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ТЕХНИКАЛЫҚ ҒЫЛЫМДАР ЖӘНЕ ТЕХНОЛОГИЯЛАР СЕРИЯСЫ / TECHNICAL SCIENCES AND TECHNOLOGY SERIES/ СЕРИЯ ТЕХНИЧЕСКИЕ НАУКИ И ТЕХНОЛОГИИ

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Review

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Modern composite armor materials

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Abstract. Currently, composite armored vehicles based on a ceramic layer, polymer and natural fibers are of great interest. This work is a review article and includes scientific works over the past 18 years. The aim of the work is to generalize literary data on research on the creation of armored vehicles. Camamosetosite armor based on various brands of Kevlar is a promising material. At the same time, natural materials in their ballistic properties are not inferior to polymeric materials. Widespread use in this field of research and nanomaterials. The use of carbon nanotubes that differ in unique strength properties can significantly reduce the mass of body armor. When using nanomaterials for body armor can reduce its thickness by 15-35 times. Promising are also multilayer metal armored vehicles obtained by explosion welding by explosion. Light metals as aluminum and titanium are used as metal materials. As a result of heat treatment in the structure of composite material, intermetallic layers of TiAl3 with a thickness of 90-100 microns are formed. It is known that intermetallic compounds are characterized by high physical and mechanical properties. In this work, various composite materials are considered for anti-ocal resistance and resistance to high-speed impact.

Keywords: armor materials, individual protection, damaging elements, fragments, composite materials, ceramics

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Introduction

Modern military conflicts, particularly in localized wars and armed engagements, highlight the crucial need to protect soldiers from various types of weaponry. The likelihood of soldiers being wounded by high-speed bullets is significantly higher in such conflicts. Consequently, the demand for advanced composite materials with superior protective properties has increased. While modern body armor effectively intercepts projectiles, the residual energy from bullets or fragments can still cause severe internal injuries, behind-armor trauma, and even fatalities.

The development of these materials prioritizes reducing weight, ensuring that the surface density remains within the optimal range of 50-80 kg/m^2.

To counter low-energy threats, textile armor made from high-modulus and high-strength polyaramid and polyethylene fibers is commonly employed. In contrast, protection against high-energy threats necessitates composite materials featuring a rigid ceramic layer (screen) combined with a laminated organoplastic backing (substrate) [1]. Thus, the primary challenge lies not only in fragmenting the incoming projectile but also in effectively decelerating or halting the resulting fragments to minimize secondary damage. In view of this, work is devoted to reviewing publications from open sources that focus on the research and development of composite armor materials with superior protective capabilities.

The methodology

This article is a literary review of scientific works over the past 18 years. When writing the article, SCOPUS, ELIBRARY, CROSSREF, SPRINERA for the above keywords were used. When writing this article, scientific publications were used, containing an evidence-based experimental approach to the subject under study.

Findings/Discussion

One of the most significant advancements in armor material development is the creation of ceramic composite armor [1]. Compared to steel armor, ceramic composite armor offers several advantages, including lower surface density (weight per 1 m2).

The test results are given in Table 1.

Table 1. Results of firing oxide ceramic-based ammunition with increased penetration 7H39 (1, 2) and 7H13 (3) from a distance of 10 m [1].

Armor type	Armor thickness, mm	Substrate thickness, mm	Layers of substrate broken through, %	Surface density, kg/m^2
Standard with fabric	19	9,5	45	46
With flat-oriented substrate	14	4	12	40,8
With flat-oriented substrate and a thin screen	13	4	18	36,7

To improve the mass-dimensional parameters of armor consisting of a ceramic layer and an organoplastic layer (substrate), the substrate was improved in [1]. A composite substrate with a flat-oriented protective structure is proposed, where untwisted threads are laid orthogonally. As can be seen from Table 1, the use of a new substrate allows for a significant reduction in armor

thickness. This results in the armor panel becoming lighter and more effective. When considering the use of composite materials in bulletproof vests, Kevlar occupies a special place [2, 3]. Kevlar fabric has a tensile strength of 3620 MPa and a low relative density of 1.44 [2].
These properties are important when protecting people from high-impact bullets [2, 3]. The properties of some Kevlar grades are given in Figure 1.

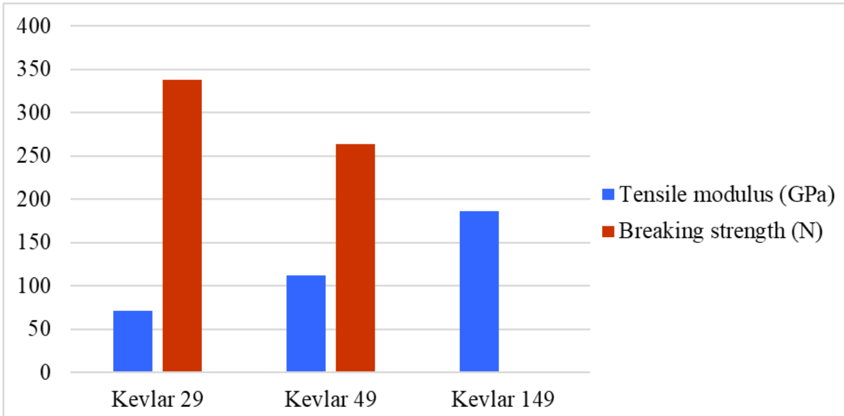

Figure 1. Comparison of tensile modulus and breaking strength of Kevlar 29, 49 and 149 [2]

The relative elongation of these materials is shown in Figure 2 [4, 5].

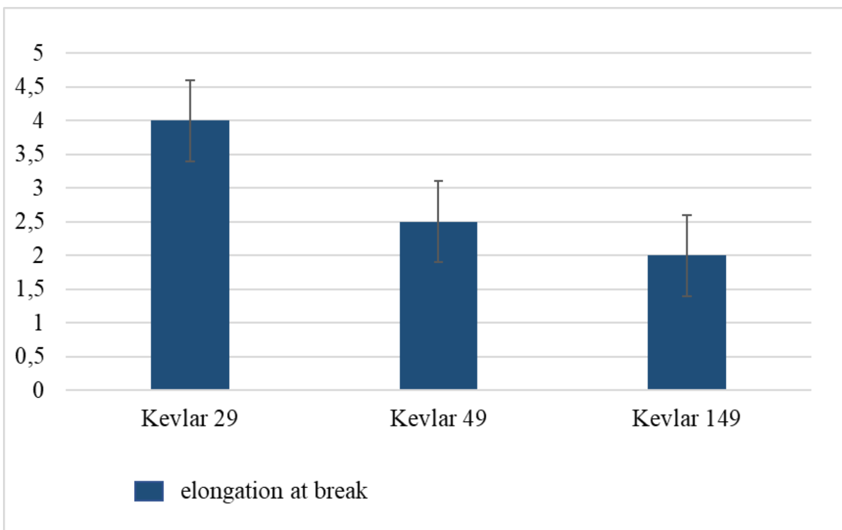

Figure 2. Comparison of the percent elongation of different grades of Kevlar

Studies on the impact behavior of Kevlar/epoxy composite plates with varying thicknesses and layup sequences showed satisfactory results [6]. The effect of thickness and layup sequence on energy absorption capacity was investigated under high-velocity impact conditions. The plates were placed at a distance of 10 meters from the muzzle of a pistol, and a Parabellum 9×19 mm bullet was fired at a velocity of 390±10 m/s. The authors demonstrated that the 0/90 layup sequence is the most effective for impact resistance. In work [7], S-2 glass fibers are used as a composite armor material. These fibers have a composition of SiO2 65 wt.%, Al2O3 25 wt.%, and MgO 10 wt.%. This material exhibits higher deformation before failure and a greater modulus of elasticity than conventional weakly alkaline alumino-borosilicate fibers, which have a composition of SiO2 54 wt.%, Al2O3 14 wt.%, CaO + MgO 22 wt.%, and B2O3 10 wt.%. Recently, strong organic fibers such as poly (p-phenylene benzobisoxazole) (PBO) and poly-{2,6-diimidazo[4,5-b:4',5'-e] pyridinylen-1,4(2,5-dihydroxy) phenylene} (PIPD, known as M5 fiber) have been used in composite materials for flexible armor. Flexible composite armor is primarily used for individual protection.

Kevlar fabrics, which are widely used in protection systems, contribute to environmental pollution during disposal and have a negative impact on the ecosystem. Researchers are increasingly proposing the use of environmentally friendly, natural materials [8-10]. For example, in study [8], an eco-friendly lightweight material is used instead of Kevlar fabric. The proposed material exhibits excellent properties for absorbing and dissipating kinetic energy. Table 2 presents comparative ballistic characteristics of soft and hard armor made from natural fibers [8]. The experimental conditions are described in the study [8].

Table 2. Ballistic characteristics of materials

№	Fiber	Matrix	Energy absorption (J)	Ballistic limit (m/s)	References
1	Kenaf/Kevlar (30/70)	Epoxy	148	-	[11]
2	Kenaf/Kevlar (Vf6/Vf 47)	Epoxy	175	590	[12]
3	Coconut sheath/Kevlar (wt% 5/25)	Epoxy	240	-	[13]
4	Curaua fiber (30 Vf)/epoxy composites	Epoxy	197	-	[14]
5	Kevlar/Basalt (50/50)	Polypropylene	112	-	[15]
6	Piassava fiber (10 vf)	Epoxy	272 ± 19	236 ± 8	[16]
7	Fique fiber	Polyester	155 ± 7	-	[17]
8	Fique fabric	Polyester	154 ± 5	-	[8]

As seen in Table 2, composite materials based on natural fibers are comparable in properties to Kevlar-based composite materials.

In study [18], a technological principle for manufacturing combined armor with a ceramic layer was developed. The ceramic material produced exhibits key characteristics that are not inferior to those of commercially manufactured armor ceramics. The work also developed a highly elastic polymer binder using the urethane elastomer SKU-PFL. Diamet X was used for curing. It was shown that to ensure the quality of poly-ceramic armor, the polymer binder content in the composite substrate should be maintained at 40%. The composite based on the developed binder significantly outperforms the epoxy-based composite: by 20% in terms of anti-fragmentation resistance and by four times in delamination strength [18]. The utilization of nanotube-based composite materials presents remarkable opportunities [19]. The properties of the developed ceramic material are presented in Table 3. The application of carbon nanotubes is linked to their unique properties, such as high mechanical strength, with a Young’s modulus reaching approximately 7000 GPa. In contrast, steel, titanium, and iridium alloys used for manufacturing military- grade body armor have a modulus value ranging from 200 to 520 GPa.

Table 3. Physical and mechanical characteristics of armor ceramics [18]

Material	Density, g/cm3	Hardness, GPa	Bending strength, MPa	Fracture toughness, MPa√m	Modulus of elasticity, GPa	Stiglitz criterion, ($GPa^2 \cdot m^3$)/kg
Aluminum oxide (Al_2O_3)	3,9	12-16	250-350	2,5-3,4	200-300	0,6-1,2
Reaction-sintered silicon carbide (SiC)	3,1	18-20	260-320	2,2-3,5	360-380	2,1-2,5
Boron carbide (B_4C)	2,5	28-34	320-400	3,3	360-400	4,0-5,4
Developed carbide ceramics	2,7	25-28	280-380	2,0-2,5	380-400	3,5-4,1

The deformation force is given by:

$$F=S\cdot E\cdot|\xi| \quad (1)$$

where S is the area of the deformable surface, E is Young's modulus, |ξ| is the relative deformation.

From the formula, the relative deformation will be equal to

$$|\xi|=F/(S\cdot E) \quad (2)$$

With equal F and S, the deformation of body armor made from ceramics and carbon nanotubes under bullet impact will be 15-35 times lower compared to body armor made from steel, titanium, and other alloys. As a result, the thickness of body armor can be reduced by 15-35 times, significantly decreasing the overall weight of the product [19]. The use of fibers based on nanostructured materials makes it possible to create highly efficient armored materials [20]. Nanotubes such as SIO2, Al2O3, SiC, inorganic fullerenes, MoS2 nanostructures, WS2 can be used as nanomaterials. The use of nanomaterials leads to a significant improvement in mechanical strength, tensile strength, modulus of elasticity of armored materials. Nanomaterials also contribute to energy absorption. When reinforcing with nanomaterials, it is necessary to pay attention to such parameters as size, morphology, distribution of nanomaterials in the polymer matrix. Control and regulation of the above parameters affects ballistic protection and energy absorption by tissue nanocomposites. By optimizing the parameters of filling with nanomaterials, it is possible to obtain ultra-strong armor material [20].

The requirements for enhanced armor reactivity include improved nanoscale properties of composite materials, such as reduced weight, high strength, increased durability, enhanced reactivity, and the ability to modify or adjust specific characteristics [20]. To protect heavy machine guns from fire, structural features of composite armor are proposed [21]. The design proposed by the authors for both small-caliber and large-caliber bullets consists of a crushing-deflecting layer made of a superhard ceramic material. Ceramic elements are made in form of cylinders with hexagonal belt. The presence of a hexagonal belt prevents the penetration of small-diameter armor-piercing bullets through this layer. Ceramic elements are assembled in one row and fixed with polymer material. The retarding layer can be made of various fibers, a polymer matrix. The main outer layer is made of durable fabric using Rusal thread. When creating composite armor material, the outer layer is immediately installed after the polymer fills the upper surface of the ceramic elements. Good adhesion of the outer layer to the polymer matrix is achieved. Other designs of armored materials are also given in the work, as well as their advantages and disadvantages are described.

Various composite materials for shatter resistance and impact resistance have been studied in [22]. It is known that when creating a composite material, the property of the product is significantly influenced by the polymer matrix. In this work, three types of matrices were studied: ED-20 epoxy resin and an amine-type hardener; polyurethane polymer; polyolefin thermoplastic. A Ruslan (58.8 tex) aramid yarn fabric was used as filler for all three composites. In the shatter resistance test V50, a positive result was obtained on a composite based on a thermoplastic matrix. V50 (m/s) of the composite under study was 538, using a plain weave fabric of Ruslan thread as a reinforcing material. But the main disadvantage of this polymer material is its destruction under the influence of heat, oxygen, ionizing radiation. As a result of these effects, the composite material becomes brittle over time. This inevitably leads to a reduction in the life of the article made of this composite. An intermediate result of V50 (m/s) was obtained for the composite based on the polyurethane matrix of 457, which is also not bad. A low result was obtained with a composite where epoxy resin was used as binder (V50 (m/s) = 391). However, when modifying the epoxy resin, it is possible to change the structure of the matrix and significantly increase the impact resistance of the composite [22].

One of the promising areas is the production of multilayer metal armor materials using light metals [23]. These materials are characterized by high bullet resistance and structural strength along with low specific gravity. The authors of the development produced a metal composite using explosion welding technology. In this case, permanent metal connections are formed at the interatomic level. To obtain a composite material of the composition B95+VT1-0+B95+VT1-0+B95, a plane-parallel explosion welding scheme was used. An aluminum alloy was used as a matrix. In order to improve the tactical and technical characteristics, an intermetallic layer was formed in the structure of the composite material due to heat treatment. The thickness of the highly hard intermetallic TiAl3 layer was 90-100 μm. The intermetallic layer was formed at a temperature of 6250C for 300 hours. Ballistic tests of the developed material showed high results, which demonstrates the prospects of the composite material. In work [24], an additional intermediate third layer is proposed for the well-known armored protection design described in work [1]. This layer has a ceramic-polymer composition. The ceramic filler consists of boron carbide powder, silicon carbide, or hollow ceramic spheres. To reduce the mass of the intermediate layer and the overall weight of the armor material, hollow spheres were primarily used. Polymer substances were employed as binders. To maintain a consistent thickness of the intermediate layer, polymer honeycomb structures were utilized. The proposed design with an intermediate layer improves ballistic performance. Particular attention should be given to the work of the authors in [25], who developed the third-generation Rusar-C fiber. This fiber exhibits high physical and mechanical properties. According to [25], the developed fiber surpasses the well-known Kevlar fiber in terms of specific breaking load (cN/tex). The tensile strength of Rusar-C fibers in microplastic (kg/mm^2) is 530–600, compared to Kevlar's 380–400. The superior performance of Rusar-C fibers is achieved through advancements in technological processes during fiber production. The dry-wet spinning method was used in this study. The developed fibers are used to manufacture threads with linear densities of 29.4, 58.8, and 100 tex for special-purpose fabrics.

Tests on products made from Rusar-C fibers for anti-fragmentation resistance in general-purpose body armor, compared to similar products made from Ruslan fiber, showed a 2% improvement. When incorporated into a composite material with a polyurethane binder, the developed fiber demonstrated a 10% increase in anti-fragmentation resistance (m/s), a 25% increase in flexural strength (MPa), and a 25% increase in tensile strength (MPa) compared to Ruslan fiber.

To provide military personnel with bulletproof vests with improved injury safety properties, the authors of the work [26] propose to provide bulletproof vests with shock-absorbing support. The developed body armor has pockets with armored panels with shock-absorbing properties. Shock-absorbing support consists of rollers forming chambers made of polyvinyl chloride. Outside, the roller is covered with a flock fabric, the inner part is covered with a polymer film of carbon nanomaterial. A feature of the design is that each roller is filled with microspheres together with a viscoelastic foam damper. The solution of the injury safety problem is achieved due to a certain height of the shock-absorbing support, increased shock-absorbing properties of the support, the presence of an internal coating made of a polymer film. This polymer film should contain at least two layers of carbon elements, which include carbon nanotubes, graphenes and other nanomaterials. Microspheres can have different diameters 20 · 103 nm - 150 · 103 nm.

The authors [27] have developed a method for obtaining a unique ceramic based on aluminum oxynitride, which can be used for armored materials. To obtain said ceramic material, the starting components are mixed in isopropyl alcohol medium. The initial components are used in the form of powders of aluminum nitride and aluminum hydroxide (grade - chemically pure). Next, the drying process is carried out, then the homogenization of the powders. The formation of aluminum oxynitride takes place at 18500C temperature in a nitrogen atmosphere for 15 minutes. The subsequent step consists in hot pressing at a temperature of 18500C, pressing time of 30 minutes at a pressure of 30 MPa. The first step forms directly the formation of a chemical compound of aluminum oxynitride for 15 minutes. A subsequent operation using a pressure of 30 MPa results in compaction of the material and the production of a dense single-phase homogeneous ceramic. In this method, a simple technology is used, which proceeds in one step. The selected 18500C temperature significantly reduces the time of ceramic formation. Tests of ceramics showed the following results: bending strength 255 MPa; Vickers microhardness 19.9 GPa.

Currently, research in the field of creating "liquid" armor is of wide interest. Earlier in this work, the use of nanomaterials was indicated, which lead to an improvement in the ballistic characteristics of body armor systems. The main component in the creation of "liquid" armor is non-Newtonian liquid [28]. This liquid (STF), when subjected to its shock load or high speed, shows an increase in viscosity and becomes solid. STF exerts great resistance to deformation in ballistic strikes by distributing the force of impact over a larger area of armor. This significantly reduces the likelihood of injury. STFs were introduced into such high-strength materials as Kevlar.

The authors of [28] STF impregnated natural fabrics that were used in body armor. Sisal fabric with simple weaving was used as a natural fabric. During the studies, an STF liquid was prepared at various concentrations of nanosilica in ethyl spiret: 10%, 20%, 30%. Mixing was carried out in a magnetic stirrer and sonicated for 20 minutes. The homogeneous mixture was then placed in an oven for 3-4 hours for baking at 1600C. When baking, personal ethanol evaporated. To impregnate the natural fabric, the previously prepared STF mixture was further mixed with ethyl alcohol in a ratio of 1:2. The resulting mixture was impregnated into the fabric by immersion.

After the complete impregnation process, the fabric was placed in an oven to dry at 900C for one hour. The STF-impregnated fabrics were then collected in a stack of 10 layers and stitched into a diamond throughout the web. Analysis of the EDS of impregnated fabrics showed that at a silica content of 10%, the impregnated fabric contained 1% silica, 80% carbon, and 18.6% oxygen. The 20% silica impregnated fabric assay contained 3.2% silica and the 30% silica impregnated fabric from 3.2% to 4.6%. Ballistic tests of 3 batches of impregnated fabrics (10%, 20%, 30%) showed the highest percentage of energy absorption (54.75%) in fabric impregnated with 30% STF. For fabric impregnated with 10% STF - 38.66%; for 20% STF tissue - 51.29%. It has been found that after the stress is removed, the viscosity of the STF returns to its original state. Research in this area continues worldwide. This area of research is clearly promising.

Conclusion

An analysis of the scientific and technical literature showed that individual protection against small arms is not always effective when the internal organs of a soldier are hit by fragments and the residual energy of a bullet. The use of ceramic composite armor, consisting of two layers: ceramic and advanced organoplastic, is promising. Kevlars of various brands have proven themselves well as composite materials in body armor. However, when using composite materials, there are disposal problems, in view of which some environmental damage is caused. The use of natural materials instead of Kevlar fabric is also a promising area. Natural materials in their ballistic characteristics are not inferior to the properties of Kevlar-based composite materials. Natural materials have good breathability, easy to recycle, environmentally friendly. The use of composite materials based on nanotubes is associated with their unique properties as high mechanical strength. The use of nanotubes in composite materials for body armor will significantly reduce their weight.A promising area is research on the creation of "liquid" armor. The use of STFs also results in reduced body armor weight.

The contribution of the authors

Zh.M. Ramazanova - significant contribution to the concept of the work; collection, interpretation of the results of the work, consent to be responsible for all aspects of the work, writing a text;
G.A. Kokaeva - writing a text, critically reviewing its content,
A.E. Zhakupova - analysis or interpretation of the results of the work,
O.K. Abdirashev - collection, analysis or interpretation of the results of the work

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Заманауи композициялық құрыш материалдары

Аңдатпа. Қазіргі уақытта керамикалық қабат, полимер және табиғи талшықтарға негізделген композициялық бронды материалдар үлкен қызығушылық тудырады. Бұл жұмыс шолу мақаласы болып табылады және соңғы 18 жылдағы ғылыми жұмыстарды қамтиды. Жұмыстың мақсаты-бронды материалдарды жасау бойынша зерттеулер туралы әдеби деректерді жалпылау. Кевлардың әртүрлі маркаларына негізделген керамикалық композиттік бронь перспективалы материалдар болып табылады. Сонымен қатар, табиғи материалдар баллистикалық қасиеттері бойынша полимерлі материалдардан кем түспейді. Зерттеу және наноматериалдар осы салада кеңінен қолданылады. Бірегей беріктік қасиеттерімен ерекшеленетін көміртекті нанотүтікшелерді қолдану броньды кеудешелердің массасын айтарлықтай төмендетуге мүмкіндік береді. Денеге арналған наноматериалдарды қолданған кезде оның қалыңдығы 15-35 есе төмендеуі мүмкін. Жарылыспен дәнекерлеу арқылы алынған көп қабатты металл броньды материалдар да перспективалы болып табылады. Металл материалдар ретінде алюминий және титан сияқты жеңіл металдар қолданылады. Термиялық өңдеу нәтижесінде композициялық материалдың құрылымында қалыңдығы 90-100 мкм болатын TiAl3 интерметалл қабаттары пайда болады. Металларалық қосылыстар жоғары физика-механикалық қасиеттерімен сипатталатыны белгілі. Бұл жұмыста сынықтарға және жоғары жылдамдықты соққыға төзімділікке арналған әртүрлі композициялық материалдар қарастырылған.

Түйін сөздер: бронды материалдар, жеке қорғаныс, зақымдайтын элементтер, сынықтар, композициялық материалдар, керамика

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Современные композитные бронематериалы

Аннотация. В настоящее время композитные бронематериалы на основе керамического слоя, полимерных и натуральных волокон представляют большой интерес. Данная работа является обзорной статьей и включает в себя научные работы за последние 18 лет. Целью работы является обобщение литературных данных об исследованиях по созданию бронематериалов. Керамокомпозитная броня на основе различных марок кевлара является перспективным материалам. При этом натуральные материалы по своим баллистическим свойствам не уступают полимерным материалам. Широкое применение находит в данной области исследования и наноматериалы. Применение углеродистых нанотрубок, которые отличаются уникальными прочностными свойствами, позволяют значительно снизить массу бронежилетов. При использовании наноматериалов для бронежилетов может уменьшить его толщину в 15-35 раз. Перспективными также являются многослойные металлические бронематериалы, полученные методом сварки взрывом. В качестве металлических материалов используются легкие металлы как алюминий и титан. В результате термической обработки в структуре композитного материала образуются интерметаллические слои TiAl3 толщиной 90-100 мкм. Известно,

что интерметаллические соединения характеризуются высоким физико-механическими свойствами. В настоящей работе рассмотрены различные композитные материалы на противоосколочную стойкость и стойкость к высокоскоростному удару.

Ключевые слова: бронематериалы, индивидуальная защита, поражающие элементы, осколки, композитные материалы, керамика.

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