stuart and Tolmen from symmetry we have $\operatorname{div} j = 0$, $\operatorname{grad} n_I = 0$, $E = 0$. Then we obtain from Eq. (5)

$$\mathbf{j}=\sigma\frac{m_0}{e}\frac{\partial \mathbf{V}}{\partial t},$$

which is in agreement with classical results (see, for example, [7]).

We will consider longitudinal deformation of a one-dimensional bar. The complete system of equations defining current and electric field then has the form

$$\left(\frac{\partial}{\partial t}-\frac{\tau v_F^2}{3}\frac{\partial^2}{\partial x^2}\right)j=\sigma\frac{\partial E}{\partial t}+\sigma\frac{m_0}{e}\left(\frac{\partial^2}{\partial t^2}-\frac{2}{3}\frac{m}{m_0}v_F^2\frac{\partial^2}{\partial x^2}\right)V, \quad (6)$$

$$\partial\rho/\partial t+\partial j/\partial x=0,\ \partial E/\partial x=4\pi\rho,\ E=-\partial\varphi/\partial x,$$

where $\rho$ is the electric charge density; $\varphi$ is the electrical potential.

Combining the equations of system (6), we find

$$j=\frac{1}{4\pi}\frac{m_0}{e}\left(\frac{\partial^2}{\partial t^2}-\frac{2\varepsilon_F}{3m_0}\frac{\partial^2}{\partial x^2}\right)V,\quad \varphi=\frac{2\varepsilon_F}{3e}\frac{(n_I-n_0)}{n_0}.$$

We will now estimate the order of magnitude of $\varphi$ and $j$. If $\varepsilon_F \sim 5\cdot 10^{-12}$ erg, $(n_I - n_0)/n_0 \sim 10^{-2}$, $V \sim 5\cdot 10^3$ cm/sec, $\omega \sim 6\cdot 10^5$ $\sec^{-1}$, we obtain $j \sim 10^{-9}$ A/cm², $\varphi \sim 30$ MV.

It is obvious that the contribution to current from the piezogalvanic effect is approximately $(v_F/s)^2 \sim 10^5$ times larger than the contribution of the electron-inertial effect.

The low value of current density is fully understandable, since in view of the electrically closed geometry of the specimen (in contrast to the Stuart–Tolmien experiment) the appearance of current in the deformation wave leads to development of volume electrical charges, which generate large counter forces which was not considered in [1-5] (see, for example, the definition of current, Eq. (1) in [2] or Eq. (2) of [3]). The current pulse parameters presented in [1-5] (amplitude $I \sim 10^{-3}$ A, duration $\tau_I \sim 10$ µsec) are inexplicable. In this case in portions of the bar located on opposite sides of the plane of the inductive sensor charges $Q \sim I\tau_I \sim 10^{-8}$ C should develop. Estimating the value of the electric field intensity corresponding to such electrical charges, with the assumption that the charges are located at a distance of a deformation wavelength $\lambda \sim 5$ cm, we obtain an electric field intensity $E \sim Q/\lambda^2 \sim 10^5$ V/cm, inexplicably high for the experimental conditions.

One possible cause of the signals recorded by the sensors in [3-5] might be the magnetostriction effect, produced by mechanical perturbations of the inductive sensor cores.

In particular, [6] presented results of experiments on study of the electromagnetic field near a duralumin bar along which a deformation wave propagates. The results presented (signals from a rod antenna of mV amplitude level at an antenna-bar spacing of several cm) agree in order of magnitude with our estimates. However, we cannot agree with the authors of [6] that the signals recorded were radiation pulses. Bivin et al. [6] properly concluded that the electromagnetic field amplitude of the radiation decays at large distances as 1/r, where r is the distance to the radiation source. However, such distances must be large not only in comparison to the dimensions of the radiating system, but also as compared to the electromagnetic wavelength itself. This region of the electromagnetic field is referred to as the wave or far zone [11]. For the frequencies of $\sim 10^4$ Hz indicated, the wave zone is realized at distances of $\geqslant 3 \cdot 10^4$ m. In [6] the distances were $\sim 10$ cm. Therefore the field intensity inversely proportional to distance indicated in [6] (like the field polarization) is not evidence that the pulses recorded were produced by a radiation field. In our opinion, upon impulsive loading of a metal bar the most marked effect is the development of volume charges and a corresponding potential electric field. The current in the deformed specimen (in the absence of an electrically closed circuit) and the corresponding magnetic field should be quite weak.

Thus, Eq. (5) (with other lateral forces included if necessary) together with Maxwell's equations forms a closed system (if the deformation wave structure is known), suitable for describing electromagnetic effects in the radio wavelength range which accompany dynamic deformation of metals. The main contribution to the electromagnetic field is produced by the piezogalvanic effect.

## LITERATURE CITED


1. B. M. Stikhanovskii, "Method for measurement of force in collision of metallic bodies," Byull. Izobret., No. 21 (1973).
2. B. M. Stikhanovskii, "Development of electrical current upon collision of metal and semiconductor bodies," Izv. Sib. Otd. Akad. Nauk SSSR, Ser. Tekh. Nauk, No. 8, 2 (1973).
3. Yu. G. Kashaev, S. A. Novikov, and V. A. Sinitsyn, "Use of the electron-inertial effect in shock loading for measurement of bar deformation," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1977).
4. Yu. G. Kashaev, S. A. Novikov, and V. A. Sinitsyn, "Study of dynamic extension diagrams of titanium and copper under explosive loading by the electron-inertial method," Probl. Prochn., No. 1 (1980).
5. A. M. Zlobin, Yu. G. Kashaev, and S. A. Novikov, "Generation of electrical signals in elastic waves propagating in metal bars," Zh. Prikl. Mekh. Tekh. Fiz., No. 2 (1981).
6. Yu. K. Bivin, V. V. Viktorov, et al., "Electromagnetic radiation during dynamic deformation of various materials," Izv. Akad. Nauk SSSR, Mekh. Tverd. Tela, No. 1 (1982).
7. I. M. Tsidil'kovskii, "Electrons and holes in an inertial force field," Usp. Fiz. Nauk, 115, 321 (1975).
8. M. Stil and B. Vyural', Wave Interaction in Solid State Plasma [in Russian], Atomizdat, Moscow (1973).
9. V. L. Ginzburg, in: In Memory of A. A. Andronov [in Russian], Izd. Akad Nauk SSSR (1955).
10. L. É. Gurevich, "Some electroacoustical effects," Izv. Akad. Nauk SSSR, Ser. Fiz., 21, No. 1 (1957).
11. L. D. Landau and E. M. Lifshits, Field Theory [in Russian], Nauka, Moscow (1973).