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Research paper

Influence of the Striker Material on the Results of High-Speed Impact at a Barrier

Yuri Voitenko1), **Roman Zakusylo**2,*), **Stefan Zaychenko**3,**)

1) *Ukrainian State Geological Research Institute,*
Avtozavodskaya 78A, 04114 Kyiv, Ukraine
2) *Shostka Institute of Sumy State University,*
Haharina 1, 41100 Shostka, Ukraine
3) *National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Peremohy Avenue 37, 03056 Kyiv, Ukraine*
* *E-mail:* r.zakusylo@ishostka.sumdu.edu.ua

** ERRATUM: In this version, the name of the 3rd co-author was changed from "Sergiy" into "Stefan"

Abstract: In this work the influence of the characteristics of the material of the striker (cumulative jet or projectile), moving at speeds of 2-10 km/s, on the volume of the resulting crater in a metal target, has been studied. The dependence of the crater volume in an aluminum alloy target of Cu-Al, W-Cu-Pb-Al composites, and steel St45 for a PTFE-Cu composite, were investigated. The outer diameter and height of the shaped charges were 26 and 28, and 31 and 33 mm, respectively. The mass of the explosive (phlegmatized hexogen) in these charges was 10 and 18 g. A comparison was made between the ratios of the kinetic energy of the striker to the volume of the crater formed for the composites PTFE-Al, PTFE-Cu, Cu-Al, Ni-Al, W-Cu-Pb, and porous materials Cu and Al. It was demonstrated that the chemical interaction of the components of the porous Cu-Al and Ni-Al composites during penetration into the barrier is possible at an impact velocity of at least 2-3 km/s and a porosity of at least 30%.

Keywords: porosity, striker, shaped charge, shock compression, penetration, shock wave front

Nomenclature

CE	Compact element
FSW	Front of the shock wave
SC	Shaped charge
SCJ	Shaped-charge jet

1 Introduction

Shock-wave loads where some ordinary materials behave as intended are realized mainly in the process of the interaction of shaped-charge jets (SCJs) and high-speed projectiles with dense targets. The areas of their application are mostly military, geological exploration, oil and gas industries, and some scientific experiments. One of the main tasks in the development of these technologies is the research and development of new materials for shaped charge (SC) liners and high-speed projectiles. The development and production of new materials which are formed at high pressures and temperatures in flat recovery ampoules, are similar to this field of science and technology [1].

2 Literature Review and Problem Statement

The materials described in this article belong to a class of functional materials which exhibit their properties as smart materials at critical values of the parameters of pressure and temperature. Many articles have been devoted to the behaviour of such materials under shock wave loads. The effects of the interaction between some metals are described in [2]. The fullest review and analysis of studies of the shock-induced interaction of components in reactive mixtures is described in [3]. As a rule, changes in the properties of materials are related to kinetic phase transitions which accompany the processes of deformation and destruction of the materials of the projectiles and targets with additional energy release occurring during the deformation of porous materials. There are phase transitions, as in monolithic (solid) and porous homogeneous materials and as in heterogeneous (composite) materials [1, 4-6]. These have the following physical effects:

- the transition of the material into a denser phase,
- an increase in the volume of the material under the heat which is released under shock compression, for example, at the front of the shock wave for the porous materials of jets or projectiles and targets [2],

- ejection of molten material of the SCJs or projectiles and the target from the crater,
- condensation of vapour on the walls of the crater in the target [4, 5].

All chemical reactions in reactive mixtures were divided by the authors of [3] into two types, according to their mechanisms of initiation and reaction time:

- reactions which are initiated by impact and proceed from a few microseconds to a millisecond, and supported by a general increase in activation energy,
- ultrafast chemical reactions which are initiated by the moving of a shock wave front, which is very dependent on the composition of the powder mixture and the dispersion of the powder.

Recent work on the penetration of elongated strikers, compact elements (CEs), and SCJs moving at speeds of 3 to 10 km/s, has shown that the penetration depth and volume of the crater are determined by the impact velocity and kinetic energy of the projectile [7]. In particular, the main parameters for the SC are not only its construction but also the detonation speed of the explosive, and the form and material of the liner [2, 8-10]. Porous projectile materials have the advantage of subsonic penetration into dense monolithic or low-porous materials, using the criterion of depth and crater volume. Furthermore, the penetration depth of porous SCJs or projectiles is substantially greater than a monolithic SCJ or projectile with the same size and density [4, 7]. The volume of the cavities is approximately the same according to [7]. At the same time, the dimensions of the cavities during the penetration of SCJs from solid conical liners are substantially smaller than from the penetration of SCJs from porous liners of the same size [2, 4, 8].

In the material of a porous projectile, the supersonic mode is realized by the presence of porosity and the reduction in the speed of sound in comparison with monolithic material. Compression of material in the projectiles occurs in two stages:

- the first is in the shock wave mode at the front of the accompanying shock wave, and
- the second is in the isentropic mode in the section from the front of the shock wave to the contact boundary, or to the rear shock wave boundary which has moved away from the point of contact.

The addition in the projectiles or SC liner composite material (Cu, Ni, Mo, W-Cu, W-Cu-Pb) of energetic additives, such as Al, Mg, B, organic additives or their compounds, leads incidentally to an increase in the volume of the cavities, which indicates that the increase in the energy of the projectiles is not only due to physical effects but also due to heats of reaction [2, 4]. To solve some specific problems, for example, disposing of ammunition without detonation, CE from solid Cu or steel liners with a low spherical shape has advantages [11]. These have a velocity of 1.7-3 km/s.

In [12], the effect of the striker material (nylon, Al, steel, Al/PTFE, Al/PTFE in shells made of: steel, Al, Ni/Al) on the destruction of an aluminum target 50.8 and 76.2 mm in thickness, was studied. The velocity of the striker hitting the target was ≈ 2100 m/s, and the impact energy was ≈ 0.47-0.60 MJ, except for one experiment (0.29 MJ). One of the main results was: aluminum shells release 10% more target material with a thickness of 76.2 mm than shells made of Al/PTFE, while a steel striker removes 25% more material than Al/PTFE projectiles and 15% more material than aluminum strikers. That is, the effect of interaction of Al/PTFE with the target material (Al), as well as with each other during impact interaction was not observed, or was insignificant (within experimental error). This result can be explained by the absence of porosity in the material of the striker and the target.

There is currently no complete understanding of which materials have advantages over others in terms of the maximum interaction energy criterion despite studies in this area. In addition, there is no answer to the question of which minimum energy of the shock interaction induces chemical transformations in the material of a composite projectile, such as Cu-Al, with the release of additional energy from the chemical interaction of the components.

The objectives of the present article are:

- to clarify the mechanisms of energy increase in the interaction centre when hitting a porous projectile from a functional material,
- to compare energy gains from compression of porous projectile material and chemical reactions of material components with energetic additives – PTFE, PTFE + Cu and Al,
- to estimate the minimum impact velocity of a porous composite projectil Cu-Al, at which chemical transformations in its material begins.

3 Materials and Methods

Experiments with shaped charges were carried out (see Figure 1) in accordance with the methodology in [4]. The charge of phlegmatized 1,3,5,7-tetranitro-1,3,5,7-tetraazacyclooctane (hexogen) (1), covered with a cap, was placed directly on the target (2), the upper part of which was constructed as follows: steel plate (steel St3, $\delta = 10$ mm) and the base (Al-Mn alloy) in the form of a pack of plates. The charge was initiated with an electric detonator through a detonating cord (3). The distance between the charge with a diameter of 26 mm and the first target (the cap of the charge) was 13.1 mm; between the charge with a diameter of 31 mm and the barrier was 50 mm. The internal angle of the conical charge with a diameter of 26 mm was 55°, with external angle 60°. The charge with a diameter of 31 mm had an internal angle in the conical liner of 44°, with external angle 48°. The properties of the explosive in the charge were: density ρ_{exp} = 1.67 g/cm^3, and detonation velocity D = 7800 m/s. SC liners were manufactured by the method of one-sided cold pressing. Coarsely dispersed Cu (20-150 μm) and finely dispersed Al (2-60 μm) were used in this series of experiments to make composite liners (Figure 2).

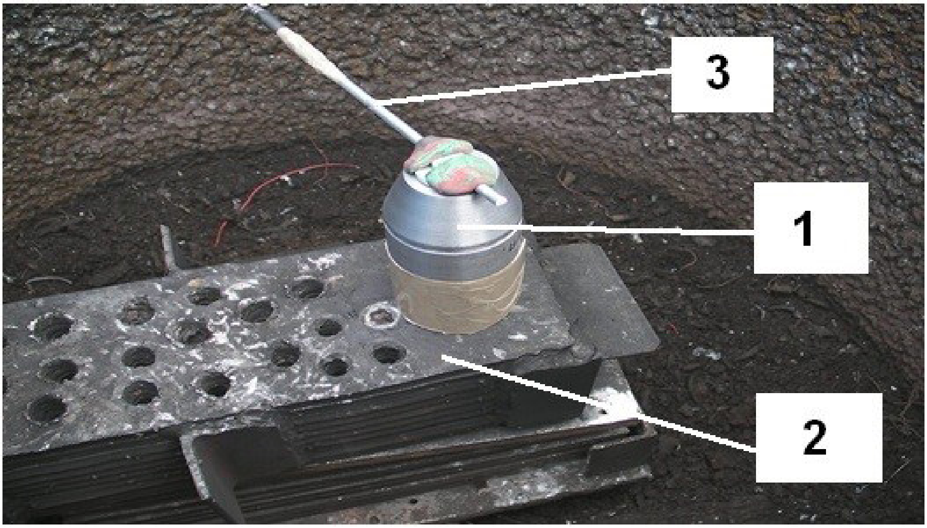
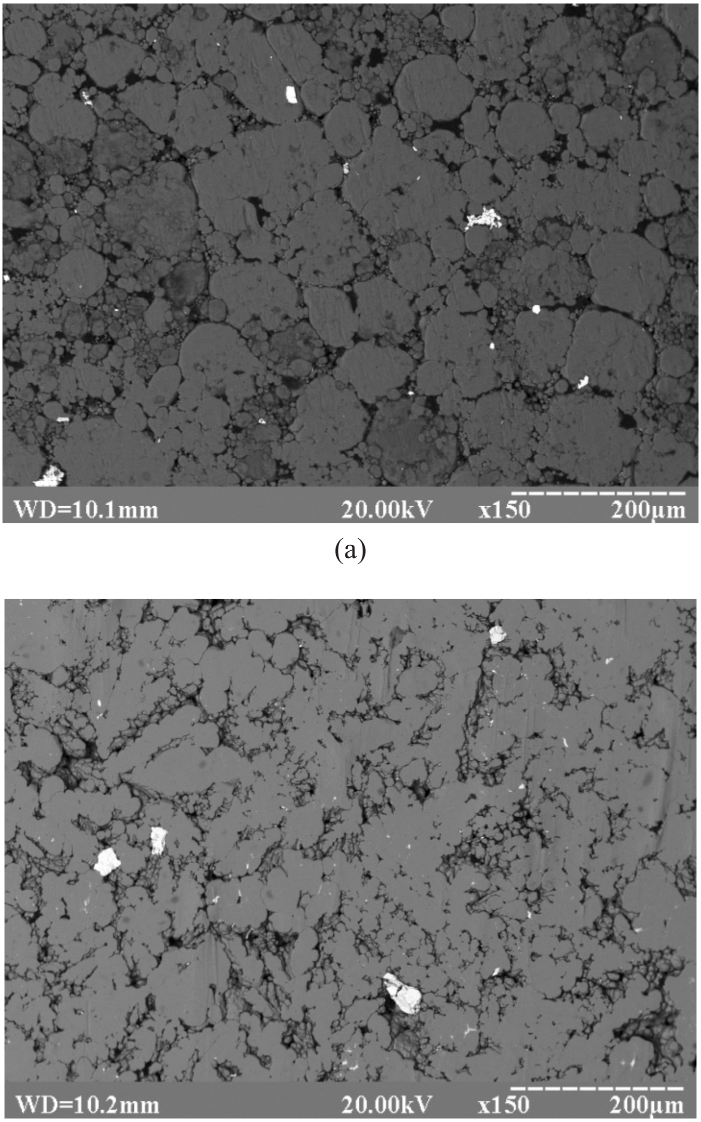


Figure 1. General view of the experimental set-up: charge (1), target (2) and detonating cord (3)



(a)

(b)

Figure 2. Micrographs of the liner materials Al (a) and Cu (b)

Experimental data from the literature [3, 6] were used to summarize the results of the research. The characteristics of the studied materials are shown in Table 1. The volumes of the craters were measured using a measuring beaker and micron-sized metal powder.

Table 1. Characteristics of the liner materials

Material of striker	Porosity [%]	Density [g/cm^3]	Composition [wt.%]
PTFE + Cu	–	2.16-6.01 [13]	100-0/0-100*)
Al	0	2.78	100
Al	8-14	2.32-2.48	100
Cu	0-50	8.93-4.47	100
Cu-Al	10-27	6.50-2.32	100-0/0-100*)
Ni-Al	10-26	6.4	91/9
W-Cu-Pb	19-35	10.73-13.31	70/20/10
W-Cu-Pb-Al	18-31	11.3-9.5	41/40/10/9

*) from 100% to 0% and from 0% to 100%, respectively

The law of shock compression of metals in the Theta form was used for the pressure and energy of cold compression estimations, which is released at the front of the shock wave (FSW) – Equation 1. The parameters of the constants *B* and *n*, which are included in the equation of shock adiabats of Cu for different relative porosities (*m*) are given in Table 2.

$$p = B\left(\left(\frac{\rho}{\rho_0}\right)^n - 1\right) \tag{1}$$

where ρ is density, g/cm^3

Table 2. Compressibility parameters of Cu with different porosities and Al alloy (ρ_0, ρ_{00} – density of monolithic and porous metals and P is the absolute porosity)

Metal	$m = \rho_0/\rho_{00}$	P [%]	ρ_0 or ρ_{00} [g/cm^3]	n	B [GPa]	$p\cdot 10^{-1}$ [GPa]
pressed Cu	1.0*)	0	8.93	4.8	31.6	0-7
	1.2**)	17	7.44		38.9	
	1.3**)	23	6.87		48.2	
	1.4**)	29	6.38		59.0	
	1.5**)	33	5.95		67.3	
	1.57*)	36	5.69		76.4	
	2.0*)	50	4.47		127.6	
Al alloy	1.0***)	0	2.785	4.2	19.7	0-5

Note: The experimental data were taken from: *) – [15], **) – [16] and ***) – [17]

The choice of such a range of porosities is due to the need to ensure the structural strength of the kinetic projectile to prevent its breakup during a shot, as well as to prevent premature destruction of the SC liners [14]. The dependences of shock compressibility $p(\rho) = p/V$ allow the dependence of the energy of shock compression on the pressure on FSW ($E(p)$), or the degree of compression $E(V)$ for each value of porosity (Figure 3), to be obtained. The increase in porosity leads to an increase in the energy of impact compression of the porous material of the projectile. Therefore, these parameters increase with increasing impact velocity.

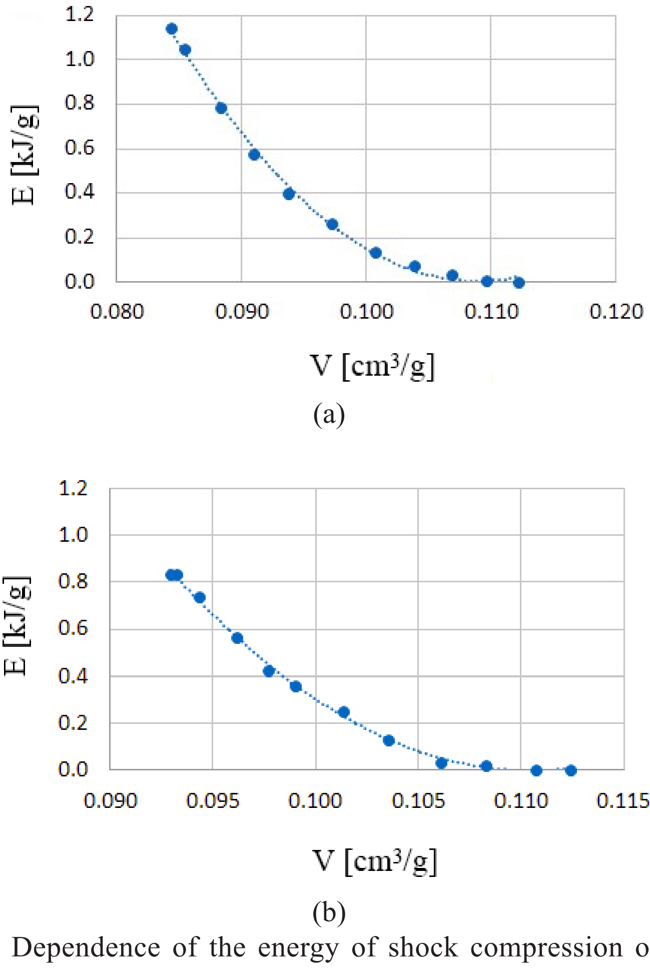


Figure 3. Dependence of the energy of shock compression on the value of the specific volume of the projectile's material (Cu) for $m = 1.0$ (a) and $m = 1.4$ (b)

4 Results

Analysis of the results of the experimental studies of the interaction of various SCJs with metal alloys showed that craters with different parameters (Figure 4 and Table 3) are formed in a semi-infinite target (Al-Mn, steel St3-(Al-Mn), steel St45). In particular, this is confirmed by the results of experimental studies and mathematical modelling of the formation and penetration of SCJs of three materials (PTFE, PTFE + Cu, and Cu), described in [13, 18, 19]. The following symbols appear in Table 3:

– u_0 is the velocity of the kinetic striker or the leading part of the SCJ,
– E_k is the kinetic energy of the projectile or SCJ,
– d_{cr} is the input diameter of the crater,
– V_{cr} is the volume of the crater,
– q is the heat of the chemical reaction,
– m_{exp} is the mass of the explosive.

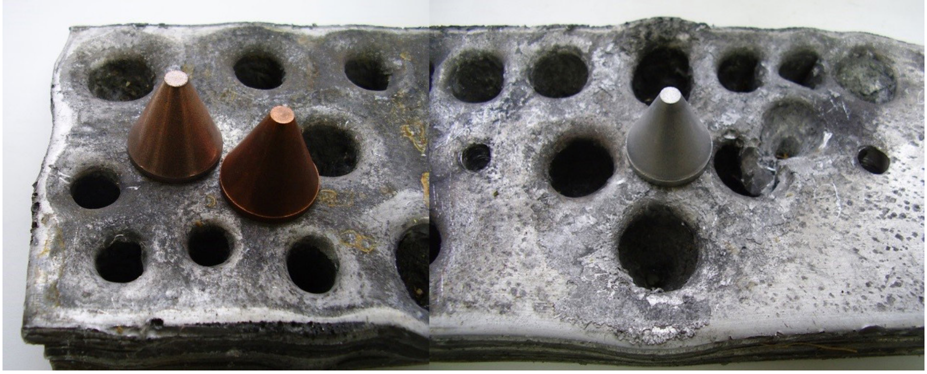


Figure 4. Appearance of the targets (Al-Mn) as a result of the impacts of SCJs of Al, Cu-Al (left, large diameter holes) and Cu (right, small diameter holes)

Table 3. Initial parameters and results of the interaction of projectiles of mass 4 g and diameter 13 mm (first line) of aluminium and from an SC of 40 mm calibre (m_{exp} = 60 g, second line) 26 mm (m_{exp} = 10 g, other lines) with different targets (Al-Mn, steel St3+Al-Mn, steel St45)

Material of projectile	u_0 [m/s]	E_k [kJ]	d_{cr} [mm]	h_{cr} [mm]	V_{cr} [cm^3]	E_k/V_{cr}	q [kJ/mol]
PTFE	923	1.7	24.3	8.1	1.9	0.895	895 [20]
PTFE+ Cu*)	5931-4666 [18, 19]	6.71-13.87	12.2-283	20.5-58.0	1.36-8.71	6.52-1.28	–
Al	8700-9050	28.3	–	–	10.71	2.642	–
Al**)	8700-9050	28.3	13.5-14.5	35-40	7.6-80	3.724-3.538	–
Cu**)	7000-7400	27.6	8.1	80-90	7.4	3.930	–
Cu+Al**)	7000-9000	27.95	9.0-16.0	122-35	8.0-11.1	3.10-2.541	40-70 [21]
Ni+Al**)	≈(7000-9000)	27.95	8.2	118	6.2	4.508	145-162 [21] 85.3 [6]
W-Cu-Pb**)	6400-6600	29.9	6.6-7.0	148-160	4.4-4.6	6.796-6.50	–
W-Cu-Pb-Al	–	–	7.7-8.2	145	4.2-6.5 [2]	–	–

*) Target material: steel St45

**) Target material: St3-(Al-Mn) (steel St3 is 3-10 mm and Al-Mn is the remainder)

The differences in velocities of the SCJs with PTFE+Cu (second line) and Cu+Al of approximately the same density, are explained by differences in the rate of detonation of the explosive, as well as the lack of a massive body on the charge in references [18, 19] and its presence in the charges in references [2, 4]. The kinetic energy of the SCJ of all charges was calculated on the assumption of a linear distribution of the velocity of elements along the jet [2, 4, 19]. Some data on the velocity of SCJs (Cu, W-Cu-Pb) had been obtained experimentally in previous investigations. Some of them (Cu+Al) were obtained by calculation. The V_{cr} value for an SCJ with PTFE+Cu was calculated by assuming the shape of the crater to be in the form of a truncated cone [19]. Therefore, they are evaluative, and slightly exceed real values.

Knowing the impact velocity (u_0) from the relation $u_0 = u_1 + u_2$, and the equations of state of the materials of the projectile and the target, one can find the pressure, mass velocities and wave velocities in the projectile (u_1) and target (u_2). Without showing the formulae in monograph [20], the results of calculations for monolithic ($m = 1.0$) and porous ($m = 1.4$; $m = 2.0$) Cu (projectile) and Al alloy (target) are presented: for an impact velocity u_0 = 2000 m/s, the impact pressure was p_x = 42, 40 and 35 GPa respectively. Given that the shock adiabats of porous metals ($m \neq 1$) lie above that of the monolithic metal ($m = 1.0$), then the energy of shock compression of a porous metal exceeds a similar value for a monolithic one (Figure 3).

Comparing the energies of shock compression of porous Cu obtained and the enthalpy of formation of aluminides, for example, $CuAl_2$, CuAl, Cu_2Al, $CuAl_3$, namely 0.34 to 0.61 kJ/g [21], one can find that the chemical component in the energy balance of the shock interaction is essentially reaching 40-60% of the energy of shock compression of a porous material (m = 1.4, 0.832 kJ/g) and 70-80% of the monolithic material (m = 1.0) of the projectile (0.456 kJ/g). The two latter values were obtained for porous and monolithic Cu, which were compressed to a density of ≈ 10.8 g/cm^3 [2].

5 Discussion of Results

The data in Table 3 show that an increase in the volume of the crater occurs not only due to a change in the density, porosity, and kinetic energy of the projectile and SCJ, but also due to the additional heat of the chemical reactions of the projectile's interacting materials, including the SCJ, or between the projectile and the target (first line). This is emphasized by the appearance of the curves shown in Figure 5. The shape of curve 3 shows that in the case of Cu-Al and W-Cu-Pb-Al composites, there is an optimal material composition at which the chemical energy in the impact interaction is at a maximum. The beginning of the chemical interaction depends on the activation energy. This, in turn, depends on the chemical properties of the components of the projectile and its porosity.

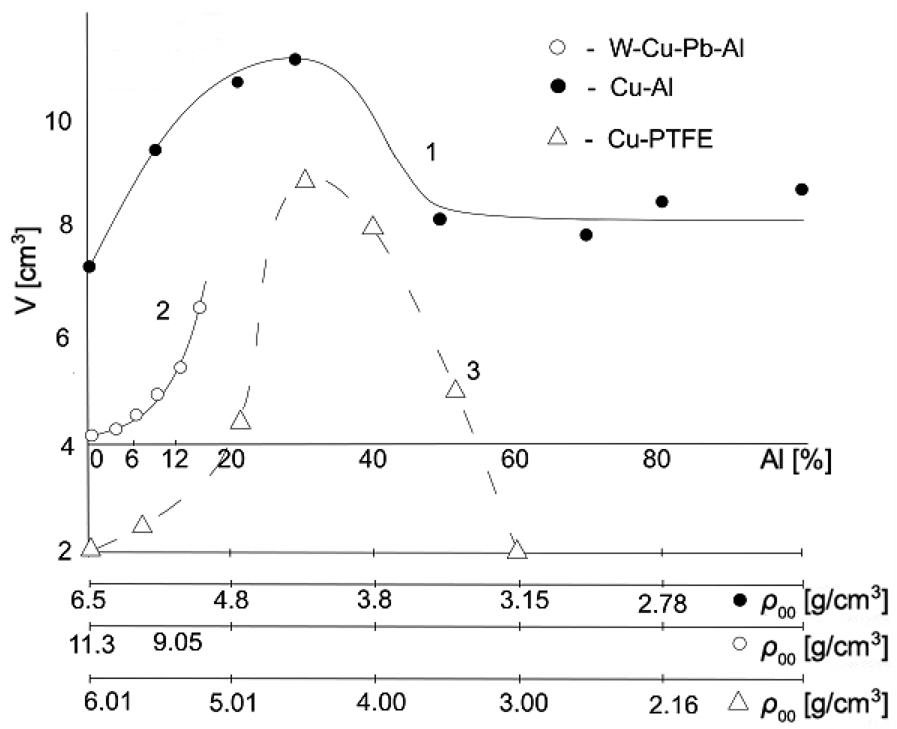


Figure 5. Dependence of the crater volume in the target of steel St3-(Al-Mn) on the Al content in the Cu-Al composite (curve 1 and ●); in the W-Cu-Pb-Al composite (curve 2 and ○); and in the target of steel C45 on the Cu content in the PTFE+Cu composite (curve 3 and Δ)

It is necessary to set the conditions of the shock wave loads to understand when a chemical reaction between the elements of the projectile's composite material begins. The conditions of the impact interaction of the shaped charge jets of porous Cu-Al, Ni-Al composites were: impact velocity $u_0 \approx$ 7-9 km/s, $p_x \approx$ 100 GPa. The experiments did not show a chemical reaction for lower impact velocities in compact elements u_0 = 2000-3000 m/s. A chemical reaction in mixtures of nano- and microbore Ni and Al powders, at average impact velocities of 1.4-5.05 km/s, pressures of 10-60 GPa and short time intervals of compression of ~1 μs, does not have time to take place [1].

The thickness of the sample in the experiments was 3 mm, and the diameter was 20 mm. At the same time, the authors of [22] observed the reaction of Ni and Al in ampoules of conservation at an average pressure of 13.5 GPa after several runs of the shock wave. This is because the energy relaxation time, under conditions of close to a closed thermodynamic system, far exceeds the pulse relaxation time, characterizing the lifetime of the samples in the experiments [1]. For a chemical reaction to commence, the corresponding activation energy is necessary *i.e.* the temperature at which the mixture begins to heat up and goes into a thermal explosion mode. For the mixture of Cu-Al, that temperature is 821 K. For Ni-Al the temperature is 913 K [21]. After determining the temperature, the parameters of the shock-wave loads upon the impact of a copper CE on an aluminium barrier at a velocity of 2000 m/s, (temperature (ΔT_H), the energy of elastic (cold) compression (E), and total internal energy (E_I), were compared. This was also compared with the temperature of a thermal explosion during the quasistatic heating of a sample [21]. The formulae were obtained from [23]:

$$\Delta T = (E_H - E)/c \tag{2}$$

$$E_H = \frac{c_0^2}{2-(m-1)G}(m-1+\varepsilon)\varepsilon \tag{3}$$

where c is the heat capacity of copper (385 J/kg·K), c_0 is the speed of sound in a solid substance (3711 km/s), G is the Grüneisen parameter ($G = 2$ for $m = 1$; $G = 1.824$ for $m = 1.4$; $G = 1.59$ for $m = 2$), $\varepsilon = (V_0/V) - 1$ is the compression ratio of the substance; and $V_0 = 1/\rho_0$ is the specific volume of the solid material.

For $m = 1$, the formula for the internal specific energy of the continuous substance $E_H \approx E = c_0^2\varepsilon^2/2$ is obtained from Equation 3. Considering if $\varepsilon << 1$, the elastic component of the pressure is $p = nV\varepsilon$. The full pressure at the shock wave is

$$p_H = \frac{2nB}{2-(m-1)\Gamma}\varepsilon \tag{3a}$$

An analysis of these formulae shows that $1 \leq m \leq 2 p_H > p$. For a porosity of $m = 1.4$ in the elastic approximation, $\varepsilon = 0.14$; $\Delta T_H = 1779$ K. In reality, these values will be larger, because the full pressure is $p_H \approx 1.57p$, and the compression ratio will be higher. According to [23], for a porosity of $m = 1.5$ and a compression ratio of $\varepsilon = 0.15$, the temperature reaches 3460 K. These values exceed the temperature at which the thermal explosion of the composite occurs, by a factor of at least 2. This may be sufficient even taking into account the dynamic mode of heating of the substance at the centre of the impact. It is significant to note that the critical velocity for projectile materials of high porosity (30-50%) may be lower because the temperature in the material increases rapidly with increasing porosity [23].

According to the classification given in [3], the reactions which occur during the penetration of CEs, SCJs, and long high-velocity projectiles, belong to the first type. Reactions occuring in short projectiles and fragments of stretched SCJs, from the start of the shock wave to the destruction of the sample by the rarefaction waves, belong to the second type. Therefore, in experiments with SCJs at the optimal distance to the target, the effect of the chemical reactions of Al with various metals on the overall result (crater volume) is observed, because the velocity of penetration of the SCJ into the target is ≈ 3-4 km/s, and its penetration time is ≈25-40 μs [2, 4, 5]. The reaction of PTFE projectiles with the aluminium of the target begins at an interaction velocity of ≈600 m/s. There were no differences between the PTFE and, for example, composite epoxy materials (CEMs) at lower speeds [17]. The process of penetration and formation of the crater is accompanied by competing mechanisms of deformation, destruction of the materials of the projectile and the target, and the chemical interaction of the materials of the projectile and the target or components of the projectile materials, with the release of additional internal energy. Projectile materials which interact directly with the target material belong to a separate group. For example, PTFE ($[C_2F_4]$) and porous metals *Me* (see Equations 4 and 5), which interact with Al and Al or Ti alloy targets, according to exothermic reactions [2, 4, 17]:

$$1.5[C_2F_4] + 2Al = 2AlF_3 + 3C + q \tag{4}$$

$$xMe + yAl \rightarrow Me_xAl_y + q \tag{5}$$

where *Me* is Ti, Cu, Ni and Nb.

Composite materials of projectiles belong to the second group. They interact at impact and during penetration and with each other and produce additional internal energy. These are porous composites based on mixtures of Al with metals, including fusible (Sn, Pb, Cu, Ni) and refractory (Nb, Mo) metals [27]. Also, there are composites based on PTFE and metals, for example, Cu-PTFE [12, 18, 19]. The value of the activation energy of the reactions of PTFE, Cu, and Ni with Al determine the direction of a reaction. The first reaction begins with the interaction of PTFE at lower energy, the second in this list is Cu, and the third is Ni. A thermal explosion of mixtures of Cu-Al, Ni-Al and Nb-Al begins at 821, 913, and 1180 K respectively under quasistatic heating [21]. There is a correlation of these parameters with specific variations of the activation energies, of temperatures and pressures.

The description of the influence of porosity on the properties of the material of SCJs or projectiles on impact and penetration is taken from [24]. This shows that, depending on the impact velocity and the characteristics of the structure (porosity, overall pore size a_0, b_0, acoustic and thermo physical parameters of the material), several modes of motion are possible.

There are two most interesting aspects in terms of activating the release of internal energy. For materials of low porosity ($m \leq 1.05$-1.1; $P \leq 5$-10%) and moderate impact velocities ($u_0 < 1$-2 km/s), there is a smooth collapse of the pores behind the shock wave front, *i.e.* at:

$$\mathrm{Re} = a_0 u/v < 8.5[1 + m(2m - 1)^{-1/2}] = \mathrm{Re}_{\mathrm{cr}} \tag{6}$$

where a_0 is the initial pore radius of the idealized spheroidal shape, u is the mass velocity behind the shock wave front and v is the viscosity of the porous metal under conditions of high-velocity deformation.

For higher impact speeds $u_0 > 3$-4 km/s at:

$$\mathrm{Re} \geq 8.5[1 + m(2m - 1)^{-1/2}] \tag{7}$$

the process of interaction of the projectile with the target is complicated by the effects of jet formation when pores collapse. The speed of microjets in the pores, depending on their shape, can reach and exceed the speed of longitudinal sound in a solid material. This increases the intensity of internal energy release, which initiates the chemical reactions. The allocation of energy supplements should be uniform in the main matrix. Taking into account pore sizes in liner materials (≈ 2-20 μm, Figure 1), the viscosity of monolithic Cu and Al. ($v = 2.3 \cdot 10^{-4}$ m^2/s) and the form of the shock adiabat of Cu in the form $D = D(u)$ [17] at impact velocities of 2-3 km/s, the condition $\mathrm{Re} < \mathrm{Re}_{\mathrm{cr}}$ is satisfied. The condition $\mathrm{Re} \geq \mathrm{Re}_{\mathrm{cr}}$ is satisfied at $u_0 \geq 4$-5 km/s. It is clear that these are approximations. There is no data on the dependence of metal viscosity on porosity. Only temperature dependences are known according to [23]. The mechanism described is realized at shock interaction with dense obstacles of SCJs from porous liners, high-speed porous compact elements ($u_0 \geq$ 5-6 km/s). In the impact charge core of porous liners (Cu, Ni) moving at speeds ≈2.5-3 km/s, the condition $\mathrm{Re} \geq \mathrm{Re}_{sr}$ begins to perform in the range of porosity m = 1.2-1.4. This follows from the analysis of impact adiabats for these porous metals in the *D-u* coordinates [15].

Obviously, for each pair (and more) of interacting materials, there is a dependence similar to curves 1-3 in Figure 5. In the case of PTFE+Cu composite, the reaction occurs between these components in a similar manner to curve 3. Analysing the known data, see [3, 21, 25], on the enthalpies of formation of compounds of different metals with Al and Zn, and the results of X-ray spectral analysis of the reaction products Ni and Al, additional to Cu-Al, mixtures of Ni-Al, Ni-Zn and some others can be considered. Given the rules of formation of intermetallic compounds, in particular, the known optimal ratio of the radii (r) of the atoms of the interacting metals A and B in compounds A_2B: $r_A/r_B = 1.225$ (Laves phase), as well as ternary compositions, in addition to the above, more complex compositions such as Cu-Mg-B, Cu-Al-B, Cu-Al-Mn and other similar compositions for which the conditions of the stoichiometry of compounds AB_2C (Heusler compound) are fulfilled, are considered promising [26]. However, this can be seen from the results of a series of physical experiments described above.

The approach described for the creation of composite materials can be used in the design of hypersonic devices moving at speeds of several km/s. In conclusion, SCs with liners made of Cu-Al material have been used in gas wells in Ukraine, to create large perforations prior to fracturing.

6 Conclusions

- The material of a porous composite of a projectile manifests itself as a functional material when reaching a value of the energy of the shock interaction which exceeds the activation energy of chemical reactions between the components. This is determined by the porosity, pore size, acoustic, thermo physical and chemical properties of the reacting components. The completeness of chemical reactions is determined by the kinetic energy of the projectile, its size and time of its operation in the target.
- Chemical interaction between the components of the Cu-Al projectile composite is possible at an impact velocity of ≥2-3 km/s and the porosity of the jet or projectile material ≥20-30%. If the porosity is halved, the impact velocity must be at least 5-6 km/s.

- The ratio of the kinetic energy of the projectile to the volume of the formed crater is lowest for the pair “PTFE-Al” (projectile-target), “PTFE-Cu” (shaped-charge jet with a ratio of PTFE-Cu – 0.250/0.750 or 0.4/0.6 wt.%). This ratio is slightly higher for the composite Cu-Al (shaped-charge jet with the ratio Al/Cu – 0.12/0.88 or 0.40/0.60 wt.%) and even higher for pure porous Al, Cu and Ni+Al, which partially interact with the target material. The highest ratio is for the W-Cu-Pb composite, for which the chemical interaction energy between the components of the shaped-charge jet and the target material is the lowest.

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