GENERATION OF ELECTRICAL SIGNALS IN ELASTIC WAVES PROPAGATING IN METAL RODS

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Investigation of the emf which arises upon shock loading of solid bodies permits, as the experimental results already obtained [1, 2] have shown, studying a broad range of subtle dynamical effects: The drag of current carriers by polarized ions, diffusion of current carriers from a shock wave front (SWF), the electron inertial effect, shock polarization of the material behind an SWF, and so on. On the other hand, the measurement of electrical signals in connection with shock loading of solid bodies opens up new possibilities for the investigation of shock interactions and dynamic physicomechanical properties of materials [3, 4].

One of the possible mechanisms for the generation of an emf upon shock loading of metals is the electron inertial effect, which is similar to the Tolman–Stewart effect [5]. It consists in the fact that in the SWF region the crystalline lattice undergoes both compression and acceleration, which due to the inertia of the current carriers leads to the onset of an external electric field. The latter induces an electric current $i(t)$ determined by the value of the acceleration $w[i(t) \sim w(t)]$. Direct measurement of the electric current and the strain as functions of the time has shown [3] that proportionality of the current and the acceleration is fulfilled with good accuracy in the investigated metals upon shock loading in the region of elastic strains.

The results of an investigation of the generation of electrical signals upon shock compression and tension of samples made out of titanium Ti and steel in the region of elastic strains are given in this paper. The simultaneous measurement of the strain tensor ε_{zz} (the z axis is orthogonal to the SWF) and the electric current $i(t)$ has permitted determining the ratio m/e (m and e are the mass and charge of the current carriers, respectively), and measurement of the currents $i(t)$ of a sample on dynamometers offers the possibility of obtaining the value of the modulus of elasticity E and the yield stress $\sigma^*_{0.2}$ of the material.

As experimental results have shown, the amount of electricity which has passed through a circuit is determined by the amount of strain and the effective mass of the current carriers m^*

$$\frac{1}{\sigma_* Sc}\int_0^t i(t')\,dt' = \frac{m^*}{(-e)}\varepsilon_{zz}(t), \tag{1}$$

where σ^* is the conductivity of the sample, S is the transverse cross section, and c is the rod speed of sound. It follows from (1) that the external electric field E_{ext} which arises upon shock loading depends on the effective mass of the current carriers:

$$E_{ext}(t) = (S\sigma)^{-1} i(t) = \frac{m^*}{(-e)}\frac{du_z}{dt}$$

(u_z is the mass velocity behind the SWF).

The nontriviality of this conclusion consists in the fact that in the classical formulation of electron inertial experiments the external field E_{ext} is determined by the mass of a free electron $m_0 : E_{ext} = (m_0/e)w$ [5]. The values of the effective mass of the current carriers m^* and the modulus of elasticity E found in experiments with shock compression and tension are in good agreement with the known results [6, 7].

In three series of experiments the samples were selected in the form of cylindrical rods 13.8 mm in diameter made out of titanium (α phase) and 30KhGSA and Kh18N10T steels. The apparatus and procedure for measurement of the strain and current in a rod are given in [3].

The strain and current in the rod were measured simultaneously in order to determine the ratio m^*/m_0. The strain was measured with 2FKPD-5–100 resistance-type strain gauges.

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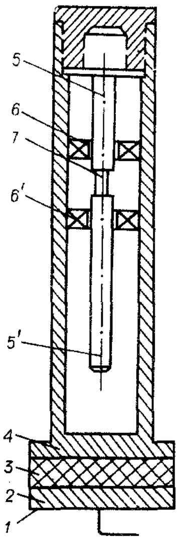

Fig. 1

A current transformer in the form of a 300NM ferrite ring wound with turns of copper was used as the inductive detector. The wires were shielded by aluminum foil from the effect of external electromagnetic noise. A gap of ~ 2 mm was adjusted between the rod and the detector.

Samples made out of VT-17 high-strength titanium were selected for the investigations in the fourth series of experiments. A compression wave was created in the waveguide 4 with the help of a layer of explosive material 1 (Fig. 1), a steel striker 2, and a foam plastic damper 3. The tensile strain of the working section of the sample 7 was measured by the current transformers 6–6', which were mounted on the dynamometer sections 5–5'. The cores of the detectors were made out of 79NM Permalloy strips of thickness ~50 μm and out of turns of copper wire 0.35 mm in diameter. The number of turns was 100. The load resistance of the transformers was 240 Ω. The latter were also shielded by aluminum foil for protection from noise. The signals from the detectors were fed without amplification to the inputs of S1-18 recorders, which were triggered from the blast pulse of the detonator through a delay line. The expressions for the strain of the working section of the sample ε and the load σ are of the form

$$\varepsilon = \frac{1}{L}\int_0^{\tau} (v_1 - v_2)\,dt, \quad v_{1,2} = \frac{k_{1,2}eE}{\sigma m^* Sc}\int_0^{\tau} i_{1,2}(t)\,dt,$$

$$\sigma = \frac{k_2 eE}{\sigma m^* Sc}\int_0^{\tau} i_2(t)\,dt, \quad i_{1,2} = \frac{U_{1,2}k_{1,2}}{2\sqrt{2}R_{l1,2}},$$

where $i_{1,2}$ is the current in the circuit of the first and second detectors, respectively, $v_{1,2}$ are the speeds of the transitional cross sections of the sample, $U_{1,2}$ are the voltages at the recorder inputs, $k_{1,2}$ and $R_{l1,2}$ are the calibration coefficients and load resistances of the detectors, L is the length of the working section of the sample, and S is the transverse cross-sectional area of the dynamometer.

The samples had a working section 10 mm in length and 4 mm in diameter, which produced in it a load state close to a uniform one [8, 9]. The length of the dynamometer 5', which is equal to 250 mm, was selected from a calculation in order that the pressure pulse reflected from the free end not affect a measured signal having a duration of 100 μsec. Upon loading of the sample the dynamometer sections were elastically deformed, and the working section elastoplastically. The stress $\sigma(t)$ which arises in the working section of the cylindrical rod was determined from the strain of the dynamometer 5 with the use of the expression $\sigma^* = \sigma\varphi = S/(S_1$ is the transverse cross-sectional area of the working section of the sample). The value of the strain $\varepsilon(t)$ and the stress $\sigma^*(t)$ obtained upon calculation from experiment were expressed in parametric form. One can obtain upon the elimination of the parameter t the value of the modulus of elasticity E, the yield stress $\sigma^*_{0,2}$ and the transient strength σ^*_{tr} of the material.

Typical oscillograms of acceleration versus the time and strain versus the time obtained for titanium (α-phase) in the first series of experiments are given in [3].

Oscillograms obtained for 30KhGSA and Kh18N10T steels, respectively, are shown in Figs. 2 and 3 (a and b correspond to measurements with the help of a current transformer and a strain gauge). Typical

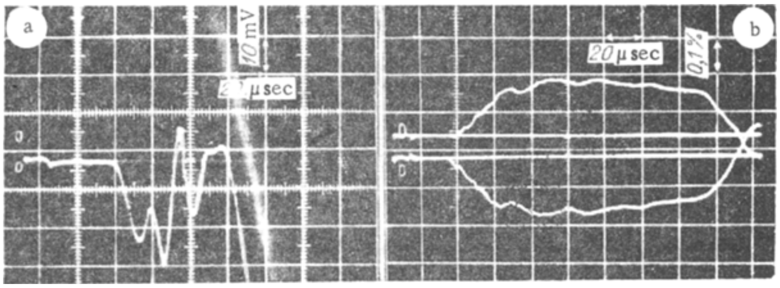

Fig. 2

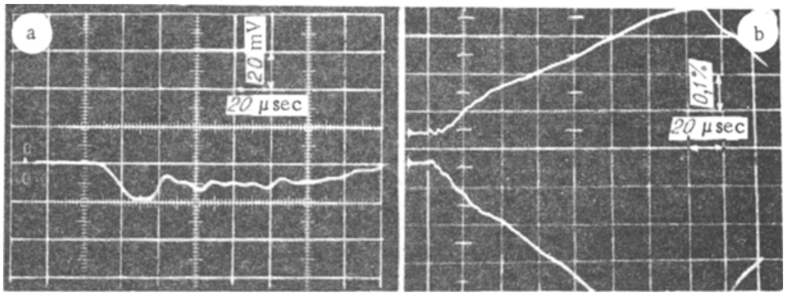

Fig. 3

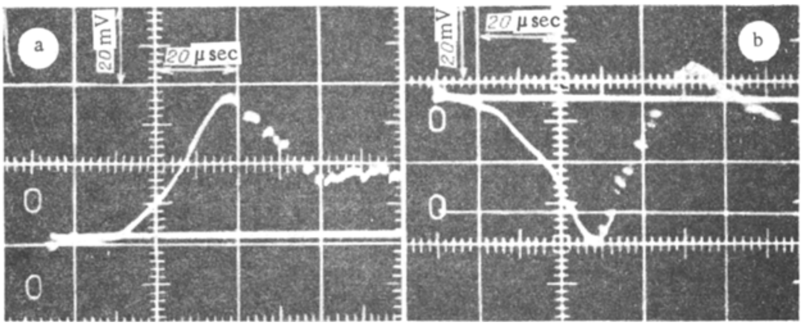

Fig. 4

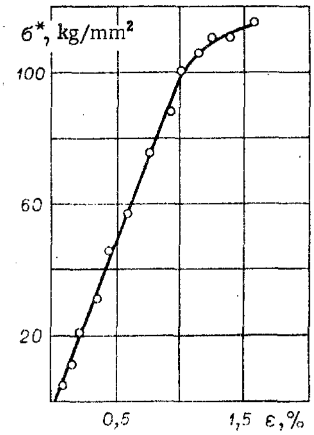

Fig. 5

TABLE 1

Type of steel	Titanium (α phase)	30KhGSA steel	Kh18N10T steel	VT-14 titanium
$\frac{m^*}{m_0}$	18,5	20	5	10

acceleration–time oscillograms obtained in the fourth series of experiments for VT-14 titanium under tension are given in Fig. 4 (a and b correspond to measurements on a dynamometer 250 mm in length). The interpretation of the oscillograms of the three series of experiments for shock-compressed steels and titanium was conducted according to the formulas of [3], from which one can determine the ratio m^*/m_0.

A diagram of the tension $\sigma^*(\varepsilon)$ for VT-14 obtained in the fourth series of experiments is presented in Fig. 5. The modulus of elasticity calculated from the diagram differed by no more than 20% from the tabular value of [6]. The values of the moduli corresponding to static and dynamic tests of the material were compared, since it is known that their difference is insignificant. The value obtained for the modulus E corresponded to a ratio $m^*/m_0 = 10$.

The results of the experimental determination of m^*/m_0 are presented in Table 1 for three series of experiments corresponding to two kinds of steels and titanium (α phase) subjected to shock compression, as well as VT-14 titanium subjected to shock tension.

The specific strength ρ of Kh18N10T steel was determined from [10], and for the remaining materials, experimentally. The mean-square error of a measurement of the current $i(t)$ and strain $\varepsilon(t)$ in an experiment was 16 and 13%, respectively. One can see from Table 1 (the values of m^*/m_0) and the data of [3] that the external field E_{ext} depends on the effective mass of the electron.

The principal difference between the result obtained and the known dependence of E_{ext} on the mass of a free electron m_0 in classical electron-inertial experiments [5] is possibly associated with the fact that in the experiments of both Tolman–Stewart and Barnet the lattice was accelerated relative to the current carriers as a whole without local perturbations. This situation resulted in the fact that the inertial properties of the current carriers in the crystal were determined by the mass of a free electron m_0. Under conditions of propagation through a fixed crystal of a local perturbation of the crystalline potential the inertial properties of the current carriers depend, as the experiments have shown, on the effective mass of the current carriers, which describes the interaction of electrons with the crystalline potential.

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