Journal of Applied Mechanics and Technical Physics, Vol. 36, No. 5, 1995

ELECTRON-INERTIAL EFFECT IN METALS UNDER SHOCK LOADING

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UDC 531.78.781

Mechanisms of generation of an electromotive force (current) in metals under shock loading and the effect of strain are considered in the present work. It has been shown experimentally that the strain rate and the effective mass are the controlling factors.

In the known setups of electron-inertial experiments, the current generated in a circuit is measured while a conductor, which is a part of the curcuit, is accelerated (Tolmen–Stuart effect), or the acceleration of a current-carrying conductor is measured while the current is changed [1]. The experimental results are expressed in termes of an extraneous field $\mathbf{E}^{ei}_{\text{extr}}$ related to the acceleration $\mathbf{W}$ of the conductor. Regardless of the effective mass of current carriers inside the conductor and of the type of conductivity (electron or hole), the field is given by the expression

$$\mathbf{E}^{ei}_{\text{extr}} = \frac{m}{e}\mathbf{W}, \tag{1}$$

where m is the mass and e is the charge of a free electron. This conclusion is confirmed by measurements within an attained accuracy of the order of 1%.

However, formula (1) is obtained without considering the strain occurring in the conductor due to its acceleration. It was shown in [2] that because of the strain of a metal in the gravitational field, an electric field $M\mathbf{g}/e$ (M is the metal ion mass) is generated which is five orders of magnitude stronger than the field $m\mathbf{g}/e$ which would exist in the absence of strain. Hence, the field $M\mathbf{W}/e$, which is many times stronger than the field $\mathbf{E}^{ei}_{\text{extr}}$, should be generated in the conductor when it is accelerated. In this connection, Ginzburg and Kogan [2] discussed the question of suitability of Eq. (1) for describing electron-inertial experiments taking into account the acceleration and strain of the conductor in analysis of the expression below for the current density j_e (for $\omega < \tau_{\text{r}}^{-1}$, $l \ll \Delta L$, $l = \mathbf{V}_{\text{F}}\tau_{\text{r}}$, where $\mathbf{V}_{\text{F}}$ is the velocity at the Fermi surface, τ_{r} is the relaxation time of the electron momentum, and ω, ΔL are the frequency of the harmonics and the long-wavelength region of the strain wave spectrum, respectively):

$$\mathbf{j}_e = \boldsymbol{\sigma}_{ij}\left(\mathbf{E}_j + e^{-1}\frac{\partial}{\partial x_i}\overline{\boldsymbol{\lambda}}_{kl}\mathbf{U}_{kl} + \mathbf{E}^{ei}_{\text{extr}}\right) + \boldsymbol{\Gamma}_{ijkl}\frac{\partial \dot{\mathbf{U}}_{kl}}{\partial x_i}. \tag{2}$$

Here $\mathbf{E}_j$ is the external electric field, $\boldsymbol{\sigma}_{ij}$ is the conductivity tensor, $\mathbf{U}$ is the lattice displacement vector, $\dot{\mathbf{U}}_{kl}$ is the strain rate tensor, and $\overline{\boldsymbol{\lambda}}_{kl}$ is the value of the strain potential $\boldsymbol{\lambda}_{kl}(\mathbf{p})$ averaged over the Fermi surface, which describs the interaction of an electron with the strain. The tensor is given by the expression

$$\boldsymbol{\Gamma}_{ijkl} = \left(\frac{e}{4\pi^3 h}\right)\int \frac{V_i V_j}{V}\,\tau_{\text{r}}^2 \boldsymbol{\Lambda}_{kl}(\mathbf{p})\,dS_{\text{r}}, \tag{3}$$

where $\mathbf{V}(\mathbf{p})$ is the velocity of an electron with quasimomentum $\mathbf{p}$; $\boldsymbol{\Lambda}_{kl}(\mathbf{p}) = \boldsymbol{\lambda}_{kl}(\mathbf{p}) - \overline{\boldsymbol{\lambda}}_{kl}$; and integration is performed over the Fermi surface.

According to [2], the field $\mathbf{E}_1 = e^{-1}(\partial/\partial x_i)\overline{\boldsymbol{\lambda}}_{kl}\mathbf{U}_{kl}$ in expression (2) exceeds the field $\mathbf{E}^{ei}_{\text{extr}}$ by approximately a factor of $M/m \sim 10^5$. However, the field $\mathbf{E}_1$ gives no contribution to the current in the sense that, as opposed to the field $\mathbf{E}_2 = \sigma_{ij}^{-1}\boldsymbol{\Gamma}_{ijkl}(\partial\dot{\mathbf{U}}_{kl}/\partial x_i)$, it does not generate a current in the bar (in

Obninsk Institute of Atomic Power, Obninsk 249020. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 36, No. 5, pp. 181–184, September–October, 1995. Original article submitted May 25, 1993; revision submitted January 31, 1994.

the curcuit) because of its potential character, since it is compensated inside the metal by the other potential electric field. Only the deformation field $\mathbf{E}_2$ can generate a current. The latter field was considered in [3], where the authors noted the possibility of measuring electric $\mathbf{E}$ and magnetic $\mathbf{H}$ fields in experiments on the propagation of a transverse sound wave. In shock loading of a metal bar,[1] the one-dimentional strain field $\mathbf{E}_2$ at $e\mathbf{\Gamma}_{1111} \sim \sigma\tau_r m \mathbf{V}_F^2$, $\Delta x = C\Delta t$ (Δt is the duration of the leading edge of the strain pulse $\varepsilon_* = V_*/C$, V_* is the lattice velocity, C is the sound speed in the bar) can be written as

$$\mathbf{E}_2 \simeq \frac{m}{-e}\frac{\tau_r}{\Delta t}\left(\frac{V_F}{C}\right)^2 \mathbf{W}(t).$$

Studies [6] of electromotive force generation in metal bars under shock loading in a broken curcuit are of interest. In these experiments the crystal lattice in the shock wave front region is subjected to both compression (tension) and acceleration. The latter, because of the of inertia of the current carriers, generates an extraneous electric field, which produces a current density $j(t)$ and is determined by the magnitude of acceleration W of the lattice and by the strain effective mass m^*:

$$\mathbf{E}_{\text{extr}}(t) = \sigma^{-1}\mathbf{j}(t) = \frac{m^*}{-e}\frac{\partial \varepsilon_*}{\partial t}\mathbf{C} = \frac{m^*}{-e}\mathbf{W}(t).$$

The nontriviality of this conclusion is that in Talman–Stuart experiments the extraneous electric field $\mathbf{E}^{ei}_{\text{extr}}$ is determined by the free electron mass m since the lattice potential does not affect the inertia force [1].

The magnitudes of the strain effective mass m^* found in the experiment on shock compression and tension are in agreement with the known results of [7].

For the actual parameters [6] $\mathbf{V}_F = 10^6$ m/sec, $\mathbf{C} = 5 \cdot 10^3$ m/sec, $\Delta t = 4 \cdot 10^5 \tau_p$, $m^* = 10m$ we have $\mathbf{E}_2 \simeq \mathbf{E}^{ei}_{\text{extr}} = (m^*/-e)\mathbf{W}$, that is, at $\Delta t = 30 \cdot 10^{-6}$ sec, $\tau_r = 10^{-10}$ sec (see [3, 6]) the extraneous field $\mathbf{E}^{ei}_{\text{extr}}$ is comparable in order of magnitude with the field $\mathbf{E}_2$, whereas at $m^* = m_0$, $\Delta t = 4 \cdot 10^4 \tau_r$ the field $\mathbf{E}_2$ and the Talman–Stuart field $\mathbf{E}^{ei}_{\text{extr}}$ are of the same order.

In the presence of the extraneous field $\mathbf{E}_{\text{extr}} = (m^*/-e)(\partial\varepsilon_*/\partial t)\mathbf{C}$, the kinetic equation for electrons can be written as

$$\left(\frac{\partial f_0}{\partial \varepsilon}\right) e\mathbf{V}\mathbf{E}_{\text{extr}} + \left[\frac{\partial f}{\partial t}\right]_{\text{extr}} = 0.$$

The current density is given by

$$\mathbf{j} = \sigma \mathbf{E}_{\text{extr}},$$

and the quasineutrality condition, by

$$\left(\frac{Z}{M}\right)\rho_l = \langle \mathbf{f} \rangle 9, \tag{4}$$

where $\mathbf{f} = f_0(\varepsilon - \mu(r,t))$ is a local equilibrium function, f_0 is a Fermi function, Z is the total charge of ions in a unit cell, M is the ion mass, ρ_l is the lattice density, and μ is the chemical potential. The space-time dependence of μ is defined by the quasineutrality condition (4); $[\partial f/\partial t]_{\text{extr}}$ is the collision integral; and ε is the energy of current carriers.

By measuring the total charge $\int i\,dt$ that has passed through the transverse cross section S of the bar during the time $\Delta\tau$ ($\Delta\tau$ is the duration of the leading edge of strain), and the magnitude of the bar strain $\varepsilon_*(x,t)$, one can determine the ratio $m^*/-e$ by the known values of σ, S, and C (see [8] as well):

$$\varepsilon_*(x,t) = \frac{e}{\sigma m^* SC}\int_0^\tau i(t)\,dt.$$

[1]The generation of a current in a metal bar was considered in [4] based on the piezogalvanic effect [5]. However, it can be easily shown that in this effect the extraneous electric field $\mathbf{E}_*$ is identical to the potential field $\mathbf{E}_1 = e^{-1}(\partial/\partial x_i)\overline{\mathbf{\Lambda}}_{kl}\mathbf{U}_{kl}$ and therefore it dose not generate current in the bar. Indeed, according to [4], the piezogalvanic field can be written as $\mathbf{E}_* = (2/3)(\varepsilon_F/en_0)\operatorname{grad} n_1$ (n_0 is the density of electrons and ions, and n_1 is the density of iones). On the other hand, the field $\mathbf{E}_* \sim e^{-1}e^{-1}\varepsilon_F/x \sim (\partial/\partial x_i)\overline{\mathbf{\Lambda}}_{kl}\mathbf{U}_{kl} = \mathbf{E}_1$.

It is seen that the currents measured in experiments according to [6, 8–13] depend on the effective strain electron mass, which characterizes the effect of the lattice potential on the inertia. The dynamics of the current carriers can be described, as in [1], by the quasiclassical equation of motion

$$m_* \frac{d\mathbf{V}}{dt} = e(\mathbf{E}_j + c^{-1}[\mathbf{V}, \mathbf{H}] + \mathbf{E}_{\text{extr}})$$

($e < 0$, m_* is the effective dynamic mass), while the kinetic coefficients (Hall constant, magnetoresistance, thermal electromotive force, etc.) can be found from the kinetic equation, which includes the field $\mathbf{E}_{\text{extr}}(t)$ along with other fields.

In the dynamic effective mass m_* approximation, in the presence of the force $m^*C\,\partial\varepsilon_*/\partial t$ described by the field $\mathbf{E}_{\text{extr}}(t)$, all the dynamic and kinetic characteristics of electrons can be expressed in terms of the dynamic effective mass. The field $\mathbf{E}_{\text{extr}}$ is determined by the effective strain mass, as opposed to the Talman–Stuart field. Thus, the fact that the action of the force $m^*C\,\partial\varepsilon_*/\partial t$ is reduced to the action of the extraneous field $\mathbf{E}_{\text{extr}}$ makes it possible to describe the motion of current carriers in metals under shock loading in the same way as in electron-inertial experiments.

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