Experimental and Numerical Research in Explosive Loading of Two- and Three-Component Solid Mixtures

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Abstract

We have conducted experimental and numerical research in two- and three-component solid mixtures placed into a cylindrical recovery ampoule under explosive loading. Behavior of the mixture is described by a mathematical model of a multicomponent medium. In the model, every component of a mixture simultaneously occupies the same volume as the mixture. Components interact with each other, exchanging momentum, energy, and mass (if the chemical reaction between the components occurs). An equality of components' pressure is chosen as a condition for joint deformation of components. Finite element method is used for solving the problems. We considered experimentally and numerically explosive loading of the aluminum-sulfur mixture, and explosive compaction of the aluminum-sulfur-carbon mixture in a cylindrical steel ampoule. The inert substance (graphite) was added to the mixture to avoid the reaction between aluminum and sulfur. Most of the focus is on simulating the action of explosion products on the ampoule. In the computations the actions of the detonation products surrounding the ampoule was simulated by the action of pressure on the upper part of the ampoule in a vertical (axial) direction and on the lateral surface of the ampoule in a horizontal (radial) direction. We varied the thickness of the explosive that acts on the upper part of the ampoule in the axial direction in order to study the influence of the parameter on a final shape and size of the ampoule. We founded the essential influence of the thickness of the explosive layer on the final result of explosive compaction. Insufficient thickness of explosives, as well as the excessive thickness may be a reason for an incompletely compacted final product or lead to the formation of cracks or damage.
Keywords: Explosive loading, compaction, solid mixtures, multicomponent medium.

Introduction

State-of-the-art technology increasingly requires high-density materials, but some of the materials can not be processed by traditional methods due to high melting temperatures or rigidity [1, 2]. The use of explosive technologies removes these restrictions. The main advantage of explosive loading is a high uniformly distributed density of final materials. These advantages ensured wide application for explosive loading, and although the first experiments were conducted long ago, the possibilities of this method were not exhausted [3-9]. There is a need to conduct further research of parameters for compacted and strengthened materials and also explosives.

To obtain homogeneous high-density materials, it is necessary to implement an explosive loading mode excluding the undesirable effects of reflected shock and rarefaction waves. An additional difficulty is to choose the desired type and amount of explosives. In the first experiments the explosives were used with a high detonation velocity, since they developed the highest pressure, which gave hope for the highest density of compacted materials [3]. However, it was not taken into consideration that high pressures would result in a further elastic or plastic compression of the compressed body. As a result, after propagation of a detonation wave the unloading wave causes a sharp increase in volume. Besides, the shock waves, reflected from each another (like from a rigid wall), reach the surface of the cylinder, are reflected from it and move back toward the axis of the sample as unloading waves. The interference of rarefaction waves results in generation of cracks.

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Experimental research along with numerical simulation of such processes allow us to control the structure formation and produce new materials with a fine-grained structure, and also gradient, layered and other materials with unique properties.

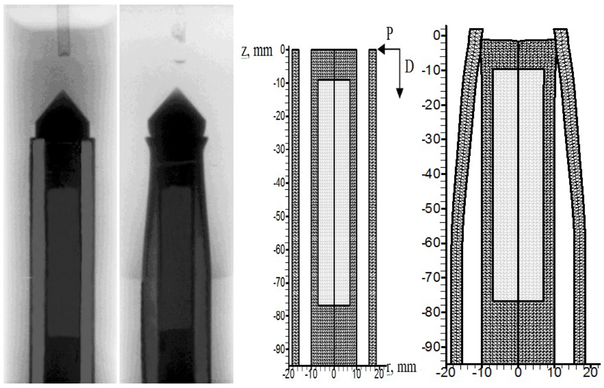
The purpose of this paper is experimental research and numerical simulation of aluminum-sulfur and aluminum-sulfur-carbon mixtures under explosive loading, taking into account the thickness of the explosive layer in the axial direction during explosive loading.

Experimental and Numerical Results for Two-Component Media

To determine experimentally the parameters for explosive loading of a cylindrical ampoule that contains a two-component mixture, we used the powder from aluminium (Al, size of particles <100 μm) and sulfur (S, size of particles 100-300 μm). The mass fractions of components were as follows: Al, 35; S, 65. Components were mixed in an AGO-2U planetary mill. The mixture was pressed into eight tablets with a diameter of 14.2 mm and thickness of 7.5 mm. The porosity was 0.15 (15% of total volume). The tablets were placed into a steel cylindrical ampoule with an external diameter of 20 mm. The ampoule was closed with top and bottom lids. The mixture in the ampoule was loaded by a steel impactor (tube) with an external diameter of 37 mm and wall thickness of 3 mm accelerated by explosion products. The mixture of ammonite/nitrate of ammonium in a proportion 1/1 with a density of 1.07 g/cm^3 was used as an explosive. The external diameter of the explosive was 64 mm. The assembly was located in the field of two X-ray tubes «Arion 600», which photographed the ampoule loading.

The X-ray photographs of the assembly are given in Figs. 1a, b before and during explosive loading. The exposure time was 1.5 ns. The analysis of X-ray photographs showed that the detonation velocity of explosive was 3.3 km/s, calculated Chapman-Jouguet pressure was 3.3-3.6 GPa depending on the assumed polytropic coefficient of detonation products 2.2-2.5. The distance passed by a detonation wave with a velocity of 3.3 km/s from the top of the impactor (ignoring the conic part of the ampoule lid) was 63.6 mm, and the angular deflection of accelerated impactor was 4.7 degrees (Fig. 1b). The external diameter of the ampoule after explosive loading was 19.2±0.2 mm in the upper part and 20±0.2 mm in the lower part.

To determine the parameters of explosive loading numerically, we considered the axially symmetric problem of interaction between a steel impactor (tube) accelerated by explosion products in the mode of sliding detonation and a cylindrical ampoule containing the two-component porous mixture of aluminium and sulfur.



a b c d

Fig. 1. X-ray photographs of the assembly with an external tube (a) before and (b) during explosive loading and the computer images of an axial section of the assembly at the moments of time (c) 0 and (d) 19 μs. P is the pressure and D is the velocity of detonation wave.

For the mathematical description of explosive loading, it is necessary to know not only the detonation velocity, but also the pressure of explosion products acting on the steel impactor versus time. In this work, it is assumed that the detonation process is stationary; the pressure of explosion products changes (drops) linearly in time.

Under these assumptions, the change in pressure can be described by the equation [10-12]:

$$P = P_0 - kt, \ (t = 0 \ldots \Delta t),$$

The coefficient k is given by:

$$k = \frac{P_0}{\Delta t}$$

Then the final equation for calculating the pressure of the explosion products takes the form:

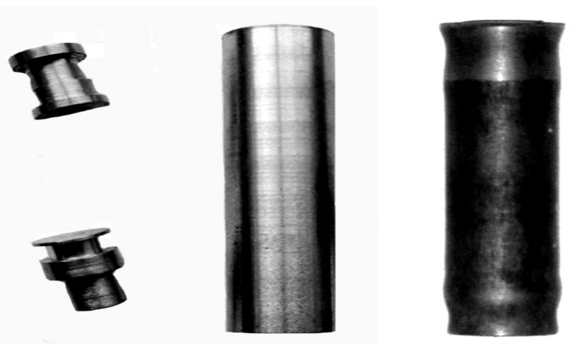
$$P = \begin{cases} P_0 - \dfrac{P_0}{\Delta t} t; & 0 \le t < \Delta t \\ 0; & t \ge \Delta t, \end{cases} \qquad \Delta t = \frac{\Delta}{c} \qquad c = \frac{D}{2}$$

where Δ is the thickness of the explosive layer, c is the average velocity of the unloading wave (assessment), D is the detonation velocity of explosives. P_0 is varied in computations to obtain good agreement between numerical and experimental results.

Figures 1c, d illustrate the computed configurations of an assembly section characterizing the simulation results of explosive loading at 0 and 19 μs for $P_0 = 4$ GPa. The numerical results showed that by 19 μs the distance passed by the detonation wave with a velocity of 3.3 km/s was 63 mm, and the angular deflection of the accelerated impactor was 4.76 degrees. The obtained numerical results for simulation of explosive loading and dynamics of the explosion product's influence on an impactor are in a good qualitative and quantitative agreement with experiments with an accuracy of 1.3%.

Experimental Results for Three-Component Media

In this series of experiments we investigated explosive loading of a cylindrical ampoule that contains a three-component mixture from aluminum, sulfur and graphite. To conduct explosive compaction, the inert substance (graphite) was added to the mixture of aluminum and sulfur in a proportion of 2/1, where graphite had two mass fractions and the mixture of Al-S had one mass fraction to avoid the reaction between aluminum and sulfur. The mass fractions of the components in the sample (mixture) were as follows: Al – 11.5, S – 21.5, C – 67; volume fractions: Al – 9.55, S – 23.35, C – 67.1. The components were mixed in an AGO-2U planetary mill, and then the mixture was pressed into eight tablets with a diameter of 14 mm and thickness of 8 mm. The measured porosity was 0.393±0.005. The tablets were placed into a steel ampoule with an inner diameter of 14 mm, an external diameter of 20 mm and a length of 84 mm. The ampoule was closed with lids (Fig. 2a).



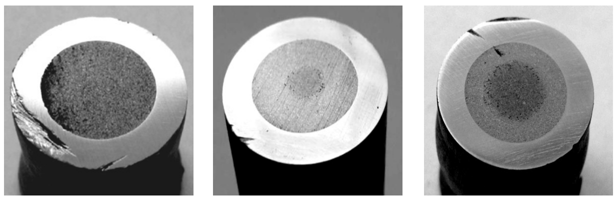
a b

Fig. 2. Ampoule (a) before and (b) after an experiment.

The ampoule was loaded by an explosive representing a composition of ammonite 21/79 (TNT/ammonium nitrate) + NaCl in the proportion 1/1 by mass. The measured explosive density was 1.2 g/cm^3. The external explosive diameter was 50 mm. The measured detonation velocity was 2.8 km/s. Figure 2b shows the ampoule after explosive loading. It is seen that the ampoule is uniformly compressed from top to bottom after the experiment. After comparison of the diameter of the ampoule before and after explosive loading, the compaction degree of the sample was ≈ 97% (residual porosity was 0.03).

To determine the phase composition of the sample, the ampoule was cut with an interval of 1 cm. Figure 3a shows the upper part of the sample after explosive loading. Composition of the mixture after loading was a homogeneous mixture of Al-S-C. The phase composition in this part of the ampoule was not changed. Approximately 15 mm from the upper part of the sample, there was the formation of the central zone different in color and, correspondingly, the phase composition from the peripheral part (Fig. 3b). The diameter of the central zone increases towards the lower part of the sample (Fig. 3c).

Phase analysis of the material from a central zone showed that it also comprised the reaction products of aluminum and sulfur (phase of aluminum sulfide). In this case, we can draw the conclusion that, despite the addition of graphite to prevent interaction between Al and S and reduce their mass fractions in the mixture, Al and S partially reacted in the axial region in the middle and bottom parts of the ampoule.



a b c

Fig. 3. Images of the (a) upper, (b) middle and (c) lower parts of the sample after explosive compaction.

Numerical Results for Three-Component Media and Discussion

For comparison with the experimental results of explosive compaction of the mixture, we numerically considered an axisymmetric problem of explosive loading of a cylindrical ampoule that contains a three-component inert mixture of aluminum, sulfur and graphite with the same mass and volume fractions as in the experiment. Behavior of the mixture is described by a mathematical model of a multicomponent medium. In the model, every component of a mixture simultaneously occupies the same volume as the mixture. Every component is characterized by the volume and mass concentration. Components interact with each other, exchanging momentum and energy. An equality of components' pressure is chosen as a condition for joint deformation of components. Finite element method is used for solving the problems.

The System of Equations Describing the Behavior of Inert Multicomponent Media under Explosive Loading

The system of equations describing the nonstationary adiabatic motion of each component in a solid compressible mixture comprises the equations of continuity, momentum, and energy [10, 11, 13, 14]:

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \alpha_i \rho_i \upsilon_i = 0, \quad (i = 1, 2, ..., N),$$

$$\alpha_i \rho_i \frac{d_i \upsilon_i}{dt} = \nabla \sigma_i + \alpha_i \sum_{j=1}^{N} \alpha_j \mathbf{R}_{ji}, \quad (i = 1, 2, ..., N),$$

$$\alpha_i \rho_i \frac{d_i E_i}{dt} = \sigma_i \varepsilon_i + \alpha_i \sum_{j=1}^{N} \alpha_j \Phi_{ji} \quad (i = 1, 2, ..., N),$$

where $$\frac{d_i}{dt} \equiv \frac{\partial}{\partial t} + \upsilon_i^k \frac{\partial}{\partial x^k}$$

Here t is the time, ρ_i is the density of the i-th component equal to the mass of i-th component per unit volume of the i-th component, υ_i is the velocity vector, E_i is the internal specific energy, ε_i is the strain rate tensor, $\sigma_i = -P_i\delta_i + S_i$ is the stress tensor, P_i is pressure, S_i is the stress deviator, R_{ji} is the intensity of the momentum exchange between the j-th and i-th components, Φ_{ji} is the intensity of the energy exchange between the j-th and i-th components, N is the number of components.

Volume fractions of the mixture occupied by each component [13] are given by:

$$\alpha_1 + \alpha_2 + ... + \alpha_N = 1, \ (\alpha_i \geq 0), \ \alpha_i = \rho_i^*/\rho_i,$$

where ρ_i^* is the reduced density (mass of the i-th component per unit volume).

Evolution of porosity in the material (compression and growth of pores) is simulated using a kinetic model of the active type, which determines changes in specific volume of pores influencing on the material properties and causing stress relaxation [15]:

$$\frac{dV_{fi}}{dt} = \begin{cases} 0, \ \text{if} \ |P_{si}| \leq P_i^* \ \text{or} \ (P_{si} > P_i^* \ \text{and} \ V_{fi} = 0) \\ -\operatorname{sign}(P_{si}) K_{fi} (|P_{si}| - P_i^*)(V_{2i} + V_{fi}), \\ \text{if} \ P_{si} < -P_i^* \ \text{or} \ (P_{si} > P_i^* \text{and} \ V_{fi} > 0), \end{cases}$$

where $P_i^* = P_{ki}V_{1i}/(V_{fi} + V_{1i})$, P_{si} is the pressure in the solid (undamaged) part of the i-th component in the mixture, V_{1i}, V_{2i}, P_{ki}, K_{fi} are the experimentally determined constants of the material.

Studying the deformation of multicomponent media, it is necessary to take into account the state and response of each component, as well as, in contrast to a homogeneous mixture [7-9, 16], not only the displacement of the external boundaries of the selected volume, but also the displacement of components in the selected volume of the mixture. In this paper, we consider the equality of pressures during the interaction of components to be a condition for joint deformation of components in the mixture, which determines volume concentrations of the components [10, 13]:

$$P = P_i (V_i, E_i) = P_j (V_j, E_j) = \ldots = P_N (V_N, E_N).$$

The temperature was calculated using the following ratio [8, 10, 16]:

$$dT_i = \begin{cases} d(E_i - E_{0xi})/c_{pi}, & \text{if} \ T_i < T_{mi} \\ 0, & \text{if} \ T_i = T_{mi} \\ d(E_i - E_{0xi} - \Delta H_{mi})/c_{pi}, & \text{if} \ T_i > T_{mi} \end{cases}$$

where the specific heat capacity c_{pi} increases linearly with increasing the temperature up to the melting point of a substance, E_{0xi} is the "cold" component of the specific internal energy, T_{mi} is the melting temperature, ΔH_{mi} is the specific melting heat of the i-th component.

Numerical Results and Discussion

We consider the axisymmetric problem of explosive compaction of a three-component mixture from aluminum, sulfur and carbon placed into a cylindrical steel ampoule. The inert substance (graphite) was added to the mixture of aluminum and sulfur in a proportion of 2/1 to avoid the reaction between aluminum and sulfur. The mass fractions of the components in the sample (mixture) were taken as in the experiment: Al – 11.5, S – 21.5, C – 67.0; the volume fractions: Al – 9.55, S – 23.35, C – 67.1.

The porosity of the mixture was 0.4 (ratio between the volume of pores and total volume). The height of the cylindrical sample was 64 mm, the diameter was 14 mm. The thickness of the lateral wall of the ampoule was 3 mm, the thickness of top and bottom lids was 10 mm. The height of the ampoule (H) was 84 mm, the external diameter was 20 mm (Fig. 4a).

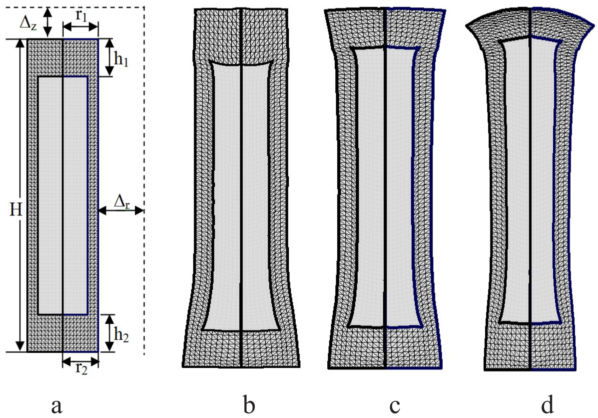


Fig. 4. Ampoule at the (a) initial moment of time and at 80 μs after explosive compaction for different thickness of the axial explosive layer Δ_z: (b) 5 mm; (c) 30 mm; (d) 40 mm.

In the computations the actions of the detonation products surrounding the ampoule was simulated by the action of pressure on the upper part of the ampoule in a vertical (axial) direction and on the lateral surface of the ampoule in a horizontal (radial) direction. In the axial direction the action started at the initial moment of the process, and in the radial direction the action stated during propagation of the detonation wave from top to bottom [10, 12]. The detonation velocity was D = 2.8 km/s on the basis of experimental data. The P_0 value was chosen on the basis of numerical and experimental evaluations and was 3.2 GPa.

In the computations we varied the thickness of the explosive Δ_z in the axial direction, that act on the upper part of the ampoule in order to study the influence of the parameter on a final shape and size of the ampoule. The value Δ_r for the explosive acting radially on the lateral wall of the ampoule was constant and equal to 18 mm. In [10-12], a similar approach was applied to the simulation of explosion products acting on the cylindrical ampoule with a reactive mixture. Attention was paid to the action of explosives on the lateral surface of the ampoule, and the possible influence of the axial explosive layer on the upper part of the ampoule was not considered.

Figures 4 b-d show the evolution process for explosive compaction of a cylindrical ampoule with an inert mixture for different thicknesses of an axial layer of the explosive. Figures are given at the time of 80 microseconds. This moment of time illustrates the final stage of explosive compaction of the inert mixture in the cylindrical ampoule. The results of computations show a significant influence of the axial explosive layer on the final results of explosive loading. When the thickness Δ_z is low, the influence of lateral load prevails, which leads to elongation of the ampoule in the axial direction (Fig. 4b). When the thickness Δ_z is high, there is an additional load on the upper part of the ampoule, which causes deformation of the top lid of the ampoule (compaction in the axial direction and elongation in the radial direction) and a portion of the mixture.

Analyzing Fig. 4, we can conclude that for positive results of compaction it is necessary to select a number of parameters for explosive loading. It is important to choose appropriate explosives and the thickness of explosives. Insufficient thickness of explosives, as well as excessive thickness will lead to unsatisfactory results of explosive compaction, in particular, the incompletely compacted final product, cracks and damages. In addition, the excessive thickness of explosives in the axial direction strongly distorts the shape of the ampoule during explosive compaction (Fig. 4d).

Table 1 shows the numerical results for the loaded cylindrical ampoule with an inert mixture from aluminum, sulfur and carbon, when the thickness of the explosive layer is varied in the axial direction. Here Δ_z is the thickness of the axial layer, H is the height of the ampoule after loading, h_1, r_1 and h_2, r_2 are the height and radius of top and bottom lids of the ampoule. The initial values of the parameters are as follows: H=84 mm; h_1= h_2=10 mm; r_1 = r_2=10 mm.

Table 1
Results of computations

#	Δ_z mm	H, mm	h_1, mm	h_2, mm	r_1, mm	r_2, mm
1	0	92.8	17.2	9.0	7.6	11.1
2	5	89.0	13.9	9.0	8.8	11.1
3	10	85.4	11.9	9.0	9.8	11.1
4	15	83.2	10.8	8.9	10.3	11.1
5	20	80.9	10.0	8.9	10.5	11.1
6	25	78.6	9.3	8.7	11.0	11.2
7	30	76.1	8.2	8.7	11.9	11.2
8	35	73.2	6.9	8.8	13.4	11.1
9	40	69.6	5.5	8.9	15.4	11.0

Figures 5 and 6 show the plots for the parameters of the ampoule with an inert mixture subjected to explosive compaction versus the thickness of the axial explosive layer. These plots are given for the moment of time 80 μs after the beginning of the compaction process. The computations show that the wave and deformation processes are completed by this moment of time, and the received data can be considered to be the final data after loading.

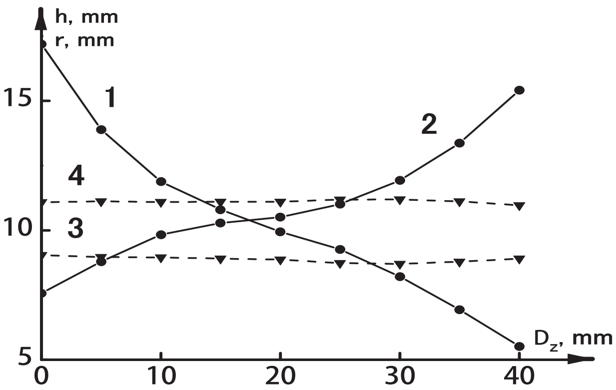


Fig. 5. Height and radius of the ampoule lids versus the thickness of the axial explosive layer: curves 1, 2 – height and radius of the upper lid of the ampoule, curves 3, 4 – height and radius of the bottom lid of the ampoule.

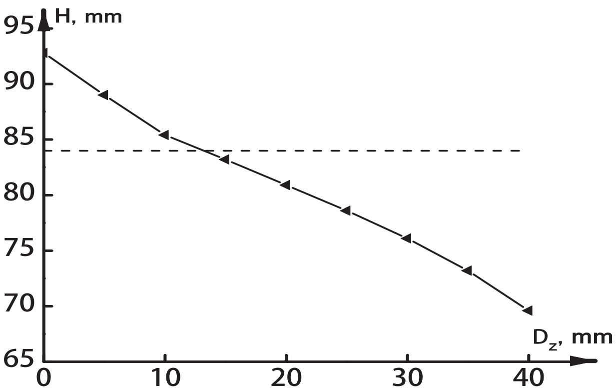


Fig. 6. Height of the ampoule after loading versus the thickness of the axial explosive layer. Dashed line is the initial value of the height of the ampoule.

The computation results show that the change in thickness of the layer Δ_z within the range of 0÷13 mm is not sufficient for compaction of the ampoule in the axial direction and leads to an increase in height of the ampoule. In addition, it is observed an increase in height of the top lid of the ampoule (Fig. 5, curve 1). The increase in axial explosive layer Δ_z leads to the decrease in height of the ampoule and, as a result, further compaction of the mixture in the axial direction. Using the thickness of the axial explosive layer within the range of 35÷40 leads to a strong distortion of the shape of the ampoule, in particular, the top lid of the ampoule and the mixture in this area. The parameters of ampoule, obtained for the thickness of the axial explosive layer Δ_z = 30 mm, are in good agreement with experimental data (Fig. 2b). The value Δ_r for the explosive acting radially on the lateral wall of the ampoule was constant and equal to 18 mm. The numerical computations have shown that in this case the degree of compaction for the porous sample of the mixture was about 97%. The parameters for the bottom lid of the ampoule changed insignificantly for all cases.

Conclusions

The article presents the results of experimental and numerical research in the process of explosive loading of cylindrical ampoules that contain two- and three-component solid mixtures. Experiments were conducted using X-ray registration of the dynamic process and subsequent analysis for the phase composition of the mixture. Numerical computations were carried out by finite element method based on the model of a multicomponent medium.

Studying explosive loading of the cylindrical ampoules with a two-component solid mixture of aluminum and sulfur, we experimentally obtained and numerically adapted the parameters of explosive loading. At the same time we proposed an approach to the mathematical description of the initiation and development of explosive loading, as well as we found the dependence for the pressure of detonation products versus time. The numerical results reflecting the dynamics of explosive loading and the influence of explosion products on an impactor are in good qualitative and quantitative agreement with experiments.

We experimentally and numerically investigated explosive loading of cylindrical ampoules that contain a three-component mixture of aluminum, sulfur and graphite. The inert substance (graphite) was added to the mixture to avoid the reaction between aluminum and sulfur. The experiment showed that Al and S partially reacted in the axial region in the middle and bottom parts of the ampoule, and the reaction region increased towards the bottom part of the ampoule.

We investigated numerically the influence of the initial thickness of the explosive layer in the axial direction on the final shape of the ampoule. We found the essential influence of the thickness of the explosive layer on the final result of explosive compaction. Insufficient thickness of explosives, as well as the excessive thickness may be a reason for an incompletely compacted final product or lead to the formation of cracks or damage.

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