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DETERMINATION OF PARAMETERS OF A FLOW OF PARTICLES COLLIDING WITH AN OBSTACLE

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The paper presents the technique developed and the experimental data (obtained by this technique) on the parameters of a flow of particles, which is formed by the energy of explosion, and the pressure caused by this flow in collision with an obstacle, during which superdeep penetration of the particle material into the obstacle occurs.

Abnormally deep penetration of material into an obstacle to a depth of 10^2–10^4 of the initial diameter (superdeep penetration) occurs at certain parameters of a flow of particles, which is formed by the energy of explosion and which collides with a metallic obstacle. The flow parameters, such as velocity, density, and time of operation, determine the value of pressure caused by collision and the state of the obstacle material, which presupposes the existence of the effect [1].

Employment of the methods of investigation of shock processes, which are associated with the use of the energy of collision under the conditions of open explosion areas of the test ground and are known from the literature, e.g., [2, 3], is difficult or virtually impossible due to the need for the availability of special, expensive equipment and instrumentation or their inapplicability for solution of the problem posed.

The present paper is aimed at the development of a technique for determination of the parameters of a flow of particles, which is formed by the energy of explosion, and the pressure due to its collision with the obstacle, during which superdeep penetration of the flow material into the obstacle occurs, and at obtaining of experimental data.

Measurement Technique. The obstacle, if not on a rigid base, i.e., there is a gap between its lower plane and the upper plane of the base (in a "suspended" state), is accelerated as a result of collision with the particle flow. The time of "passage through the gap" is determined by the velocity gained by the obstacle, which depends on the amount of momentum imparted by the flow to the obstacle, and the obstacle mass. The momentum of the obstacle depends on the time of contact of the flow with the obstacle, which is equal to the time of "passage through the gap." An increase of this time (flow effect) results in an increase of the momentum gained by the obstacle. The time of contact can be controlled by the obstacle mass an increase of which leads to a decrease in the velocity gained by the obstacle and, consequently, an increase of the time of contact. All these hold at a time of flow effect larger than the time of "passage through the gap," i.e., during collision the particle flow did not cease or the velocities of the flow and the obstacle did not become equal, and also at a constant value of the "gap." An increase of the obstacle mass to a value at which its momentum does not increase with the time of "passage through the gap" indicates termination of the flow (which has a finite length) or decrease of its velocity and density to values at which the flow effect can be neglected. The measurement of the time of "passage through the gap" as a function of the obstacle mass (estimation of the obstacle momentum) allows one to estimate the momentum of the flow, pressure of collision, and main parameters of the flow.

The flow parameters are calculated in terms of the time of "passage through the gap" T_g in the following way. Under the effect of pressure P_f of the particle flow which has an area S_f and interacts with the obstacle of mass M, the latter acquires acceleration dV_{ob}/dt, i.e.,

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$$M = \frac{dV_{ob}}{dt} = P_f S_f ,$$

but $M = \rho_{ob} l s_{ob}$. Then

$$\rho_{ob} l S_{ob} \int_0^{T_g} \frac{dV_{ob}}{dt}\, dt = S_f \int_0^{T_g} P_f dt .$$

In the first approximation, having substituted $\int_0^{T_g} \frac{dV_{ob}}{dt} dt$ by a mean velocity equal to

$$V_{ob,m} = \frac{2h}{T_g} , \qquad (1)$$

and assuming that

$$\int_0^{T_g} P_f dt = P_{f,m} T_g , \qquad (2)$$

i.e., the mean pressure affecting the obstacle during this period of time T_g is constant and equals $P_{f,m}$, we obtain

$$P_{f,m} = \frac{2\rho_{ob} lhS_{ob}}{T_g^2 S_g} . \qquad (3)$$

Changes in the obstacle thickness l result in changes in its mass and, consequently, the velocity acquired in collision with the flow, which determines the time of "passage through the gap." Thus, measurement of the time of "passage through the gap" by obstacles of various thicknesses allows one to find the dependence of the mean pressure of the flow on this time (contact of the flow with the obstacle during which the obstacle moves).

We denote the mean pressure of the flow on the obstacle during the time T_{g1} as $P_{f,m1}$ (the first experiment with the obstacle of a minimum thickness l_1) and the mean time of its effect during T_{g2} as $P_{f,m2}$ (the second experiment with the obstacle of a larger thickness l_2). In the ith experiment, we obtain $P_{f,mi}$ which is the mean pressure on the obstacle of thickness l_i during T_{gi} and in the $(i+1)$th experiment, we have $P_{f,m(i+1)}$, which is the mean pressure on the obstacle of thickness l_{i+1} during $T_{g(i+1)}$. In interaction of the flow with the obstacle, when the flow velocity is much larger than the velocity gained by the obstacle, the momentum of the latter is an additive quantity. Proceeding from the above, we write

$$P_{f,m(i+1)} T_{g(i+1)} = P_{f,mi} T_{gi} + P_{f(i+1)}(T_{g(i+1)} - T_{gi}) ,$$

whence

$$P_{fi} = \frac{P_{f,mi} T_{gi} - P_{f,m(i-1)} T_{g(i-1)}}{T_{gi} - T_{g(i-1)}} , \qquad (4)$$

where P_{gi} is the pressure of the flow during the time interval from T_{gi} to $T_{g(i+1)}$ or at a time instant T'_{gi} (we assume with a certain degree of accuracy which depends on the number of experiments performed), which is determined as

$$T'_{gi} = \frac{T_{gi} - T_{g(i-1)}}{2} . \qquad (5)$$

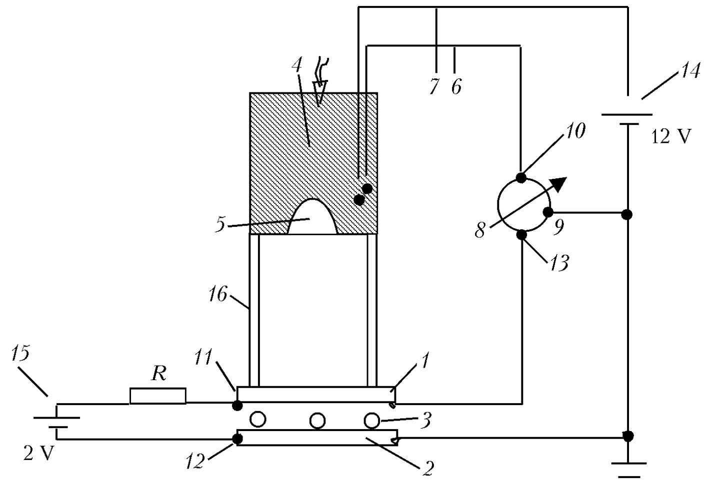

Fig. 1. Schematic of the determination of the time of "passage" of the obstacle through the "gap."

Thus, the pressure P_f which affects the obstacle at the current instant of time after collision with the obstacle is found from approximation of the graphical dependence $P_{gi} = f(T'_{gi})$, where P_{fi} and T'_{gi} are, in turn, determined from (4) and (5).

The time of the effect of the flow T_f is equal to the time of decrease of the flow pressure P_f to zero, i.e., when its effect can be neglected. The instant of the zero flow pressure is determined from the constructed dependence of variation of the pressure exerted on the obstacle on the time of the flow effect $P_f = f(T)$ (its approximation) by the point of intersection of the curve with the time axis.

Assuming that the time of collision is equal to the total time of interaction between the flow and the obstacle, neglecting the mass of particles which penetrated into the obstacle, due to the small number of them (≈0.01% of the flow mass), and proceeding from the laws of conservation of momentum and energy, we determine the mean (mass) velocity of the flow by the formula

$$V_f = \frac{M+m}{2m} V_{ob} . \tag{6}$$

In this approximation, we can estimate the "length" L_f of the flow based on the estimate of the flow effect and the velocity calculated:

$$L_f = V_{f,m} T_f . \tag{7}$$

The pressure of the flow of particles colliding with a motionless (massive) obstacle is [4]

$$P_{f,m} = \rho_{f,m} V_f^2 . \tag{8}$$

Hence, the value of the mean density of the flow $\rho_{f,m}$ is found by substitution of the obtained values of V_f and $P_{f,m}$.

The time of passage of the "gap" by the obstacle is measured and the dependence of it on the obstacle mass is found by the suggested scheme of measurements (Fig. 1).

The obstacle 1 lies on the base 2 on the isolating "gaps" 3. The particles thrown and the obstacle are used as a pair of electrical contacts which close at the beginning of interaction between the flow and the obstacle. This pair transfers a signal of a certain value from the source 14 to the oscillograph, which indicates the instant of the initiation of contact between the flow and the base and motion of the obstacle toward the base. The second pair of contacts, which represents the obstacle itself and the base, are closed on termination of motion of the obstacle toward the base.

When the obstacle and the base are in contact, the recorded level of the signal diminishes to zero. The time difference between the closure of the contacts and transmittance of different-level signals determines the time of "passage of the gap" by the obstacle. The contact leads 6 and 7 for triggering the oscillograph 8 from the 12-V power

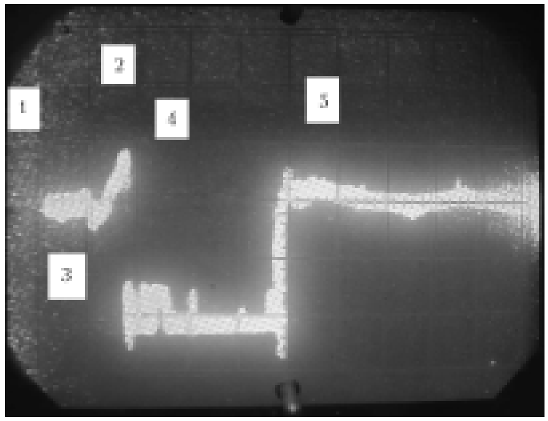

Fig. 2. Oscillogram of measurement of the level of the signal in collision of the particle flow with a 90-mm-thick obstacle.

source are introduced to the case with the explosive 4 and the collecting lens 5. In explosion and actuation of the explosive, the contacts 6 and 7 are closed and the 12-V signal supplied to the leads 9 and 10 (9 — "Earth," 10 — "Start") initiates operation of the oscillograph. A voltage of 2 V from the source 15 is fed to the input 13 of the oscillograph. Under the effect of the products of detonation of the explosive, the lens with powder (particles), which is at a distance from the obstacle specified by the plastic thin-walled cylinder 16, is compressed and a flow of particles moving to the obstacle is formed. In collision of the flow with the obstacle, contacts 7 and 11 are closed and the 2-V "signal" is delivered to the input 13 of the oscillograph from the source 14. Under the action of the flow the obstacle moves downward to the base and closes the contacts 11 and 12 — the oscillograph reading is 0 V. The time of voltage change from the initial 2 V to 0 V (contact of the obstacle with the base) is the time of obstacle motion and "passage through the gap".

The obstacle and the base, which are metal cylinders (St3 steel), have plane-parallel ground end surfaces.

Results. A series of experiments on measurement of the time of "passage through the gap" by the obstacle depending on the obstacle thickness, which were conducted by the developed and above-described technique, gave oscillograms of the signals recorded in loading of obstacles with a thickness of 15, 36, 53, 90, 115, and 216 mm and a diameter of 100 mm. The value of the "gap" in all the experiments was h = 3 mm.

As an example, we give the decoding of the recorded signal of the experiment with an obstacle thickness l = 90 mm (Fig. 2, i = 4). We divide the oscillogram into four sections with a certain level of the signal which characterize the processes of flow formation and collision between the flow and the obstacle.

Section 1–2 is the time from the onset of detonation of the explosive and triggering of the oscillograph sweep, i.e., closing of the contacts 6 and 7 (see Fig. 1) by the detonation products till their penetration to the "gap" between the obstacle and the base, since these products have a velocity higher than the formed flow of particles ($T_{1–2} \approx 170$ μsec). The medium between the obstacle and the base (contacts 11 and 12) becomes partially electroconducting (detonation products are ionized), which results in a change (decrease) of the signal from the battery 15, which is recorded by the oscillograph 8. (The electric circuit current-conducting "gap"–battery 15 becomes closed, and the drop of voltage recorded by the oscillograph depends on the degree of ionization of the medium in the "gap" and the ratio of the total resistance of the circuit, which consists of the inner resistance of the battery and the resistance of the "gap," to the resistance of the "gap".)

Section 1–3 is the time of the formation of the particle flow and its motion till contact with the obstacle (from the instant of explosive blasting to collision of the flow front with the obstacle) ($T_{1–3} \approx 200$ μsec).

Section 2–3 is the period between the closure of the "gap" by the detonation products and collision of the flow with the obstacle ($T_{2–3} \approx 30$ μsec).

Section 3–4 is the period of contact between the obstacle and the particle flow till the touch of the obstacle with the base — the time of "passage through the gap" by the obstacle ($T_{3–4} \approx 150$ μsec).

Section 4–5 is the time of the contact between the obstacle and the base before the "recoil" of the obstacle.

TABLE 1. Time of Passage through the "Gap" T_{gi}, Mean Velocity of Obstacle Motion till Collision with the Base $V_{ob,mi}$, Mean Pressure of the Particle Flow $P_{f,mi}$, and Density of the Momentum of the Flow $P_{f,mi}T_{gi}$ for an Obstacle Thickness l_i or Its Mass M_i in the Series of Experiments i

i	1	2	3	4	5	6
M_i, kg	0.92	2.15	3.26	5.54	7.08	13.29
l_i, mm	15	36	53	90	115	216
T_{gi}, μsec	60	90	110	150	180	340
$V_{ob,mi}$, m/sec	50	33.3	27.3	20	16.7	8.8
$P_{f,mi}$, GPa	0.78	0.84	0.82	0.75	0.67	0.35
$P_{f,mi}T_{gi}$, kPa·sec	46.8	75.6	90.2	112.5	120.6	119

TABLE 2. Flow Pressure P_{fi} at Time Instant T'_{gi}

i	0	1	2	3	4	5	6
P_{fi}, GPa	0	0.78	0.96	0.73	0.56	0.27	0
T'_{gi}, μsec	0	30	75	100	130	165	180

Table 1 gives the values of T_g measured, V_{ob} calculated by (1), and M, l, and $P_{f,m}T_g$ (momentum of the flow per unit of its area) for different l calculated by (2). The data obtained are the average of at least three experiments for each selected thickness of the obstacle.

The values of acting pressures as a function of the current time from the onset of the process of interaction between the flow and the obstacle, which are found by (4) and (5), are presented in Table 2.

The dependence of the pressure of the particle flow on the current time of interaction between the flow and the obstacle (or on the time of collision with the obstacle) is shown in Fig. 3. An approximating equation of this dependence within the period from 0 to 180 μsec with a sufficient degree of accuracy has the form

$$P_f = -9\cdot 10^{-9}T^4 + 4\cdot 10^{-6}T^3 - 0.00067T^2 + 0.0433\,T\,. \tag{9}$$

The flow area was assumed to be equal to the diameter of the base of a powder container (lens) of 50 mm [2].

It is seen from Table 1 (dependence of the density of the flow momentum $P_{f,m}T_g$ on the time of flow action) that in 180 μsec from the onset of interaction between the flow and the obstacle the momentum transferred by the flow to the obstacle does not increase but remains constant (within the accuracy of measurements), which can take place only on cessation of the flow or decrease of its velocity to a value smaller than 33.4 m/sec — the velocity gained by the obstacle in its interaction with the flow. Proceeding from these data, we can estimate the time of flow effect on the motionless obstacle as ≈180 μsec. Consequently, the mean flow pressure on the obstacle during the flow action is 0.67 GPa (see Table 1).

We calculate the mean velocity of the flow V_f by (6). Since only the total mass of the powder thrown is known, calculation can be made on the assumption that to the instant of obstacle collision with the base the whole flow interacts with the obstacle. This assumption is justified by the results of the experiment i = 5 (Table 1), i.e., when the change of the obstacle momentum (increment) with the changes in the mass of the obstacle, which leads to an increase of T_g, is zero. In the calculation, having taken the sum of the mass of the thrown powder and the estimated mass of the products of explosive detonation, which passed to the flow, as the mass of the striker m = 0.14 kg and the obstacle mass M = 7.08 kg, from (6) we obtain that the mean velocity of the flow is $V_f \approx 860$ msec.

The mass of the detonation products in the particle flow to the mass of the whole explosive is estimated in proportion of the surface area of cumulation to the entire surface of scattering of the detonation products. The maximum value of the velocity, which the obstacle reaches in this case, is 33.4 m/sec and the value of 16.7 m/sec (Table 1), which is the mean velocity of "gap passage" by the obstacle, is assumed to be equal to half of the maximum velocity. Then, from (7), the length of the flow is $L_f \approx 155$ mm.

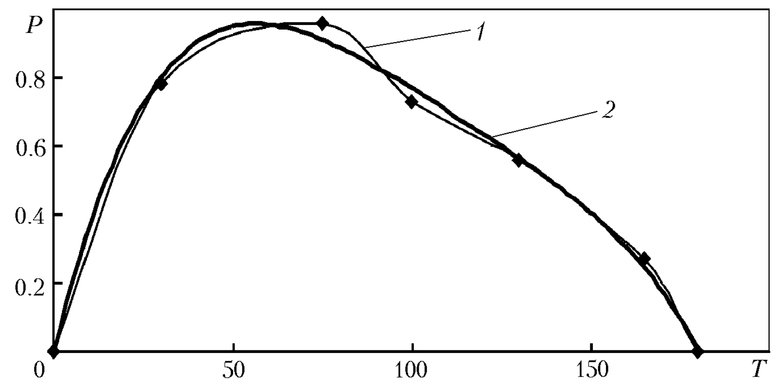

Fig. 3. Pressure of the particle flow on the obstacle during interaction between the flow and the obstacle: 1) experimental curve; 2) approximation. *P*, GPa; *T*, μsec.

We estimate the mean density of the flow. Having assumed that the obstacle is motionless (this is true at a ratio of mean velocities of the obstacle and the flow larger than 25) and substituted the calculated value of the mean flow velocity 860 m/sec, from formula (8) we obtain $\rho_{f,m} = 0.9 \cdot 10^3$ kg/m^3.

It is worth noting that traces of the cycle of $\alpha \to \varepsilon \to \alpha$ transformations which are the result of high static or dynamic pressures of about 12 GPa are recorded by the method of metallographic analysis in samples of iron-nickel alloys treated by a flow of powder particles of silicon carbide [5]. In our opinion, the obtained zones of such a high pressure at a relatively low mean pressure over the flow area are the result of a lengthy nonstationary loading of the obstacle and the appearance of complex shock-wave phenomena in it (with high gradients of density and velocity over the cross-section area of the flow). This is caused by the method of flow creation — compression of a cumulative recess filled by the powder of the products of explosive detonation. In this case, a flow with an appreciable central region of much higher density and velocity is formed.

CONCLUSIONS

1. The technique developed allows one to estimate the main parameters of the particle flow colliding with the obstacle.

2. The flow parameters which provide superdeep penetration of particles to the obstacle are the following: mean (mass) velocity ≈860 m/sec, mean density $\approx 0.9 \cdot 10^3$ kg/m^3, length ≈150 mm, mean pressure on the obstacle during the flow effect ≈0.67 GPa, and the time of interaction between the obstacle and the flow ≈180 μsec. The equation of the dependence of pressure on the time of collision with the obstacle has the form of (9).

NOTATION

L_f, flow length; M, mass of the obstacle; m, mass of the flow; P_f, pressure of the particle flow on the obstacle; $P_{f,m}$, mean pressure of the particle flow on the obstacle; R, ohmic resistance; ρ_{ob}, l, and S_{ob}, density, thickness, and area of the obstacle, respectively; $\rho_{f,m}$, mean density of the flow; S_f, flow area in the frontal cross section; h, value of the "gap"; i, number of the experiment; T, current time instant after collision of the flow with the obstacle; T_g, time of passage of the obstacle through the "gap"; T_f, time of flow action; V_f, flow velocity; $V_{ob,m}$, mean velocity of the obstacle; V_{ob}, velocity of the obstacle; t, time; S_g, area of the gap. Subscripts: g, gap; f, flow; ob, obstacle; m, mean.

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