EFFECT OF THE INITIAL DENSITY OF A SUBSTANCE ON THE CONDITIONS OF OBLIQUE COLLISION OF SHOCK WAVES

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It is well known that for the oblique collision of plane shock waves in gases and in condensed media either regular or irregular conditions can arise. The angle of collision of shock waves for which there is a transition from regular to irregular conditions is called critical. Problems in the study of physicochemical transformations, brought about by shock waves in multicomponent porous media, as well as in the study of the explosion compaction of noncompact materials, make the question of the effect of the initial density of exactly the same material on the conditions of the reflection of colliding shock waves very timely. In the present work this problem was studied using the example of aluminum, for which there is a known equation of state, describing data on shock compression over a wide range of density. Schemes for which the shock waves in a porous material are generated by a running load are of great interest. For example, this kind of loading arises with the detonation of a charge of explosive, distributed over the surface of a compressible sample. The results of investigations [1, 2] have shown that, under the conditions described, powdered materials cannot be considered in a gasdynamic approximation. This circumstance does not permit the use, to answer the question posed, of the theory of a transition from regular reflection to irregular, constructed with application to media with a spherical tensor of the stresses [3, 4].

We consider a layer of substances, on whose surface an explosive of finite thickness is distributed. The charge is initiated in such a way that the front of the detonation MN is a plane perpendicular to the boundary of the substance (Fig. 1). We postulate that, in this case, in the material near the boundary with the explosive there exists a region in which the damping of the shock wave generated can be neglected and the shock front can be regarded as plane. This assumption is based on the result of [5-7], in which it is shown that the damping of oblique shock waves in solid metals and in powders of aluminum and titanium oxides, at a depth approximately equal to the thickness of the explosive, does not exceed 10%.

All the further discussions will relate to the plane part of a shock wave. Let w be the detonation rate of the explosive. Then the velocity of the shock wave $D = w \sin\omega$, where ω is the angle between the direction of the propagation of the detonation front and the shock front AM. We introduce a system of coordinates (x, y, z) connected with the front of the detonation and oriented as shown in Fig. 1, where CM is the interface between the compressed substance and the detonation products. The y axis is directed along the front of the shock wave and the z axis, normal to the plane of the sketch. Since w = const, in the selected system the picture of the flow is stationary. We write the laws of conservation of mass and momentum for a continuous medium in the following fashion:

$$\frac{\partial}{\partial t}\iiint\limits_V \rho dV = -\oint\limits_S \rho v_k n_k dS; \quad (1)$$

$$\frac{\partial}{\partial t}\iiint\limits_V \rho v_i dV = -\oint\limits_S (\rho v_i v_k - \sigma_{ik}) n_k dS, \quad (2)$$

where ρ is the density; σ_{ik}, v_k, and n_k are, respectively, the components of the tensor of the stresses, the mass velocity of the substance, and a vector normal to the surface S, bounding the volume V. Applying (1) and (2) to a region containing a discontinuity, and assuming that $v_x = D$, $v_y = D \operatorname{ctg}\omega$, $\sigma_{ik} = 0$, $\rho = \rho_0$, we obtain the following conditions at the shock wave:

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$$\sigma_{xx} = \rho_0 D(D - v_x), \ \sigma_{xy} = \rho_0 D(D \operatorname{ctg} \omega - v_y).$$

The angle of the deviation of the flow of the shock wave is determined from the expression

$$\theta_1 = \operatorname{arctg} [(1 - \sigma_{xx}/\rho_0 D^2)/(\operatorname{ctg} \omega - \sigma_{xy}/\rho_0 D^2)]. \tag{3}$$

In the general case, (3) is a surface of the second order in the space θ_1, σ_{xx}, σ_{xy}. However, if in the chosen system of coordinates

$$\sigma_{xy} \ll \rho_0 D^2 \operatorname{ctg} \omega, \tag{4}$$

then the deviation of the flow depends only on the normal to the front of a component of the stress tensor. This condition means that the chosen system of coordinates is disposed rather close to the principal axes of the tensor of the stresses. It is well known that for high pressures the gasdynamic approach is adequate to describe the flow behind an oblique wave [5]. In porous media, with small intensities of the shock waves, condition (4), along with the requirement of the absence of an elastic forerunner, is a limitation from below on the intensity of the shock wave. Taking account of the limitation on σ_{xy}, the expression for the deviation of the flow can be written in the form

$$\theta_1 = \operatorname{arctg} [(1 - \sigma_{xx}/\rho_0 D^2)/\operatorname{ctg} \omega] = \omega - \operatorname{arctg}\left(\frac{\rho_0}{\rho} \operatorname{tg} \omega\right). \tag{5}$$

To verify the applicability of formula (5) to porous aluminum, experiments were made in a pulsed x-ray unit with a different initial density of the samples. The experiments were made according to a scheme described earlier in [6]. The measured quantities were the angles θ_1 and ω. There was satisfactory agreement between the experimental values of θ_1 and values calculated using (5), with intensities of the shock waves from 20 to 60 kbar. The values of σ_{xx} and ρ were calculated from data on the dynamic compressibility of aluminum powder with monaxial loading, published in [8], and from the known detonation rate of the explosive.

We return to the description of the oblique collision of two shock waves of identical intensity. From considerations of symmetry, the given problem can be replaced by the problem of the reflection of shock wave from an absolutely rigid barrier EF, arranged in the plane of symmetry. In the case of regular reflection conditions, the shock fronts (AO, the front of the incident wave; BO, the front of the reflected wave) divide the half-space above the reflecting barrier into three regions; O is the region of the uncompressed material; 1 is the region of onefold compression; and 2 is the region of twofold compression (Fig. 2). It is assumed that in the neighborhood of the line of intersection of the shock waves (point O in Fig. 2) in each of these regions the flow is homogeneous and, in a system of coordinates connected with the line of intersection of the shock waves, the process is fully established. The problem consists in finding a position of the reflected shock wave such that, in regions O and 2, the flow will be parallel to the barrier. If the barrier is an absolutely rigid wall, the condition of regular reflection has the form

$$\theta = \theta_1 - \theta_2 = 0, \tag{6}$$

where θ_1 and θ_2 are the angles of deviation of the flow due, respectively, to the incident and reflected shock waves; θ is the total angle of deviation of the flow after twofold compression. It is well known that for an intensity of the incident wave in a powder equal to several kilobars the substance behind the front has a high mass velocity and a density close to the density of a monolith. As a result, the pressure behind the front of a reflected shock wave exceeds by many times the stresses in the incident wave, and the state in region 2 is described by a gasdynamic approximation. As variables we take the angle between the incident shock wave and the barrier, φ (the angle of incidence); the stress normal to the front of the incident wave in region 1, p_1; and the pressure in region 2, p_2. Using the laws of conservation of mass and momentum of the sub-

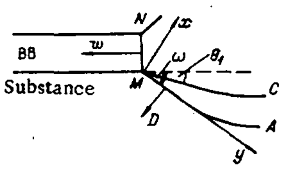

Fig. 1

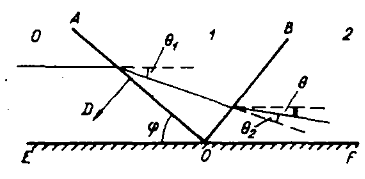

Fig. 2

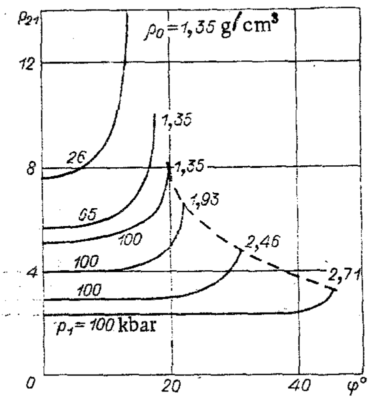

Fig. 3

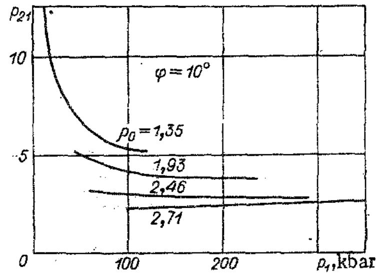

Fig. 4

stance at the front of an oblique shock wave, the value of θ can be expressed in terms of the chosen variables in the following manner:

$$\theta(\varphi, p_1, p_2) = \varphi - \operatorname{arctg}(x_{10} \operatorname{tg} \varphi) - \nu + \operatorname{arctg}(x_{21} \operatorname{tg} \nu),$$

where $x_{10} = \rho_0/\rho_1$; $x_{21} = \rho_1/\rho_2$; the subscripts 0, 1, and 2 denote the state of the medium in regions 0, 1, and 2, respectively;

$$\nu = \arcsin \{[p_2(x_{21}) - Q_1]\, x_{10} \sin^2 [\operatorname{arctg}(x_{10} \operatorname{tg} \varphi)]/\rho_0 u_1^2 (1 - x_{21})\}^{1/2},$$

$$u_1 = x_{10}[p_1/\rho_0(1 - x_{10})]^{1/2},$$

Q_1 is the stress normal to the front of the reflected shock wave in region 1. Below, in the calculations it was assumed that $Q_1 = p_1$. For small values of ρ_0 and p_1 such an assumption is justified, since $p_2 \gg p_1 \gtrsim Q_1$, while for values of ρ_0 close to the density of a monolith the calculations were made for shock waves of rather great intensity. The degree of correctness of the assumptions made allows us to verify a comparison between the results of calculations and the experimental data. The relationships needed to calculate the adiabat of twofold compression $p_2(x_{21})$ were borrowed from [9] and the dynamic adiabatics $p_1(x_{10})$, from [8]. Since these dependences are used in numerical calculations, their form plays no role and they can be given in tabular form.

An analysis of Eq. (6) shows that, for any given pair of values of φ and p_1, there exist two solutions for p_2 only if the value of φ is less than some limiting value of φ_l, depending on p_1. Experiments made in solid materials [10, 11], as well as experiments with aluminum powder, described below, show that the parameters of the reflected wave correspond to the smallest root of Eq. (6). Figures 3 and 4 show the effect of φ and p_1 on the degree of the rise in the pressure in the reflected shock wave $p_{21} = p_2/p_1$. The dashed line in Fig. 3 bounds the region of states which are possible for regular reflection conditions at $p_1 = 100$ kbar. From Fig. 3 it can be seen that the coefficient of the rise in the pressure increases sharply with angles of incidence close to a limiting value; this increase is greater the lower the initial density of the substance. An interesting special characteristic is also the qualitative difference in the effect of the intensity of the incident shock wave on the coefficient p_{21} in solid and porous materials. Thus, for a solid material, with an increase in the amplitude of the incident wave, the pressure behind the reflected wave rises, while for materials with a small density, it falls (Fig. 4).

For $\varphi > \varphi_l$ (p_1), Eq. (6) has no solution in the region of the real variables, i. e., regular reflection conditions are impossible. The dependence φ_l (p_1) is found by simultaneous solution of (6) and the equation

$$\partial\theta(\varphi, p_1, p_2)/\partial p_2 = 0. \tag{7}$$

The mutual positions of the calculated curves of $\varphi_l(p_1)$ for different values of ρ_0 (1-3 are experimental points) are shown in Fig. 5.

The solution of the question of the effect of the initial density of the substance on the reflection conditions reduces to the plotting of a one-parameter family of curves $\varphi_l(\rho_0, p_1)$ in the plane (φ_l, ρ_0). This can be done by determining in Fig. 5 the points of intersection of the calculated curves with the straight lines $p_1 = \text{const}$. For an initial density $\rho_0 = 2.5$ g/cm³, the value of $\varphi_l = 31°$ and does not depend on the intensity of the incident shock waves; therefore, the indicated family constitutes a bundle of curves passing through the point (31; 2, 5). The difference in the states of solid and porous materials with the collision of shock waves is due to the differ-

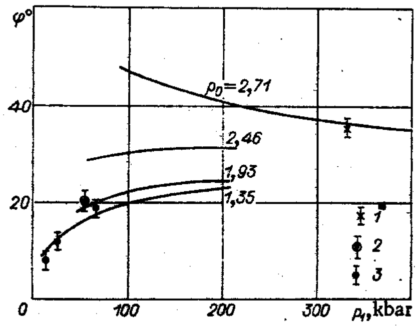

Fig. 5

TABLE 1

ρ_0, g/cm³	φ_l°	φ_*°
1,35	19,6	19,6
1,93	22,5	20
2,46	30,6	23
2,71	45,5	—

ences in their compressibility. With an increase in the intensity of the colliding shock waves, this difference decreases.

Solution of the system (6), (7) gives the value of the upper limit of the angles of incidence for which regular reflection conditions are still permissible. For irregular reflection conditions, there is the possibility of conditions for the formation of a three-impact configuration, where, from the line of intersection of the incident and reflected shock waves, there depart a third shock wave (front) and one contact discontinuity. According to the generally accepted theory [3], the pressure and direction of the mass velocity behind the front of a leading wave (region 3) and behind a reflected front coincide. Solving the following system of equations for φ:

$$\theta(\varphi, p_1, p_2) = 0,\ \delta - \mathrm{arctg}\,(x_{30}\mathrm{tg}\,\delta) = 0,$$
$$\delta = \arcsin \sqrt{p_{21}(1 - x_{10})/(1 - x_{30})},\ x_{30} = \rho_0/\rho_3, \tag{8}$$

we find the value of the angle of incidence φ, (ρ_0, p_1), starting from which irregular conditions with a three-wave configuration become possible. The results of such an analysis for solid metals showed that, in aluminum with an intensity of the incident shock wave $\lessdot$330 kbar, the existence of a three-shock-wave configuration is impossible with such values of φ [11]. Values of φ_* for p_1=100 kbar and different values of ρ_0 are given in Table 1. The dependences of $p_2(x_{30})$ for porous Al with large pressures were taken from [12].

We note that in a porous substance $\varphi_* < \varphi_l$ i.e., simultaneously with regular conditions a three-wave configuration is also admissible. However, even an insignificant increase in the angle φ leads to a situation in which for a fixed value of ρ_0 in the investigated region of change in the value of p_1 the solution of the system of equations (5), (6), (8) has no physical sense. Thus, the region of angles of incidence for which three-shock-wave conditions are possible is very narrow. For p_1 =100 kbar, it amounts to approximately 1°. For an exact calculation of the upper limit of the region under study, account must be taken of the rate of increase in the dimension of the leading wave. Here there appears an additional variable quantity, i.e., the angle between the direction of the motion of the line of intersection of the three shock waves and the surface of the barrier. At the present time, for condensed media there exists no theory which would enable us to express this quantity in terms of the other variables of the problem. It can be shown qualitatively [11] that an exact calculation would lead to a narrowing of the region of angles φ for which a three-shock-wave configuration is admissible. Unfortunately, the experimental errors do not permit us to give an unequivocal answer to the question of which of the two permissible sets of conditions is realized in the above region. In accordance with the principle of physical continuity, regular conditions are preferential.

To verify the calculated results given in Fig. 5, experiments were made on determination of the critical angle in aluminum samples with a density of 1.35 and 1.93 g/cm³. In these experiments, the powder being investigated was put between two layers of an identical explosive, which were initiated simultaneously. With the

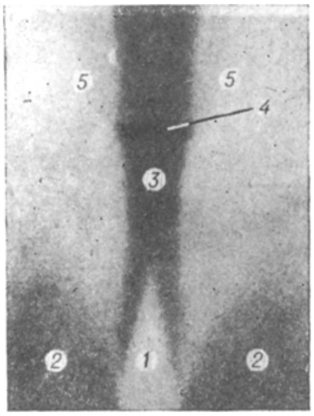

Fig. 6

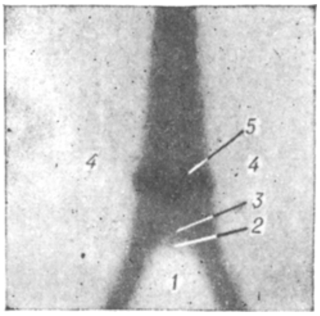

Fig. 7

detonation of the explosives, two colliding shock waves were set up in the powder. A change in the angle of the collision of the shock waves and in their intensity was effected by a change in the angle between the two plates of explosive and the use of different types of explosives. The dimensions of the samples were so selected that the collision of the shock waves would take place between their plane sections. The shock-wave configurations arising with the collision was recorded on film using a pulsed x-ray unit. The results of the experiments showed that for small angles of collision the shock waves come together at an acute angle, i.e., regular collision conditions are realized (Fig. 6, where 1 is the uncompressed material; 2 is the detonation front; 3 is the compressed powder; 4 is a lead foil; and 5 is a shock wave in the detonation products). In the photographs, we can see the shock waves and the detonation products forming with the exit of the reflected shock waves from the compressed material to the interface between the compressed material and the explosion products. Thus, although the reflected shock wave itself is not recorded on the photos, the point of its arrival at the surface of the sample can be established rather exactly. This enables us to determine the angle between the front of the reflected shock wave and the plane of the collision, and then, using the equation of state of the substance, to calculate p_2. In all the experiments, satisfactory agreement was obtained with the "weak" solution of Eg. (6). For collision angles greater than some critical value, depending on the intensity of the colliding waves, a leading wave appears between the incident shock waves. To fix the character of the flow of the compressed material, a method proposed in [1] was used. In the sample, normal to the plane of the collision of the shock waves, thin layers of a material "nontransparent" for x-ray beams are arranged. These layers were made of lead foils with a thickness of 25 μ. From the form which they assumed behind the shock front, the character of the flow of the material could be judged. For regular collision conditions, the form of the foils behind the reflected waves bears witness to the homogeneous flow of the material (see Fig. 6). In the case of irregular conditions, that part of the foil through which the leading wave has passed is shifted the most (Fig. 7), where 1 is the uncompressed powder; 2 is the leading shock wave; 3 is the compressed powder; 4 is the shock wave in the detonation products; and 5 is a lead foil . This means that, in a laboratory system of coordinates, the mass velocity of the substance behind the leading shock wave is greater than the mass velocity of the adjacent layers. The difference in the mass velocities and the dimension of the leading wave depend to a considerable degree on the angle of collision of the shock waves. For values of the collision angles close to the critical value, the leading wave becomes difficult to distinguish on the x-ray photographs, and the difference in the mass velocities increases. Therefore, the criterion for the existence of irregular conditions was the presence of a "splash" in the middle part of the lead foil.

The results of the experiments are given in Fig. 5. The value of the critical angle for solid aluminum was borrowed from [11]. The satisfactory agreement obtained between the experimental values and the calculated values allows us to hope that the method expounded will be found suitable for determining the critical angles and the parameters of the flow of a powder with regular reflection conditions and that the assumptions made in the work are valid.

In conclusion, we note that, although a three-wave scheme with one tangential discontinuity is not applicable to the irregular conditions described in the present work, there is a considerable difference between the mass velocity behind the leading wave and the total mass velocity behind the incident and reflected shock waves. A similar fact has been observed experimentally for Plexiglas cylinders and is described in [13].

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PIERCING OF A BARRIER UNDER THE IMPACT OF GLASS PARTICLES SIMULATING STONY METEORITES

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Articles [1-3] discuss a number of the problems of high-speed impact, solved on the basis of experimental data obtained for the impact of steel particles on different barriers. In the present work, this information is analyzed with application to the conditions of a collision, more exactly modelling a meteoritic impact (the impact of glass particles simulating stony meteorites).

For the acceleration of spherical glass particles, a method was developed on the basis of the well-known principle of a cumulative explosion [4]. A decrease in the density of the gas cumulative jet in comparison with the schemes ordinarily used [4] has made it possible to conserve the integrity of glass particles with acceleration up to 8 km/sec or more. The parameters of the particles used in the work are given in Table 1 (d is the diameter of a particle; ρ_0 is its density; and v_0 is the impact velocity). The accuracy in measurement of the

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