Materials Physics and Mechanics 42 (2019) 711-716 Received: April 18, 2018

USE OF ADVANCED MATERIALS IN PROTECTION AGAINST HIGH-VELOCITY IMPACT AND EXPLOSION

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Abstract. Numerical studies of the behavior of combined barriers consisting of solid and porous materials were carried out during high-speed impact on them with thin plates. It is shown that the introduction of plates of porous materials into the composition of combined barriers can significantly reduce the amplitude of compression waves and reduce the likelihood of spall damage. Comparison of the results of numerical modeling of high-speed impact interaction processes with the experimental results of other authors showed their good qualitative and quantitative agreement.

Keywords: high-velocity projectiles, high-velocity explosion, fracture, multilayered targets

1. Introduction

Recent studies have shown that combined (multilayered) targets have higher protective properties compared to solid ones. The composition of such targets, in addition to solid metal materials, includes ceramics [1], metal ceramics [2], metal composites [3], functionally gradient materials [4-5] and porous materials [6-9]. Porous fillers, screens and protective layers play an important role in reducing the level of loads in protected objects to prevent fracture. Materials with a continuous or discrete-continuous change in properties are commonly referred to as functionally gradient materials [10]. These materials can be used in pulsed dynamic loading as hardening coatings due to the unique capability to transform an incident pulse (weaken, delay in time, redistribute over the volume of material in the desired direction).

Some structural materials consist of several components which have different physical and mechanical characteristics. The effect of technological processes on modern construction materials leads to the formation of property gradients caused by this effect and/or the different concentration of initial components at nearly points. The use of technological processes allows us, in addition to the gradients of physical and mechanical properties, to obtain the initial porosity gradients in materials, i.e. to create functionally gradient porous materials (FGPM). A work [10] is devoted to the investigation of the propagation and transformation of shock waves in gradient materials, the component concentration of which smoothly varies through the thickness.

2. Model of deformation and fracture of a porous multicomponent elastic-plastic medium with a continuous change in physical and mechanical characteristics

A model of a perfectly elastic-plastic porous material with a continuous spatial distribution of physical and mechanical properties is used to describe the behavior of layers in materials [10].

http://dx.doi.org/10.18720/MPM.4262019_3

This model describes the behavior of isotropic, layered, porous, mixed, and functionally gradient materials which can be used in an advanced composite target. The close link of mathematical simulation and experimental research allows us to improve the efficiency and effectiveness of modern protection. Many experiments [11] confirmed the validity of using the model of a perfectly elastic-plastic compressible body for calculating the strain-stress state of structural elements at moderate impact velocities and under explosive loading. The numerical simulation of high-velocity impact, explosive loading and fracture of shells and plates (for practical purposes) [12] is in good agreement with real experiments, which also demonstrates the applicability of this model to the calculation of structural elements under intensive shock and explosive loading.

3. Test calculations

A number of test problems were solved [10] to test the proposed model. The results obtained were compared to the results in [11], numerical calculations for the equation of state in [10] and the equation of state in [12]. The work [10] provides the shock adiabatic curve of solid copper and the velocity of the rear surface during the interaction of two copper plates. The similar calculations were conducted for tungsten, and the work [13] provides calculated and experimental data on the compaction of porous copper. The equation of state [10] was estimated for a number of Cu-W alloys with different contents of copper and tungsten. The experimental data were taken from [11]. The interaction of two copper plates with a thickness ratio of 2:1 was considered to test the spall fracture model. The localization of a spall crack at the center of the target is in good agreement with the theoretical concepts. In addition, the velocity of spall plates is compared with that of an aluminum projectile (0.2 cm in thickness) accelerated at a velocity of 450 m/s during the interaction with a copper target (1.4 cm in thickness). In the experiment [14] the obtained velocity was 213 m/s and 209 m/s in the calculation.

4. Results and discussion

The proposed model was used to calculate a number of multilayered targets listed below.

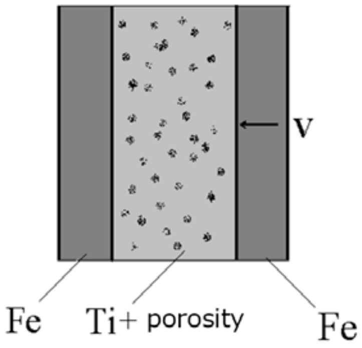


Fig. 1. Target protected by a layer of porous Titanium

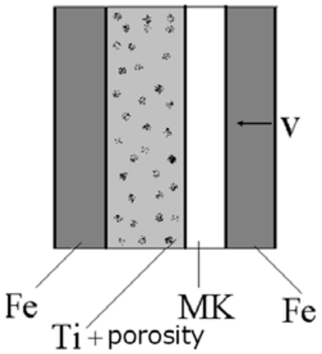


Fig. 2. Target protected by a layer of porous Titanium and metal ceramics (MC)

The material of the target and projectile is steel. The thickness of the target is 0.3 cm, and the thickness of the projectile is 1.2 cm. The total thickness of the protective layer is 2.7 cm. In the case when a layer of metal ceramics is used, its thickness is 1.2 cm. The equation of state was taken from the work [11] to calculate metal ceramics. The main physical and mechanical material characteristics required for conducting numerical computations were taken from the works [10-11]. The velocity of the projectile was 1000 m/s. A porous titanium protective layer was used in the layered system under study. The solid line corresponds to

1 μs, the dashed line corresponds to 6 μs and the dash-dotted line corresponds to the moment of fracture. The same notations will be used further in the text of the paper.

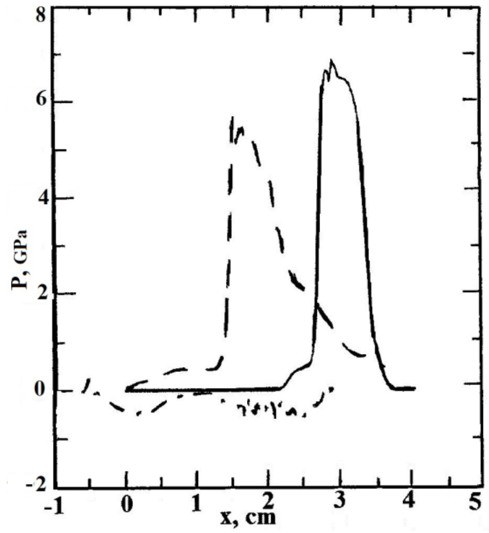


Fig. 3. Pressure distribution

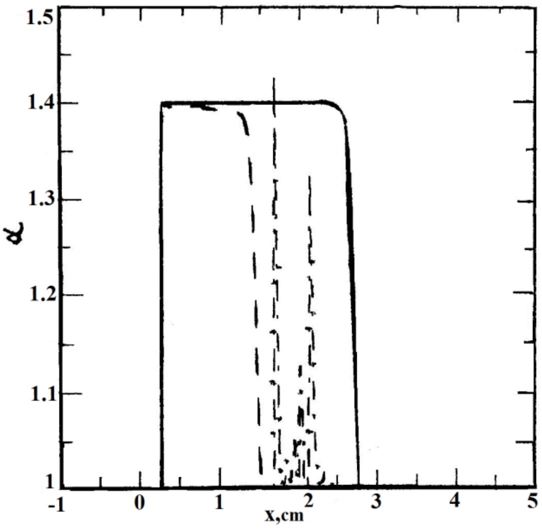


Fig. 4. Porosity distribution

Figure 3 shows the propagation of a shock wave through a layered system with a porous protective layer. Adding the porous layer led to a displacement of the fracture zone in the projectile and an increase in the time for the fracture of the projectile to 23.5 μs (Fig. 4).

Next, a layered system was considered where a plate of metal ceramics was placed between a layer of porous titanium and a projectile. The composition of metal ceramics was as follows: 20% Al_2O_3+80% Al. The change in pressure in a shock wave is shown for three moments of time in Fig. 5. In Fig. 6 the solid line demonstrates the initial porosity distribution in the layered system. The dashed line shows the porosity distribution at the moment of time t=6 μs. There is a section of not fully compressed porous titanium. Noticeable damage is observed in the titanium layer (α=1.27) and in the projectile (α=1.31) at the moment of time t=11.2 μs corresponding to the spall fracture of the target.

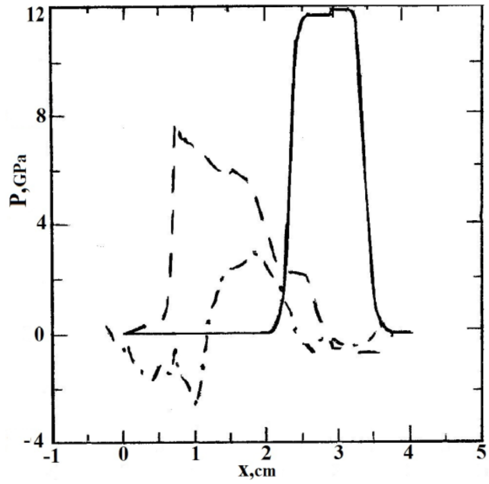


Fig. 5. Pressure distribution

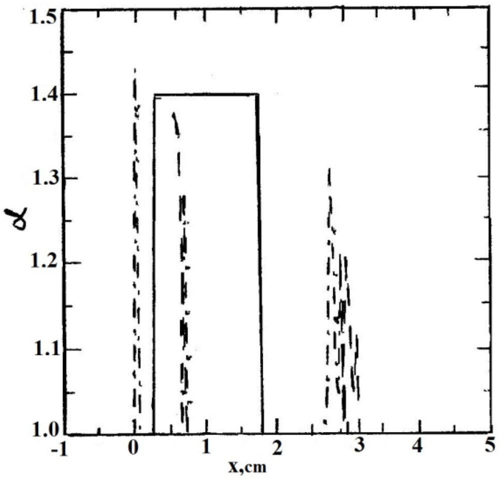


Fig. 6. Porosity distribution

We consider a layered system consisting of the barrier, a protective layer, a layer of the explosive and a throwing plate. In this situation it is necessary to maintain the barrier integrity and prevent spall fracture because of explosives impact.

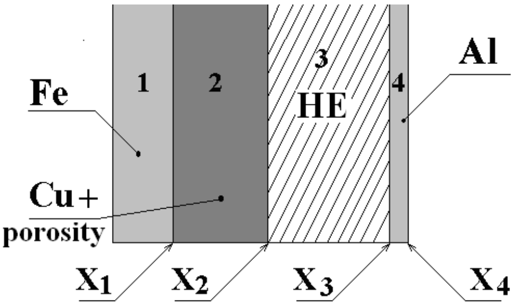
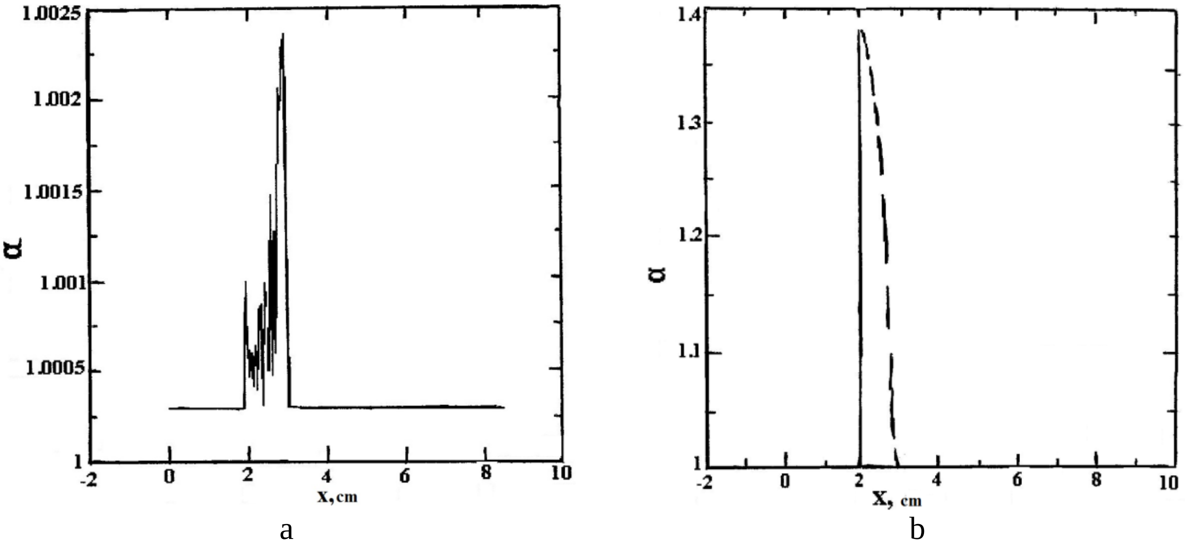


Fig. 7. Type of layered systems

In the one-dimensional approximation we considered (Fig. 7) type of layered systems consisting of two solid elastic-plastic plates (1, 4), porous copper elastic-plastic plate having a porosity distribution (2) (Fig. 7). The plate (1) is a steel throwing plate and (4) – aluminum plate, initial density of HE ρ_0=1.36 g/cm^3, detonation velocity D=0.62 cm/μs. For base variants thickness of the barrier (1) was 2 cm, of the protective layer (2) - 1 cm, HE (3) - 2 cm and that of the metal plate (4) - 1 cm, X_1 - the right boundary of layer 1; X_2 - the right border of layer 2; X_3 - right boundary of layer 3; X_4 - right boundary of layer 4.



a b

Fig. 8. The distribution of current porosity α in the layered system at t = 19 μs for protective layers which equal cm 2 (a) and 3 cm (b) (α_0 = 1.4)

The protective properties of the porous layers were examined. When the thickness of the protective layer 2 cm and α_0=1.4 (Fig. 8, a) spalling does not occur, although little damages visible in the barrier. Increased protective layer 3 cm fully protects the barrier from damage and, as seen in Fig. 8, b porous layer is not even fully compressed. Furthermore, the weight of the porous protective layer is significantly less than the weight of the continuous protective layer.

For next calculations used a gradient distribution of porosity along the thickness of the protective layer. Porosity values varied from α_0= 1.0003 at the interface with the HE to a value α_0=1.4 at the contact with the barrier. Gradient distribution of porosity allows to form protective layers with different along thickness a physic-mechanical properties. In the cases considered we have a more strength protective layer in contact with a surface of HE, and then the protective layer reduces its strength properties along its thickness. It should be noted that the speed of the back surface of barrier is 300 m/s, speed of metal plate (4, Fig. 7) 1400 m / sec (Fig. 9), i.e. the introduction of porous layers we can reduces the rate of the back surface, and prevent spalling and throw plate with required speed.

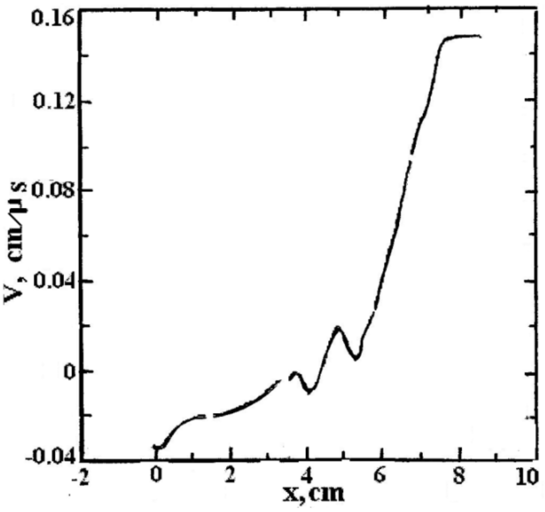


Fig. 9. The velocity distribution in a layered system having a gradient porosity. A protective layer thickness of 2 cm, t=19 μs

5. Conclusions

A set of numerical experiments was carried out to calculate the high-speed collision of thin metal plates (impact velocity ~1000m / s and more) with combined obstacles based on the model of an ideal elastic-plastic porous body proposed by the author in [10]. These plates consist of solid metal plates and plates of porous metals (porous titanium, porous copper), as well as porous cermets. The effectiveness of the use of porous materials has been shown as part of combined barriers that perform the function of protecting the main structure from high-speed impact.

It is shown that the introduction of porous layers into the composition of combined barriers allows one to significantly change the amplitude of elastic-plastic waves as they propagate deep into the barrier. This achieves a reduction in the impulse load on the protected structural elements.

A numerical calculation of the combined barrier, which in addition to solid and porous plates includes a layer of explosives, was performed. It is shown that by changing the thickness of the protective layer of porous copper, it is possible to avoid damage in the explosive in the form of multiple spalls.

Acknowledgements. *The work is financially supported by the Federal Targeted Program for Research and Development in Priority Areas of Development of the Russian Scientific and Technological Complex for 2014-2020 under the contract No. 075-15-2019-1702 (unique identifier RFMEFI60519X0183).*

References

[1] Gerasimov AV, Pashkov SV. Numerical simulation of the perforation of layered barriers. *Composites: Mechanics, Computations, Applications, International Journal.* 2013;4(2): 97-111.

[2] Goncalves DP, de Melo FCL, Klein AN, Al-Qureshi HA. Analysis and investigation of ballistic impact on ceramic/metal composite armour. *International Journal of Machine Tools and Manufacture.* 2004;44(2-3): 307-316.

[3] Zhu D, Wu G, Chen G, Zhang Q. Dynamic deformation behavior of a high reinforcement content TiB2/Al composite at high strain rates. *Materials Science and Engineering: A*. 2008;487(1-2): 536-540.

[4] El-Hadek M, Kaytbay S. Mechanical and physical characterization of copper foam. *International Journal of Mechanics and Materials in Design.* 2008;4(1-3): 63-69.

[5] Eghtesad A, Shafiei AR, Mahzoon M. Study of dynamic behavior of ceramic-metal FGM under high velocity impact conditions using CSPM method. *Applied Mathematical Mo*deling. 2012;36(6): 2724-2738.

[6] Ipatov AA, Belov AA, Amenitskiy AV. Study of viscoelastic parameter influence on dynamic response in poroviscoelastic prismatic solid. *Materials Physics and Mechanics.* 2016;28(1-2): 91-95.

[7] Igumnov LA, Litvinchuk SY, Petrov AN. A numerical study of wave propagation on poroelastic half-space with cavities by use the BEM and Runge-Kutta method. *Materials Physics and Mechanics*. 2016;28(1-2): 96-100.

[8] Igumnov LA, Ipatov AA, Belov AA, Litvinchuk SY. Boundary Element Method in solving dynamic problem of poroviscoelastic prismatic solid. *Materials Physics and Mechanics*. 2017;31(1-2): 1-4.

[9] Igumnov LA, Litvinchuk SY, Petrov AN, Aizikovich SM. Simulation of a compressional slow wave in partially saturated poroelastic 1-D column. *Materials Physics and Mechanics*. 2017;31(1-2): 9-11.

[10] Gerasimov AV, Krektuleva RA. Deformation and fracture model for a multicomponent elastoplastic porous medium with continuous variation of physicomechanical characteristics. *Strength of Materials.* 1999;31(2): 210-218.

[11] Stanyukovich KP. *Physics of Explosions*. Moscow: Nauka; 1975. (In Russian)

[12] Wilkins ML. *Computer simulation of dynamic phenomena.* Heidelberg: Springer; 1999.

[13] Kinslow R. *High-Velocity Impact Phenomena.* New York: Academic Press; 1970.

[14] Kanel GI, Razorenov SV. *Shock wave loading of metals: The motion of the free surface of sample.* Chernogolovka: Institute of Chemical Physics, USSR Academy of Sciences; 1989. (In Russian)