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Abstract

Full Text

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EXPERIMENTAL INVESTIGATION OF THE STABILITY OF SHOCK WAVES AND OF THE MECHANICAL PROPERTIES OF MATTER AT HIGH PRESSURES AND TEMPERATURES*

The question of the stability of a plane shock wave has more than once been considered theoretically ([1]-[3]). It has been shown that, for an ideal fluid with an adiabat of the usual type, the front is stable, and expressions have been obtained describing the course of the change of perturbations with time. However, up to the present time there have been no works in the literature devoted to an experimental verification of the results of the theory. At the same time this question deserves attention—in particular, it is of interest to compare experimental data on the stability of a shock wave in matter in the condensed state with the results of calculation for an ideal fluid. It may be expected that in this way information will be obtained on the mechanical properties of matter under conditions of high pressures and temperatures behind the shock front.

Below we present the principal results of work devoted to the investigation of the stability of shock waves in condensed media and to a comparison of the experimental data with calculation. The experiments were set up in such a way as to satisfy, as far as possible, the boundary and initial conditions appearing in the specially made calculation: at $t = t_0$ the surface of the front has a sinusoidal profile, while the flow behind the front and ahead of the front is constant. The calculation was carried out in the linear approximation ($ka \ll 1$), where a is the amplitude of the perturbation, $k = 2\pi/\lambda$, λ is the wavelength.

Fig. 1. Experimental arrangement. 1—high-explosive charge; 2—disk with grooves; 3—wedge; 4—Plexiglas plate.

The experimental arrangement is shown in Fig. 1. When a plane shock wave, produced by the explosion of a high-explosive charge, passes through sinusoidal grooves from disk 2 into wedge 3, perturbations with the same wavelength as that of the grooves appear on it (the wedge and the disk are made of the material

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

under investigation). Upon further propagation through the wedge, the wave carrying the perturbations enters the gap between the beveled surface of the wedge and the Plexiglas plate, where the perturbations are recorded by means of the resulting luminescence with an SFR-2M apparatus. Using a system of slits perpendicular to the direction of the wedge bevel, it is possible in one experiment to record the perturbation at several successive instants of time. By choosing sufficiently large values of the length and diameter of the high-explosive charge, the diameter of the profiled disk, etc., one can approximately ensure the constancy of the flow behind the front necessary for agreement between calculation and experiment.

* The results of the work were reported at the Conference on High Pressures at the Institute of Chemical Physics of the Academy of Sciences of the USSR in May 1963.

The method of imposing perturbations violates the constancy of the flow behind the front at distances of order a_0. As the calculation shows, this leads to corrections of second order of smallness in ka_0. In each specific case, the effect of deviations of the experimental setup from the conditions of the calculation was studied experimentally, and the results of the experiments were corrected.

Fig. 2. Streak photograph of an experiment. The direction of the sweep is shown by the arrow.
1 mm = 0.33 μsec

The development of perturbations was studied most fully on shock waves in an aluminum alloy of grade AL-9 (Al $\sim$ 90%). The pressure at the wave front in this case was P = 310 thousand atm, the temperature T = 630°K, and the density ρ = 3.4 g/cm^3. These parameters were obtained by calculation using the equation of state taken from (4).

Fig. 3. Some experimental curves for the development of perturbations at the shock-wave front. 1 –calculated curve; 2 –λ = 2 cm, ka_0 = 0.872; 3 –λ = 1 cm, ka_0 = 0.872; 4 –λ = 1 cm, ka_0 = 1.74

The experimental curves for perturbation development were obtained for various wavelengths (λ = 1; 2; 3.3 cm) and initial perturbation amplitudes (ka_0 = 0.29 $\div$ 1.74). In experiments with different wavelengths, all linear parameters of the experimental assemblies were varied in proportion to the wavelength in order to eliminate the influence of boundary conditions on the desired dependence on λ.

Fig. 4

Figure 4: Fig. 4

Qualitatively, the experimental curves have the same character as in the calculation: the disturbances, oscillating, decay with time. A typical photographic chronogram of an experiment is shown in Fig. 2, where it is clearly seen how the disturbances at the front change phase. At the same time, quantitatively, the course of the curves in the coordinates $y = a(t)/a_0$ and $x = S/\lambda$ (S is the path traversed by the shock wave) turns out to be different for different a_0 and λ, and different from the course of the calculated curve even after a correction taking into account the influence of the boundary conditions (the finite length and diameter of the charge, etc.). Figure 3 shows some of the experimental curves obtained and gives the calculated curve for the wave parameters indicated above.

As comparison parameters characterizing the difference between the curves, let us choose the position of the first zero x_1, and also the position x_2 and magnitude y_2 of the first minimum of the curves. We can restrict ourselves to considering these quantities, since fixing them determines the position of the experimental curves within the accuracy of the measurements.

Fig. 4. Dependence of the position of the first zero of the experimental curves on the wavelength and amplitude of the disturbance. The data are reduced without corrections for the deviation of the experimental conditions from the calculation. 1 –calculation; 2 –$\lambda = 3.3$ cm; 3 –$\lambda = 2$ cm; 4 –$\lambda = 1$ cm

The dependence of the indicated quantities on the wavelength and the initial amplitude of the disturbance was investigated. Figure 4 gives the dependence of the quantity x_1 on $a_0/\lambda \equiv z$ for various wavelengths. As is seen, there is a clearly expressed dependence both on λ and on z. The indicated dependence reveals three characteristic features. First, the experimental points corresponding to different λ at fixed z depart from the calculated value the more strongly, the smaller λ is. Next, at large z ($z > 0.14$) the dependence $y = f(z)$ approaches a linear one, with the slopes of the straight lines the same for all investigated λ, while the deviation from the calculation increases as z increases. Finally, for $\lambda = 3.3$ cm at small z a bend of the curve is clearly expressed, so that the deviation from the calculation increases as z decreases.

The experimental points are described fairly well by an expression whose separate terms correspond to the indicated features:

$$x_1 = 1.07 - \frac{0.354}{\lambda} - 1.42\frac{a_0}{\lambda} - 0.0202\left(\frac{a_0}{\lambda}\right)^{-1}. \quad (1)$$

In this expression, corrections associated with the deviation of the experimental conditions from the calculation are also taken into account. Similarly, the experimental values of x_2 and y_1 are described by the expressions

$$x_2 = 1.26 - \frac{0.292}{\lambda} - 1.19\frac{a_0}{\lambda} - 0.0153\left(\frac{a_0}{\lambda}\right)^{-1}; \tag{2}$$

$$y_1 = 0.17 + \frac{0.255}{\lambda} + 0.450\frac{a_0}{\lambda} + 0.0156\left(\frac{a_0}{\lambda}\right)^{-1}. \tag{3}$$

All terms in expressions (1)–(3) can be easily interpreted physically. In the present case we can attribute the dependence found only to the following factors: nonlinearity, since in most experiments the condition $ka_0 \ll 1$ was not fulfilled, and the influence of the mechanical properties of the substance. The dependence given by the second term of each formula is characteristic of the influence of viscosity, which is described by the Reynolds number ($\Pi_1 = \rho v \lambda/\eta$; here η is the coefficient of viscosity; ρ, v are the density and velocity of the substance behind the front). As analysis of the Euler equations shows, a dependence of the type

of the third term must describe the influence of nonlinearity, which is characterized by the parameter $\Pi_2 = a_0/\lambda$. The dependence given by the fourth term is characteristic of ideally plastic flow, which, as is seen from the Euler equation, is described by the parameter

$$\Pi_3 = \frac{\sigma_0}{\rho v^2}\frac{\lambda}{a_0},$$

where σ_0 is the yield strength. The presence of a_0 in the denominator in this case is characteristic. Physically this is explained by the fact that the term describing the mechanical stress in the Euler equation is constant, and its role increases as the amplitude decreases. As for the first term, it must correspond to the values of the comparison parameters x_1, x_2, and y_1 under the calculation conditions for an ideal liquid within the linear approximation, when there should be no dependence on λ and a_0. Comparison of the experimental values of these quantities with the calculated ones reveals their rather close agreement:

Experimental values	Calculated values
$x_1 = 1.07$	$x_1 = 1.10$
$x_2 = 1.26$	$x_2 = 1.41$
$y_1 = 0.17$	$y_1 = 0.09$

The dependences (1)–(3) can be used to determine the values of the coefficient of viscosity and of the yield strength under the conditions of pressures and temperatures behind the shock-wave front, provided that calculations are carried out on the influence of the indicated factors on the development of perturbations. For viscosity, such a calculation was performed and gave the value of the coefficient of viscosity $\eta = 2 \cdot 10^4$ poise. For plastic flow no calculation was performed.

An experimental study of the development of perturbations in shock waves can be used as a method for studying the viscosity and yield strength of a substance at high pressures and temperatures. By this method the viscosity of a number of different substances was measured at different pressures and temperatures.

For the various materials investigated (lead, copper, aluminum, organic glass, steel, water), using the same charge, the phase shift between the curves for different wavelengths and the viscosity are approximately the same.

When the pressure in the shock wave in aluminum is increased to 1 million atm, the coefficient of viscosity changes only slightly, not exceeding 10^5 poise.

It is interesting to note that the curves for the development of perturbations for different λ coincided in the case of porous aluminum with an initial density of 0.68 g/cm^3. It is possible that this indicates melting of the aluminum behind the shock-wave front, since the use of a porous substance leads to considerable heating of the latter behind the front [5].

The indicated results will be presented in greater detail in subsequent communications.

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Note: Figure translations are in progress. See original paper for figures.