PHYSICAL CAUSES AND MECHANISMS OF THE FORMATION OF BOUNDARY REGIONS IN THE TWO-DIMENSIONAL EXPLOSIVE COMPACTION OF POWDERED MATERIALS

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UDC 532.593:621.7.044.2

1. Introduction. Regions characterized by structural inhomogeneity may be formed during the compaction of powdered materials (PM) by explosive plane loading. These regions are near the boundaries separating the PM and the barrier within which the powder is compacted. Such inhomogeneities are seen, for example, in cylindrical powder compacts placed inside a monolithic rod [1, 2] or in the application of a PM on a flat metal substrate [3, 4]. The results of metallographic studies make it possible to distinguish two main types of irregularities: high-temperature ("hot") zones, whose structure provides evidence of appreciable heating of the PM during compaction [1, 3, 4]; low-temperature ("cold") zones, where the compaction process is not accompanied by a significant increase in temperature [2].

There is currently no consensus on the mechanism responsible for the formation of these inhomogeneities. The reason for this is that the conclusions reached in most studies were based on metallographic study of compacts that remained intact after loading. This approach leaves out the most valuable information – that pertaining to the dynamic behavior of the PM, i.e., its behavior at the moment of loading. The metallographic results offer only indirect information on dynamic processs occurring in the composite and can often be interpreted in several ways. This in turn gives rise to a wide range of different explanations for the phenomena in question.

A natural approach to clearing up the confusion is to conduct comprehensive studies that combine an analysis of the structure of intact specimens with direct experimental observations of the pattern of flow of the PM at the moment of loading and numerical calculation of regions in which different flow regimes exist. This is the approach taken in the present study, which involves examination of possible flow variants that develop in the oblique reflection of shock waves (SW) in a PM from the surface of a monolithic metal barrier. We also explore the effect of the flow pattern on structural features of the resulting compacts.

2. Test Materials. The experiments were conducted on powdered titanium, nickel, copper, titanium nickelide (TiNi), and tin bronze. The bronze particles had a form close to spherical, while the other particles were irregularly shaped. Dispersity ranged from 20-50 to 400-630 μm. The initial density of the PM was 30-63% of the density in the monolithic state.

The barrier assemblies used in the tests were made of aluminum, copper, nickel, and molybdenum. We also used beryllium in the numerical calculations. These choices were dictated by the wide range of physicomechanical characteristics thus represented and the practical importance of certain ones for the solution of specific problems.

3. Methods of Experimental Study and Numerical Calculation. Experimental observations of flow regimes and numerical calculations were performed in a two-dimensional formulation, while the structure of the PM after explosive loading was studied on axisymmetric compacts with a centered rod. The loading schemes were similar to those used in [1-4]. In most experiments the thickness of the PM layer was much less than the diameter of the central rod. This allowed us to ignore the initial motion of the SW as it converged on the specimen axis. The parmeters of the axisymmetric loading of the PM were close to the loading parameters in a two-dimensional formulation. The rate of detonation of the explosive charge varied within the range 3.0-7.6 km/sec. The intensity of the incident SW in the PM was 1-5 GPa.

Novosibirsk. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 6, pp. 154-161, November-December, 1991. Original article submitted July 30, 1990.

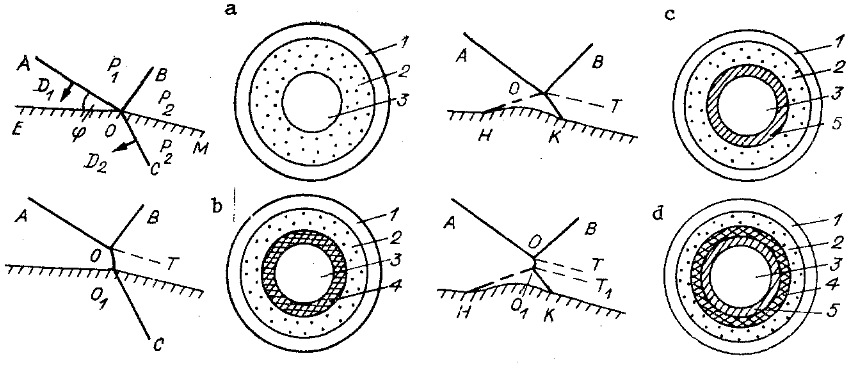

Fig. 1

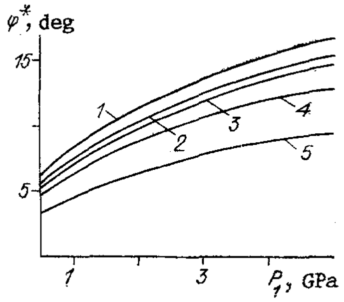

Fig. 2

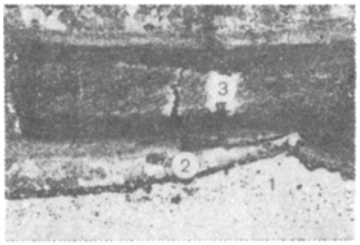

Fig. 3

Fig. 4

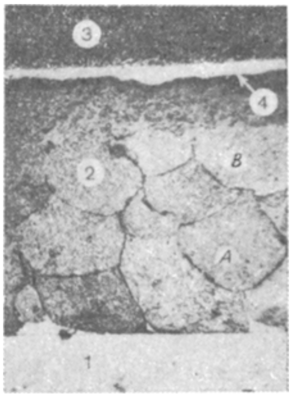

Fig. 5

The pattern of flow of the PM at the moment of loading was recorded by the methods of impulsive x-ray diffraction [5] and ultra-high-speed optical recording [6] of shock-wave configurations at the moment the waves reached the free surface of the experimental assembly. The numerical calculations were performed on the basis of the method described in [7, 8]. The structure of the intact compacts was studied on an optical microscope.

4. Results. A. Regime of Two-Dimensional Flows and Structure of the Boundary Zones.

Figure 1 shows results of studies of possible flow variants which arise with the oblique reflection of the incident SW alloy from the surface of the barrier EM. A regular reflection regime is realized with small angles of incidence (Fig. 1a). It is characterized by the presence of two shock-wave fronts in the PM (the front of the incident wave alloy and the front of the reflected wave OB) and one front OC in the material of the barrier. The branch point of the fronts is located on the reflecting surface. Specimens compacted with such a flow regime have a homogeneous structure throughout region 2, including zones adjacent to the wall of the storage ampoule 1 and the barrier (rod) 3.

When the angles of incidence φ exceed a certain critical value φ^*, there is a qualitative change in the flow pattern. The branch point of the incident and reflected fronts moves away from the surface of the barrier and a third SW – the Mach wave OO_1 – is created in the PM. Such reflection regimes are called Mach or irregular regimes. The flow behind the Mach and reflected SW's may be fairly complex. Figure 1b shows the simplest case, when the flow regions behind the fronts of the Mach and reflected SW's are bounded by surface of tangential discontinuity OT.

A significant difference between the state of the PM behind the Mach SW and the adjacent layer of material compressed by the reflected SW is a substantially larger increment of thermal energy. This may sometimes lead to fusion and even vaporization of the PM during subsequent unloading [9]. Metallographic studies that we conducted show that specimens compacted with irregular SW reflection have "hot" zones 4 adjacent to the surface of the barrier. The thicknesses of the zones are comparable to the height of the Mach front OO_1.

Comparison of our results with the data in [3, 10, 11] confirms that the physical mechanism responsible for the formation of the hot zones is the same as in the creation of "central" zones accompanying the explosive compaction of cylindrical porous bodies. The formation of the hot zones can be attributed to redistribution of the energy associated with shock compression over the volume of the compact with irregular SW reflection regimes. It can be suggested that the mechanisms of formation of the hot zones are for the most part similar to the mechanisms examined in [10, 11]. Evidence of this comes from the identical qualitative changes in the structure of both ("hot" and "central") zones accompanying quantitative changes in the parameters of the Mach SW.

Figure 2 shows results of numerical calculations of the dependence of the critical angle φ^* on the intensity of the incident SW P_1 in porous copper (initial density 5.6 g/cm^3) for different barriers; 1) copper; 2) nickel; 3) molybdenum; 4) aluminum; 5) beryllium. We should make one other observation. The flow in unidimensional shock-wave reflections is usually determined by a single barrier parameter – its acoustic impedance (with a given PM and a fixed amplitude for the incident SW). The mutual location of the curves in Fig. 2 shows that, with two-dimensional reflections, acoustic impedance is not the only parameter which determines the flow structure and, ultimately, the state of the shock-compressed PM. It follows from analysis of the theoretical equations that a second parameter which appreciably affects the position of the boundaries we are examining is the velocity of propagation of the plastic SW in the barrier material.

The flow schemes shown in Fig. 1a, b, are realized under the condition $V(P_1) > D_2(P_2)$ ($V(P_1) = D_1(P_1)/\sin\varphi$ is the rate of propagation of the load over the surface of the barrier; $D_1(P_1)$ is the rate of propagation of the incident SW in the PM; $D_2(P_2)$ is the rate of propagation of the plastic SW in the barrier PM; P_2 is the back pressure).

With a fixed amplitude for the incident wave P_1, an increase in φ leads to weakening of the inequality. When φ exceeds a certain critical value φ^0, there is a change in the sign of the inequality and an associated change in the character of the flow. A qualitatively new regime (Fig. 1c) appears. The expressence of this regime is the appearance of a jump in strain on the barrier surface in the neighborhood of the high-pressure region HK and consequent impulsive loading of the PM on the barrier side.

This is shown by the results of x-ray diffraction study of the structure of flow of the PM at the moment of loading. Visible on the diffraction patterns is a high-density zone (the front boundary of which is designated OH). Optical recording of shock-wave configurations in such loading regimes becomes impossible as a result of shielding of the light. The shielding occurs because disturbances propagating through the barrier material reach the surface of the experimental assembly first.

The concept of the front boundary of the high-density zone OH is highly conjectural. The boundary may be the front of a weak shock-wave or the leading edge of a compression wave. Metallographic study of specimens left intact after loading showed that the thickness of the given zone may differ significantly as a function of the loading conditions: it may either be comparable to the mean particle size or may exceed the latter by an order of magnitude. Obviously, in such a situation the concept of "compression wave" is not always applicable in the generally accepted sense of the term. However, to simplify our description of the mechanism of formation of structural inhomogeneities near the surface of the barrier, we will henceforth refer to the boundary OH as the front of a receding compression wave. In our opinion, such a simplification will not introduce significant errors into the qualitative arguments made below.

Thus, in the present case, the incident SW interacts not with the surface of the barrier, but with the boundary region of the compacted PM. Such interaction is accompanied by the formation of reflected waves OB, OK and surface of tangential velocity discontinuity OT (Fig. 1c). Meanwhile, in contrast to the flow regime shown in Fig. 1b, most of the compaction of boundary region 5 is done by the relatively weak pulse OH. Thus, it is "cold" compared to region 4.

The thickness of the cold boundary region depends on several factors. One of the main factors is the amplitude of the strain jump, which is in turn determined by the rate of displacement of the barrier material along a normal to the surface and the time interval over which this displacement occurs. The latter depends on the velocity difference $D_2 - V$.

Incident and receding waves may interact in an irregular regime (Fig. 1d) occurring with angles of incidence in excess of the critical value $\hat{\varphi}$. The resulting Mach wave OO_1 makes it own contribution to the formation of the structure of the boundary region: it consists of alternating cold 5 and hot 4 layers.

The structure of the hot layer 4 may differ appreciably, depending on the amplitude of the incident SW and the angle of incidence [12-14]. In particular, it is either a cooled homogeneous melt or is composed of alternating layers differing in porosity, microhardness, character of etching, etc. Qualitatively similar structures have been seen in the "central" zone of axisymmetric compacts [10, 11].

The three critical values examined above for the angle of incidence of shock-waves on the barrier surface (φ^*, φ^0, and $\hat{\varphi}$) depend on the dynamic compressibilities of the loaded PM, the material of the barrier, and the resulting flow parameters. Here, we do not calculate $\hat{\varphi}(P_1)$ due to difficulties connected with determination of the flow parameters in the region OHK. However, based on data from impulsive x-ray diffraction and metallographic analysis, we can state that the relations $\varphi^* < \varphi^0 < \hat{\varphi}$ are satisfied within the investigated range of loading parameters.

B. Boundary Effects on the Surfaces of Barriers of Complex Form. A special series of experiments was conducted to study the structure of axisymmetric compacts containing central rods of complex configuration. The rods had the form of a multistep dumbbell, i.e., they consisted of several cylindrical sections of different diameters connected by conical surfaces of opposite orientation. Such a rod configuration made it possible to vary the angle of incidence of the SW on the reflecting surface in the direction of increases or decreases relative to the angle of incidence on a cylindrical surface. The angle of incidence reached ±20°, which corresponded to a change in velocity V from several percent to several hundred percent (depending on the initial angle φ).

Metallographic analysis of intact specimens after loading showed the existence of a direct correlation between the velocity difference $D_2 - V$ and the thickness of the "cold" zone: the latter increased with an increase in this difference and reached 15-20 PM particle diameters. Cold zones were absent from those sections of the specimen where the inverse ratio prevailed.

Under certain loading conditions, we observed a "stopped" strain jump. Figure 3 shows a photograph of the strain jump 1 on the surface of an aluminum rod. The PM consisted of bronze particles 50-100 μm. Numbers 2 and 3 denote the cold and hot zones in the PM. The given effect is usually seen on conical surfaces, the orientation of which helps increase the rate of load propagation V. A "stopped" jump was seen in those compacts where the flow of the PM above the cylindrical surface of the rod occurred in the regime in Fig. 1d.

Taking into consideration the finite rate of change in the amplitude of the strain jump with a change in loading parameters, we hypothesize that its "stoppage" on conical surfaces is due to an abrupt transistion of the velocity difference $D_2 - V$ from a positive to a negative value and, as a result, overtaking of the leading edge of the jump by the front of the Mach SW.

C. Boundary Effects on Barrier Surfaces with Different Acoustic Properties. In certain experiments, we used cylindrical rods composed of two or more sections of the same diameter. The sections were made of materials with distinctly different acoustic impedances and (or) rates of disturbance propagation. The ends of the sections were carefully ground. Such an experimental setup made it possible to obtain information on the effect of the acoustic properties of the barrier on the structure of the boundary region of the PM.

Metallographic study of the compacts that we obtained showed that, with fixed loading parameters, a cold zone developed on the surfaces only in those sections in which the condition $(D_2 - V) > 0$ was satisfied. We did not observe any interrelationship between the effect examined above and the acoustic impedance of the barrier material.

It is fairly difficult to account for and evaluate the effect of mechanical characteristics of the barrier material on the thickness of the cold zone. Qualitatively speaking, this effect consists of a reduction in the thickness of the cold zone with an increase in the strength properties of the barrier.

It should be noted that there was a smooth change in the thickness of the cold zone within a certain initial portion of the section. The length of this transitional region (i.e., that part of the section on which the thickness of the cold zone acquires a steady value) depended on the loading parameters and the physicomechanical properties of the barrier. We did not examine this question further, taking this to be the subject of a larger independent investigation.

D. Effect of the Dispersity of the PM on the Structural Features of Compacts near the Surface of the Barrier. One of the main characteristics of porous media is dispersity (or mean particle size). In the general case, the study of porous media without allowance for their discrete structure constitutes an idealized situation. However, this statement applies in varying degrees to different problems, i.e., some problems are more sensitive to the characteristic dimension of the porous medium than others. Explaining the effect of PM dispersity on the structural features of compacts near the barrier surface is important for several reasons, one of them being the need to properly select the determining parameter in the construction of a mathematical model to decribe the formation of the "cold" boundary zone.

We conducted a series of experiments to study the structure of explosive compacts obtained from PM's of different dispersities under different loading conditions. Loading was done in axisymmetric ampoules with a central rod. The powder was placed in the ampoule in layers. Although the layers differed in particle size, they had the same initial density. To prevent interpenetration of the layers, we separated them with strips of metal foil. The height of each layer (i.e., the size along the axis of the ampoule) was much greater than its thickness.

Metallographic studies showed that, within the investigated range of loading parameters and the range of PM dispersities we examined, the thickness of the cold zone is independent of particle size, while the number of particles for which there is space in the zone decreases with an increase in their size. It should be noted that this conclusion is consistent with the findings in [15].

In light of the problem we have examined here, we should emphasize that the severalfold change in PM particle size which is seen for a fixed initial density and fixed loading parameters leads to a proportional change in the width of the fronts of the incident and Mach SW's [15]. Thus, we can state that there is no correlation between the width of the SW front and the thickness of the cold zone.

In connection with this, we should note that the amplitude of the Mach SW in our experiments was generally several GPa. This means that the width of its front did not exceed the mean size of the particles [15, 16]. However, the thickness of the cold zone was capable of changing by an order of magnitude – depending on the dispersity of the PM and the material of the barrier (rod).

These results can be readily understood within the context of the flow structures shown in Fig. 1c, d. Fixing the initial density of the PM and the loading parameters makes it possible to suggest that, regardless of PM particle size, the conditions which prevail are similar to those which exist during the formation of the strain jump on the barrier surface. Thus, the same impulsive effects should be exerted on the PM on the barrier side due to the presence of the jump. This in turn means that there will be identical volumes of pore space formed in the PM as a result of these factors and, consequently, identical cold-zone thicknesses.

It is clear from this that the characteristic parameter in the problem of mathematically modelling the cold boundary region is not PM particle size, but the amplitude of the strain jump which occurs on the barrier surface.

E. Deformation of Spherical PM Particles. It is well-known [17] that the use of PM's of spherical particles in explosion testing is very useful and informative. For example, results of metallographic study of the character of deformation of particles can yield additional information on the velocity of propagation of impulsive loads over the volumes of the specimen.

Our studies (in an axisymmetric formulation) of the form of spherical bronze particles after explosive compaction permit the following statements to be made.

1. With regular regimes of SW reflection from the barrier surface (Fig. 1a) the change in the shape of spherical particles is of the same character throughout region 2. Figure 4 shows a typical photograph of a longitudinal section of a compact. It is evident that the form of the particle in region 2 correspond to the direction of propagation of the pressure pulse from the wall of the ampoule (not shown in the photograph) to barrier 1.

2. In the flow regimes depicted in Fig. 1c, d, the pressure pulses in the peripheral 2 and cold 5 zones have different directions: toward the barrier in the peripheral zone and away from the barrier in the cold zone.

3. The intensity of the impulsive loading of the PM in the cold zone is determined by the properties of the barrier material (other conditions being equal).

4. The density of the PM in the cold zone is close to the density seen in the monolithic state. However, in most experiments we did not see explicit metallographic signs of the presence of inter-particle bonds. According to [12-14], this can be attributed either to the low amplitude of the receding wave or the smooth increase in the loading parameters. In certain cases – such as with high-amplitude incident SW's and barrier materials with low strength characteristics – the impulsive loading of the PM on the barrier side is of a shock-wave nature. This is evident from the photograph of the longitudinal section of a compact shown in Fig. 5, where 1 is an aluminum rod, 2 is a cold zone, 3 is the lower part of a hot zone, and 4 is a narrow band of material which could not be etched during the preparation of the specimen. The intensive plastic strains of the rear surfaces of the PM particles in zone 2 and, in particular, the jet-like character of interaction of particles A and B suggest that the amplitude of the receding SW was several times greater than the strength of the compacted material [17]. Here, we did not observe any jet flows of particles in the zone compacted by the incident SW.

One very interesting fact is the presence of the light band 4 in the photograph; we propose that its formation is connected with additional heat release due to the tangential velocity discontinuity on the surface O_1T_1 at the moment of loading. The impulsive character of such heat release and the high heat-transfer rates [14] in the direction of the cold zone permits the conclusion that metastable structures may be formed in zone 4. Further evidence in support of this comes from measurements of the hardness of the particles: 100 Hv in the initial state, 190 in zone 2, 130 in zone 3, and 380 in zone 4.

The results of our experiments allow us to make the following conclusions. 1. The formation of hot and cold boundary regions during the explosive compaction of PM's is attributable to the features of two-dimensional flows near the barrier: discontinuities of velocity, thermal energy, density, and other parameters. 2. The physical nature of the occurrence of the hot zones is analogous to the case of the "central" zones formed in the explosive compaction of cylindrical porous bodies [10, 11]. The hot zones are formed as a result of irregular regimes of SW reflection from the barrier surface, accompanied by a substantial increase in thermal energy and the mass velocity of the PM behind the front of the Mach wave compared to the relatively cold adjacent layers. 3. The formation of cold zones is seen only when the velocity of the load over the surface of the barrier is lower than the velocity of the plastic SW in the barrier material. This effect is due to impulsive loading of the PM on the side of the barrier, which is in turn attributable to the appearance of the plastic-strain jump on its surface.

It is quite possible that we have overlooked certain aspects of the given problem and that the flow schemes discussed above do not exhaust all of the possible variants. At the same time, we believe that these schemes are the most representative and by themselves are quite adequate to gain an understanding of practically important principles of the formation of structural inhomogeneities. This information can also be used to influence their formation and to solve specific problems.

In conclusion, we note that the first "cold" zone was experimentally recorded on axisymmetric compacts in [2]. However, the authors attributed its appearance to the finite width of the SW front in the PM. It is not hard to show that such an interpretation seriously limits the accuracy that can be attained in determining the critical angles associated with the transition from regular to irregular regimes of SW reflection. It therefore also casts doubt on the results obtained in [6-8]. Thus, it must be stated in particular that the data we have obtained here undermines the conclusions reached in [2].

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