INCREASE OF INITIAL VELOCITY AND PRESSURE UPON IMPACT ON AN INHOMOGENEOUS TARGET

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It is proved on the basis of an analysis conducted by means of the method of (p, u)-diagrams in an acoustic approximation that the mass velocity of the material of a target increases when a shock wave propagates along a target in which the acoustic resistance of the layers decreases in the direction of propagation, and it can even exceed the initial velocity of the striker. An increase in pressure behind the wave front similar to the example of unbounded accumulation in a plane shock wave considered in [2] is observed when a striker impacts on a target in which the acoustic impedance of the layers increases in the direction of propagation of the shock wave. The increase in velocity is experimentially verified.

We will consider in a one-dimensional formulation the propagation problem for a shock wave formed in the impact of a striker with a target, which is a set of plates.

We denote by the subscript 0 parameters characterizing the striker and by the subscript i (i = 1, 2, ..., m) the parameters of the target plates, the plate i = 1 being the striker. The contact surfaces between the plates will be denoted by $a_i a_i$ ($a_1 a_1$ is the contact surface between the striker and the first plate of the set, and $a_{m+1} a_{m+1}$ is the rear free surface of the plated target) (Fig. 1).

Suppose prior to impact the fixed target has parameters

$$\rho_i,\ c_i,\ u_i = 0,\ p_i = 0$$

and the flying plate of finite thickness has parameters ρ_0, c_0, u_0, and $p_0 = 0$ (ρ is the density of the material, c is the speed of sound in the material, u is the mass velocity, and p is the pressure).

Shock waves are formed upon impacting both in the target and in the striker and propagate from the impact surface $a_1 a_1$ in opposite directions. We denote the speed of the inner faces $a_i a_i$ by u_{ai} and by the p_{ai} the pressure in the region between the wave fronts that experience a drop in disturbance on the contact surface $a_i a_i$.

Plate collision can be conveniently examined in the coordinates p, u. The initial states of the quiescent target ($p_i = 0$, $u_i = 0$) and of the striker ($p_0 = 0$, $u = u_0$) are depicted by the points 0 and M (Fig. 2).

Let us consider the problem in the acoustic approximation

$$u_0 \ll c_0,\ c_i \tag{1}$$

The plane curve for the variables p and u with center at (u_{ai}, p_{ai}) has the form

$$(p - p_{ai})\,(1/\rho_{ai} - 1/\rho\,(p)) = (u - u_{ai})^2 \tag{2}$$

An empirical equation of state of the type

$$p = \frac{\rho_i c_i^2}{n}\left[\left(\frac{\rho}{\rho_i}\right)^n - 1\right] \tag{3}$$

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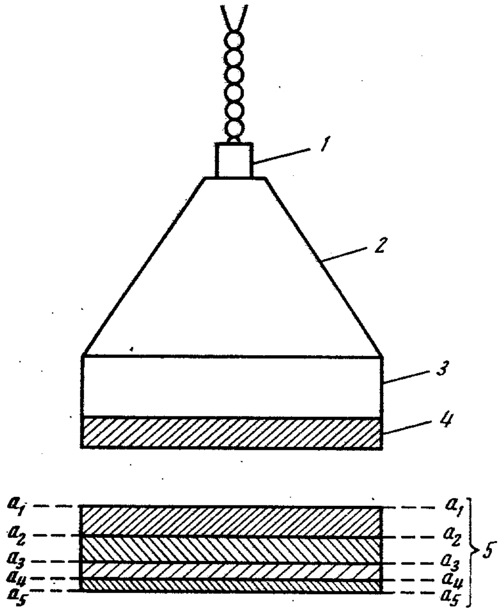

Fig. 1

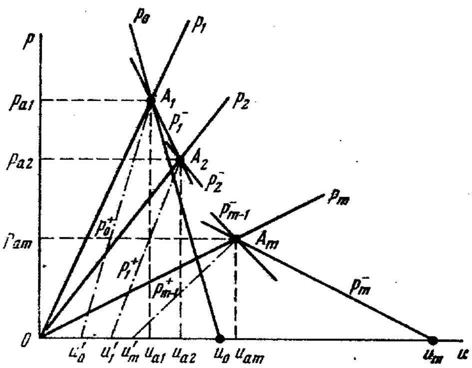

Fig. 2

in which n is assumed constant, is often used for metals at pressures on the order of 10^5 atm.

For weak shock waves we set

$$\rho/\rho_i = 1 + \varepsilon,\ \varepsilon \ll 1,\ \rho_{ai}/\rho_i = 1 + \varepsilon_{ai},\ \varepsilon_{ai} \ll 1 \tag{4}$$

Substituting Eq. (3) in Eq. (2) and taking into account Eq. (4), we have

$$p - p_{ai} = \pm[(p_{ai} + \rho_i c_i^2)(p + \rho_i c_i^2)]^{1/2}\frac{u - u_{ai}}{c_i} \tag{5}$$

The maximum pressure the striker can develop is realized when retarded by an absolutely rigid target,

$$p_* = \rho_0 c_0 u_0 \tag{6}$$

The quantities p and $p_{\alpha i}$ in Eq. (5) are therefore, in view of Eqs. (1) and (6), negligible in comparison with $\rho_i c_i^2$.

We then obtain from Eq. (5)

$$p - p_{ai} = \pm \rho_i c_i (u - u_{ai}) \tag{7}$$

which proves that the shock adiabats in the plane pu are the straight lines of Eq. (7) in an acoustic approximation.

Let us use several properties of (p, u)-diagrams. It is evident from Eq. (2) that the curve is symmetric about the line $u = u_{\alpha i}$, which is also implied by Eq. (7); the (p, u)-diagram consists of two branches intersecting in its center at a finite angle whose tangent is equal to the size of the acoustic impedance.

The problem of calculating shock-wave parameters in the impact of a striker and the first plate of a target reduces to calculating the point A_1 at which the lines p_0 and p_1 intersect (Fig. 2),

$$p_0 = -R_0(u - u_0),\ p_1 = R_1 u \tag{8}$$

where $R_0 = \rho_0 c_0$ is the acoustic impedance of the striker material, and $R_1 = \rho_1 c_1$ is the acoustic impedance of the material of the first plate.

$$u_{a1} = \frac{R_0}{R_0 + R_1} u_0, \qquad p_{a1} = \frac{R_0 R_1}{R_0 + R_1} u_0 \tag{9}$$

It is necessary to consider the drop in disturbance on each contact surface $\alpha_i \alpha_i$ (i = 2, 3, ..., m + 1) for the propagation of the resulting shock wave through the plates of the target.

TABLE 1

Target			Mean experimental value of u_m/u_0	u_m/u_0 from Eq. (12)
i	material	thickness mm		
1 2 3	copper brass Duralumin	3 2 1	1.66	1.48—1.5
1 2	copper Duralumin	3 1	1.33	1.44—1.46
1 2	Duralumin polyethylene	3 1	2.06	2.45

Let us consider the case of a striker impacting a target in which the acoustic impedance of the plates decreases from plate to plate in the direction of propagation of the shock wave generated by the striker. We set

$$R_0 \geqslant R_1 > R_2 \;\ldots > R_m \tag{10}$$

We select a target, such that for every plate

$$l_k/c_k = l_{k+1}/c_{k+1} \tag{11}$$

where l_k and l_{k+1} are the thicknesses of the preceding and next plate in the target, respectively. In this case the final mass velocities in the k-th plate are determined solely by the drop in disturbance on the (k + 1)-th contact surface.

The states of the plated target are described in the plane of the variables p, u by a pencil of lines leaving the point 0 (Fig. 2).

$$p_i = R_i u \;\; (i = 1, 2, \ldots, m)$$

As a shock wave with parameters $p_{\alpha 1}$, $u_{\alpha 1}$ (point A_1) passes from the first plate of the target into the second α wave with parameters $p_{\alpha 2}$, $u_{\alpha 2}$ propagates from the contact surface $\alpha_2\alpha_2$ in both directions. The mass velocity and pressure in this wave are determined by the point A_2 at which the line p_2 intersects the line p_1^- symmetric to p_1 about $u = u_{\alpha 1}$ (p_i^- are symmetric to the lines p_i about $u = u_{\alpha i}$). This process subsequently repeats. Evidently (Fig. 2), the mass velocities behind the shock-wave front grow from plate to plate as the shock wave passes through a plated target whose acoustic impedance decreases from plate to plate. Plate acceleration is based on this effect.

An equation can be found from Fig. 2 relating the mass velocity u_m of the last plate of the target and the initial velocity u_0 of the striker,

$$u_m = \frac{2^m}{\prod\limits_{i=1}^{m} (1 + R_i / R_{i-1})} u_0 \tag{12}$$

It is evident from Eq. (12) that if Eq. (10) holds for a plated target, $u_m > u_0$. The acoustic approximation for the (p, u)-diagrams simplifies the cumbersome mathematical calculations while preserving and revealing the physical meaning of the phenomenon.

Mass velocity will increase when the striker impacts a plated target, and also for high impact velocities, when the acoustic approximation is inapplicable.

To verify Eq. (12) experiments were performed on plate—striker impact with a plated target. The set-up of the experiment can be seen in Fig. 1. Here 1 is a detonating cap, 2 is a plane detonation wave generator, 3 is the explosive charge (TG 50/50) in contact with the striker 4, and 5 is the plated target.

The striker velocity (u_0) and velocity (u_m) of the last target plate were measured in the experiments. In all the experiments the explosive charge measuring 10 mm in thickness, and the steel striker 3 mm in thickness remained constant; the combination of plate material in the target was varied. Photographing was conducted both by a pulsed radiograph and by a streak camera operating in frame photography conditions. The measured velocity of the striker was 1.46 km/sec ± 14%. The results of the experiments are presented in Table 1.

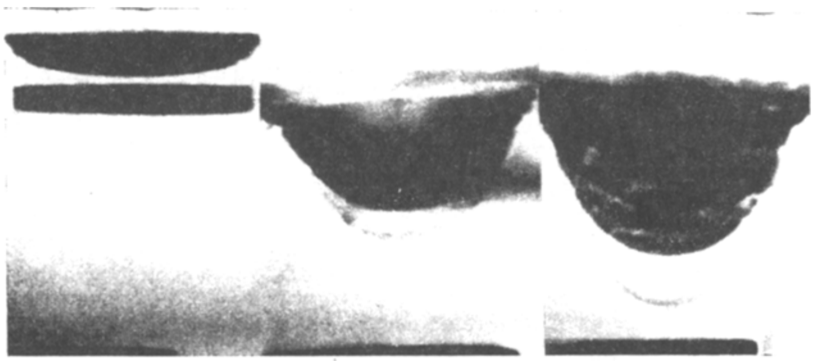

Fig. 3

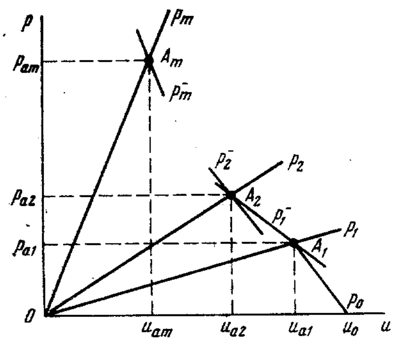

Fig. 4

In the last column of Table 1 values are presented for u_m/u_0 calculated using Eq. (12), and the values for ρ_i and c_i for the striker and target plate materials were taken from [1].

Pulsed radiography makes it possible to determine the velocity of any plate of the target. This allows us to additionally control the correctness of our discussions. In Fig. 2 the states of the striker and target plates after a shock wave has passed through them are indicated by the points u_0', u_1'. ... on the u axis [the k-th plate passes from the state $p_{\alpha k}$, $u_{\alpha k}$ into the state p = 0, $u = u_k'$ along a line p_k^+ symmetric to the line p_k^- about $u = u_{\alpha(k+1)}$].

Photographs are presented in Fig. 3 of frame radiographs of the impact of a steel plate against a target consisting of 3 mm copper, 2 mm brass, and 1 mm Duralumin plates. The moving striker can be seen in the first frame prior to impact with the target (16 μsec) and in the last frame, the dispersion of the target plates (35 and 40 μsec). Times were counted off from the moment the detonator cap was set off.

The experiments confirmed the increase in mass velocity upon impact of a striker on a target made of plates in which the acoustic impedance satisfies Eq. (10).

If we consider the states behind the shock-wave fronts on each contact discontinuity $a_i a_i$ in Fig. 2 from right to left, i.e., from the point A_m to A_1, an important physical effect is apparent, namely, an increase in the pressure amplitude as a shock wave propagates in a plated target in which

$$R_1 < R_2 < \ldots < R_m \tag{13}$$

i.e., the acoustic impedance increases from plate to plate in the direction of propagation of the shock wave.

Zababakhin [2] indicated a similar cumulation effect in a plane shock wave. He treated the motion of a wave with a front parallel to the layers in systems with alternating plane layers made of light and heavy substances. If the thicknesses of the heavy layers are equal (likewise for the light layers), i.e., the system is periodic, a shock wave may pass in it possessing a periodically varying pressure on the front. If every heavy layer is made thinner than the preceding one (likewise for the light layers), it will reach a higher velocity upon impact, transmitting to the next layer a still higher velocity, and so on, i.e., the shock wave will be amplified.

The case of a plated target also indicates the possibility of increasing the amplitude of a shock wave in plane systems of layers with different acoustic impedances obeying Eq. (13). Only if energy losses upon heating are small will such an increase occur. Calculations must be carried out for actual (p, u)-diagrams of the material of target layers made of layers taking into account Eqs. (11) and (13) in order to estimate energy losses upon heating and the residual kinetic energy of the layers.

The corresponding equations for pressure and mass velocity for m + 1 target layers can be obtained from Fig. 4,

$$p_{a(m+1)} = \frac{2^m}{\prod_{i=1}^{m}(1 + R_i / R_{i+1})} p_{a1}, \quad u_{a(m+1)} = \frac{2^m}{\prod_{i=1}^{m}(1 + R_{i+1} / R_i)} u_{a1} \tag{14}$$

where $p_{\alpha i}$ and $u_{\alpha i}$ are determined by Eq. (9). Since $R_i < R_{i+1}$ for the target of Eq. (13), Eq. (14) indicates an increase in pressure in the transmitted shock wave with a simultaneous decrease in the mass velocity.

LITERATURE CITED

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