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Study of high-speed interaction processes between fluoropolymer projectiles and aluminum-based targets

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Abstract

The experimental results and numerical modeling of penetration process of fluoropolymer projectiles in aluminum-based targets are presented. Analysis of mathematical models for interaction of elastoplastic projectile and target without taking additional energy released during interaction of fluoropolymer and aluminum into consideration is carried out. Energy fraction which is spent effectively on the increase in cavity volume is determined. The experimental and calculated results of penetration by combined and inert projectiles are compared.

Keywords: Reactive materials; Fluoropolymer; High speed strain; Interaction; Aluminum; Titanium alloy; Numerical modeling

1. Introduction

A promising direction in arms development is an application of "reactive materials" instead of inert ones in its design. One of the first works in this direction was the experiments carried out in Ural Federal University during 1984 and 1988 [1,2]. In the USA, the first works on reactive materials were published in the late 1990s and the early 2000s. Beside USA, UK and China are also involved in research and testing of new principles of damage increase for kinetic, shaped charge and fragmentation projectiles, including the reactive materials in their design. Application of reactive materials could allow to solve a wide range of tasks in the future – from increasing the damage and effectiveness of the projectiles to enhancing their safety and reliability.

One of the components of modern mixture reactive materials is fluoropolymer (TFE). Fluoropolymer has the ability to develop chemical reactions with energy released under certain conditions, not only under static loads and heating [1–3], but also under high-speed deformation together with targets containing aluminum [4–6]. The goal of the investigation is to determine the behavior of fluoropolymer under the condition of dynamic high-speed loading during its interaction with titanium alloy, and also to determine the behavior of target material.

2. Experimental results

Additional energy, which is released in the exothermic chemical reactions of fluoropolymer, is transferred into a mechanical work on cavity expansion in target; the amount of effective work increases with the impact velocity. In order to

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check this effect, the experimental data of dynamic interaction of textolite and monolith metal projectiles containing fluoropolymer and inert filler with semi-infinite targets from aluminum alloys AlMn1 and D16-AT was comparatively analyzed.

Projectiles with $d_0 = 0.013$ m and elongation $\lambda = L_0/d_0 = 2.4$, where L_0 *is* projectile length, were used in the experiments. The experimental results are presented in Tables 1 and 2. After the experiments, the cavity parameters in targets were measured (Fig. 1). The depth h_{cav}, diameter d_{cav}, and volume W_{cav} of cavity were determined.

The cavity in the semi-infinite target is formed by the kinetic energy of the projectile and partially by the energy released from thermochemical reaction of fluoropolymer with aluminum-based target. The energy balance equation can be written as

$$E_0 + E_{ch} = E_{ep} + E_{cav} \tag{1}$$

where E_0 is kinetic energy of the projectile; E_{ch} is energy released during chemical reaction and spent on cavity formation; E_{ep} is energy spent on elastic and plastic deformation of the projectile; and E_{cav} is energy spent on cavity formation.

The amount of energy spent on cavity formation for undeformable projectile can be determined by the amount of specific displacement work A_{sp} of target material.

$$A_{sp} = \frac{E_0}{W_{cav}} = \frac{\int_0^{h_f} F_r \mathrm{d}h}{\int_0^{W_{cav}} \mathrm{d}W} \tag{2}$$

where h, h_f are current and final penetration depth, respectively; F, E_0 are target resistance force and kinetic energy of the impact, respectively; W_{cav} is cavity volume.

Table 1
Cavity parameters from fluoropolymer projectile impact ($d_0 = 0.013$ m, $\lambda = 2.4$) on a AlMn1 target.

V_0/mps	h_{cav}*10^{-3}/m	d_{cav}*10^{-3}/m	W_{cav}*10^{-6}/m^3
507	0.0046	0.0207	1.20
514	0.0077	0.0229	2.05
564	0.0036	0.0187	0.52
624	0.0049	0.0215	0.95
625	0.0049	0.0205	0.87
629	0.0050	0.0210	0.93
685	0.0056	0.0225	1.45
722	0.0070	0.0238	1.74
744	0.0080	0.0240	2.08
879	0.0111	0.0250	3.25
930	0.0140	0.0253	4.00
962	0.0127	0.0255	4.05
1104	0.0170	0.0269	6.40
1108	0.0171	0.0270	6.50
1165	0.0190	0.0273	7.00
1250	0.0200	0.0285	8.25
1256	0.0200	0.0280	7.60
1406	0.0195	0.0342	11.50

Table 2
Cavity parameters from fluoropolymer projectile impact ($d_0 = 0.013$ m, $\lambda = 2.4$) on a D16-AT aluminum alloy target.

V_0/mps	h_c*10^{-3}/m	d_c*10^{-3}/m	W_{ex}*10^{-6}/m^3
322	0.00070	0.012	0.08
430	0.00125	0.012	0.15
439	0.00100	0.012	0.11
477	0.00075	0.012	0.10
505	0.00160	0.012	0.20
525	0.00180	0.013	0.25
542	0.00210	0.014	0.30
625	0.00330	0.016	0.60
778	0.00520	0.022	2.40
791	0.00620	0.018	2.30
803	0.00820	0.023	4.00
866	0.00860	0.025	3.90
889	0.00940	0.024	4.20
1025	0.01110	0.029	6.40
1010	0.01060	0.027	6.20

Fig. 2 shows the results for the experimental determination of the specific displacement work A_{sp} for fluoropolymer, textolite and steel projectiles. The analysis of the results shows that the specific displacement work necessary for the formation of the cavity with same volume in the fluoropolymer strikers is less than that in the steel strikers.

A_{sp} was determined based on the method of continuous acceleration registration during reverse ballistic experiments.

In order to determine the specific displacement work of material targets, the experiments on penetration of undeformable projectile ($d_0 = 0.005$ m and elongation $\lambda = 10$) were carried out. The nose part of projectile was a cone with $\alpha = 60°$. The targets AlMn1 and D16-AT were 80 mm in thickness with Brinnell hardness of 30 MPa and 43.5 MPa, respectively. The obtained results are presented in the form of functional relations

$$A_{sp}/HB = f(V_0/V_{cr}) \text{ and } A_{sp}/HB = f(\overline{h}) \tag{3}$$

The critical velocity [7] is expressed as

$$V_{cr} = \sqrt{\frac{HB}{\kappa\rho_0}} \tag{4}$$

The value of critical velocity was determined from the hardness of the projectiles, which is equal to 663 mps for AlMn1 and 788 mps for D16-AT alloy. The functional dependencies for both alloys in the ascending branch of the

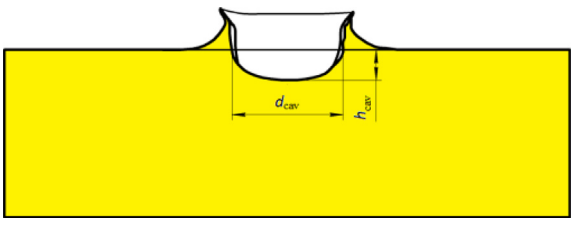

Fig. 1. Measured parameters h_{cav} and d_{cav} of semi-infinite target.

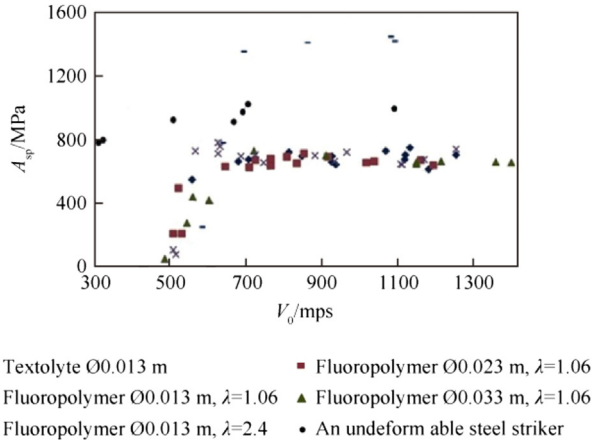

Fig. 2. Specific displacement work for target material AlMn1 from impact velocity.

curve (in Fig. 3) can be expressed with a second-order polynomial and have the following shape, for example, for AlMn1

$$\frac{A_{sp}}{HB} = -1.5 + 17.86\frac{V}{V_{cr}} - 16.96\left(\frac{V}{V_{cr}}\right)^2 \tag{5}$$

$$\frac{A_{sp}}{HB} = -2.96 + 5.21\overline{h} - 1.08\overline{h}^2 \tag{6}$$

After the maximal penetration is achieved in the deep layers of the target ($h \geq 2.5\ d_0$), the specific displacement work stays constant (Fig. 3).

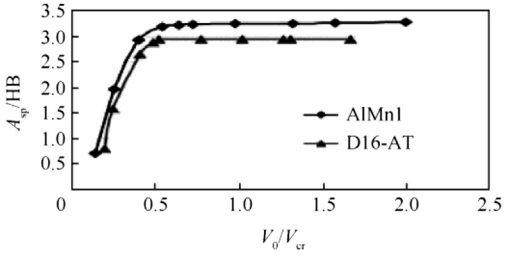

Fig. 3. Dependency of $A_{sp}/HB = f(V_0/V_{cr})$.

3. Penetration modeling

In order to determine the amount of energy used on elastoplastic deformation E_{ep}, the penetration of fluoropolymer projectile into semi-infinite aluminum-based alloys under the same experimental conditions mentioned above (Tables 1 and 2) was test. The projectile was considered an elastoplastic body, and no additional thermochemical energy was assumed to be released during the penetration.

The calculations were made with the software package TIM-2D [8] designed for calculations of two-dimensional continuum mechanics problems on unstructured polygonal Lagrangian meshes with arbitrary number of connections Fig. 4.

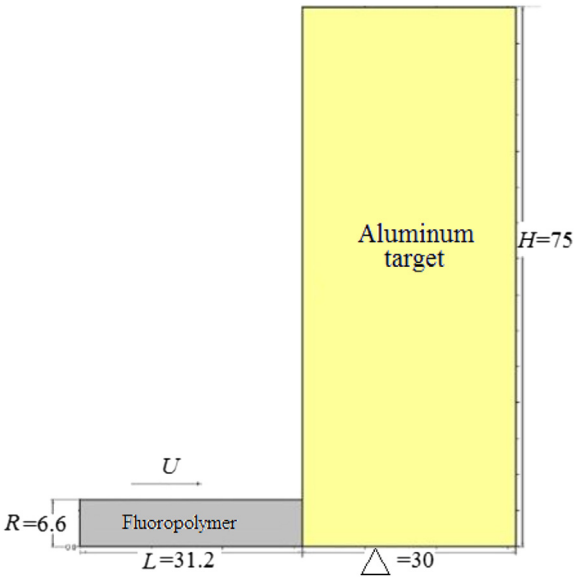

Fig. 4. Initial set-up of fluoropolymer projectile interaction with target.

3.1. The equation of state and elastoplastic qualities of fluoropolymer projectile

3.1.1. The equation of state of fluoropolymer projectile

The equation of state of fluoropolymer projectile was calculated from three-term Zababakhin equation of state [9]. In the equation of state, two parts are distinguished for pressure and unit internal energy calculation

$$P = P_C + P_T \tag{7}$$

$$E = E_C + E_T \tag{8}$$

where P_C, E_C are the potential ("cold") components of pressure and unit energy, respectively; and P_T, E_T are the thermal components of pressure and unit energy, respectively.

Potential pressure and potential energy are calculated by the relations

$$P_C(\delta) = \frac{C_0^2 \cdot \rho_0}{n} \cdot (\delta^n - 1) \tag{9}$$

$$E_C(\delta) = \frac{C_0^2}{n} \cdot \left(\frac{\delta^{n-1} - 1}{n-1} + \frac{1}{\delta} - 1\right) \tag{10}$$

where $\delta = \rho/\rho_0$ is relative compression; ρ_0 is material density under normal conditions; ρ is current material density; C_0 is speed of sound in monolith uncompressed material; and n is adjustable parameter.

Thermal pressure is calculated by

$$P_T = \Gamma \cdot \rho_0 \cdot \delta \cdot E_T \tag{11}$$

where $E_T = E - E_c$, and Γ is Gruneisen coefficient.

Gruneisen coefficient Γ is expressed through parameter h_Γ, which characterizes the value of limit material compression (maximal density) that could be reached in the calculations of shock adiabat

$$\Gamma = \frac{2}{h_\Gamma - 1} \tag{12}$$

Thermal energy can be expressed as heat capacity multiplied by temperature $E_T = C_V \cdot T$. This gives an opportunity to write the thermodynamic functions. This form of equation of state allows to write the relations for free energy and entropy

$$F(\delta, T) = E_C(\delta) + C_V \cdot T \cdot \left(\Gamma \cdot \ln\delta - \ln\frac{T}{T_0} + 1 \right) - S^0_{298} \cdot T \tag{13}$$

where T_0 is temperature at normal conditions, which determines the start of entropy calculations (in the equation of state $T_0 = 298$ K);S^0_{298} is standard value of entropy.

From Eq. (13) for entropy calculation

$$S(\delta, T) = C_V \cdot \left(\ln\frac{T}{T_0} - \Gamma \cdot \ln\delta \right) + S^0_{298} \tag{14}$$

In the equation of state, the parameters have following values: $\rho_0 = 2190$ kg/m^3 − initial material density; $C_0 = 2045$ mps − speed of sound in uncompressed cold material; $n = 4.972$ − power parameter in the relationship $P_C(\delta)$; $\gamma = \Gamma + 1 = 2.481$, where Γ is Gruneisen coefficient; $C_v = 1$ kJ/gK − specific heat capacity.

In the second case, fluoropolymer was calculated with the equation of state of polymer materials form [10].

3.1.2. Elastoplastic qualities of fluoropolymer projectile

Consideration of fluoropolymer elastoplastic qualities was made with the help of two models: Von Mises: For calculations Y_0 (yield stress) was set to 0.15 GPa, or − 0.035 GPa; Shemyakin: In the Shemyakin model, Y_0 is a linear function of thermal energy; thermal softening is taken into consideration.

$$Y(E_{sp}) = \begin{cases} Y_0 \cdot \left(1 - \dfrac{E_{sp}}{E_0}\right), & E_{sp} < E_{melt}, \quad \nu = \nu_0 \\ 0, & E_{sp} \geq E_{melt}, \end{cases} \tag{15}$$

where Y_0 is yield stress under normal conditions; E_{sp} is thermal component of specific internal energy; E_{melt} is effective energy of material melting; and ν is Poisson's ratio. $K = \rho \cdot C_S^2$ is bulk modulus, and Poisson's ratio ν is chosen as a main independent elasticity parameter. Shear modulus is calculated as

$$G = \frac{3 \cdot K \cdot (1 - 2 \cdot \nu)}{2 \cdot (1 + \nu)} \tag{16}$$

3.2. The equation of state and elastoplastic qualities of target

3.2.1. The equation of state of target

For aluminum-based targets, the equation of state was calculated from Zababakhin's equation with maximal density reduced to standard conditions. The thermodynamic qualities of aluminum alloy target are described with Mie-Gruneisen equation of state with variable Gruneisen coefficient and reduced to standard conditions.

3.2.2. Elastoplastic qualities of target

The elastoplastic qualities of AlMn1 were taken into consideration using three models.

(a) Von Mises model [13].

In its standard form, $Y_0 = 0.18$ GPa and $\nu = 0.32$.

(b) Johnson−Cook model [14].

$$\sigma_T = \left(A + B\varepsilon_p^n\right)\left(1 + c\ln\frac{\dot\gamma_p}{\dot\gamma_0}\right)(1 - T_m) < Y_{max} \tag{17}$$

$$T^* = \frac{T - T_0}{T_m - T_0} \tag{18}$$

$$T = \frac{E_{stie}}{c_p} \tag{19}$$

where σ_T is yield point; m is parameter of thermal loss of strength, $m = 1$; A is yield point with quasistatic tension or contraction, $A = 0.18$ GPa; B, n are deformation hardening parameters, $B = 0.426$ GPa, $n = 0.34$; c is dynamic hardening parameter, $c = 0.015$; $\dot\gamma_0 = 10^6$ 1/ms is fixed multiplier of deformation velocity, $\gamma_0 = 10^6$ 1/ms; ε_p^n is plastic deformation; $\dot\gamma_p$ is velocity of plastic deformation; Y_{max} is maximum of yield point, $Y_{max} = 0.7$ GPa; T_0 is initial temperature, $T_0 = 293$ K; T_m is temperature calculated by Lindemann's law; c_p is heat capacity, $c_p = 0.00875$ kJ/g•K; and E_{stie} is specific thermal interior energy (kJ/g).

(c) Glushak model

The determination the equations for viscoplastic Glushak model is dependent on the deformation rate. In this case, a yield condition becomes heterogeneous with respect to time variable because this condition contains a scale material parameter − relaxation time τ_γ. Yield stress is a sum of two functions: Glushak yield function $Y_S(\varepsilon_p, P, T)$ and a viscoplastic term.

$$Y_{max}\left(\varepsilon_p, \dot\varepsilon_p, P, T\right) = Y_S\left(\varepsilon_p, P, T\right) + 3 \cdot G \cdot \dot\varepsilon_p \cdot \tau_\gamma\left(\dot\varepsilon_p, T\right) \tag{20}$$

$$Y_S\left(\varepsilon_p, P, T\right) = Y_0 \cdot Y_1\left(\varepsilon_p, T\right) \cdot Y_2(P) \cdot Y_3(T) \tag{21}$$

where $Y_1(\varepsilon_p, T)$, $Y_2(P)$, $Y_3(T)$ are the functions of deformation and compression hardening and thermal softening, respectively. Deformation hardening multiplier depends on plastic intensity deformation and temperature

$$Y_1\left(\varepsilon_p, T\right) = 1 + a_1 \cdot \left(1 - a_2 \cdot \left(\frac{T}{T_m}\right)^{a_3}\right) \cdot \left(1 - a_4 \cdot \mathrm{Exp}\left(-a_5 \cdot \varepsilon_p\right)\right) \tag{22}$$

Multiplier of compression loss of strength is expressed as

$$Y_2(P) = 1 + (a_6 \cdot P)^{a_7} \tag{23}$$

where P is total pressure. Multiplier of thermal loss of strength is expressed as

$$Y_3(T) = \left(1 - a_8 \cdot \left(\frac{T}{T_m}\right)^{a_9}\right)^{a_{10}} \tag{24}$$

where T is current temperature; a_1, ..., a_{10} are empiric constants; and ε_p is accumulated plastic deformation.

The shear modulus defines a deviator component of stress tensor for elastic field

$$G = \frac{3}{2}\frac{1-2\nu}{1+\nu}\cdot\rho\cdot C_s^2,\ C_s^2 = \left(\frac{\partial P}{\partial \rho}\right)_s \tag{25}$$

where ρ is density of matter; and C_S is current volumetric acoustic velocity.

Poisson's ratio depends on dimensionless parameter T/T_m

$$\nu = \begin{cases} \nu_0 \cdot \left(1 + c \cdot (\overline{T})^k\right), & \overline{T} < 1 \\ 0.5, & \overline{T} \geq 1 \end{cases} \tag{26}$$

where ν_0, c, k are constant coefficients.

Following values were used in calculations: $Y_0 = 0.18$ GPa – yield stress for AlMn1 alloy and $Y_0 = 0.28$ GPa for D16-AT; $a_1 = 1.4$, $a_2 = 1$, $a_3 = 2$, $a_4 = 1$, $a_5 = 2$ -deformation hardening parameters; $a_6 = 0.08$ GPa^{-1}, $a_7 = 1$ – compression hardening parameters; $a_8 = 1$, $a_9 = 1$, $a_{10} = 1$ – thermal

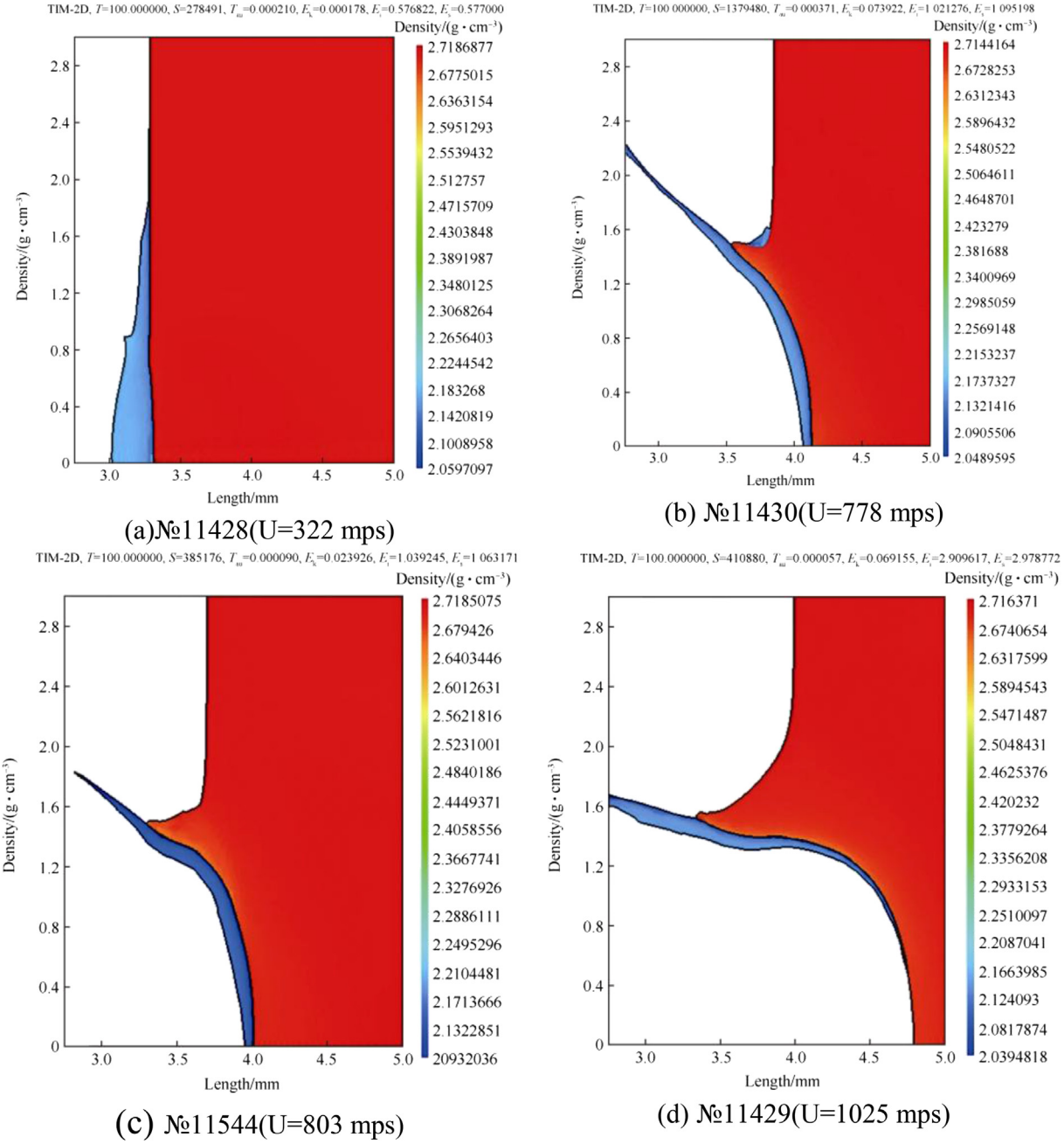

Fig. 5. The density distribution at time $t = 1000$ mks and different impact velocities using Mises model for D16 target.

softening parameters; $v_0 = 0.268$, $c = 0.8657$, $k = 1$ – parameters describing Poisson's ratio temperature dependence.

4. Comparison of modeling and experimental results

Figs. 5 and 6 show the cavities obtained in numerical calculations for different impact velocities and target parameters according to the von Mises model and Glushak model, respectively.

Comparison of the results with experimental data (Fig. 7) shows that all models show a good agreement with experiment in the description of cavity diameter. It is possible to conclude that the cavity formation, especially at the initial stage of penetration, is caused only by projectile kinetic energy.

Additional energy of thermochemical reaction has not been released yet. Release of this energy is delayed, thus its influence starts to appear in the deeper layers, which leads to an increase in the penetration depth. This can explain the significant difference in the calculated and experimental penetration depths.

Amount of additional chemical energy can be determined as

$$E_{\mathrm{ch}} = A_{\mathrm{sp}}\left(W_{\mathrm{cav}}^{\mathrm{ex}} - W_{\mathrm{cav}}^{\mathrm{calc}}\right) \tag{27}$$

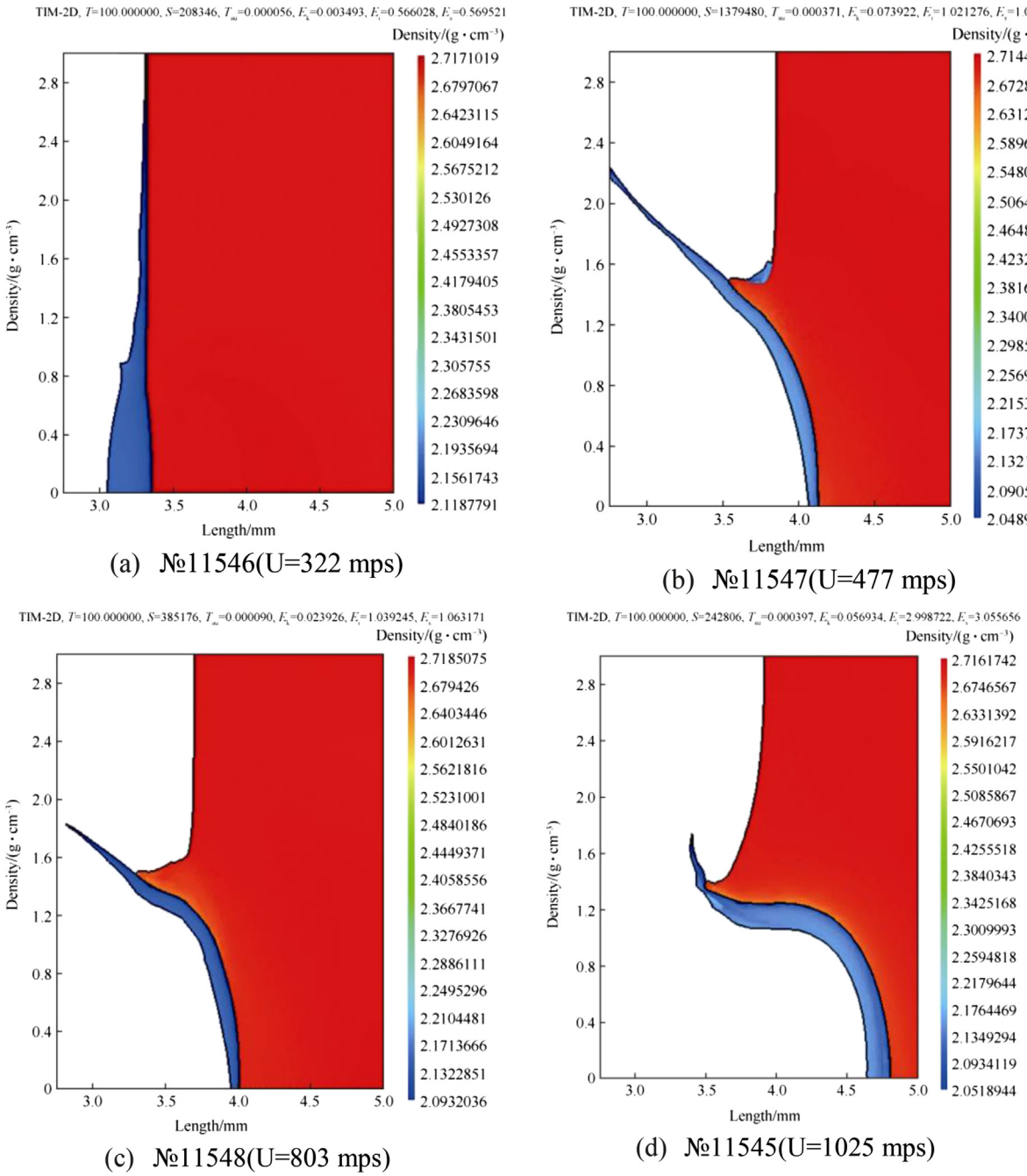

Fig. 6. The density distribution at time t = 1000 mks and different impact velocities using Glushak model for D16 target.

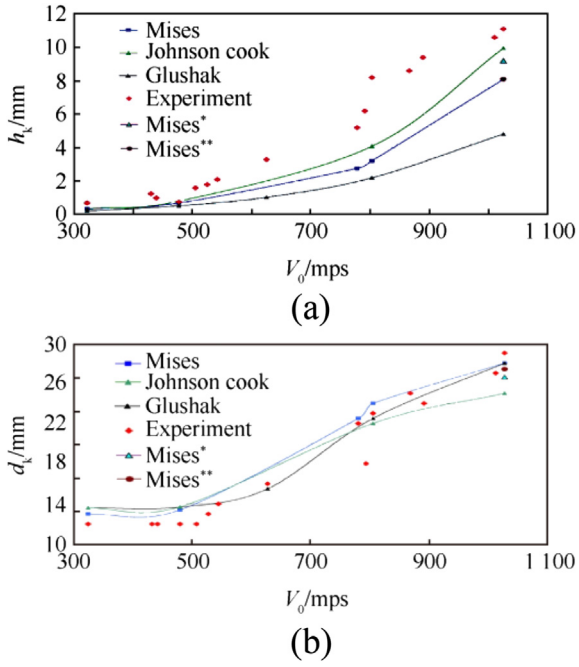

Fig. 7. The relationship among cavity dimensions (diameter and depth) and velocity of fluoropolymer projectile interaction with D16-AT target.

where W_{cav}^{ex} and W_{cav}^{calc} are experimental and calculated cavity volumes, respectively.

The calculated results for D16-AT are presented in Tables 3 and 4. In Table 3, the calculations labeled as "Glushak 1" were made with von Mises model for fluoropolymer with $Y_0 = 0.15$ GPa and Glushak model for D16-AT. Calculations labelled as "Glushak 2" were made with von Mises model for fluoropolymer with $Y_0 = 0.35$ GPa and Glushak model for D16-AT.

Unfortunately, the format of the article does not allow to present a more detailed analysis of the calculations carried out with the models. However, the results shown in Fig. 6 show that the results calculated using these models have the same trend as those calculated using the basic model (Table 3).

Analysis of the results (Table 3 and Fig. 7) shows that the proportion of the chemical energy decreases with the increase in the interaction velocity for all models, except Johnson–Cook model, which contradicts with physical concepts and experimental data [1].

In Tables 3 and 4: V_0 is velocity of fluoropolymer penetration into the target mps; W_{cav}^{ex}, W_{cav}^{calc} are experimental and calculated volumes of cavity, cm^3; E_{ch} is energy released by chemical reaction between fluoropolymer and aluminum of target, kJ; Glushak 1 is the elastic plastic states of fluoropolymer calculated by Mises model with $Y_0 = 0.15$ GPa and AlMn1 calculated by Glushak model with $Y_0 = 0.18$ GPa; Glushak 2 is the elastic plastic states of fluoropolymer calculated by Mises model with $Y_0 = 0.035$ GPa and AlMn1 calculated by Glushak model with $Y_0 = 0.18$ GPa.

In other cases, the elastic plastic states of fluoropolymer were calculated by Mises model with $Y_0 = 0.035$ GPa, and the elastic plastic states of AlMn1 and D16-AT were calculated by Glushak and J-Cook and Mises models.

The quantity of chemical energy spent in cavity forming obtained by the calculations based on the Johnson–Cook model is in sufficiently good agreement with the experimental results.

Experimental dependence for E_{ch} was determined by comparing the cavity volumes produced by the penetration of fluoropolymer projectiles and those made of inert material with the same density and geometrical dimensions into semi-infinite AlMn1 target (Fig. 8).

The chemical reaction of aluminum with fluoropolymer proceeds as follows with the release of a significant portion of thermal energy

$$3C_2F_4 + 4Al \rightarrow 4AlF_3 + 6C + Q\uparrow \tag{28}$$

The amount of thermal energy for 3 mol of reacting fluoropolymer is $Q = 897$ kJ [11,12,13]. Projectile mass $m_p = 8.6$ g, and molar mass μ (C_2F_4) = 100 g/mol. The amount of chemical energy released in full thermochemical destruction of fluoropolymer can be determined from the relation

$$E_{chp} = \frac{m_p Q}{N \cdot \mu} \tag{29}$$

where N is the number of reacting moles, $N = 3$.

As a result, the effective projectile mass used in the thermochemical reaction to increase the volume of cavity in the semi-infinite target equals

$$m_{ef} = \frac{m_p \cdot E_{ch}}{E_{chp}} \tag{30}$$

Analysis of the plots in Fig. 9 shows that the obtained effective mass of projectile does not exceed 20% of its initial mass. In order to improve the effectiveness of the released energy, it is possible to use the preformed fragments with a solid shell.

Table 3
The energy released in a chemical reaction during penetration into the target made of D16-AT.

N№	V_0/mps	W_{cav}^{ex} *10^{-6}/m^3	W_{cav}^{calc} *10^{-6} (Mises)/m^3	W_{cav}^{calc} *10^{-6} (Glushak)/m^3	W_{cav}^{calc} *10^{-6} (J–Cook)/m^3	E_{ch} (Mises)/kJ	E_{ch} (Glushak)/kJ	E_{ch} (J–Cook)/kJ
1	322	0.08	0.0023	0.0026	0.0011	0.0996	0.0992	0.1011
2	477	0.10	0.0100	0.0135	0.0059	0.1154	0.1108	0.1206
3	625	0.60						
4	778	2.40	0.2489		0.0252	2.7571		0.7368
5	803	4.00	0.3559	0.5041	0.1330	4.6708	4.4808	4.9565
6	1025	6.40	3.1410	3.4271	1.7248	4.1772	3.8106	5.9925

Table 4
The energy released in a chemical reaction during penetration into the target made of AlMn1.

N№	V_0/mps	$W_{cav}^{ex}10^{-6}$/m^3	$W_{cav}^{calc}10^{-6}$ (Mises)/m^3	$W_{cav}^{calc}10^{-6}$ (Glushak1)/m^3	$W_{cav}^{calc}10^{-6}$ (Glushak2)/m^3	$W_{cav}^{calc}10^{-6}$ (J-Cook)/m^3	E_{ch} (Mises)/kJ	E_{ch} (Glushak1)/kJ	E_{ch} (Glushak2)/kJ	E_{ch} (J–Cook)/kJ
1	507	1.20	0.065	0.077	0.149	0.015	1.088	1.076	1.006	1.135
2	685	1.45	0.537	0.683	1.004	0.064	0.875	0.735	0.428	1.328
3	930	4.00	3.270	3.147	3.828	0.620	0.699	0.817	0.165	3.237
4	1108	6.50	6.055	5.827	6.512	2.276	0.427	0.645	−0.012	4.046
5	1406	11.50	13.010	11.743	12.160	6.369	−1.446	−0.232		4.914

5. Conclusions

One of the components of modern mixture reactive materials is fluoropolymer (TFE). Fluoropolymer has the ability to develop chemical reactions with energy released under certain conditions, not only under static loads and heating, but also under high-speed deformation together with targets containing aluminum.

Conducted studies allowed to determine the behavior of fluoropolymer under the condition of dynamic high-speed loading during its interaction with titanium alloy, and also to determine the behavior of target material. And we have done such conclusions:

1) The proportion of the chemical energy released by the reaction between fluorine and target material was determined effectively to increase the volume of cavity.
2) The mass fraction of the projectile spent on effective chemical energy was determined. It was shown that the effective mass fraction of the unjacketed projectile does not exceed 20%. One of the possible ways to increase the effective mass is to create a preformed fragment with thin-walled shell. Wall thickness should be optimized with respect to effective energy.
3) The model that accurately describes fluoropolymer projectile penetration into aluminum-based target was chosen without taking into account energy of the thermo oxidation reaction. In the future, the assessment of the possible influence of chemical reaction for reactive materials and the evaluation of its influence on the penetration and cavity parameters will be conducted. This can be done by introducing the kinetics of the slow energy release which appears behind the shock wave front as a result of chemical reaction between the reactive material components.

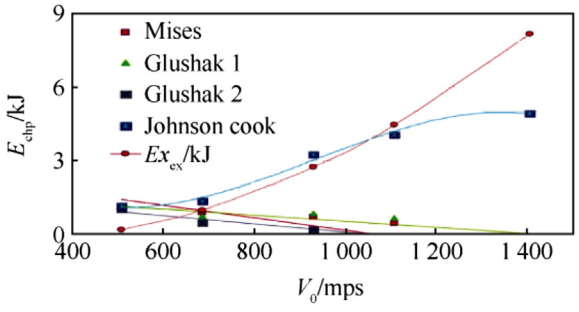

Fig. 8. Energy released in the reaction between fluoropolymer and target material AlMn1.

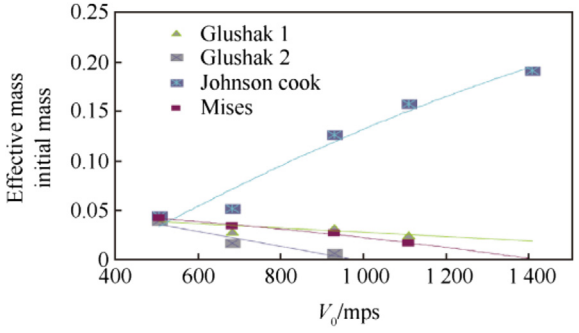

Fig. 9. Mass fraction of fluoropolymer projectile reacted with a target made of AlMn1.

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