AIP | Conference Proceedings

High-speed impact of the metal projectile on the barrier containing porous corundum-based ceramics with chemically active filler

Alexander Ischenko, Svetlana Afanas'eva, Nikolai Belov, Vasiliy Blinov, Vladimir Burkin, Leonid Korolkov, Konstantin Rogaev, Marat Khabibullin, and Nikolai Yugov

---

Articles you may be interested in

Enhanced heat transfer through filler-polymer interface by surface-coupling agent in heat-dissipation material: A non-equilibrium molecular dynamics study
J. Appl. Phys. **114**, 193512 (2013); 10.1063/1.4831946

Chemical response of aldehydes to compression between (0001) surfaces of α-alumina
J. Chem. Phys. **134**, 014702 (2011); 10.1063/1.3528980

SAND PENETRATION BY HIGH-SPEED PROJECTILES
AIP Conf. Proc. **1195**, 1361 (2009); 10.1063/1.3295061

High-pressure phase transition of mullite under shock compression
J. Appl. Phys. **96**, 4126 (2004); 10.1063/1.1794904

High-speed impact of dry-ice projectiles on thin plates
AIP Conf. Proc. **309**, 1853 (1994); 10.1063/1.46358

High-speed Impact of the Metal Projectile on the Barrier Containing Porous Corundum-based Ceramics with Chemically Active Filler

Alexander Ischenko[1,a)], Svetlana Afanas'eva[1,b)], Nikolai Belov[2,c)], Vasiliy Blinov[3,d)],
Vladimir Burkin[1,e)], Leonid Korolkov[1,f)], Konstantin Rogaev[1,g)], Marat Khabibullin[1]
and Nikolai Yugov[1,h)]

[1]*National Research Tomsk State University, 36, Lenin Ave., 634050, Tomsk, Russia*
[2]*Tomsk State University of Architecture and Building, 2, Solyanaya Sq., 634003, Tomsk, Russia*
[3]*Military Academy of the Strategic Missile Forces named after Peter the Great, 9, Kitaygorodsky passage, 109074, Moscow, Russia*

[a)] Corresponding author: ichan@niipmm.tsu.ru,
[b)] s.a.afanasyeva@mail.ru, [c)] n.n.belov@mail.ru, [d)] 7172284@mail.ru, [e)] v.v.burkin@mail.ru,
[f)] korolkov.leo@rambler.ru, [g)] rogaev@ftf.tsu.ru, [h)] n.t.yugov@mail.ru

Abstract. The paper presents a calculation-experimental study on high-speed interaction of the metal projectile with a combined barrier made of porous corundum-based ceramics filled with chemically active composition (sulfur, nitrate of potash) in the wide range of speeds. A mathematical behavior model of porous corundum-based ceramics with chemically active filler is developed within the scope of mechanics of continuous media taking into account the energy embedding from a possible chemical reaction between a projectile metal and filler at high-speed impact. Essential embedding of inlet heat is not observed in the considered range of impact speeds (2.5 … 8 km/s).

INTRODUCTION

Modern protective structures against high-speed impact may contain a wide range of composite materials among which there are ceramic materials. Porous corundum-based ceramics with chemically active filler (CAF) can be applied to strengthen protection because heat flows from the excited under impact chemical reaction additionally take effect on the high-speed projectile. Inorganic substances with oxidizing properties which intensively interact upon contact with metal in particular sulfur are used as CAF of porous ceramics.

A great number of publications are devoted to research of properties of complex composites and high-speed impact phenomena in them, including papers on mathematical modeling [1-4].

The object of this research is the stress-strain state and destruction of the metal projectile under high-speed interaction with a barrier containing porous corundum ceramics filled with sulfur. Mathematical modeling on the basis of mathematical model and calculation procedure [4] allows describing the major processes under this interaction appropriately.

MATHEMATICAL MODEL

Mathematical modeling of high-speed interaction of the metal projectile with porous corundum ceramics containing chemically active filler is carried out within the model of the porous elasto-plastic medium.

Specific volume of the porous medium υ is given as a sum of matrix specific volume υ_m and pore specific volume υ_p. Porosity of a material is characterized by the relative void volume $\xi = \upsilon/\upsilon_p$ or the parameter $\alpha = \upsilon/\upsilon_m$ called porosity, which are connected by the dependence $\alpha = 1/(1-\xi)$. The system of equations describing the motion of porous elasto-plastic medium is of the form [5]:

$$\frac{d}{dt}\int_V \rho \, dV = 0, \quad \frac{d}{dt}\int_V \rho \mathbf{u} \, dV = \int_S \mathbf{n}\cdot\boldsymbol{\sigma}\, dS, \quad \frac{d}{dt}\int_V \rho E \, dV = \int_S \mathbf{n}\cdot\boldsymbol{\sigma}\cdot\mathbf{u}\, dS, \quad \mathbf{e} = \frac{\mathbf{s}^{CR}}{2\mu} + \lambda\mathbf{s}, \quad \mathbf{s}:\mathbf{s} = \frac{2}{3}\sigma_T^2 \tag{1}$$

where t – the time; V – the integration volume; S – the surface of integration volume; $\mathbf{n}$ –the outer normal unit vector; ρ – the density; $\boldsymbol{\sigma} = -p\mathbf{g} + \mathbf{s}$ $\boldsymbol{\sigma} = -p\mathbf{g} + \mathbf{s}$ – the stress tensor; $\mathbf{s}$ – its deviator; p – the pressure; $\mathbf{g}$ – the metric tensor; $\mathbf{u}$ – the velocity vector; $E = \varepsilon + \mathbf{u}\cdot\mathbf{u}/2$ – the total specific energy; ε – the internal specific energy; $\mathbf{e} = \mathbf{d} - (\mathbf{d}:\mathbf{g})\mathbf{g}/3$ – the strain velocity deviator; $\mathbf{d} = (\nabla\mathbf{u} + \nabla\mathbf{u}^T)/2$ – the strain velocity tensor; $\mathbf{s}^{CR} = \mathbf{s} + \nabla\mathbf{u}\cdot\mathbf{s} + \mathbf{s}\cdot\nabla\mathbf{u}^T$ – the Kotter-Rivlinco rotational derivative; $\mu = \mu_{m0}(1-\xi)[1 - (6\rho_{m0}c_{m0}^2 + 12\mu_{m0})\xi/(9\rho_{m0}c_{m0}^2 + 8\mu_{m0})]$, $\sigma_T = \sigma_S/\alpha$, – the effective shear modulus and yield stress respectively; $\rho_{m0}, c_{m0}, \mu_{m0}$ – the initial density, volume sound velocity and shear modulus of matrix material; σ_S - the dynamic yield stress of matrix material. The parameter λ is eliminated by the Mises plasticity condition.

The energy equation from (1) taking into account the energy influx due to mass power sources in the case of chemical reaction will be written over in the form:

$$\frac{d}{dt}\int_V \rho\left(\frac{\mathbf{u}\cdot\mathbf{u}}{2} + \varepsilon\right)dV = \int_\Sigma \mathbf{n}\cdot\boldsymbol{\sigma}\cdot\mathbf{u}\, d\Sigma + \int_V \frac{dq^*}{dt}\rho \, dV, \tag{2}$$

where $\dfrac{dq^*}{dt}$ – the specific energy influx due to the heat effect of the chemical reaction in the contact zone of the projectile and chemically active filler per unit time.

The system of equations from (1) and (2) is ended by the relations describing the growth kinetics and pore flowing, and the equation of state.

Compaction of an initially porous material under compression is described by the equation:

$$\frac{\rho_{m0}c_{m0}^2\left(1 - \dfrac{\gamma_{m0}}{2}\eta\right)\eta}{(1 - S_{m0}\eta)^2} + \rho_{m0}\gamma_{m0}\varepsilon - \frac{2}{3}\sigma_s \ln\left(\frac{\alpha}{\alpha-1}\right) = 0 \tag{3}$$

The kinetics equation of pore compaction is used for determining the parameter α under the condition $p - \dfrac{2}{3}\dfrac{\sigma_s}{\alpha}\ln\left(\dfrac{\alpha}{\alpha-1}\right) > 0$, otherwise $\dfrac{d\alpha}{dt} = 0$. The growth of pores in the plastically deformed material when stretching is described by the equation:

$$\frac{\rho_{m0}c_{m0}^2\left(1 - \dfrac{\gamma_{m0}}{2}\eta\right)\eta}{(1 - S_{m0}\eta)^2} + \rho_{m0}\gamma_{m0}\varepsilon - a_s \ln\left(\frac{\alpha}{\alpha-1}\right) = 0 \tag{4}$$

The kinetics equation of pore growth describes the evolution of the parameter α in the range $1 < \alpha_{00} < \alpha \le \alpha_*$. It is used at

$$\alpha p + a_s \ln\left(\frac{\alpha}{\alpha-1}\right) < 0 .$$

Otherwise $\dfrac{d\alpha}{dt} = 0$. The equation includes three easily determined parameters: $a_S, \alpha_{00}, \alpha_*$. $a_S = \dfrac{2}{3}\sigma_s$. α_{00} - there is dual porosity in the material, α_* - the critical value of porosity when destruction of the material occurs.

When solving the problems on high-speed impact of solids (the range of impact speeds is higher than 10 km/s), impacts of powerful energy flows on substance, it is necessary to use the equation of state which considers various aggregate states of a substance (melting and evaporation).

The interpolation wide range equation of state looks like this:

$$p_m(v_m, \varepsilon) = p_s(v_m) + \frac{\gamma(v_m, \varepsilon)}{v_m}(\varepsilon - \varepsilon_s(v_m)), \qquad (5)$$

where

$$\varepsilon_s(v_m) = \frac{9 B_0 \upsilon_{m0}}{2 \delta_m^2} \left\{ \exp\left[L\left(1 - V_m^{1/3}\right) - 1\right]\right\}^2 ;$$

$$p_s(v_m) = -\frac{d\varepsilon_s(v_m)}{dv_m};$$

$$\gamma(v_m, \varepsilon) = \frac{\frac{2}{3}V_m + \beta y}{V_m + y}\frac{\left(\gamma_0 - \frac{2}{3}\right)\left(1 + kyV_m^2\right)}{\left(1 + V_m^2 y\right)^2};$$

$$y = \frac{\varepsilon}{Q_0}; L = \begin{cases} \delta_m \ at \ \rho_m \le \rho_{m0}, \\ \mu \ at \ \rho_m > \rho_{m0}; \end{cases}$$

$$v_m = \upsilon_m \Big/ \upsilon_{m0};$$

γ_0 – the thermodynamic Grüneisen coefficient;

β, k, L – parameters of the formula;

B_0 – the modulus of volume adiabatic compressibility.

The value δ_m is determined by sublimation energy:

$$Q_0 = \frac{8 B_0}{2 \rho_{m0} \delta_m^2}.$$

The value μ is determined by the derivative of compressibility on pressure:

$$\mu = \frac{dB_0}{dp} - 1.$$

To find numerical values μ and B_0 the shock adiabatic curve may be used that looks like this:

$$D_m = C_{m0} + qu,$$

then:

$$B_0 = C_{m0}^2 \rho_{m0}, \ \mu = 4q - 2.$$

Porous corundum-based ceramics with CAF is considered as two-component medium (mix) with the initial density ρ_{m0}, which is calculated by the formula:

$$\rho_{m0} = \nu_1 \rho_{m01} + \nu_2 \rho_{m02},$$

where ν_i and ρ_{m0i} are initial concentrations and densities of corundum-based ceramics and CAF respectively ($i = 1, 2$) $(\nu_1 + \nu_2 = 1)$.

The parameters of the shock adiabatic curve and strength properties of the mix are also determined by the mix model.

The parameters of the shock adiabatic curve of the mix by means of the shock adiabatic curves of its components $D_i = c_{0i} + q_i u$ are determined in terms of ratios in the front of the shock wave:

$$D = \upsilon_{m0} \sqrt{\frac{p_m}{\upsilon_{m0} - \upsilon_m(p_m)}}, \ u = \sqrt{p_m(\upsilon_{m0} - \upsilon_m(p_m))},$$

where $\upsilon_{m0} = \dfrac{1}{\rho_{m0}} = \sum\limits_{i=1}^{n} m_i \upsilon_{m0i}$ $\upsilon_{m0i} = \dfrac{1}{\rho_{m0i}}$ $m_i = \nu_i \dfrac{\rho_{m0i}}{\rho_{m0}}$.

The initial density, volume and mass concentration of the i mix component are designated by ρ_{m0}, ν_i, m_i respectively.

Invariables (υ_m, p_m), the shock adiabatic curve of the matrix material of a composite has the form:

$$\upsilon_m(p_m) = \sum_{i=1}^{n} \left\{ \upsilon_{m0i} - \frac{1}{p_m} \left[\frac{c_{0i}}{q_i} \sqrt{\frac{p_m q_i}{p_{m0i} c_{0i}^2} + \frac{1}{4}} - \frac{1}{2} \right]^2 \right\} m_i \tag{6}$$

the Grüneisen coefficient γ_0, the shear modulus and yield stress are calculated by the respective values of the mix components: $\gamma_0 = \dfrac{\upsilon_{m0}}{\sum\limits_{i=1}^{2} \dfrac{m_i}{\rho_{m01}\gamma_{0i}}}$, $\mu_{m0}^{-1} = \sum\limits_{i=1}^{n} \nu_i \mu_{m0i}^{-1}; \sigma_s = \sum\limits_{i=1}^{n} m_i \sigma_{si}$.

The local criterion of separated destruction of a material is the limiting value of the relative void volume. $\xi_* = \dfrac{\alpha_* - 1}{\alpha_*}$. The local criterion of shear destruction is the limiting value of intensity of plastic deformations e_u^*.

The destroyed material is modeled by the granulated medium withstanding the compressive loadings but not withstanding the stretching stresses.

EXPERIMENTAL AND MATHEMATICAL MODELING

To verify the mathematical model and calculation procedure the test calculations of interaction of the conic copper projectile with the target consisting of a set of plates made of porous corundum-based ceramics filled with sulfur were carried out under the impact speed $V_0 = 2531$ m/s. These test calculations copied the conditions of the corresponding experiment (Fig. 1). As a result of impact, the set of plates was punched, in the barrier-"witness" a crater of depth $h = 20.7$ mm was produced.
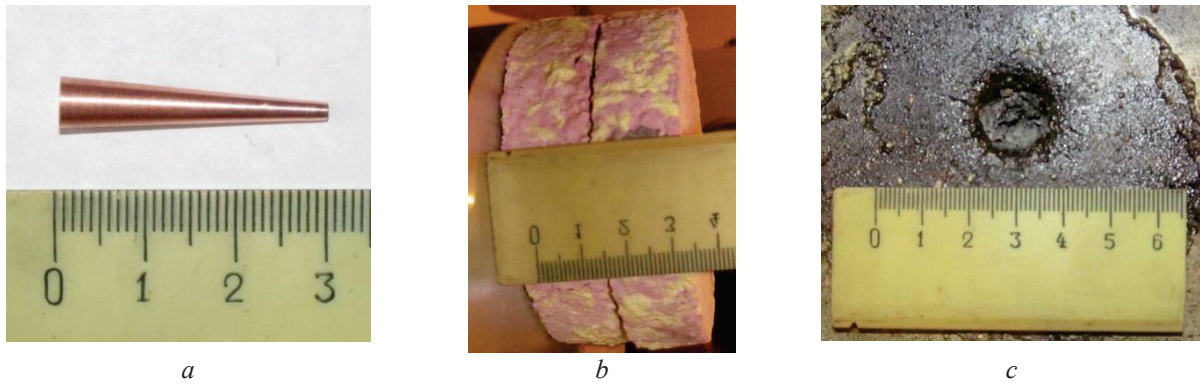
| *a* | *b* | *c* |

FIGURE 1. Experimental data of interaction of the copper projectile (*a*) with a set of plates made of porous corundum-based ceramics filled with sulfur (*b*) fixed on the duralumin cylinder-"witness" and the view of the crater in "witness" (*c*) at $V_0 =$ 2531 m/s

Figure 2 shows experimental results of penetration of the copper projectile into barriers made of porous corundum-based ceramics filled with sulfur (*b*) fixed on the duralumin cylinder-"witness" at the impact speed $V_0 =$ 2.5 km/s. The density of corundum-based ceramics is 3.71 g/cm^3, that of sulfur makes 2.0 g/cm^3. The increase in porosity of ceramics, therefore, sulfur content in it, leads to reduction of average density of samples. Judging by the graphics, this chemical component has insignificant impact on interaction of the projectile with porous corundum ceramics filled with sulfur, namely, the increase in filler content leads to reduction of penetration depth of the projectile into "witness".
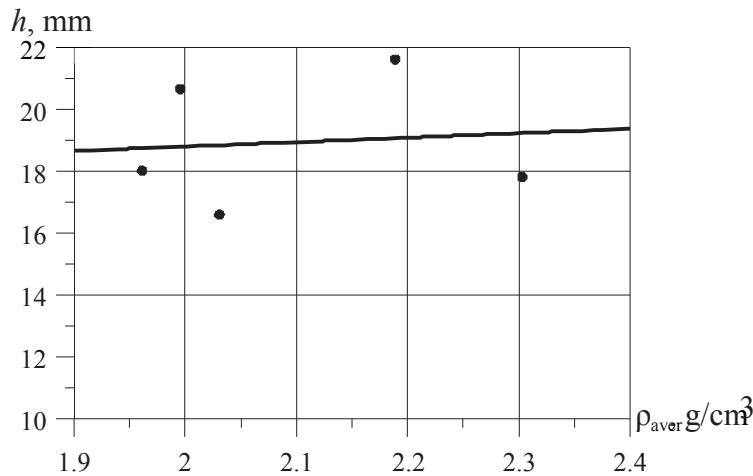

FIGURE 2. Dependence of penetration depth of the projectile into duralumin "witness" on average density of porous corundum-based ceramics filled with sulfur

At the first stage, the calculation was carried out without energy release as a result of chemical reaction of copper and sulfur. Figure 3 illustrates the calculated chronogram of interaction of the conic projectile with a set of plates made of porous corundum-based ceramics filled with sulfur and fixed on the duralumin cylinder-"witness", at $V_0 =$ 2531 m/s. Figure 3 presents the distribution field of mass velocity vector and pressure, center-of-mass velocity of the projectile U_{cm}, the maximum P_{max} and minimum P_{min} values of pressure and the maximum value of internal energy e_{max}.
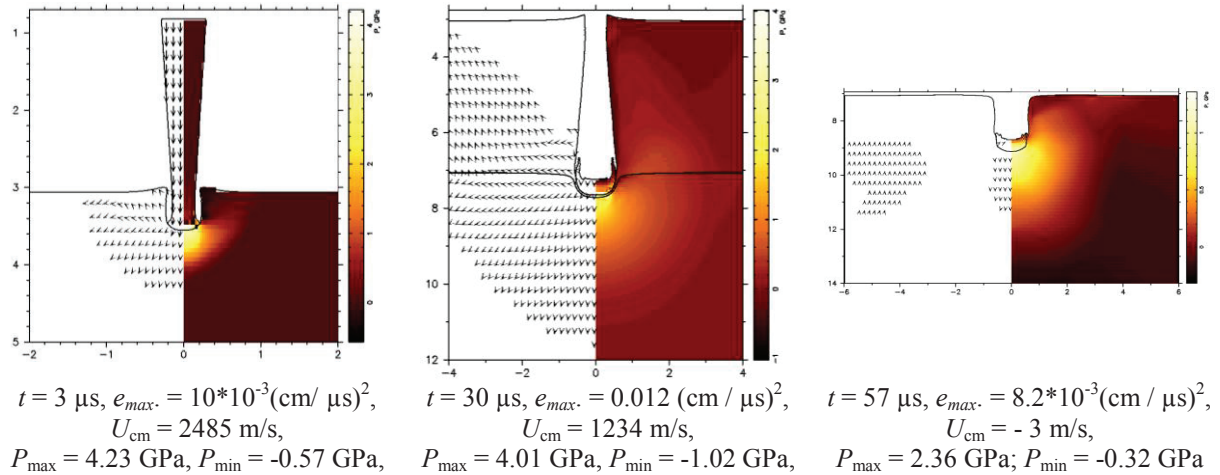
$t = 3$ μs, $e_{max.} = 10*10^{-3}$(cm/ μs)^2,
$U_{cm} = 2485$ m/s,
$P_{max} = 4.23$ GPa, $P_{min} = -0.57$ GPa,

$t = 30$ μs, $e_{max.} = 0.012$ (cm / μs)^2,
$U_{cm} = 1234$ m/s,
$P_{max} = 4.01$ GPa, $P_{min} = -1.02$ GPa,

$t = 57$ μs, $e_{max.} = 8.2*10^{-3}$(cm / μs)^2,
$U_{cm} = -3$ m/s,
$P_{max} = 2.36$ GPa; $P_{min} = -0.32$ GPa

FIGURE 3. Chronogram of interaction of the conic projectile with a set of plates made of porous corundum-based ceramics filled with sulfur, fixed on the duralumin cylinder-"witness", at $V_0 = 2531$ m/s

The analysis of the presented chronogram shows the following. Penetration of the projectile into this compound target is followed by its intensive deformation and reduction. Strong braking of the projectile is observed during its passing of the ceramic plates. By 30 μs, the rest of the projectile had passed the layers of ceramics and starts penetrating into "witness" at a speed of 1234 m/s. The ceramic plates are destroyed. By 57 μs, penetration of the projectile into "witness" is finished. The depth of the crater makes $h = 20.65$ mm. The disarrangement with the result of experiment makes 0.3%.

By 3 μs the projectile penetrates into the first plate at a depth of 4.3 mm. The value of the maximum pressure increased to 4.23 GPa. Along the crater surface the value of internal energy makes $e_{max} = 0.010$ (cm/sec)^2. In spite of the fact that in this area the values of internal energy exceed the value of energy of sulfur sublimation $Q_0 = 5.3 \cdot 10^{-3}$ (cm/ μs)^2 the evaporation of sulfur does not happen. Sulfur is in liquid state. Evaporation is only possible in unloading waves when the thermodynamic state in isentropic line reaches two-phase area "liquid – steam". The projectile material in the contact zone is in solid. In the contact zone there is no contact of sulfur and copper. From the crater surface, in area where the destroyed material is unloaded, evaporation of sulfur and its interaction with copper occur on the projectile surface.

By 30 μs punching of the second plate happens. The rest of the projectile starts to interact with the "witness" material at a speed of 1446 m/s. A thin layer between the projectile and "witness" of plate material is observed. In the contact area, at the symmetry axis, the specific internal energy makes $e = 9 \cdot 10^{-3}$(cm/ μs)^2. Along the internal crater surface in plate material $e = 5.5 \cdot 10^{-3}$(cm/ μs)^2 what causes evaporation of sulfur in this area.

The solution of the task on penetration of the 11.2 cm long copper cylinder having diameter of 0.3 cm into a two-layer target at a speed $V_0 = 8$ km/s is considered below. The first layer of thickness 10 cm and density of 2.3 g/cm^3 consists of porous corundum ceramics of Al_2O_3 with the chemically active filler - sulfur. The second layer is steel plate – "witness" of thickness 10 cm.

In the first calculation the contribution of heat effect of chemical reaction on interaction of copper and sulfur in the contact zone of the projectile with the first layer of the barrier is not considered. The second calculation is performed taking into account temperature gain in the contact zone of copper and sulfur due to reaction of combustion ($\dfrac{dq^*}{dt} = 0.01$ cm^2/ μs^2). The contact zone should be understood as two layers of calculated cells: one layer before and the second is after the contact border of the projectile and the first layer of the barrier. The diameter of the contact zone is equal to the diameter of the projectile.

Figures 4 and 5 show the chronograms of pressure field and mass velocity vector for the first and second calculations respectively.
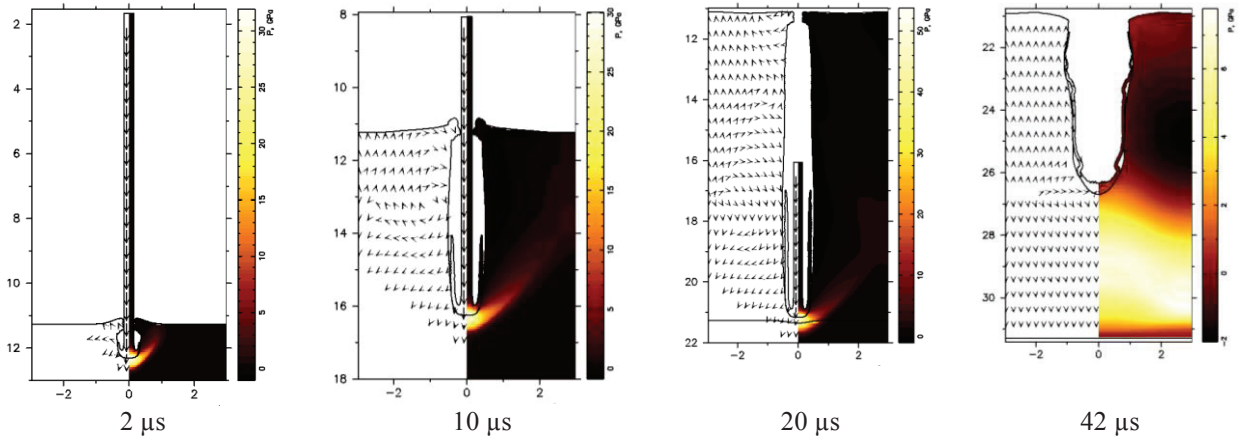
FIGURE 4. Chronogram of interaction of the copper cylinder with porous corundum-based ceramics filled with sulfur, fixed on the steel cylinder-"witness" without considering the heat effect of the chemical reaction at $V_0 = 8$ km/s
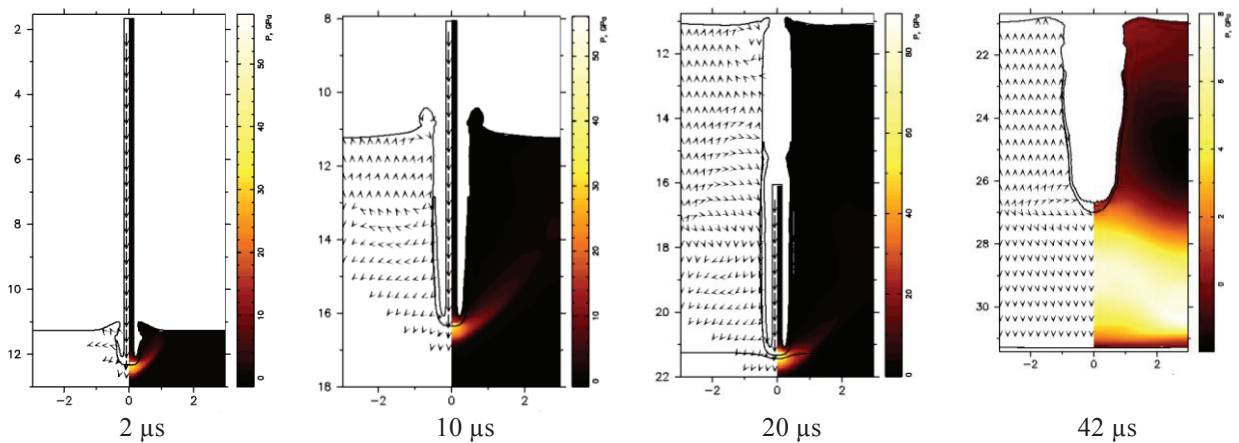

FIGURE 5. Chronogram of interaction of the copper cylinder with porous corundum-based ceramics filled with sulfur, fixed on the steel cylinder-"witness" considering the heat effect of the chemical reaction at $V_0 = 8$ km/s

The area of the maximum pressure is located on the symmetry axis around the contact of the projectile with the barrier. The maximum pressure when passing the first layer without considering the heat effect of the chemical reaction is equal to ≈ 31 GPa, but taking it into account - ≈ 57 GPa (2 and 10 µs). When the projectile approaches the second layer the pressure increases due to the reflected shock wave (20 µs). The final depth of the crater in the first calculation makes $h = 5.44$ cm, and in the second – $h = 5.74$ cm.

Thus, in calculations the consideration of the heat effect from the assumed chemical reaction under interaction of the copper projectile with porous ceramics filled with sulfur does not bring a big disagreement in the depth of penetration under the suggested modeling of influence of chemical reaction.

CONCLUSIONS

A mathematical behavior model of porous corundum ceramics with chemically active filler – sulfur in the conditions of high-speed interaction with the metal projectile is developed. The mathematical model considers influence of possible chemical reaction between the metal of the projectile and sulfur by introduction the energy influx from chemical reaction into the energy equation.

In the considered range of impact speeds (2.5 … 8 km/s) essential contribution of the introduced heat caused by chemical reaction between the metal of the projectile and chemically active filler is not observed.

ACKNOWLEDGEMENT

REFERENCES

1. V.M. Fomin, A.I. Gulidov, G.A. Sapozhnikov et al. *High-speed interaction of solids* (Novosibirsk, 1999), pp. 600 (in Russian).
2. G.I. Kanel, S.V. Razorenov, A.V. Utkin, V.E. Fortov *Shock-wave phenomena in the condensed media* (Yanus-K, Moscow, 1996), pp. 408 (in Russian).
3. N. N. Belov, N. T. Yugov, D. G. Kopanitsa, and A. A. Yugov, *Dynamics of High-Speed Impact and Related Physical Phenomena* (Northampton, Tomsk, 2005), pp. 356. (in Russian).
4. *High-velocity Impact Phenomena*, edited by R. Kinslow (Academic Press, New York and London, 1970), pp. 579.
5. L.I. Sedov, *Mechanics of continuous medium* (Nauka, Moscow, 1973), **1**, pp. 536 (in Russian).