MAGNETOELECTRIC METHOD FOR DETERMINING THE DENSITY BEHIND THE FRONT OF COLLIDING SHOCK WAVES

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Of data obtained using shock waves, the most accurate are those obtained with a study of the one-time compressibility of substances which, under compression, do not go over into other crystalline modifications. In elastic-plastic media and in substances which undergo phase transitions, instead of a single surface of discontinuity, there is formed a sequence consisting of several shock waves. With respect to accuracy and singularity, the recording of their parameters is much inferior to the experimental analysis of one-time compressibility. The study of relaxing media, through which shock waves are propagated with a variable velocity, also presents serious difficulties. For the investigation of these complex phenomena, it is essential to dispose of direct methods for recording the density of a substance subjected to the effect of high pressures, over the course of a period of time which is as long as possible. It is important, in particular, to study states arising with the frontal collision of shock waves having a "table-shaped" profile. By this means, identical pressures are achieved over the whole volume of the sample, exceeding by several times the pressures in the incident waves. With a collision, the medium undergoes "two-stage" loading which, compared to single-stage loading, brings about a smaller increase of the entropy.

To study the density of a substance behind the front of colliding waves, in [1] pulsed x-ray photos of compressed elements of the medium were obtained. In this manner, states of two-stage compression were recorded over a pressure range of 500 to 900 kbar for paraffin, water, Plexiglas, magnesium, and aluminum. The present communication describes the determination of the density of shock-compressed nonconducting bodies. It gives the results of measurement of the double compression of paraffin, clay, as well as of crystals of potassium chloride and sodium chloride. The method used was based on E. K. Zavoiskii's well-known magnetoelectric method for recording mass velocities [2].

1. Scheme of Experiment. To determine the degree of compression, the medium under study is placed in a constant magnetic field, and into it there is introduced a conductor, forming an almost closed loop. The plane of the conductor is perpendicular to the magnetic lines of force. During the process of compression of the loop, an electromotive force is induced in it

$$E = -H\frac{dS}{dt}10^{-8}\frac{\text{cm}^2}{\text{sec}}, \quad H\frac{dS}{dt} = \frac{d\Phi}{dt} \tag{1.1}$$

TABLE 1

Material investigated	ρ_0	D_1	u_1	p_1	ρ_1	D_{12}	p_2	ρ_2
KCl	1.99	4.36	1.44	125	2.97	7.70	454	3.66
		4.71	0.96	97.5	2.71	6.36	263	3.20
NaCl	2.16	4.77	1.00	103.2	2.76	5.45	252	3.35
		5.26	1.37	155.7	2.92	5.97	395.7	3.81
A	2.13	4.49	1.42	137.5	3.12	5.68	387	4.10
B	0.9	5.96	2.03	109	1.37	8.43	344	1.81

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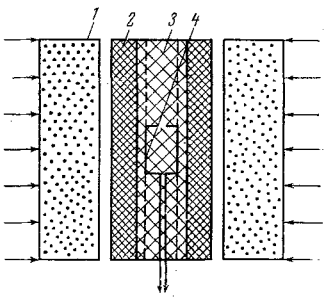

Fig. 1

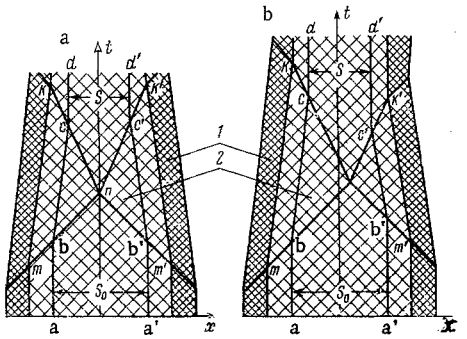

Fig. 2

Here Φ is the magnetic flux.

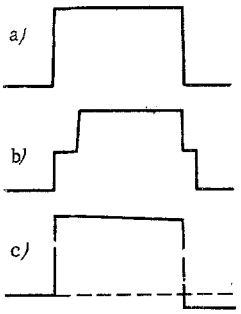

Fig. 3

As follows from squaring Eq. (1.1), for an arbitrary moment of time, t, after the start of compression, the area of the loop is

$$S(t) = S_0 - \frac{1}{H}\int_0^t |E|\,dt \tag{1.2}$$

In this case, the mean density of the substance in the loop is

$$\rho_2 = \rho_0\left[1 - \frac{J(t)}{S_0 H}\right]^{-1}, \quad J(t) = \int_0^t |E|\,dt \tag{1.3}$$

Here, S_0 and S are the initial area of the loop and the area at the moment of time, t, respectively; E is the potential, V; H is the intensity of the magnetic field, Oe; ρ_0 is the initial density of the medium; ρ_2 is the density of the medium in the compressed state.

To obtain the final values of the density, ρ_2, the function J(t), determined by the area under the amplitude curve of the oscillograph, is found for the moment when the compression process is complete, and the reflected shock waves pass beyond the limits of the loop. The form of the loop does not affect the results of the measurements, and it may have an arbitrary configuration. It is essential to know only its original area. In addition to the density, to obtain the necessary information on the compression process, the pressures during collision must also be determined. This problem can best the solved using manganin pickups, introduced in the plane of the loop. This solution permits obtaining the parameters of the process without recourse to the kinematic parameters of the shock waves, i.e., it is a new and completely independent method.

To determine the pressures, the authors made use of information with respect to the amplitude of the incident shock waves.

Figure 1 gives a schematic diagram of an experiment for determining double compression, in which 1 is the charge of explosive; 2 is a paraffin screen; 3 is a sample of paraffin, clay, or salt; 4 is the loop of the magnetoelectric pickup. The pickups used for the measurements were made in the form of rectangular loops, whose long sides were installed parallel to the fronts of the incident shock waves. Figure 2 gives x-t diagrams of the motion of the loops with synchronous (a) and nonsimultaneous (b) approach of the shock waves to the pickup (abcd and a'b'c'd' are the trajectories of the motion of the pickups; mbn and m'b'n' are the trajectories of the incident shock waves; nck and nc'k are the trajectories of the motion of the reflected waves; 1 is the screen; 2 is the sample; S_0 and S are the initial and final thicknesses of the sample). Figure 3 gives a schematic representation of oscillograms of the emf for synchronous (a) and non-synchronous (b) approach of the incident shock waves to the pickup. In the first case, the mean mass velocity of the motion of the sides of the pickup under the effect of the incident waves is proportional to half of the peaked trace; in the second case

$$u_1 = (J_1 + {}^1/_2\, J_2 + J_3)\,(Ht)^{-1} \tag{1.4}$$

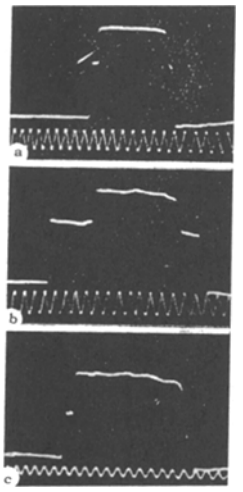

Fig. 4

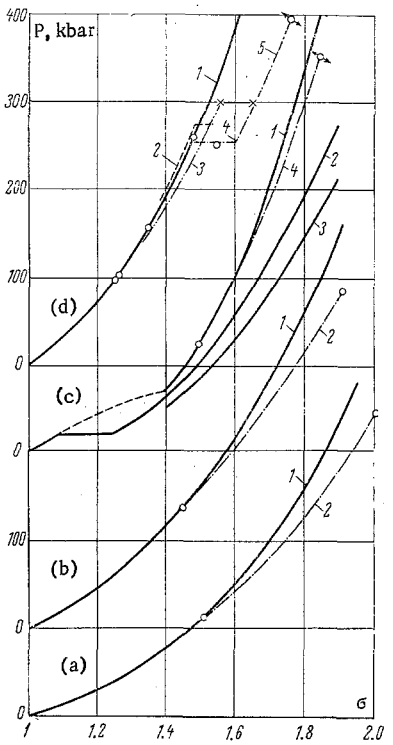

Fig. 5

The function J_2 corresponds to the period of combined motion of the sides of the pickup, and functions J_1 and J_3 to the separate motion of its left or right-hand sides at the start and at the end of the collision process. If, behind the front of the incident waves, their intensity decreases, there is also a decrease is the rate of approach of the oppositely arranged loops. Under these conditions, behind the front of the reflected waves, the substance acquires a small negative rate of expansion; a schematic diagram of the oscillographic recording of the emf, for waves which do not have a strictly table-shaped profile, is shown in Fig. 3c. The experimental results for this form of recording are interpreted in the same way as for the other variants, i.e., the area of the oscillogram determines the actual displacement of the sides of the loop, while the mean value of the peaked trace determines the effective amplitude of the first shock wave. The pressure of the reflection was found using the equation for the conservation of momentum

$$p_2 = p_1 + \rho_1 D_{12} u_1 \tag{1.5}$$

Here p_1 is the pressure in the incident wave; ρ_1 is the density of the substance in the incident wave; u_1 is the mean effective velocity of the substance in the first shock wave; D_{12} is the velocity of the propagation of the reflected shock wave with respect to the substance ahead of its front

$$D_{12} = u_1 \frac{\rho_2/\rho_1}{\rho_2/\rho_1 - 1} = \frac{\rho_2}{\rho_2 - \rho_1} u_1 \tag{1.6}$$

It is assumed that the shock adiabatic curve for one-time compression has been previously found over a range of pressure including the pressure of the incident wave.

In this case, the value of u_1 permits calculating the pressure and the density

$$p_1 = \rho_0 u_1 D_1, \qquad \rho_1 = \rho_0 D_1 (D_1 - u_1)^{-1} \tag{1.7}$$

The method of carrying out the experiments is shown schematically in Fig. 1. Two-stage compression of the samples was produced by plane shock waves, obtained using two simultaneous cylindrical charges of explosive, with a diameter of 90 mm and a height of 40 mm, arranged one opposite the other. The samples were covered by paraffin screens with a thickness of 10 mm, and consisted of three layers. The thickness of the middle layer was 12-18 mm, and of the side layers, 3-4 mm, in various experiments. As shown in

Fig. 1, between the layers there was installed a magnetoelectric pickup, made of aluminum foil with a thickness of 0.1 mm. The intensity of the constant magnetic field passing through the loop was ~ 450 Oe, and was measured before each experiment with an error of ~1%.

The oscillograms shown in Fig. 4 were obtained in samples of paraffin (a, b) and in a sample of potassium chloride (c). The first peaked trace of the beam corresponds to the approach of the shock waves to the loop of the pickup. As pointed out previously, the small offsets in the middle of the front of the first peaked trace characterize the degree of non-simultaneity in the approach of the shock waves to the loop from opposite sides.

The table-shaped part of the oscillograms corresponds to the time of motion of the two sides of the loop of the pickup, right up to the moment when the reflected waves arrive at the loop, after which the latter leave, and the induced emf in the loop becomes equal to zero. This moment corresponds to the break of the beam on the oscillogram downward toward the zero line.

The offset in the middle of the trailing edge of the pulse corresponds to the non-simultaneous arrival of the reflected compression waves at the loop. Their lack of simultaneity is considerably less than the lack of simultaneity in the arrival of the primary shock waves, which is explained by the compression of the loop and by the considerably greater propagation rage of the reflected shock waves. As has been shown by experiments, carried out under identical conditions, in spite of certain individual differences in the course of the oscillographic curves, the overall characteristics of the process (the total displacement, the mean velocity) remain stable to a great degree.

2. Double Compression of Clay, Paraffin, Potassium Chloride, and Sodium Chloride. Determination of the pressures and densities behind the front of colliding waves was carried out for paraffin, clay, and for monocrystalline potassium chloride and sodium chloride. For using the mass velocities of the primary shock waves to determine their remaining parameters, use was made of data on the compressibility of these substances, given in [1, 3, 4]. The following relationships, taken from these sources, were used: $D = 3.30 + 1.31\,u$ for paraffin; $D = 2.78 + 1.21\,u$ for so-called "white" clay; $D = 3.40 + 1.35\,u$ for NaCl; and $D = 2.05 + 1.62\,u$ for the second phase of KCl.

The experimental data obtained are correlated in Table 1 for the case when the mass velocity of the paraffin screen $u = 2.03$ km/sec.

Table 1 gives, in order, for the materials investigated, i.e., KCl_{100}, $NaCl_{100}$, "white" clay (A) with a moisture content of ~4%, and paraffin (B): the initial density of the samples, ρ_0, g/cm^3; the parameters of compression of the samples by the primary shock waves (the wave, D_1, and mass, u_1, velocities, in km/sec, the pressure of the shock compression p_1, in kbar, the density of the substance behind the front of the primary shock wave, ρ_1, in g/cm^3), the parameters of compression of the samples by the reflected shock waves (the rate of propagation of the reflected shock waves with respect to the moving material, D_{12}, in km/sec, the pressure of double compression, p_2, in kbar, and the final density, ρ_2, in g/cm^3). The data given in Table 1 are compared in Fig. 5 with shock adiabatic curves [1-4] and with the data of Drickamer [5] and of Bassett [6] for the static compression of KCl and NaCl. Figure 5a shows the dependence p-σ for paraffin (were 1 is the adiabatic curve for one-time compression; curve 2 is the probable position of the adiabatic curve for two-stage compression). Figure 5b gives the dependence p-σ for clay (curve 1 is the adiabatic curve for one-time compression [3]; curve 2 is the probable position of the adiabatic curve for double compression).

Figure 5c gives the dependence $p-\sigma$ for KCl (curve 1 is the shock adiabatic curve for one-time compression [4]; curve 2 is the isotherm for 20°C from [5]; curve 3 is the isotherm for 0°K from [4]; curve 4 is the probable position of the adiabatic curve for double compression).

Figure 5d gives the dependence p-σ for NaCl (curve 1 is the adiabatic curve for one-time compression from [4] and [8]; curve 2 represents the data of Marsh, MacKeen, et al. on shock compression; curve 3 is the isotherm for 20°C from [5]; curve 4 represents data on static compression from [6]; curve 5 represents the results of measurements of double compression). The results of measurements of the double compression of paraffin, clay, and KCl are in good agreement with the position of the adiabatic curves for one-time compression, i.e., as follows from the theory, the experimental points are displaced from the curves to the right, toward the side of high densities.

The position of the points for NaCl, compressed in the direction of the (100) axis, is convincing evidence that, at pressures of ~270 kbar, in NaCl there is a polymorphic transition to a structure evidently of

the CsCl type. The results obtained confirm the data of Bassett [6], who recorded a phase transition in NaCl at close pressures.

The appearance of a polymorphic transition in NaCl under conditions of double shock compression is explained by the authors by an increase of the shear deformations since, with the one-time shock compression of NaCl, only the initial stages of the transition have been recorded [2, 7]. The point of inflection in the adiabatic curve for NaCl at ~ 1.5 Mbar, noted in [9], is evidently connected with fusion.

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