Research paper

New Functional Materials in Mechanical Engineering and Geology

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Abstract: New composite materials are proposed, which allow shaped charges to be used with increased efficiency, for purposes, such as special engineering and geotechnical applications, as well as in other industries. The main determinant of efficiency is the volume of the hole created in the target. The future directions of new materials production for shaped charges are shown.

Keywords: shaped charge, liner, polytetrafluorethylene, pores, penetration

Synonims:
D	Detonation velocity [m/s]
E_{exp}	Total energy of explosion [kJ]
E_j	Jet energy [kJ]
SHS	Self-propagating high-temperature synthesis
SWF	Shock wave front

1   Introduction

Composite materials for explosively formed projectiles and shaped charge jets were developed in the 1980s. Recently they have been replaced by porous analogues [1, 2]. In the past few decades, along with intelligent devices and technologies, functional or smart materials have occupied a prominent place in modern scientific and technological progress.

Functional (smart) materials are those that are capable of changing their properties in response to environmental changes. Their main property is the ability to transform one kind of energy into another. From a practical point of view, the most interesting materials are those that convert mechanical energy into thermal, chemical, electrical, magnetic and *vice versa*. Classical examples of the smart materials are: piezoelectric; shape-memory materials; chemically active materials which, for example, swell in conditions of high humidity; magnetorheological fluids; materials that can self-cure during destructive processes conditions within them (cracks and microcracks) [3].

Functional materials are hybrid in that they consist of dissimilar phases, which change significantly in the application of any external stimuli such as temperature, voltage, magnetic or electric fields. Proper modeling and the determinations of impact parameters are the basis of a design system of smart materials.

The objective of the research reported here is analysis of achievements in the field of new materials development for the production of shaped charge liners and determination of future directions of research.

2   Literature Review and Problem Statement

The vast majority of shaped charge applications are related to special machine building and military operations. Civil-purpose shaped charges are used in geological exploration, and the oil and gas industries, and in the construction and mining industries. In modern shaped charge design, solid liners of heavy metals are used, such as copper, nickel, molybdenum, tungsten, tantalum and their composites. One of the main parameters of shaped charge effectiveness is the depth of the hole in the target. This is determined predominantly by the charge structure, the detonation velocity of the explosive used, the precision of liner production, as well as other parts of the charge [4]. A number of shaped charges form not jets, but projectiles, which move a few times slower than jets and have a mass comparable to that of the liner. The shape of the liner

is the most relevant factor, directly affecting the structure of the formed jets or projectiles. In the first case the liner is a cone with an acute angle vertex or a spatial structure close to it that can be created by rotation of a paraboloid, ellipsoid, *etc*. In the second case, the liner is a spherical segment, spheroid, tri-axial ellipsoid or a structure similar to the cone but with blunt ending at the top. There are possible intermediate variants of a liner's shape, designed to create high-speed compact projectiles [5].

The influence of the shape of the liners (porous and solid) on the degree of target damage has been determined experimentally using liners made of powdered metals such as Cu, W, Pb, Ni, Al as well as solid liners made of Al and Cu in conditions of shock-wave loads and jets flows on brittle and ductile materials [6-9]. According to [10] the influence of the pore air and alloying additives (WC, C, MoS_2, B_2O_3) on the copper sintered porous material to the jet's motion in free flight was analyzed. Evaluation of following types of energies that influence the behavior of jets during their flight and depth of a target branch was carried out:

– an expansion energy of the air inside the porous material during jet lengthening,
– potential energy of the volumetric deformation of the jet's composite material,
– the energy of exothermic oxidation reactions.

The influence of highly compressed components, including pore air, on the depth of the breach (hole) and the behavior of jets is reported.

3   Materials and Methods of Research

Experiments with shaped charges were carried out according to a well-known methodology [6]. RDX (hexogen) or Okfol (octogen/inert material 96.5/3.5) charge, covered with a cap was installed directly on the target, which the top part was constructed as follows: made of steel plate (St3) ($\delta = 10$ mm) and the base was made of Al-Mn alloy in the form of a pack of plates. The charge was initiated with an electric detonator through a detonation cord. The distance between the charge with a diameter of 26 mm and the first target (the cap of the charge) was 13.1 mm; with a diameter of 31-50 mm. The internal angle of the conical liner of the charge with a diameter of 26 mm – 55°, external angle – 60°. The charge with a diameter of 31 mm had an internal angle in a conical liner of 44°, external angle – 48°.

The materials for the conical liner were powders of Al (1-50 µm), Cu (60-160 µm), Pb (1-40 µm), W (50-160 µm), Ni (1-50 µm) and the mixtures:

Cu/Al, W/Cu/Pb, W/Cu/Pb/Al, Ni/Al, W/Cu/Pb/Al/Ni, Ni/Pb. The basic composite was W/Cu/Pb (50/40/10) wt.%. The rest of compositions are given below:

–   content of Al in the experimental compositions was 9 wt.%,
–   content of Ni in the composite W/Cu/Pb/Al/Ni was 4 wt.%,
–   content of Pb in the composite Ni/Pb was 5 wt.%.

The liners were produced *via* compression in a hydraulic press; the same pressure was used for all investigated samples. The porosity of the liners so obtained was measured using the method of hydrostatic weighing. The volumes of the craters were measured using a measuring beaker and micron-sized copper powder. In some experiments, the speed of the projectile was measured using contact sensors [6].

4   Results of Studying of Interaction between the Shaped Charge and a Target

Obviously, the main determinant of the energy of jets or projectile shock interaction with a target is the volume of the resultant hole. The liner made of solid Al with the angle of 55°/60° at the top produced a hole 1.8-1.9 times larger in volume, as a result of the explosion of a charge with a diameter of 26 mm. The mass of the explosive material (RDX or Okfol) was 10 g [6-8]. The pressure of the charge's compression was $(8.1-10.8) \cdot 10^8$ Pa. The density of the explosive material within the charge was $(1.65-1.75) \cdot 10^3$ kg/m^3. The range of sizes of explosive materials crystals before compression was (0.01-0.1) mm. Approximately the same effect was obtained for solid and porous copper liners when the exploding charges were characterized by a diameter of 31 mm (15 g). The porosity of the liner made of Al was 8-16%, that made of Cu was 11-28%. This is why introducing porosity into a solid metallic liner is one way of creating smart materials.

It also confirms the result obtained in the work [2]. The depth of penetration in a steel target of a porous projectile made of the composite W/Ni/Fe/Co and the volume of the formed crater significantly exceed the same parameters created with a projectile made of a solid alloy of W/Ni/Fe. The speed of impact was about 2800 m/s. To obtain the same specific volume under deformation, the pressure and internal energy of the porous substance should be substantially larger than the solid.

Therefore, with the same dimensions of porous and continuous (solid) jets or projectiles, the pressure on a target, the temperature

and energy of the shock interaction will be greater in the first case. This was demonstrated using the example of solid and porous Cu, Ni and Al. To do this, we used the dependences of pressure $p(\rho)$ for these materials given in the monograph [11]. From the dependences $p(\rho)$, it is easy to obtain the dependences of pressure p on the specific volume V:

$$V = \frac{1}{\rho} \qquad (1)$$

The internal energy of shock compression is equal to the area under the curve $p(V)$. In the range of pressure and porosity used the behavior of materials, including composites, is described by the normal process of adiabatic shock [6, 7, 9]. The results of calculations for copper, nickel and aluminum are given in Table 1.

Table 1. Internal energy of porous and solid metals deformation

Liner material	Internal energy [GJ/kg]	Shock pressure [GPa]	Specific volume of shock compressed metal [m³/kg]
Cu, porous	0.832	100.0	0.093
Cu, solid	0.456	59.0	
Ni, porous	0.724	100.0	0.096
Ni, solid	0.383	52.0	
Al, porous	5.406	100.0	0.29
Al, solid	2.524	49.3	

The pressure at the target with a solid liner jet, was evaluated according to the hydrodynamic theory [11]. They show that the internal energy of compression of jets of porous metals with a porosity coefficient m close to the porosity coefficient of the liner materials exceeds the compression energy of a solid liner by 83% (Cu), 89% (Ni) and 114% (Al):

$$m = \frac{\rho_0}{\rho_{00}} \qquad (2)$$

where ρ_0 – is the ratio of the density of the solid material and ρ_{00} – is the density of the pores. Those results are indirectly confirmed by studies on the effects of porous liners' jets on metallic and nonmetallic materials [8, 9].

Another way of increasing the energy of shock interaction is adding into the liner material components that react with each other, transforming the mechanical energy of shock wave into heat energy of chemical transformations

[6, 7, 12]. Experiments have shown that the use of porous composites Cu/Al, Cu/Pb/Al, Ni/Al, W/Cu/Pb/Al, W/Cu/Pb/Al/Ni (Figure 1) allows us to obtain holes with greater volume compared with the basic composites without Al (*i.e.* Cu, Cu/Pb, Ni/Pb, and W/Cu/Pb) by 20-90%. This indicates the transformation of mechanical energy of shock interaction into chemical and thermal reactions through the interaction of Al with the other components of the composites [6, 7]. According to [13], the enthalpy of $CuAl_2$ formation is 40.1 kJ/mol, or 0.34 kJ/g. The mass of the liner was 10-15 g depending on the contents of Al. Even if the mass of the produced product ($CuAl_2$) will be 0.5-2 g (in experiments it was not less than 0.5 g), the additional energy will be 0.17-0.68 kJ. This is proportional to the internal energy of compressed porous metals (Cu and Ni) (Table 1).
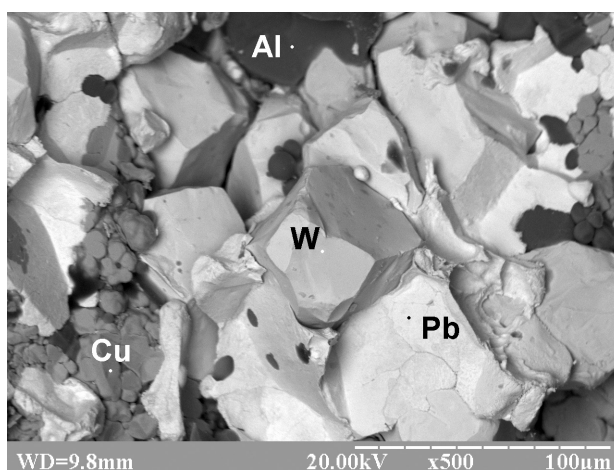

Figure 1.   Micrograph of composite material of the liner W/Cu/Pb/Al

It should be noted that the usage of Al, B, Mg and their compounds in explosive and combustible (high-energy) materials is well known [14]. The study of the same interaction of these substances and their compounds with other metals and nonmetals in terms of shock wave load is reported in a much smaller number of works. Al interaction with Cu, Ni, Nb, Co, Pd during explosion was investigated in many studies, and the most complete in [13].

The modes of heating and the rate of combustion of metals in exothermic reactions can be described as quasi-static. At the same time, shock-wave behavior was investigated, including the thermal effects of chemical reactions behind the shock wave front [15-17]. It was shown that under certain critical parameters behind the shock wave front the chemical interaction of the components begins in a mixture with the formation of new substances and the emission of additional

energy. Thus, according to [15], the interaction of the pyrotechnic mixture CuO-Al components begins at pressure of about 10 GPa. In this process, the temperature rises to about 3000 °C, with the additional energy release of about 4 kJ/g. A similar effect has been observed in the mixture of S with Al (45/55) when struck by a steel striker with a diameter of 40 mm and a length of 15 mm, at a speed of over 2000 m/s [17]. The criteria of chemical transformations executes, both in terms of pressure and temperature. Similar transformations occur when a jet or a projectile strikes between the SWF and a contact surface. The temperature at the shock point of the Cu/Al jet reaches not less than 3000 °C. The reaction products between the components of a jet with Cu and $Al/CuAl_2$, Cu_4Al_9 and other unidentified Cu and Al compounds are reported in [7]. Additional heat emission at the point of shock increases plastic deformation and material discharge from a crater at the hydrodynamic stage of penetration (Table 2). The data shown in the Table 2, were obtained in not less than 3-4 experiments.

Table 2. Dependency of the liner material and detonation speed of explosives on the hole volume in St3/Al/Mn target

Liner material [wt.%]	L [mm]	$d_{inlet\ opening}$ [mm]	$V \cdot 10^6$ [m³]	Explosive
Al, solid	32.0	12.0-13.2	4.2	RDX [a]
Al	36.0	13.9-16.0	5.3	
Al	35-40	13.5-14.5	8.7	Okfol [b]
Cu	80	8.2-8.8	7.4	
Cu/Al (100…0/0…100)	122-35	9.0-16.0	8.1-11.1	
Cu/Al (91/9)	122	8.2-8.8	6.4	RDX [a]
Cu/Pb (90/10)	81	7.5-8	5.0	
Ni/Al (91/9)	118	8.2-8.3	6.2	
Ni/Pb (95/5)	121	7.8	5.6	
W/Cu/Pb (50/40/10)	148	6.5-7.0	4.3	
W/Cu/Pb/Al (41/40/10/9)	145	7.7-8.2	4.1-6.6	
W/Cu/Pb/Al/Ni (37/40/10/9/4)	123	7.4-8.1	4.8	

[a] D = 7800-8100 m/s, [b] D = 8400-8700 m/s.

5. Discussion of Results of Studying the Interaction between the Shaped Charge and the Target

The results presented in Table 2, show there is a dependence of the hole volume on the composition of the liner material. The presence of Al in all composites

contributes to increasing the volume of the target crater. The thermal behavior, mechanical properties and reaction characteristics of Al-Me composites and other composites with reactive components under shock compression have been presented in many papers.

The fundamental review [18] analyzed the available data on the reaction of various powder systems to shock compression. The authors believe that there is an inextricable link between the propensity of a mixture to react and its internal properties. In this case, the threshold pressure of the start of the reaction can be altered by changing the relative size or morphology of the particles in the mixtures.

An article [19] reported the behavior of the explosive fragmentation of a ring made of Ni + Al energetic material by an internal TNT charge. In the experiment, signs of burning of small particles of the material were found. The simulation results of the impact of the material with a foam polystyrene barrier at a speed of 2000 m/s did not show the ignition of the polystyrene foam and do not provide confidence in the possible ignition of the Ni + Al fragments. Perhaps this is due to the low impact speed.

The thermal behavior, mechanical properties, and reaction characteristics of Al/Ni/PTFE composites were studied in [20]. A result of quasi-static compression tests showed that the heat of reaction of Al-Ni was 12.5 higher than in the Al-Ni-PTFE system. The reaction between Al and PTFE preceded reaction between Al and Ni.

In [21], the effectiveness of punching aluminum armor with cylindrical and conical nylon, aluminum, steel and Al-PTFE impactors with an impact speed of 2100 m/s was experimentally investigated. On average, Al-PTFE shells remove a slightly smaller mass than aluminum projectiles.

The increased efficiency of shaped charges with porous composite liners is explained by the fact that composites containing Al or metals with a melting point below 3000 °C interact under high pressure and temperature with the formation of aluminides and the release of additional heat, similar to a thermal explosion. Presumably thermal explosion is initiated by a shock wave. Similar processes occur when some metals, for example Al and Cu, interact with a polymer containing fluorine, *e.g.* polytetrafluorethylene (PTFE, $[C_2F_4]_n$) [18]. In paper [22], holes in target created using shaped charges with PTFE and Cu-PTFE (38.5-61.5 wt.%) are compared. The charge diameter was 40 mm, the angle at the base of the cone was 55°. The diameter of the inlet was increased by 18.5%, the outlet in the rear plate of the barrier – by 12.6%. At the same time, the speed of the leading part of the jet was 5363 m/s, the diameter was 3.2 mm. The penetration depth into the steel target St45 was 30.3 mm. For comparison,

a jet of PTFE with a diameter of 2.7 mm with a tip speed of 5575 m/s produced a crater with a depth of 22.1 mm. An increase in the channel diameter along the entire length indicates the emission of additional energy during penetration of the target.

The authors of [11] draw attention to the mechanism of energy increase of the same nature when impacting targets containing Al, Mg, Ti with PTFE shock drivers as a result of the chemical exothermic reaction of metals with PTFE. It is possible that the porous Al jet also partly interacts with the target materials: iron (steel St3) and manganese, copper and zinc in the Al-Mn alloy. Besides that, the internal energy of compressed porous Al exceeds the same parameter when compressing porous copper (Table 1). This is evidenced by the stable excess of the channel volume formed by an Al jet compared to the volume of a channel formed by a Cu jet as being on average 8% [7]. Some experiments showed the difference to be 20-30% which is outside experimental error (10-12%). In principle, any combination of materials that react in shock wave loading with additional energy release is useful for increasing the effect of a jet and compact shockwaves with the exception of some refractory metals. Thus, using of the W/Al composite material in a shaped charge liner showed that the size of a target channel made of steel St3 with the contents of Al is changed, but the volume does not depend very much on the amount of Al [6]. The main reason is the absence of reactions:

$$W + Al \rightarrow W_xAl_y$$
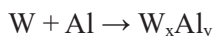
in this range of energy of shock interaction. Figure 2(a) shows the products of the Cu/Al composite reaction at the jet-target "St3/Al/Mg" impact point, including the tungsten crystal (Figure 2(b)), which accidentally fell into the material of the liner from the press tool.
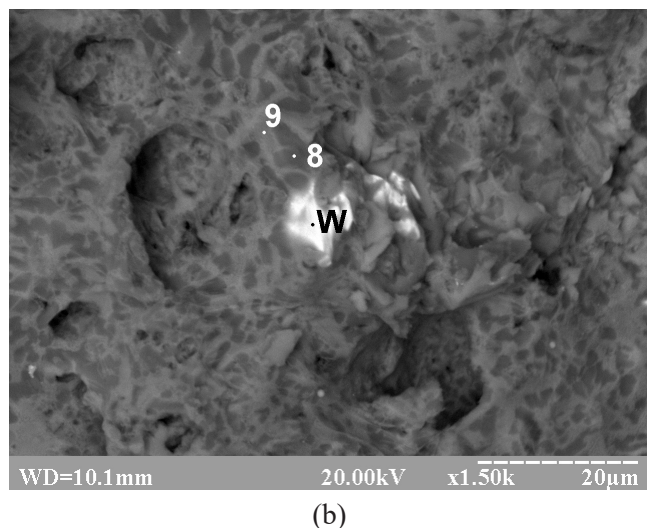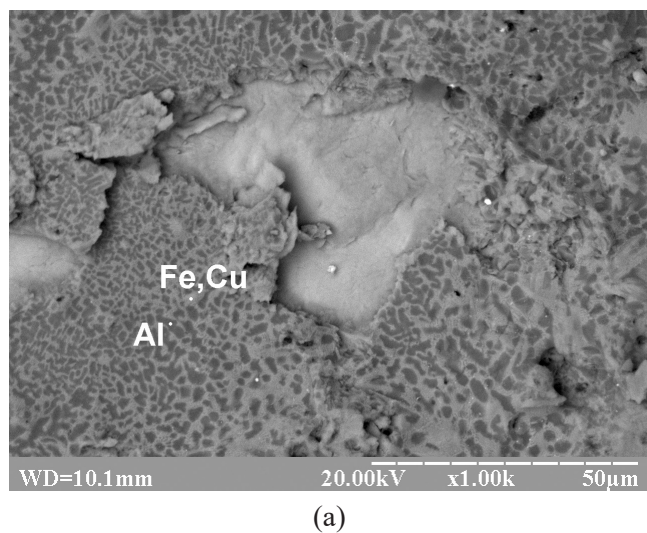
(a)

(b)

Figure 2. Products of the interaction between jet made of composite material Cu/Al and the target St3/Al/Mn

Experiments show that the impact energy can be estimated as 22.6-33.5 kJ for charges of the abovementioned diameters ($\approx 0.4 \ E_{exp}$). Jet energy (E_j) estimation, taking into account the experimental data on the speed of the main part of a jet, the channel diameter at the input to a steel target and the effective length of a jet [6], gives the following values: 27.6 kJ, 28.3 kJ and 29.9 kJ,

respectively, for copper, aluminum and composite (W/Cu/Pb) jet. The charge diameter was 26 mm. It shows that different jet energy for different liner materials does not cause a sharp change in shock properties. These are the heat that generates porosity in the zone of deformation of the jet, and the heat of chemical reactions in conditions of shock wave loads. Of particular interest to science and practice is the possibility that dense metals (Mo, Ta, W, U) interact chemically with energy additives behind the SWF of the jet.

It is known that in the mode of thermal explosion Al interacts with refractory metals (Nb), and molybdenum – with boron during SHS [23]. For this reason the same effect can occur between Mo + Al, Mo + B components during shock wave loads at certain rates of shock interaction, greater than some critical value.

Zhukov *et al.* [24] and Horie *et al.* [25] investigated the interaction of Al and Ni under the conditions of shock wave load. In the experiments reported in [24] it was shown that the structure and composition of the material being formed (AlNi) is not very different from the analogous product produced by the traditional method (the high-temperature synthesis itself).

If the presence of chemical transformations is directly or indirectly proved in experiments with composite jets with Cu/Al, Ni/Al, W/Cu/Pb/Al [6, 7], then the question of such transformation possibilities in the case of other mixtures and metals used, or their compounds such as Mo + B, Mo + 2Si, or some high-energy materials (MgB_2, AlB_2) remain open. At the same time, some compositions availability are beyond doubt, because of the mass heat of combustion in oxygen is [26]:
–   for Al: 7.4 kcal/g (31.0 kJ/g),
–   for B: 14.1 kcal/g (59.0 kJ/g),
–   for MgB_2: 9.18 kcal/g (38.4 kJ/g),
–   for AlB_2: 9.1 kcal/g (38.1 kJ/g).
This list can be supplemented with boron compounds: CrB_2, TiB_2 *etc*.

It should be noted that the heat of formation, for example, copper, nickel, and titanium aluminides is 40-70 kJ/mol, 130-162 kJ/mol, 25-42 kJ/mol, respectively [13], which is in favor of the Ni/Al composite. However, the best results were obtained in experiments with the Cu/Al composite. Perhaps this is due to a higher melting point of Ni comparing with copper, and possibly with an unsuccessful choice of the number of components in the Ni/Al composite. The only way to optimize the composition of this and other possible composites is to obtain the dependencies v (Al content), as was done for the composites of Cu/Al and W/Cu/Pb/Al in [7] (see Figure 3).
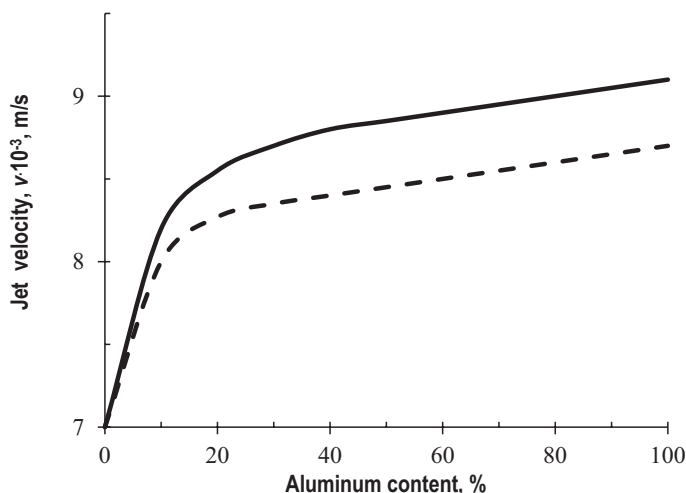
Figure 3.   The changes of the speed of jet made of composite material Cu-Al on Al content. The upper curve – detonation speed of explosive $D = 8100$ m/s; the lower curve – detonation speed of explosive $D = 7800$ m/s

One of the practical applications of the shaped charges is initiation of detonation in explosives with the help of a jet or a projectile. It is sometimes used in explosive mining, but is, mainly, used in military conflicts to blast explosive materials in vehicles, warehouses and enemy arsenals. The presence or absence of detonation of each explosive when a jet or a projectile has struck is determined, for example in [11], by the criterion of Held:

$$G = dv^2 > G_{cr} \tag{3}$$

where d, v – are the diameter and velocity of a jet, respectively, G_{cr} – is the critical value of the parameter at which the probability of detonation is equal to one). It is clear that in the case of a chemically active jet or projectile, the value of G_{cr} will be a slightly lower for each explosive than those given in [11]. The velocity of a jet v increases (Figure 3) with increase of Al content. The composite porosity for the calculations was taken equal to 8% (the peak of the conical liner) and increased to 16% (basis of the liner). At Al content = 0, the copper jet speed was determined experimentally by the method of contact sensors [6]. Different forms of liners were used, and the charge initiation point changed [27] to increase the parameter d. For physical reasons, a similar effect will occur when composite jets or projectiles hit a wall of a tank containing

a flammable substance (oil, rocket fuel, fuel oil and lubricants). The possibility of utilizing such an effect in terrorist attacks makes necessary effective protection development of relevant objects (tankers, reservoirs, *etc.*) against shaped charges jets or projectile impact. In certain schemes of shock wave loading of initial powder mixtures, new structural materials can be obtained in preservation capsules, for example, nickel aluminide [24, 28].

6 Conclusions

The class of new functional materials for shaped charges was established and the requirements for them were formulated:
– optimal porosity of liner material,
– maximum energy (0.724-5.406 GJ/kg) of chemical reactions between components in shock-wave loading conditions of a jet/projectile material occurs at the penetration point on a target.

Prospective energy additives to known metals (Cu, Ni, Mo, W, Ta) used in shaped charges, beside Al may be B, MgB_2, AlB_2, TiB_2 and their combinations.

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