4. A. L. Gonor and V. Ya. Rivkind, "Dynamics of drops," Itogi Nauki Tekh., Ser. Mekh. Zhidk. VINITI, Moscow, 17 (1982).
5. O. G. Engel, "Fragmentation of waterdrops in the zone behind an air shock," J. Res. Nat. Bur. Stand., 60, No. 5 (1958).
6. A. A. Ranger and J. A. Nicholls, "Aerodynamic shattering of liquid drops," AIAA J., 7, No. 2 (1969).
7. A. A. Borisov, B. E. Gel'fand, et al., "Drop fragmentation regimes and criteria of their existence," Inzh.-Fiz. Zh., 40, No. 1 (1981).
8. R. I. Nigmatulin, "Compression zones in two-phase media," Vestn. Mosk. Univ. Mat. Mekh., Ser. 1, Mat. Mekh., No. 4 (1969).
9. A. I. Ivandaev, "Propagation of small perturbations in a mixture of vapor with water drops," Akust. Zh., 24, No. 1 (1978).

STRUCTURE OF A FLOW OF BINARY MIXTURES OF SOLID PARTICLES UNDER CONDITIONS OF TWO-DIMENSIONAL SHOCK-WAVE LOADING

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Study of the behavior of mixtures of dissimilar particles during shock-wave loading is interesting in connection with problems concerning the explosive compaction of powder composites, the generation of physicochemical changes in powder mixtures, etc. Currently, one of the most common sources of information on processes taking place in the shock compression of powdered materials is investigation of the structure of specimens which remain intact after loading. However, this method has a serious shortcoming: the data obtained generally do not permit unambiguous interpretation, and the subsequent analysis represents only one of several possible approaches to explanation of the causes and mechanisms of the phenomena in question. A more objective conclusion can be obtained on the basis of direct observation of the dynamical flow pattern of the substance, particularly by the method of impulsive x-ray diffraction analysis.

Here, we use this method for the first time in experiments to directly observe the structure of the flow of mixtures of dissimilar solid particles during their shock loading under conditions simulating their practical application.

The objects of our study were two-component systems consisting of particles of a lightweight material ("transparent" to x-rays) and intervening particles of a heavier ("opaque") material. The sizes of the particles of each component were roughly the same and amounted to 0.5-1.0 mm. The ratio of the volume fractions of the light and heavy components was much greater than unity, so we will henceforth refer to the heavy component as the impurity component and the light component as the main component. We used particles of aluminum, graphite, sand, and sodium chloride as the main component. The impurity particles used were granules made from an alloy of tungsten with molybdenum, sintered tungsten powder, and lead. The granules were close to spherical.

Shock-wave loading was done in a two-dimensional formulation (Fig. 1). The particles of the main component were arranged in the form of a layer 5 of uniform thickness on a massive steel base 6. The thickness of the layer was 15-20 mm, while the mean density was 30-50% of the density of the material of the particles. Lead-foil "control samples" 20 μm thick (numbered 4 in Fig. 1) were placed inside the layer at certain depths. The foil surfaces were parallel to the surface of the base. We used only two foils located at different depths in one test. The particles of the impurity component 3 were located on top of the lead foil in one row and were in direct contact with the foil. The distance between the particles was 5-10 particle diameters. A plane charge of explosive 1 was placed on the top surface of the layer. The charge was detonated from one end, so that we generated an oblique shock wave (SW) OA in the system. The cumulative interaction of the wave with the surface of the base in turn produced a reflected wave OB. This method of loading is a good approximation of the conditions under which powders are explosively compacted.

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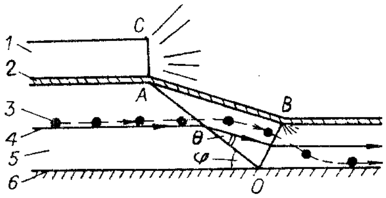

Fig. 1

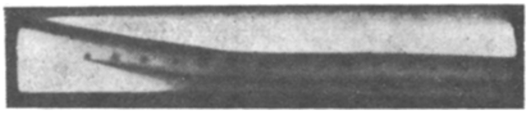

Fig. 2

The charges were made from ammonite 6ZhV, hexogen, and alloy TG 50/50. Metal sheets 0.5-1 mm thick (numbered 2 in Fig. 1) were placed between the explosive and the surface of the loaded layer to prevent the explosion products from filtering into the interparticle space.

The experimental rigging was located between the source of x-rays and the cassette holding the photographic film in such a way that the planes parallel to the base were projected on the film in the form of lines. At the moment of loading, the lead foils were brought into motion by the particles of the main component, without introducing significant distortions into the flow behind the shock front [1]. In the movable coordinate system connected with the detonation front, the projections of the foils coincided with the streamlines of the main component, while the impurity particles were located along their paths. Typical x-ray diffraction patterns are shown in Figs. 2-4. There are no images of the explosive charges because the massive steel slab located between the charge and the cassette shielded the radiation. The slab was provided to protect the cassette from damage by the explosion products.

We should point out the informativeness of the method of impulsive x-ray diffraction analysis. It makes it possible not only to fix the mutual position of the streamlines of main component and the paths of the impurity particles, but also to determine the parameters of the shock loading. For example, it follows from the laws of conservation for an oblique shock that the compression of the main component — defined as the ratio of its density ρ behind the front to its initial density ρ_0 — can be calculated from the formula $\rho/\rho_0 = \tan\varphi/\tan(\varphi - \theta)$ (φ and θ are the angles of inclination of the shock front to the surface of the base and the deviation of the flow behind the front).

The velocity of the front of the shock wave D is calculated from the known detonation velocity W and the angle φ: $D = W\sin\varphi$. The remaining shock-wave parameters are determined from the conservation laws for a shock discontinuity. In the tests, detonation velocity was recorded with the aid of electrocontact sensors. The amplitudes of the incident waves ranged from 1 to 7 GPa. The ranges of the loading parameters were limited by the power of the x-ray source and by difficulties connected with protection of the film from the explosion.

Analysis of the x-ray diffraction patterns obtained shows that the position of the impurity particles relative to the lead foil may change considerably during loading, i.e., the paths of these particles do not always coincide with the streamlines of the main component. This indicates the presence of velocity disequilibrium between the particles of different components. The physical nature of this phenomenon is fairly simple. The flow of particles of the main (lightweight) component undergoes a sharp change of direction as it traverses the fronts of the incident and reflected shock waves, and the streamlines are broken lines consisting of individual sections. The impurity particles have a larger store of kinetic energy than the particles of the main component. They are slowed less as they cross the wavefronts and continue to move, changing direction under the influence of particle interaction forces. In the general case, final equalization of velocities occurs a certain distance from the front, so that the paths of the impurity particles are relatively smooth lines. Their geometry depends on the ratio of the densities of both components and the particle interaction forces.

If these forces are small, then the velocity disequilibrium may remain substantial during the entire time of loading. As a result, the impurity particles are shifted closer to the upper boundary of the layer. Such flows took place when aluminum or sodium chloride were used as the main component and the amplitudes of the SW's exceeded 2 GPa (Fig. 2). In certain tests, the velocity disequilibrium proved so great that impurity particles partially or completely pierced the metal sheet (Fig. 3). Conversely, if the particle interaction forces are large, then the size of the velocity equalization region may be comparable to the characteristic particle size. In this case, the impurity particles will move along the

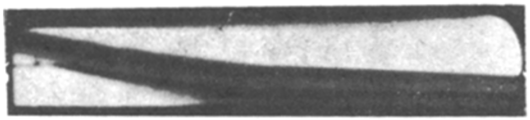

Fig. 3

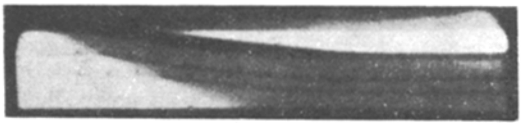

Fig. 4

streamlines of the main component. Such conditions are realized in sand at SW amplitudes up to 5 GPa (Fig. 4). It is evident that one-velocity models of porous media are adequate for describing such systems.

It is possible to have flow variants in which the ratio of the dimensions of the velocity equalization regions behind the incident and reflected waves is such that the impurity particles reach the reflecting surface. In this case, the particles "settle" on the surface of the base (Fig. 1). Such flows were seen in graphite and sodium chloride loaded by relatively weak SW's.

The particle interaction force is determined by many factors. Among them are the thermophysical and mechanical characteristics of the materials of the particles, their morphology, and the relative velocity of the particles. Establishing the relationship between the force and these factors is a complex problem in its own right. Only after this problem is solved can the effects being discussed here be described theoretically. At present, it is useful to conduct a qualitative energy analysis of the phenomena.

It was noted that with fixed values of the parameters of the loaded system, the velocity disequilibrium is determined to a significant extent by the energy of the SW. In the range we investigated, the general tendency is for disequilibrium to increase with an increase in the loading energy. This result seems natural on the basis of the inertial nature of the disequilibrium, since an increase in the energy of the shock wave means an increase in the velocity of the flow behind the wavefront. However, it should be kept in mind that the character of the dependence of the particle interaction force on the energy of the SW may prove to be quite complex. In fact, in the presence of velocity disequilibrium, the material of the main component flows around the impurity particles. To simplify subsequent discussions, we will assume the impurity particles to be "perfectly rigid." In relatively weak shock waves, the process of flow about the impurity particles is accompanied by intensive plastic deformation or brittle fracture of the material nearest the particle in the flow. Here, the particle interaction force depends to a considerable extent on the strength characteristics of the material.

The effective strength of the powdered material behind the shock front (in the present case, the material of the main component) is determined by two factors: the individual strength of the particles themselves and the strength of the interparticle contacts which develop during shock compression. The curve depicting the dependence of the individual strength of the particles on the energy of shock loading has a maximum, which is attributable to the effect of the loading rate and temperature: dynamic strength increases with an increase in loading rate and decreases with an increase in temperature. The strength of the interparticle contacts is also nonmonotonic in character. The formation of such bonds becomes possible only at shock-loading energies exceeding a certain value dependent on the thermophysical properties of the particle material and particle morphology [2, 3]. There is an optimum value of energy at which the strength of the contacts becomes maximal. The drop in strength with a subsequent increase in loading energy is attributable to the adverse effect of temperature.

In powerful SW's with shock-loading energies exceeding $E^* = c(T_{mt} - T_0) + H_{mt}$ (where c is the specific heat of the material, T_0 is the initial temperature, T_{mt} is the melting point at the pressure associated with the shock loading, and H_{mt} is the latent heat of fusion at this pressure), the material of the main component is transformed to the liquid state. In such a situation, the main contribution to the total particle interaction force is made by viscous friction, which increases with an increase in the relative velocity, i.e., with an increase in shock-loading energy.

The above considerations permit us to suggest that the monotone increase in the dependence of the velocity disequilibrium on shock-loading energy seen here is not a general law but is instead due to the limited range of variation of the loading parameters.

When the impurity component is a low-strength or low-melting-point material, the interaction process may be complicated by plastic deformation or brittle fracture of the impurity

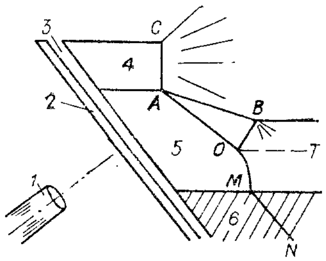

Fig. 5

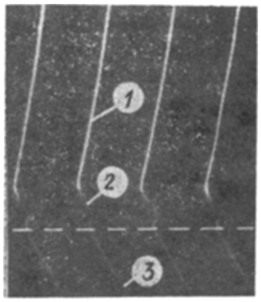

Fig. 6

particles. Also, mass transport may occur in the velocity disequilibrium zone. Here, the impurity particles leave a "wake" — a thin layer of material removed from their surface by friction. Such phenomena were recorded in SW's with an intensity greater than 2 GPa in the loading of systems which included impurity particles of lead or sintered tungsten powder and a main component of sodium chloride. It should be noted that the strength of tungsten granules is relatively low: they fracture in a brittle manner under a static load on the order of 100 N. The above-described effects were not observed throughout the investigated range of loading parameters when we used high-strength, high-melting-point granules of the alloy of tungsten with molybdenum.

We did not perform any x-ray diffraction analyses of the flow structure obtained with irregular reflection of the shock wave from the surface of the base, since this would have required a considerable increase in the size of the rigging. Such an increase would have been intolerable due to the limited power of the radiation source that was available to us. It is natural to assume that the flows which develop behind the incident and reflected waves with an irregular reflection regime would be similar to the flows which develop with regular reflection. It can be expected that, for irregular reflection, there will be flow regimes in which the ratio of the sizes of the velocity equalization regions behind the incident and reflected waves will be such that some impurity particles will penetrate the region compressed by the Mach wave. Since the flow behind the Mach wave is essentially subsonic, perturbations which occur as a result of impurity particle penetration will have an effect on the geometry of the shock front. The experiments confirm this. We conducted special studies involving optical recording of Mach-wave configurations in different powder mixtures. The above effect was observed for a mixture of powders of boron nitride and Nichrome in a weight ratio of 15/85. The dimensions of the boron nitride particles did not exceed 10 μm, while the dimensions of the Nichrome particles were not greater than 60 μm.

Figure 5 shows a diagram of the experimental unit, where 1 is a high-speed camera, 2 is a Plexiglas sheet, 3 is a gap filled with gaseous argon, 4 is the explosive charge, 5 is the experimental powder mixture, 6 is the base, CA denotes the detonation front, OA is the front of the incident SW, OB is the front of the reflected SW, OM is the front of the Mach wave, MN is the front of the SW in the base, and OT is a surface of tangential discontinuity. When the shock-wave configuration reaches the end of the assembly, the argon in the gap between the Plexiglas sheet and the end of the assembly briefly fluoresces. The fluorescence ceases due to dispersion of the Plexiglas in the shock wave. The fluorescence was recorded on the high-speed camera in the slit scanning regime with the beam moving over the film at a velocity of $3 \cdot 10^3$ m/sec. To increase the resolving power of the method, the end of the experimental assembly was made so that it was inclined to the surface of the base and, in the set-up for the experiment, was oriented perpendicular to the axis of the camera. It is clear from geometric considerations that the projection of the front of the Mach wave on the end of the assembly is inversely proportional to the sine of the angle between the reflecting surface and the end. In our tests, this angle was 30-20°. This allowed us to increase the projection of the wavefront by a factor of 2-3.

Figure 6 shows a photochronogram of the process. The direction of the scan is from right to left. The dashed line indicates the position of the reflecting surface, while the numbers 1-3 denote the regions of fluorescence caused, respectively, by the incident wave, the Mach wave, and the shock wave in the material of the base. A distinct inflection is visible in the central part of the front of the Mach wave. We believe this inflection to be due to filtration of Nichrome particles from the flow region behind the reflected wave into the flow region behind the Mach wave. No such inflection was observed in [4] in a study of Mach-wave configurations in one-component powders. Additional evidence of the occurrence of filtration comes from the increase in the concentration of Nichrome particles near the surface of the base that was discovered in metallographic inspection of specimens which remained intact after loading.

Thus, the completed study confirmed that the shock-wave loading of a mixture of dissimilar solid particles may result in velocity disequilibrium behind the shock front. This disequilibrium may either be negligible or quite significant. In a quantitative sense, the effect is determined by the physicomechanical properties of the particles and the energy of the shock loading.

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LITERATURE CITED

1. N. A. Kostyukov, "Oblique reflection of shock and detonation waves in porous media," Physical-Mathematical Sciences Candidate's Dissertation, Novosibirsk (1978).
2. P. Kasiraj, T. Vreeland Jr., et al., "Shock consolidation of a rapidly solified steel powder," Acta Metall., 32, No. 8 (1984).
3. O. V. Roman, V. F. Nesterenko, and I. M. Pikus, "Effect of the size of particles of a powder on the process of explosive consolidation," Fiz. Goreniya Vzryva, No. 5 (1979).
4. N. A. Kostyukov, "Features of the oblique reflection of shock waves from a barrier in powders," Din. Sploshnoi Sredy, 29 (1977).