Interaction of the conical impactor with barriers containing an explosive

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Abstract. This paper presents the actual problem of the dynamic interaction of a high-speed impactor with a screened explosive. The interaction mathematical model is based within the framework of continuum mechanics considering the mechanism of the shock-wave initiation of detonation in solid explosives. Testing of the method was conducted using experimental data in one dimension. Some problems of interaction of the conical impactor with the explosive protected one-layered and spaced metal barriers are numerically considered.

1. Introduction

In solving a lot of practical problems, including the development of containers for safe storage and transportation of explosives, it is necessary to predict the effects of impact interaction between a solid deformable body and a screened explosives.

The results of experimental and theoretical studies show that the main features of the mechanism of the shock-wave initiation of detonation in solid explosives are determined by their initial inhomogeneity [1-10]. As a result of the shock wave interaction with inhomogeneities due to various mechanical processes (pore collapsing, microclusters on inclusions and pores, grain cracking, friction between the particles, etc.), there are explosive local nucleation sites or ‘hot spots’ forming at the spots where exothermic decomposition originates. The necessity of introducing the concept of ‘hot spots’ based on the fact that volumetric average temperature of the explosive is too low to cause the observed degradation in case of the shock-wave initiation.

The less heated mass of the explosive burns out in the reaction waves propagating from the centers. The development of the explosive transformation process leads to an increase in the pressure behind the initiating shock wave and its amplification. The temperature and the amount of the nucleation site for the reaction igniting surrounding substance increase with the increase of the shock wave. When the shock wave becomes sufficiently strong to react with all of explosives, detonation begins.

The purpose of the research is mathematical modeling to predict the effects of high-speed interaction of the elongated metal conical impactor with the solid explosive screened by a thin plate.

2. The mathematical model of the shock-wave initiation of detonation in solid explosives

According to the model of reaction initiation and the growth [11], the macrokinetics formula includes two parts where the first one describes the ignition process and the second one describes the posterior reaction growth:
\[
\frac{dw_i}{dt} = A_i w_i \left( \frac{1}{\delta_i} - \frac{1}{\delta_e} \right)^m + B_i w_i^z \rho^\gamma,
\]  

(1)

where \( w_i, \delta_i = \frac{\rho_{i_0}}{\rho_i} \) – the mass fraction and fractional specific volume of the explosive;

\[ w_2 = 1 - w_i \] – the mass fraction of detonation products;

\( \delta_e, A_i, B_i, m, z \) – constants determined by reference to experimental data;

\( x, y \) – exponents depended on the combustion geometry.

For describing of explosives \((i = 1)\) and decomposition products \((i = 2)\), the equation of state is applied in the Mie-Grüneisen form, where isentrope is used as a supporting curve with constant Grüneisen parameter \( \gamma_0 \) in the following form:

\[
\varepsilon_i = \frac{C_i}{R_i \exp (R_i \delta_i)} + \frac{D_i}{R_i \exp (R_i \delta_i)} + \frac{E_i}{\gamma_0 \delta_i^{\gamma_0}} - \varepsilon_{i_0},
\]  

(2)

where \( \delta_i = \frac{\rho_{i_0}}{\rho_i} \);

\( C_i, D_i, E_i, R_{i_1}, R_{i_2}, \varepsilon_{i_0} \) – empirical constants.

To close the system of equations, describing the movement of reactive mediums as a part of the hydrodynamic model, additivity of volume phases is introduced:

\[
\frac{1}{\rho} = \frac{w_1}{\rho_1} + \frac{w_2}{\rho_2}.
\]  

(3)

And the local pressure equilibrium is assumed to be performed in the medium:

\[
p = p_1 \left( \rho_1, \varepsilon_1 \right) = p_2 \left( \rho_2, \varepsilon_2 \right).
\]  

(4)

Additionally, the difference between the sum of two internal energies (where the first one is the explosion products energy defined by isentrope and the second one is explosive energy determined by the Hugoniot adiabatic) and the total internal energy of the elementary volume is believed to be distributed among the components in accordance with the ratio of the first internal energy to the second internal energy. Then:

\[
\varepsilon_1 = \varepsilon_{H1} + \left[ \frac{\varepsilon - w_i \varepsilon_{H1} - w_2 \varepsilon_{H2}}{w_i \varepsilon_{H1} + w_2 \varepsilon_{H2}} \right] \varepsilon_{H1},
\]

\[
\varepsilon_2 = \varepsilon_{H2} + \left[ \frac{\varepsilon - w_i \varepsilon_{H1} - w_2 \varepsilon_{H2}}{w_i \varepsilon_{H1} + w_2 \varepsilon_{H2}} \right] \varepsilon_{H2},
\]

(5)

where

\[
\varepsilon_{H1} = \frac{C_i \delta_i - \gamma_0 \varepsilon_{i_0}}{R_i \delta_i} + \frac{D_i \delta_i - \gamma_0 \varepsilon_{i_0}}{R_i \delta_i} + \varepsilon_{i_0},
\]

(6)

– the explosive internal energy on the Hugoniot adiabatic.

3. Testing of the mathematical model

To verify the model [11] of shock wave initiation of detonation in heterogeneous explosives and to determine the constants of the macrokinetics formula within the one-dimensional deformed state, the calculation for the collision process of the copper plate thickness of 0.76 mm with an open charge explosives PBX-9404 density of 1.844 g/cm³ at a velocity of 550 m/s was conducted. Results of experimental studies are described in [12]. The calculation was performed using the modified
numerical method of large particles [13]. Table 1 shows the parameters of the state equation and the initiation model and reactions progressing in the heterogeneous explosive.

Table 1. The parameters of the state equation, the initiation model and reactions progressing.

| Parameters          | PBX-9404 | Reaction product |
|---------------------|----------|------------------|
| $C_i$, GPa·cm$^3$/g | 10889.37 | 462.26           |
| $\gamma_{ii}$       | 0.4541   | 0.38             |
| $R_{ii}$            | 9.0      | 4.6              |
| $D_i$, GPa·cm$^3$/g | -141.43  | 9.77             |
| $R_{2j}$            | 4.5      | 1.3              |
| $\varepsilon_{0i}$, GPa·cm$^3$/g | 0.3 | 5.53 |
| $E_i$, GPa·cm$^3$/g | –        | 0.6726           |
| $A_i$, µs$^{-1}$    | 20.0     | –                |
| $B_1$, GPa$^2$/µs  | 6000     | –                |
| $z$                 | 1.2      | –                |
| $m$                 | 4.0      | –                |
| $x$                 | 0.2222   | –                |
| $y$                 | 0.6667   | –                |
| $\delta$            | 0.9822   | –                |

Figure 1 shows a comparison of the calculated pressure profiles in the three sections of the charge (solid lines) and experimental (dashed) pressure profiles. At the initial moment, sensors were apart from the impact surface at distances of 0, 3 and 7 mm. A satisfactory agreement of the data is observed. A decrease of the shock wave amplitude and pressure over the time did not happen as quickly as it did in the experiment.

At different times, Figure 2 shows (microseconds) the calculated pressure profiles and shares of the unreacted explosive depending on the distance by which one can judge the dynamics of the reaction development.

Shock waves with the amplitude of 2.9 GPa, propagating from the moving contact surface, are produced during the collision in the copper impactor and charge of explosive PBX-9404. Explosive decomposition begins directly from the impact surface. The pressure pulse, growing in size and propagating deep into the charge, is generated. This pressure pulse subsequently catches up with the shock wave front and amplifies it. The copper plate shock wave reaching the free surface is reflected in the shock-compressed material as expansion waves. As a result of their action, in spite of the expansion process, the explosive pressure is firstly reduced and then increased (figure 1). At 3.5 µs, the sample pressure reaches the value of the Chapman-Jouquet point, and afterwards, shock wave transition occurs relatively fast with the detonation reaction. The computed pressure in the chemical peak is 54 GPa and in the Chapman-Jouquet point, it is 37 GPa. The detonation wave propagates at a velocity of 8791 m/s, this agrees sufficiently with the experimental data.
4. The results of numerical research

Let us consider a numerical solution for some axisymmetric impact problems of the truncated cone (0.12×0.7×8.5 cm) made from composite TNI-95 containing explosive PBX-9404 in design. In all cases, the minimum velocity (accuracy to 100 m/s), when the shock detonation has been initiated for the given target, is taken as the bodies interaction initial rate.

Numerical modeling results are presented in cylindrical coordinates $z$ (cm), $r$ (cm). The right half-plane of the images shows a pressure field (MPa); the left one shows a mass velocity vector field. Here, $u_{\text{max}}$ is the longest vector module, $t$ is time. The destroyed material area [14] is marked by the black color in the left half-plate of the images; the reaction zone is marked by red.

Figure 3 shows a collision process with an explosive charge in the AlMg-6 aluminum alloy shell of 0.8 cm thickness with a velocity of 800 m/s.

$t = 30 \text{ } \mu\text{s}, \ u_{\text{max}} = 803 \text{ } \text{m/s}$ $t = 32 \text{ } \mu\text{s}, \ u_{\text{max}} = 1474 \text{ } \text{m/s}$ $t = 33 \text{ } \mu\text{s}, \ u_{\text{max}} = 2320 \text{ } \text{m/s}$

Figure 3. The detonation of explosives in the AlMg6 shell
The impactor had punctured the shell by the time of 30 µs. And at a certain distance, in the explosive, the impactor initiated the explosive decomposition.

An area occupied by the reaction products had been formed by the time of 32 µs. A detonation complex was formed by 33 µs.

Figure 4 shows the chronogram of shock-wave initiation for detonation of the explosive in the VT1-0 titanium alloy shell of 0.8 cm thickness. A minimum velocity for the barrier blasting is already 1200 m/s.

![Figure 4. The detonation of explosives in the VT1-0 shell](image1)

$t = 1 \mu s, u_{\text{max}} = 1199 \text{ m/s}$

$t = 18 \mu s, u_{\text{max}} = 2349 \text{ m/s}$

![Figure 5. The detonation of screened explosives](image2)

$t = 97.74 \mu s, u_{\text{max}} = 889 \text{ m/s}$

$t = 97.8 \mu s, u_{\text{max}} = 1747 \text{ m/s}$
Figure 5 depicts a shot at a velocity of 800 m/s in the design, consisting of the AlMg6 aluminum alloy screen of 0.8 cm thickness and the bilayer barrier situated at the distance of 5 cm behind it: the first layer is the AlMg6 aluminum alloy of 0.4 cm thickness, the second one is explosive PBX - 9404. The cone punctured the screen and shell by 97.74 µs. The explosive pressure value reached the Chapman-Jouquet point, and afterwards the shock wave transition was relatively fast with the detonation reaction ($t = 97.8 \mu s$).

5. Conclusion
The interaction mathematical model of the high-speed impactor with explosive protected by the metal barrier in the framework of continuum mechanics, taking into account the mechanism of the shock-wave detonation initiation in solid explosives, is developed.

Numerical modeling of the conical impactor influence on barriers, containing explosive PBX-9404, is conducted in the impact velocities range involving the shock-wave detonation initiation.

We considered the explosives protection by aluminum alloy (AlMg6) and titanium (VT1-0) alloy plates when plates are both adjacent to the explosive surface and separated from the explosive by some distance. Stable initiation of the charge protected by both the AlMg6 aluminum alloy single plate and the two plates spaced by a distance occurs at velocities of about 800 m/s. To initiate the charge in the shell of VT1-0, the considered drummer must have the speed of about 1200 m/s. For initiation of the charge in the VT1-0 titanium alloy shell, the considered impactor must have a velocity of about 1200 m/s.

References
[1] Tarver C M 2012 *J. Ener. Mat.* **30**(3) 220-251
[2] Lee E L, Tarver C M 1980 *Physics of Fluids* **23**(12) 2362-2372
[3] Sheffield S A, Bloomquist D D, Tarver C M 1984 *The J. Chem. Phys.* **80**(8) 3831-44
[4] Wei L, Dong H, Pan H, Hu X, Zhu J 2014 *J. Ener. Mat.* **32**(4) 238-251
[5] Bel'skii B M 2012 *Combustion, Explosion and Shock Waves* **48** 328-334
[6] Lee J, Kuk J, Cho Y, Song S, Lee J W 1997 *Propellants, Explosives, Pyrotechnics* **22** 337-346
[7] Treadway S K, Lloyd A N 2013 *Procedia Engineering* **58** 550-559
[8] Tarver C M, Parker N L, Palmer H G, Hayes B, Erickson L M 1983 *J. Ener. Mat.* **1**(3) 213-250
[9] Gruau C, Picart D, Belmas R, Bouton E, Delmaire-Sizes F, Sabatier J and Trumel H 2009 *Int. J. Impact Eng.* **36**(4) 537-550
[10] Picart D, Ermisse J, Biessy M, Bouton E, Trumel H 2013 *Int. J. Ener. Mat. and Chem. Prop.* **12**(6) 487-509
[11] Green L 1981 *Detonation and Explosives* (Moscow: Mir) pp 107-122
[12] Wakerly J 1981 *Detonation and Explosives* (Moscow: Mir) pp 269-290
[13] Habibulin M V 1997 *Issues of Nuclear Science and Technology* **3** 18-24
[14] Belov N N, Korneev A I, Simonenko V G 1990 *Proc. of Academy of Sciences* **310**(5) 1116-20