DOI: http://dx.doi.org/10.15407/tpwj2018.08.07

MATERIALS FOR INDIVIDUAL ARMOUR PROTECTION (Review)

A.A. BABINETS[1], **I.A. RYABTSEV**[1] and **A.I. PANFILOV**[2]
[1]E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazimir Malevich Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua
[2]LLC «Steel Wrok», Kryvyi Rih, Ukraine. E-mail: a.panfilov@steel-work.net

In the paper the available literature data on the properties of different materials, currently used in the means of individual armour protection, were analyzed and the methods for improving their bulletproof and other operational properties were evaluated. It is shown that at the present time to create the means of individual armour protection, a variety of materials are used: fabric aramid or polyethylene fibers, metal plates based on steels, titanium, aluminum and their alloys, as well as ceramics based on boron and silicon carbides, etc. The main advantages and disadvantages of these armoured materials are shown. On the basis of literary data, it was established that for the 3rd–5th class of protection, the armoured plates of structural alloyed steels were widely used. To minimize the disadvantages inherent in steel armoured plates, it is necessary to apply bimetallic compositions with alternating hard and soft layers, produced, among others, by welding or surfacing methods. 20 Ref., 4 Tables, 3 Figures.

Keywords: *individual armour protection, classes of protection, armoured plates, properties of armoured materials, bulletproof, armour steels, composites, multilayer materials*

At present, for manufacturing of means of individual armour protection a wide range of materials is used, ranging from light armour based on aramid or polyethylene fibers to hard «shells» of different steels, alloys and ceramics intended for protection of a person from the most dangerous threats during the combat actions [1–6]. Each of these materials has its advantages and disadvantages, depending on which it can be applied in different circumstances. Thus, due to its high degree of protection, relative ease of manufacturing and low cost, the armoured plates of different steels became widespread [7, 8]. At the same time, a large majority of such armoured plates, which is the result of increasing their thickness, negatively affects the manoeuvrability of a person, the ability to perform certain tasks, and, thus, exposes him to the greater danger [9].

The aim of the work was to analyze the properties of different armoured materials currently used in the individual means of armour protection and to evaluate the methods of improving their bulletproof and other operational properties.

The use of armoured materials is regulated by the requirements of special standards, in particular, in Ukraine this is DSTU 4103–2002 «Means of individual protection, armour vests. General technical specifications» [10] (Table 1). According to these requirements, the means of individual armour protection are divided into three main classes: soft one with a protective structure based on special fabrics; semi-hard one with a basic fabric structure and additional hard protective elements and hard one on the basis of hard protective and shock proof elements.

The textile armoured materials and armoured panels of polyethylene fibers are used in soft means of individual protection of the 1st, 2nd classes and can withstand low-energy weapons such as revolvers and pistol bullets. To protect against high-energy weapons

Table 1. Characteristics of classes of protective structures [10]

Protection class	Destruction weapon	Bullet type	Weight, g	Speed, m/s
1	Pistol PM, 9 mm, bullet of type 57-N-181s	Steel jacket with steel core	5.9	315±10
2	Pistol TT, 7.62 mm bullet of type 57-N-134s	Same	5.5	430±15
3	Gun AK-74, 5.45 mm bullet of type 7N6	»	3.4	910±15
	Gun AKM, 7.62 mm bullet of type 57-N-231	»	7.9	730±15
4	Gun AK-74, 5.45 mm bullet of type 7N10	Steel jacket with steel heat-hardened core	3.6	910±15
	Riffle SVD, 7.62 mm bullet of type 57-N-323s	Steel jacket with steel core	9.6	850±15
5	Gun AKM, 7.62 mm bullet BZ of type 57-N-231	Steel jacket with steel heat-hardened core	7.4	745±15
6	Riffle SVD, 7.62 mm bullet B-32 of type 57-N-323s	Same	10.4	830±15

Table 2. Comparative characteristics of protection, made from different armoured materials [13]

Type of armoured material	Class of protection according to DSTU 4103–2002				
	1	2	3	5	6
Steel and its alloys	135/1.7	187/2.4	343/4.4	500/6.4	860/11.0
Titanium alloys	135/3.0	155/3.5	310/7.0	445/10.0	–
Aluminum alloys	135/5.0	190/7.0	590/22.0	860/32.0	1160/43.0
Ceramics based on corundum	–	–	–	380/19.5	440/35.6

*In the numerator, the surface density in g/dm^2, and in the denominator, the sheet thickness in mm are indicated.

with a high penetrability (3rd class and higher), for example, armour-piercing riffle bullets with heat-hardened cores, it is necessary to use semi-hard and hard means of protection with armour elements made of metals, alloys or ceramics [1–6, 11]. In this case, the weight of the bulletproof vest of the 3rd class is 6–9 kg, that of the 4th class is 10–12 kg and those of the 5th–6th classes are in the range from 11 up to 20 kg [7, 9].

A large mass, as was indicated above, is one of the main drawbacks of steel armour plates. Therefore, in the armour vests of the 5th and 6th classes, ceramic materials based on boron and silicon carbides began to be used [8, 12–14]. The main advantage of this type of materials is that they effectively resist bullets of armour-piercing and high-speed type, because the rate of cracks formation in ceramics is lower as compared to the rate of bullet penetration. This means that a high-speed bullet spends a lot of energy on fragmentation of material. In the process of ceramics fragmentation, a bullet starts decomposing into small elements, which are then easily retained by the aramid fibers [2].

However, if low-speed or pointed bullets hit the armour of ceramics, they behave in different way: separating pieces of ceramics, which subjected to cracking, such a bullet does not lose energy and accordingly, it is not destroyed and does not break up into several fragments. This can lead to an after-barrier impact of the bullet, i.e. to preserving of its properties after overcoming the armour protection. Hitting the same area with several bullets can be fatal [2, 12]. In other words, the «survivability» of the ceramic armour, i.e., its ability to withstand several shots, is noticeably worse than that of the metal analogs, especially during hitting the butt between separate ceramic inserts, and a considerable thickness of protective structure creates great problems to designers of armour vests and limitations in service for users [13, 14].

The comparative characteristics on a bulletproof resistance of ceramics and traditional metal armour are presented in Table 2 [13]. From Table 2 it follows that for the protection of 5 and 6 classes, the thickness of the steel sheet of 6.5–11.0 mm and that of ceramic panel of several times higher is required.

One of the methods to provide simultaneously a sufficient class of protection and reduce the weight of armoured plates by 15–30 % is the use of light alloys based on aluminum and titanium [7, 8, 14]. One of their advantages is also the absence of fragments during hitting of a bullet and a low degree of after-barrier injuries. Nevertheless, these alloys are expensive, difficult in processing, and exclude the creation of armour vests of the highest classes [8]. Thus, for the 3rd class of protection and higher at the present time, the armoured plates of structural steels with the necessary mechanical properties became the most widely applied, the main of which are hardness, strength, elongation and toughness [1–3, 13]. The main difficulty in creating bulletproof steel is determined by the need in combining high values of hardness and strength, which provide a resistance to penetration of bullet into the metal and a sufficient class of ductility and toughness to prevent its brittle fracture [1–3]. Thus, brittle steels of high hardness, as well as tough ductile steels of low hardness, are characterized by a low bullet resistance. The main alloying elements in armour steels are carbon, chromium, nickel, molybdenum, silicon [1–3]:

- carbon, first of all, provides an increase in the steel strength. At the same time, carbon significantly reduces the resistance of steel against the formation of solidification cracks. At a carbon content being lower than 0.44 % in combination with other alloying elements and their respective mutual influence, it is not possible to obtain a hardness of steel higher than *HRC* 50, however, a carbon content of more than 0.48 % is not advisable;
- chromium mainly increases the strength and hardenability of steel, and also contributes to some increase in its toughness due to the austenite grain refining. The chromium steels are sensitive to temper brittleness, the appearance of which can be avoided by their additional alloying with molybdenum;
- nickel increases the steel resistance to brittle fracture, ductility and toughness of steel, reduces sensitivity to stress concentrators and provides a high resistance to brittle fracture, but the disadvantage of these steels is a greater sensitivity to temper brittleness. As in the

case of alloying with chromium, this can be avoided by additional alloying by molybdenum;

• molybdenum inhibits the growth of austenite grain. It is introduced to prevent temper brittleness. At the same time, the molybdenum by some increasing the hardness of ferrite, reduces its impact toughness;

• silicon like carbon hardens steel and increases the steel strength and reduces its toughness more than other alloying elements. In steel, there should be a sufficient amount of silicon, but not reducing the resistance against cracks formation.

Thus, most often the armoured steel represents a medium-carbon, medium-alloyed steel of the martensitic class (σ_t is at least 1500 MPa, hardness is *HV* 360–600). The high strength characteristics of armoured steels are achieved as a result of heat treatment, including hardening for martensite and low tempering [1–5]. Moreover, as to its structure, such armour can be homogeneous, i.e., uniform in hardness and toughness across the section, and heterogeneous: having an outer layer of higher strength and a rear tough, ductile layer which does not produce fragments [11]. The hardness of the outer layer of such materials is enhanced by surface hardening [1–3]. The typical representatives of armoured steels corresponding to the specified requirements are: MARS 240–300 (France); ARMOX 400–600 (Sweden); 4340 TOD (USA); 44S, 56 (Russia); RAMOR 550 (Finland), etc. [4, 6]. The chemical composition, as well as mechanical properties of some of these steels, are given in Table 3. For example, a sheet of steel 44S with a thickness of 5.5 mm, having a hardness at the level of *HRC* 55–57, provides protection against simple bullets of AKM, AK74 and SVD (3rd class) and with an increase in sheet thickness to 6.5 mm the protection against bullets with a steel hardened core of 5.45 mm caliber is provided, which corresponds to the 4th class of protection [1–4]. To provide a higher class of protection by the 5th and 6th classes, the thickness of sheets of 44S steel type should be at least 7 and 15 mm, respectively. At the same time, the bulletproof steel of grade 56 provides a protection according to the 6th class even at the sheet thickness of 12 mm (see Figure 1).

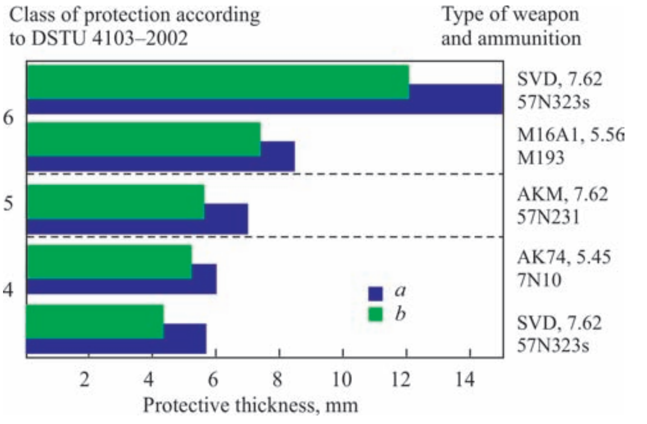

Figure 1. Comparison of protective characteristics of steels of grades 44S (*a*) and 56 (*b*) [2, 3]

However, with increase in thickness of the steel armoured sheet, the problem of its mass appears again. In addition, such armoured plates are not capable to save a person from the after-barrier impact of bullet. Even in case of impenetration of armoured vest, a bullet with a superpower after-barrier effect strikes the user's body [12, 15]. In addition, the armoured plates should provide a protection not only from the hitting of bullets, but also from the fragments, caused by a close burst of grenades or shells, and destruction of natural and artificial objects, as well as from the impact of air wave as a result of increasing (or decreasing) pressure in the places of explosions [16]. One more dangerous phenomenon to which steel armoured plates are exposed is a ricochet. When the bullet interacts with the protective plate at large angles from the normal, a bullet can ricochet and defeat the unprotected parts of the body, as well as the people around [1–3].

These drawbacks can be eliminated by optimizing the properties of the armour material [11] and the application of bimetallic composite armour panels [6, 17]. The basic principle of operation of such a two-layer armoured plate is the following [5, 14]. The face layer should destroy or at least delay the jacket of the bullet, partially absorb its energy, flatten or break the core and

Table 3. Chemical composition and mechanical properties of bulletproof steels [4]

Steel grade	Rated chemical composition	Sheet thickness, mm	σ_t MPa	Hardness *HV*
MARS 270	0.35C–0.75Cr–3.10Ni–0.40Mo	< 25	2000	534–601
MARS 300	0.50C–0.80Si–4.0Ni–0.40Mo	≤ 8	2180	578–655
ARMOX 560	0.35C–1.0Mn–1.2Cr–3.0Ni–0.65Mo–0.002B	8–20	1850	534–601
ARMOX 600	0.43C–0.3Mn–0.25Si–0.5Cr–2.0Ni–0.35Mo–0.002B	4–10	2150	570–640
4340 TOD	0.4C–0.3Si–0.6Mn–0.8Cr–1.5Ni–0.2Mo	–	1900	477–514
RAMOR 550	0.36C–0.7Si–1.5Mn–1.5Cr–2.5Ni	3–15	2100	540–600
77Sh	0.35C–1.4Si–1.1Cr–2.4Ni–0.3Mo	–	1900	477–522
Ts85	0.42C–1.5Si–1.1Cr–1.2Ni–0.45Mo	–	2050	485–522
SPS43	0.43C–1.65Si–1.2Cr–1.3Ni–0.45Mo	–	2050	444–552
44S	0.44C–1.1Cr–0.9Ni–0.8Mo	–	2100	560–610
56	0.50C–3.0Cr–1.7Ni–1.95Mo–0.3V	–	2300	570–600

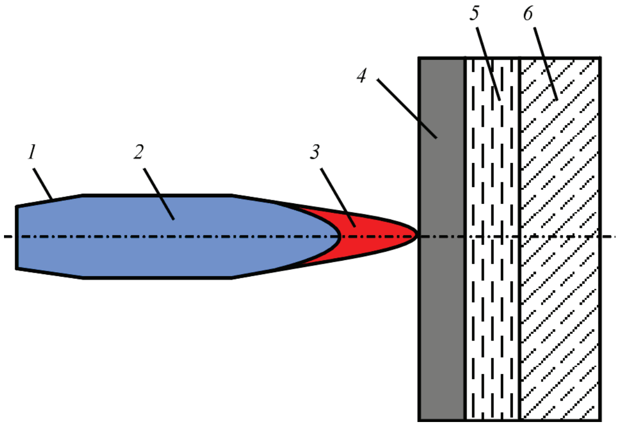

Figure 2. Scheme of shock interaction of a bullet with a bullet-proof protection: *1* — jacket of a bullet; *2* — core with a jacket; *3* — incendiary composition; *4* — hard layer of armoured plate; *5* — tough layer of armoured plate; *6* — shockproof layer

distribute its action to a possibly larger area. To do this, it should be as solid and strong as possible, and not allow breaking with the entire bullet. The inner layer should absorb the energy of the remaining part of the bullet as much as possible, delay the secondary fragments and possible breaks of the first layer and not produce the secondary fragments by itself.

The shock of a bullet with a steel core against steel can be considered as a collision of bodies of two identical materials (Figure 2). There are data [15] on the increased ability of certain classes of materials and alloys to dissipate the energy of dynamic effects for a period of time which is commensurable with the time of interaction of a bullet with a barrier (see Table 4).

As is seen from the data in Table 4, the low-carbon steel St3 reduces the effect of after-barrier action to a lesser extent. The higher shockproof values are observed in complexly-alloyed steels, some titanium and nickel alloys and in the case of using bimetal Steel 25 + Kh6VF [15]. The similar results were obtained in [6], according to which the multilayer armour made of a combination of steels St3 and U12A, showed a bullet proof at the level of special armour steel of type RAMOR 550, and at the same time allowed reducing the mass of armoured plates by 20 %.

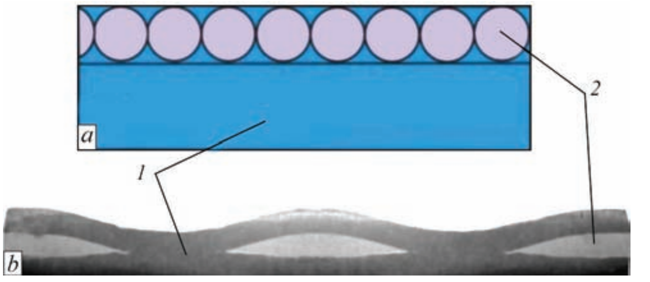

Figure 3. Variant of layers arrangement in the composite armoured plates (*a*) and macrostructure of joint (*b*) produced by explosion welding [7, 17]: *1* — Ti layer; *2* — intermetallic $TiAl_3$ inclusions

At the same time, the serial production of bimetal armour at the territory of CIS was not mastered [1-3], although in the EU countries such armour is used rather extensively [11]. There are data [11, 17, 18] on single attempts to create bimetallic armour by different welding methods. Thus, in the works [11, 18] with the help of explosion welding a composite of spring steel 65G and aluminum AD0 was produced. The tests of the produced materials showed that they can serve as effective plates for armour vests according to the 5th class of resistance.

In the works [7, 17] it is proposed to improve the ballistic characteristics of titanium armoured plates by creating high-strength intermetallic compounds of titanium aluminides. The realization of this idea, which consists in alternating the layers of high-strength intermetallic with soft aluminum layers, is achieved by diffusion welding (Figure 3). In the authors' opinion, such an approach allows excluding brittle fracture of titanium armoured plate, as well as increasing the area, to which a pulse during hitting a bullet is transmitted, thus reducing the after-barrier effect.

From the scientific and practical point of view, the investigations on application of coatings of carbon nanotubes, characterized by a high elastic modulus of about 1.0 TPa (0.21 TPa for steel) and by an ultimate strength, as an outer layer of bimetallic armour plates — up to 45 GPa [1, 19, 20] are of interest. However, for today nanomaterials are still very expensive,

Table 4. Results of firing the armoured packages of different materials by bullets PST from PM [15]

Material grade	Sheet thickness, mm	Nature of defeat	After-barrier effect, %
St3	2.4	Through penetration	6–9
17Kh18N9	2.5	60 % impenetration	0
Steel 25 + Kh6VF	2.0 + 0.5	Destruction/impenetration	0
AD31	4.0	Through penetration	15
V95	4.5	80 % impenetration	5
AD31 + V95	2.0+2.0	Through penetration	5–6
VT9	2.0	Through penetration	0
VT9	3.0	Impenetration	0
VT20	2.0	Through penetration	3–5
KhN77TYuR	2.0	Impenetration	0

which makes it difficult to conduct investigations in this direction.

Conclusions

1. To create means of individual armour protection, a wide range of different materials was developed: fabric aramid or polyethylene fibers; metal plates of steels as well as titanium, aluminum and their alloys; ceramics based on boron and silicon carbides, etc. Each of these materials has its own advantages and disadvantages, depending on which it can provide protection by the 1st–6th class.

2. Due to sufficient reliability, low cost and versatility, for protection by the 3rd–5th classes the armoured plates of low-alloyed structural steels with high hardness, ductility and toughness found a wide application.

3. To reduce the weight of steel armoured plates, as well as to reduce the probability of obtaining after-barrier injuries and ricochet, it is proposed to use bimetallic plates with alternating hard and soft layers produced by different methods of welding and surfacing.

1. Kobylkin, I.F., Selivanov, I.F. (2014) *Materials and structure of light armour protection*. Moscow, N.E. Bauman NSTU [in Russian].
2. Gladyshev, S.A., Grigoryan, V.A. (2010) *Armoured steels*. Moscow, Interment Engineering [in Russian].
3. Grigoryan, V.A., Kobylkin, I.F., Marinin, V.M., Chistyakov, E.N. (2008) *Materials and protective structures for local and individual armouring*. Moscow, RadioSoft [in Russian].
4. Anastasiadi, G.P., Silnikov, M.V. (2004) *Operating capability of armour materials*. St.-Petersburg, Asterion [in Russian].
5. Bajdak, V.I., Blinov, O.F., Znakhurko, V.A. et al. (2003) *Concept basics for development of means of individual armour protection*. Moscow, Armouring. Politics. Conversion [in Russian].
6. Manzhura, S.A. (2017) Selection of armoured plate materials for individual means of armour protection of law enforcement forces. *Systemy Ozbroennya i Vijskova Tekhnika*, **2**, 89–93 [in Ukrainian].
7. Bolotov, M.G., Ganeev, T.R., Novomlynets, O.O., Prybytko, I.O. (2015) New trends of application of titanium aluminides. *Tekhnichni Nauky ta Tekhnologii*, **2**, 51–55 [in Ukrainian].
8. Novikov, V.A. (2015) Flak jacket: Modern materials and their properties. *In: Proc. of Int. Sci.-Techn. Conf. of Young Scientists of V.G. Shukhov BSTU (1–30 May, Belgorod)*, 1443–1446.
9. Gorbunov, I.M., Kharchenko, E.F., Aniskovich, V.A. (2006) Analysis on scientific and technical level of development of modern armour protection means in Russia and abroad. *Oboronny Compleks — Nauchno-Tekhnicheskomu Progressu Rossii*, **4**, 32–35 [in Russian].
10. (2002) *DSTU 4103–2002*: Means of individual protection, bulletproof vests. General specifications [in Ukrainian].
11. Zagoryansky, V.G. (2015) Substantiation for application of steel-aluminium bimetal on calculation criteria of bulletproof armour. *Visnyk NTUU KPI. Seriya: Mashynobuduvannya*, **3**, 37–41 [in Ukrainian].
12. Guskov, A.V., Milevsky, K.A., Pavlova, O.V. (2014) Bulletproof vests with ceramic armour elements of honeycomb structure. *Evrazijsky Soyuz Uchyonykh*, **8–8**, 45–46 [in Russian].
13. Mylnikov, V.V., Abrosimov, A.A., Romanov, I.D., Romanov, A.D. (2014) Analysis of materials and their properties, applied for means of individual armour protection. *Uspekhy Sovremennogo Estestvoznaniya*, **9–2**, 143–147 [in Russian].
14. Chernyshov, E.A., Mylnikov, V.V., Mylnikova, M.V., Romanov, A.D. et al. (2014) Development of metal-ceramic elements of ballistic protection using aluminium-based ceramics. *Sovremennye Naukoyomkie Tekhnologii*, **4**, 97–100 [in Russian].
15. Aleksentseva, S.E., Zakharov, I.V. (2011) Effect of shock-proof properties of alloys on bulletproofness. *Vestnik Samar. STU. Seriya: Tekhnicheskie Nauki*, **4**, 88–95 [in Russian].
16. Radonjic, V.M., Jovanovic, D.M., Zivanovic, G.Z., Resimic, B.V. (2014) Ballistic characteristics improving and maintenance of protective ballistic vests. *Vojnotehnicki glasnik*, **62** (Is. 4), 89-103. DOI: 10.5937/vojtehg62-4992.
17. Kryukov, D.B., Kozlov, D.B. (2016) Perspectives of application of metal composite materials for development of armouring of new generation. *Vestnik Penzenskogo Gos. Unta*, **2**, 103–108 [in Russian].
18. Dragobetsky, V.V., Shapoval, A.A., Zagoryansky, V.G. (2015) Development of elements of individual protection means of new generation based on laminated metallic compositions. *Izv. Vuzov, Chyorn. Metallurgiya*, 58, **1**, 44–48 [in Russian].
19. Morka, A., Jackowska, B. (2010) Ballistic resistance of the carbon nanotube fibres reinforced composites — numerical study. *Comput. Mater. Sci.*, 50(**4**), 1244–1249. DOI:10.1016/j.commatsci.2010.03.046.
20. Kurkov, S.N., Kukanov, S.A., Zajtsev, Yu.M. (2016) Application of nanostructured materials in protective compositions of individual armour means. *Izv. Tulskogo Gos. Un-ta. Tekhnicheskie Nauki*, **3**, 53–59 [in Russian].

Received 19.06.2018