https://doi.org/10.46813/2026-162-101

UDC 621.774.38

MODERN TECHNOLOGIES FOR STRENGTHENING STEELS FOR THE MANUFACTURE OF PROTECTIVE ELEMENTS OF BULLETPROOF VESTS

Part 1

L.M. Deineko[1], V.L. Pinchuk[1], A.V. Panchenko[2]
[1]Ukrainian State University of Science and Technology, Dnipro, Ukraine;
[2]Sumy State University, Sumy, Ukraine
E-mail: v.l.pinchuk@nmt.org.ua

In the conditions of a full-scale war that is ongoing in Ukraine, the issue of protecting the lives and health of citizens has acquired particular importance. Reliable personal protective equipment, in particular personal protective equipment (PPE) – bulletproof vests, are vital to save lives and minimize the risks of injuries and wounds not only from bullets, but to a greater extent from fragments. The key requirement for the armor plate material is the ability to withstand the action of ammunition of a certain type without penetrating and damaging a person with fragments that can peel off from the opposite plane of the armor plate. Armor steels provide such ballistic resistance with high-strength low-alloy or alloyed grades and the structural state of the metal, which is provided by preliminary and final thermal (or combined) treatment. The specific level of properties of the metal of armor plates already depends on the protection class (for which they are planned), chemical composition and metal processing parameters. The purpose of this article is to study the influence of the chemical composition of steels and the modes of thermal (for a homogeneous state) and chemical-thermal treatments (to obtain a heterogeneous state) on the properties of the steels selected for the study and to choose a rational composition of steels for the manufacture of protective sheets of armor and to develop modern processing modes to ensure 4–5 classes of protection according to DSTU 8782:2018, which is one of the key ones in Ukraine in this area. Based on the results of theoretical and experimental research, parameters of the technology of heat treatment with volumetric strengthening of protective elements of body armor are proposed, using chromium-nickel-molybdenum-vanadium steel as an example to obtain bulletproof effect up to class 5 of protection in the conditions of operation of body armor.

INTRODUCTION

A bulletproof vest is one of the most common means of personal protection (PPE) for a person. First of all, it protects the body from small arms bullets, but it also copes well with ammunition fragments after their explosions. When choosing a bulletproof vest, it is recommended to pay attention to its main characteristics and properties of the metal of the elements of bulletproof vests (bulletproof plates or ballistic plates) – protection class, method of wearing, protection area, effective wearing time, etc. When choosing a bulletproof vest, the most important parameter is its protection class. Thus, the higher this parameter, the shorter the time of continuous wearing of the bulletproof vest (due to increased weight) and the larger the area of body protection. In modern military equipment, soldiers can use body armor plates manufactured according to different standards of the USA, NATO countries and Ukraine:

- In the USA, the most common version is the NIJ 0101.06 standard of the National Institute of Justice, which divides body armor plates into the following levels of protection, depending on the type of ammunition they are able to stop [3]:

– IIA – provides protection against pistol bullets of calibers 9x19 mm and 40SW;

– II – protects against impact with bullets of caliber 9x19 mm and 357 Magnum JSP;

– NIJ IIIA – protects against bullets of caliber 44 Magnum SJHP and 9x19 mm with increased velocity (the most common level for soft armor plates);

– III – the first level, which protects against rifle ammunition, including 7.62x51 mm NATO (this is the standard version of a military body armor);

– NIJ Level 4 (IV) – the highest level of protection, designed to stop armor-piercing ammunition Z0-06 M2 AP.

- STANAG NATO Standards are in effect in NATO countries (provides not only for personal protection STANAG 2920 but also for armored vehicles) [3]. This standard provides for testing armor plates for the V50 test, i.e. determines the speed of 50% of ammunition that penetrates armor, and 50% do not (i.e. a test to determine the speed of ammunition at which 50% of bullets penetrate armor). This is explained by the fact that ammunition has different kinetic energy depending on the bullet speed and angle of impact.
- In Ukraine, the ballistic standard DSTU 8782:2018 is in effect, which has a six-level system for classifying levels of protection that provide protection against specific ammunition. According to this DSTU, class 3 body armor provides a minimum level of protection for military personnel in a combat zone [2].

Thus, the standards differ in the methods of testing armor plates:

– NIJ has 5 fixed levels (IIA – IV (NIJ Level 4), which are determined by shots of fixed calibers of ammunition;

– STANAG 2920 assesses the level of protection by the speed of defeat (i.e., by the speed at which 50% of the bullets penetrate the armor);

– DSTU assesses the level of protection by dividing the ammunition into fixed classes (1–6).

For example: NIJ IIIA class of protection of armor plates is similar to class 4 of protection of body armor according to DSTU and STANAG 650 m/s.

Starting from class 4 of protection and above, body armor according to DSTU (Table) protects well not only from automatic weapons (for example, AK type, caliber of defeat: 5.45x39 mm (international designation – 5.45x39) – bullet (PP) with thermoset bullet in a steel (bimetallic) casing, bullet speed ≈910 m/s), but also from rifles (caliber of defeat 7.62x54 mm (7.62x54R) – light bullet (LPS) with a steel non-heat-strengthened bullet in a steel (bimetallic) casing, bullet speed ≈850 m/s). In particular, such means of protection are used by army units and the police.

Metal armor plates (except steel ones) can also be represented by light and strong alloys of aluminum or titanium, capable of increasing the protection of body parts [6, 7]. In some cases, it is possible to use metal-ceramic plates, which increase the level of protection to class 5 or even 6 [6].

The key requirement for the armor plate material is the ability to withstand the action of ammunition of a certain type without penetrating and damaging a person.

The thickness of the armor plates depends on the material and protection class according to DSTU. Steel plates of classes 3–4 usually have a thickness of 5…8 mm, and ceramic plates of classes 4–6 (for example, SAPI) can be thicker due to the presence of a ceramic layer (15…25 mm and more). Not only thickness is important, but also the ability to withstand the impact of specific calibers and ammunition. Thus, it is known that steel plates (Armox, Miilux and others) usually have a thickness of 5…6 mm for class 4 (protection from AK-74, AKM, SVD or similar), and ceramic plates have a greater thickness, but less weight. Often used for body armor of classes 4–5 protection, where ceramics destroy the bullet, and the lining (NVMPE/Kevlar) stops fragments. The standard (DSTU 8782:2018), for example, stipulates that for steel plates of body armor of classes 5–6 protection (ceramics/steel) It is necessary to significantly increase the thickness of the plates (compared to class 3–4 plates) to protect against armor-piercing bullets (for example, 7.62x54 B-32). Taking into account the additional protection, class 4+ plates usually have an anti-ricochet coating and a damper (up to 8…10 mm), which increases their overall thickness.

ANALYSIS OF LITERARY DATA AND STATEMENT OF THE PROBLEM

As practice has shown, effective protection in the above-mentioned plate thicknesses for classes 4+ is provided by steels, which, in addition to carbon (0.27…0.45%), contain additives of chromium, manganese, nickel, molybdenum, boron and other alloying elements (see Table).

High-strength wear-resistant and impact-resistant steels are a progressive dual-purpose structural material that allows you to save up to 40% of metal by reducing the thickness or diameter of the product compared to carbon and low-alloy steels. Such steels have found wide application in many industries, for example, for the manufacture of platforms of heavy-duty dump trucks, buckets of excavators, excavators and many parts and mechanisms operating under conditions of various types of wear. In addition to high strength, such steels must have sufficient plasticity and toughness, increased wear and cold resistance. It is believed that the higher the hardness, temporary resistance of steel, the higher its wear resistance. But research and practice of operation of such steels show that impact and wear resistance also depend on other qualitative characteristics of steel. For example, it is known that the wear resistance of steel with an increase in temporary resistance from 450…500 to 700…800 N/mm^2 when operating in conditions of operation of cutting elements of earthmoving machines, platforms of heavy-duty dump trucks and other products increases slightly (up to 30…50%) and only an increase in the temporary resistance of steel to the level of 1050…1200 N/mm^2 leads to a sharp (3–5-fold) increase in wear resistance. Dual-purpose impact and wear-resistant steels also include steels that are traditionally considered armor-grade (see Table – steels 1; 3; 71; 96; Hardox type steels and analogues – the digital indices of these grades indicate the Brinell hardness of the steel): ARMSTAL 500 – Poland; RAMOR 450 and Protection 500 – Finland; Quardian 500 – Belgium; ARMOX – Sweden) [1, 3–9].

Chemical composition of welding, wear-resistant machine-building steels, including steels for body armor, which provide after hardening and tempering the level $\sigma_T \geq$ 1200…1500 MPa and HRC 50–56 [1, 4, 5, 7, 9]

Steel grade	Chemical composition, % by mass (Ladle analysis, samples, maximum values)									
	C	Si	Mn	P	S	Cr	Ni	Mo	B	Other elements
1	2	3	4	5	6	7	8	9	10	11
Hardox 500	0.30	0.70	1.60	0.020	0.010	1.50	1.50	0.60	0.005	–
Hardox 550	0.37	0.50	1.30	0.020	0.010	1.40	1.40	0.60	0.004	–
Hardox 600	0.47	0.70	1.00	0.015	0.010	1.20	2.50	0.70	0.005	–
Hardox Extreme	0.47	0.50	1.0	0.015	0.020	1.20	2.50	0.80	0.005	–
ARMSTAL500	0.29	0.24	0.89	0.009	0.005	0.74	1.03	0.23	0.002	0.06V
Quardian 500	0.26	0.21	0.78	0.012	0.006	0.42	0.74	0.27	0.001	0.001V
Protection 500	0.28	0.49	0.96	0.016	0.011	0.58	0.37	0.25	0.002	0.002V

1	2	3	4	5	6	7	8	9	10	11
30KhGSA (DSTU 806:2015)	0.28–0.34	0.9–1.2	0.8–1.1	≤0.025	≤0.025	0.8–1.1	≤0.3	≤0.15	–	V≤0.05; W≤0.2; Cu≤0.3; Ti≤0.03; N≤0.008
30ХГН2А (30ХГСНА) chromansil	0.27–0.34	0.9–1.2	1.0–1.3	≤0.025	≤0.025	0.9–1.2	1.4–1.8	–	–	up to 0.3 Cu
71	0.31	1.16	0.74	0.016	0.01	1.66	2.26	0.3	–	0.202 V
77Ш	0.35	1.4	-	≤0.01	≤0.01	1.1	1.4	0.3	–	–
88Ш	0.4	1.4	-	≤0.01	≤0.01	1.1	2.4	0.3	–	–
KVK-37	0.37	–	0.8	≤0.01	≤0.01	2	1	0.5	0.02	0.7 W 0.03 Nb
KVK-42	0.42	–	0.8	≤0.01	≤0.01	2	1	0.5	0.02	0.7 W 0.03 Nb
SPS-43	0.43	1.65	–	≤0.025	≤0.025	1.2	1.3	0.45	–	–
42	0.42	1.35	–	≤0.025	≤0.025	1.5	1.6	0.4	–	–
A3 (according to TU7399-002-4621835-06), analogues of 55X4H3S2GM and 45XH2MF	0.42–0.5	0.17–0.37	0.5–0.8	≤0.025	≤0.025	0.8–1.1	1.3–1.8	0.2–0.3	–	0.1…0.18 V Cu up to 0.3
96 (45X2NMFBA) according to TU 7399-002-14621835-06	0.48	–	–	≤0.025	≤0.025	1.6	1	0.5	–	0.25 V
Steel for bulletproof light armor [RF JSC “Steel”]	0.38–0.43	0.5–0.8	0.3–0.5	≤0.01	≤0.01	1.2–1.5	0.9–1.2	0.75–0.85	–	Nb 0.02–0.05 Cu≤0.3
High-strength armor sheet steel [RU2185459C1]	0.44–0.48	0.2–0.4	0.4–0.7	≤0.01	≤0.01	1.12–1.4	1.3–1.8	0.31–0.5	–	0.15–0.25 V
55Х4Н3С2ГМ [RU2185460C2]	0.54	1.8	0.85	≤0.01	≤0.01	2.4	3.3	0.5	–	0.3 V
Armor heat-resistant welding steel [RU2520247C1]	0.01–0.41	0.1–2.6	0.1–1.8	≤0.008	≤0.004	0.1–8.6	0.1–1.9	0.1–0.6	–	Cu 0.1–1.9 Co 0.05–4.6
Б1500^x Stal village $\sigma_T \geq 1500$ MPa [Prometheus]	0.36–0.39	0.1–0.3	0.8–1	0.015	0.010	0.6–0.8	0.45–0.6	0.35–0.45	0.001–0.005	0.01–0.03 V 0.01–0.03Ti; 0.01–0.04 Nb
К65 [RU2806620C2]	0.05–0.07	0.2–0.32	1.6–1.7	0.003–0.012	0.001–0.002	0.15–0.25	0.15–0.25	0.15–0.25	–	Cu 0.1–0.2 Al 0.025–0.045 Nb 0.075–0.095 Ti 0.01–0.02 V 0.01–0.03 N 0.001–0.006

Hardox steels (see Table) are classified as impact and wear-resistant, undergoing quenching in the rolling mill line and subsequent tempering (≤ 250 °C) or more often self – tempering [9]. These steels differ in chemical composition, but almost all contain boron and are designed for production technology with obtaining high-strength steel in the rolling mill line using quenching from rolling heat. The carbon concentration in such steels usually does not exceed 0.45% (with an increase in the carbon concentration above 0.4…0.45%, the crack resistance of the metal decreases).

As armor (for ≥ 4 levels of protection) other steels with a hardness of HB 500...600 are also used in thermomechanically strengthened rolled products or in processed plates as a result of thermal (combined) treatment with separate heating to the level of σ_T ~ 1500…1700 MPa and higher. One of the promising directions for obtaining ultra-high-strength steels ($\sigma_b \geq$ 2000 MPa with a satisfactory level of plasticity – δ = 5…15%) of dual purpose, with their economical alloying, can be considered the technology of heat treatment according to the "Quenching-and-Partitioning" (Q-n-P) scheme [10–13].

In the CIS countries, the production of high-strength wear-resistant hot-rolled welded steels of the following grades was mastered: 18KhGNMFR, 14KhG2SAFD, 16KhGN2FBR, 13KhG2NDF and others in thicknesses of 8.0…50.0 mm [7]. The maximum tensile strength of such general-purpose steels reached 850…900 N/mm^2 in the past decades. Abroad, high-strength welding steels of the Hardox® 400–600 grades and other manufacturers are used for the manufacture of heavy-duty dump truck platforms, as well as for protective elements of bulletproof vests. At the same time, in new wear-resistant steels, increased temporary resistance ($\geq$1050 N/mm^2) is achieved due to the mechanisms: solid solution strengthening, as well as dispersion of structural components and dispersion (or secondary) hardening (separation of dispersed particles of carbides or carbonitrides during subsequent tempering). In this case, the steel hardened in the process line is strengthened as a result of the formation and separation of dispersed particles of cementite (alloyed cementite for low-alloy steels at temperatures of ≈ 280…380 °C) or carbonitrides at tempering temperatures ≥ 500 °C for alloyed steels. Such strengthening allows saving on basic, expensive, alloying elements, in particular nickel and molybdenum. In steels with carbonitride hardening due to dispersed particles of the secondary phase, the size of the austenite grain is sharply reduced during rolling and heating for hardening, and with further cooling this leads to an increase in the dispersion of the martensitic – bainite structure, and during subsequent tempering, secondary hardening occurs due to the release of dispersed particles of carbides (carbonitrides). Due to this process of structure formation, both the strength and toughness characteristics of the steel increase. For example, industrial enterprises produce high – strength structural steels Quend 700, 960 (standard EN 10025-6), the level of which is obtained as a result of quenching after rolling and subsequent tempering at 500...550 ^{0}C (the numbers indicate the minimum yield strength of 700 or 960 MPa) with a guaranteed level of impact toughness ≥ 27 J at – 40 °C.

When creating new or improving existing technologies for the production of high-strength products, it should also be taken into account that in the case of impact or abrasive wear, the operational stability of the steel will also be determined by the level of ductile properties, relative elongation and uniformity of the structural state. Fig. 1 shows data on the comparison of wear resistance of steels processed to the same hardness, but having different impact toughness and plasticity. From the data shown in Fig. 1, it is clear that the greatest wear resistance among the tested steels was shown by 25KhGN3MFB (1), which has high toughness and plasticity – its resistance is twice as high as the wear resistance of the widely used 65G steel taken for comparison (4).

With a decrease in the viscosity and plasticity of the experimental steels 25KhG3MF (2) and 25 KhG (3), their wear resistance decreased accordingly. The increased wear resistance of steel with high viscosity and plasticity, compared with steels with lower specified characteristics, with the same strength, is explained by the fact that viscous materials better resist the detachment of microscopic pieces of metal from the sheet surface under the action of hard minerals during loading and unloading of the rock. It was also established that if the steel has a heterogeneous structure consisting of a mixture of martensite (bainite) and polygonal ferrite, its wear resistance decreases, despite the high hardness. The purity of the steel in terms of non-metallic inclusions also affects wear resistance. The higher the purity, the less wear. An important and mandatory condition for high impact and wear resistance of steel, for example, for dump truck platforms or for armor protection of people and equipment, is its martensitic hardening over the entire thickness of the sheet [8, 9].

The need to create high-strength steel armor arose after the appearance of a new bullet with a steel thermoset core (TUS) PS-43 TUS caliber 7.62 mm for AK-47 assault rifles and a bullet 7N6 TUS caliber 5,45 mm for AK-74, instead of the previously used LPS 4N3 for AK-47 and AK-74, respectively. The hardness of the steel thermoset core of PS-43 TUS and 7N6 TUS bullets is 55-56 HRC, while the hardness of the steel core of PS-43 LPS and 7N6 LPS bullets is 30–32 HRC. Therefore, the penetration effect of these bullets when hitting a steel obstacle at approximately the same bullet speeds V_{cp} = 715 m/s (AK-47) and V_{cp} = 790 m/s (AK-74) is very different.

Due to the fact that the back surface layers of the armor plate metal must have an increased level of plasticity and toughness (to reduce the likelihood of chipping of metal particles from the back plane of the armor plate) after the final strengthening heat treatment of the plate, it is advisable to subject the surface layer of the back plane of the armor plate to additional tempering, for example, by heating with high-frequency current (thin layer ~2 mm). Such a technological method can be used for plates made of high-strength metal obtained by various strengthening schemes. The possibility of implementing such a technological method is confirmed by the results of works known in technical sources on the creation of functional gradient materials.

Analysis of possible mechanisms for strengthening structural steels shows that it is advisable to increase the complex of mechanical properties of the metal for light armor from protection level 4 and above (4…10 mm thick) primarily through rational thermal or combined treatment, which implements the most universal factors of influence on the structural state and properties of the metal – solid solution strengthening, grain structure refinement, complete replacement of pearlitic and bainite components of the structure with martensite, creation of a cellular or polygonal substructure in the metal, obtaining in the structure a large number of dispersed particles of the carbide phase, evenly distributed throughout the volume of the metal due to the correctly selected tempering temperature and the formation of compressive stress plates in the metal [5]. In the case of ensuring the metal properties for protection levels ≤ 4, it was rational to use sheet metal obtained according to the regulated rolling scheme using hardening from the rolling temperature and self-tempering (or low tempering from separate heating).

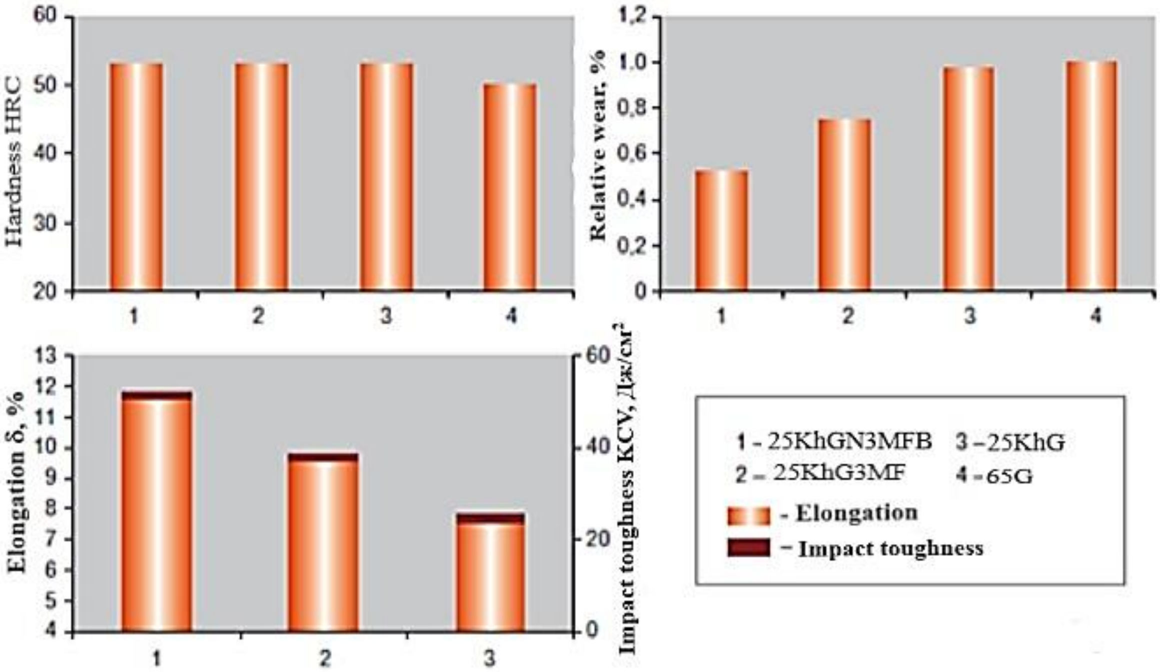


Fig. 1. Wear resistance of steels depending on impact toughness and plasticity (data from the Central Research Institute of Metallurgy and Metallurgy)

The main questions that require analysis and research when creating a comprehensive technology for thermal (combined) strengthening of sheet metal or plates (considered for the heat treatment scheme from separate heating) include:

– The chemical composition of armor steels for light armor and methods for ensuring in the ingot (rolled) metal a minimum level of non-metallic inclusions and gases (especially hydrogen to prevent hydrogen embrittlement of the metal or even the appearance of flocs), sulfur and phosphorus, as well as low-melting compounds (to ensure the metal has a flash point of ≥ 1260…1280 °C);

– Austenization parameters (for the option of volumetric strengthening heat treatment of plates with separate heating), which contribute to the maximum use of the alloying level of steels (for the implementation of effective solid-solution strengthening and additional strengthening due to the release of dispersed particles of the secondary phase during subsequent tempering), as well as contributing to obtaining a small austenitic grain size during the implementation of finish hardening;

– Temperature-time parameters of subsequent tempering (or the feasibility of using multiple temperings) of volumetrically hardened metal with a martensitic structure in order to achieve the desired level of mechanical properties in the metal of finished plates, which can be used as light armor;

– Determine a rational scheme of the sequence of technological operations when implementing plate treatments with separate heating to obtain a heterogeneous structure (strengthening heat treatment → chemical-thermal treatment (nitriding, carbonitriding or others) or vice versa – chemical-thermal treatment (nitriding, carbonitriding) → strengthening heat treatment to the required level of hardness and strength of the surface layer of the metal on the front side of the body armor + additional softening treatment of the surface layer of the back side of such an armor plate.

MATERIALS AND RESEARCH METHODS

This work considers experimental steel plates (No. 1–3) made of armor sheet steel 0KhN3MF with a size of ≈220x220 mm, a thickness of 6.8 mm and "OX ARMOX-500T" with a thickness of 5.8 mm, which were tested by shooting at 4–5 levels of protection. These plates underwent thermal and combined (chemical-thermal) treatment according to the following modes:

– plates No. 1–3 (size ≈220 x 220 mm, a thickness of 6.8 mm., steel 0KhN3MF) – treatment mode: double austenitization at different temperatures, bulk hardening in oil and tempering after the first and second hardening;

– a plate made of ARMOX-500T steel, with a size of 125x125 mm, a thickness of 5.8 mm (No. 2) – carbonitriding (Carbaz LLC) with subsequent heating for hardening and cooling in oil and subsequent tempering (information will be provided in the materials of the article part 2).

Microstructural and X-ray structural analysis of the samples was carried out, hardness measurements were made along the cross-section of the samples, as well as testing of the plates for cross-fire in a military training ground using various types of small arms, which is provided for by the requirements of DSTU 8782:2018 for ballistic materials for 4–5 levels of protection.

THEORY AND ANALYSIS OF THE OBTAINED RESULTS

Analysis of the quality of steels that can be used as high-strength materials for critical products such as light armor, torsion shafts, cold and hot rolling rolls, hot and cold deformation dies, etc. shows that over the past 30–40 years, due to the decommissioning of open-hearth units and the production of liquid metal from a charge that is mainly formed from scrap metal, changes have been observed in the kinetics of structure formation in the metal of products made of such metal. And the main issue that arises for enterprises that process such metal is a decrease in the level of the metal's reflow temperature by ≈ 1500 °C (and even more), which significantly limits the metal heating temperatures for implementing an effective mode of homogenization annealing and hardening. This factor greatly affects the heat treatment regimes (preliminary and finishing) of metal products made of alloyed and high-alloyed steels, which require austenitization at temperatures above 1100…1150 °C, and for tool steels above 1200 °C.

It is also necessary to take into account the results of research in recent decades, which are known from the technical literature and change the ideas of specialists about the processes of hydrogen embrittlement and the appearance of flocs in steels of various chemical compositions, especially in steels with an increased concentration (≥1.5…2.0%) of nickel.

When smelting steels for products of responsible purpose, all known methods of their purification from harmful impurities (sulfur, phosphorus, non-metallic inclusions and gases) should be used, including vacuum treatment of liquid steel.

The traditional technological route for the production of rolled sheet metal in the conditions of metallurgical enterprises of many countries usually includes smelting in an electric steelmaking plant (ESPT) or in a converter shop, casting in a continuous steel casting plant (UNRS), cutting the cast slab into measured lengths, rolling and heat treatment (from rolling or separate heating). At the same time, steels that belong to categories 3–5 (flake-sensitive – especially flake-sensitive) according to the classification, for example, of ZAO NKMZ and which are used for the production of critical parts (for example, armor, gun, roll, tool steels) should be subjected to thermal anti-flake treatment at the stages of obtaining an ingot or rolled sheet (even if there is an operation of vacuuming the liquid metal in the technological chain).

According to the analysis of the chemical composition (see Table), many armor steels (for example, steels of the Hardox 600; Hardox Extreme; 1; 3; 71; 96, etc.) are alloyed with nickel at a level of more than 1.5…2.0%, which significantly increases their flocculation sensitivity and the likelihood of hydrogen embrittlement or flocculation in the metal. Therefore, when determining the parameters of anti-flocculation heat treatment (FHT) of such steels, the influence of the sulfur concentration in the metal (Fig. 2) on the critical concentration of diffusion-mobile hydrogen for each chemical composition of the metal should be taken into account.

It is known that steels of type 3 or 0KhN3MF are classified into 5 categories (groups) of flocculation sensitivity (for example, according to the classification of ZAO NKMZ), in which group 1 includes low- and medium-carbon steels, the least sensitive to the formation of flocculation at a content of diffusion-mobile hydrogen ≥2…2.5 cm^3/100 g of metal (often taken equal to 1 cm^3/100 g = 1 ppm). Group 5 (especially flocculation-sensitive) includes alloyed steels in which the Ni concentration ≥2.5%.

Research has established [15–17] that the following factors have a significant impact on the properties of the metal during and after thermal hardening:

1 – The initial hydrogen content in the metal. For example, it is known that at the same initial hydrogen concentration in the metal of one melt, its content in the thermally hardened metal is 1.5–2.0 times or more than in the metal in the normalized state.

The results of studies of the last decades [17] of the structure and properties of steel metal products, as well as the influence of temperature-time parameters of anti-flock heat treatments have shown (Fig. 3) that even at low heating temperatures of the processed metal and its isothermal holding times, hydrogen diffusion in the metal quite actively removes hydrogen from the metal products and reduces its concentration to safe levels (approximately ≤ 2.0…2.5 ppm or 2…2.5 cm^3/100 g), i.e. to the level when such a concentration of diffusion-mobile hydrogen does not lead to the appearance of flocs in the metal. The results of the studies presented show the feasibility of using isothermal holding times in a wide temperature range in the technological line for the production of sheet metal or forgings from floc-sensitive steels.

2 – The ratio of sulfur concentration and diffusion-mobile hydrogen in the metal. In recent decades, the results of studies of flocculent-sensitive steels have been obtained and presented in the literature [16], which show that depending on the ratio of sulfur and diffusion-mobile hydrogen (see Fig. 2) in the metal, the critical hydrogen concentration can vary and be significantly lower than the data given in old sources of information. It was found that at a sulfur concentration of 0.005% in the metal from 65 melts (there were about 110 melts from different steels in total), 65 of the especially flocculent-sensitive steels (melts) were affected by flocculents. And at a sulfur concentration of 0.006…0.010%, the rejection of forgings was 6.1%. An increase in the sulfur concentration in the metal to 0.011…0.035% has little effect on the level of rejection due to flocculents, which is ~ 4%. At a sulfur concentration in steel of at least 0.015%, the critical hydrogen level is 2 cm^3/100 g (2.0 ppm). When the sulfur concentration decreases below 0.015%, flocculation occurs at a lower hydrogen concentration in the metal. These factors (as well as others) must be taken into account when creating an end-to-end technology for manufacturing products for critical purposes from flocculation-sensitive steels, i.e., from

the crystallization of liquid metal to the final thermal or combined treatment of the finished product.

3 – Analysis of the influence of austenitization parameters in the process of preliminary and final heat treatment of armor plates for the option of their strengthening heat treatment with separate heating showed that high-temperature heating (except for homogenizing annealing) contributes to the maximum use of the alloying level of steels (for the implementation of effective solid-solution hardening and additional strengthening due to the release of dispersed particles of the secondary phase during subsequent tempering), and also has a positive effect on the fracture toughness of high-strength steels. It is known [18] that increasing the austenitization temperature during heat treatment leads not only to an increase in the yield strength, but also to fracture toughness. For example, when the austenitization temperature changes from 900 to 1200 °C for C-Mn-Mo steels with different carbon contents (0.32…0.41%), both the yield strength and the stress intensity coefficient (K_1C), which is a strength characteristic of crack resistance (GOST 25.506-85), increase.

It is known [14, 16, 18] that the fracture toughness of steels (estimated by the values of K1S) is one of the most structurally sensitive characteristics of the metal and significantly depends on the type, dispersion of secondary phase particles and the uniformity of their distribution in the metal (especially those present at grain boundaries). It is believed that the stress intensity factor (K1S) is a force characteristic of crack resistance (fracture toughness) under static loading of the metal (GOST 25.506-85).

Based on the complexity of the technology for manufacturing sheet blanks for bulletproof vest elements, the elements of which negatively affect the quality of the metal of the product throughout the entire processing cycle, it is advisable to carry out studies when setting up sheet plates for production, which would make it possible to assess the resistance of the metal after finishing thermal (or combined) treatment to crack formation, taking into account the maximum possible number of parameters of its structural state after all processing.

The greatest interest for this purpose is the method [19–23], which proposes to determine the mechanical characteristic of the metal (RMC), which takes into account the influence of such basic structural parameters as the size of the actual grain or martensite packet, the shape and size of the particles of the secondary phase. This method more fully characterizes the complex of mechanical properties of the metal and the structural strength of the product in general. The resistance of microcrack resistance (RMC) to the action of external factors – temperature, deformation rate, to the type of stressed state allow us to attribute this characteristic in combination with the yield strength of the metal (in the form of the ratio $R_{MC}/\sigma t=KV$) to the most important fundamental constants of the material. This method of studying the susceptibility of high-strength steels to brittle fracture is also valuable in that it allows us to assess the influence of hydrogen-induced embrittlement of the metal.

In the case of high-temperature austenitization [14, 18], which allows dissolving the particles of the secondary phase, the fracture toughness of alloys 0.3C-5Mo and 0.41C-5Mo after austenitization at 1200 °C and quenching is higher than after a similar regime with austenitization temperature of 8700 °C. The results of these works show that under such conditions (in the absence of particles of the secondary phase at the grain boundaries) the fracture toughness of the metal does not depend on the austenitization temperature. At the same time, practice shows that in the case of using high-temperature heating of the metal without further heat treatments before final quenching, which create conditions for grinding austenite grains during finishing austenitization, the level of impact toughness decreases, and the temperature of the cold brittleness threshold of the metal increases significantly. The results of work [24] also convincingly confirm the decrease in the level of K1C under conditions of increasing the grain structure of steels. Therefore, it is advisable to use other rational treatments before the final austenitization at temperatures that ensure the grinding of austenite grains. It is also known that the use of double hardening (the first from the high-temperature state, the second from normal temperatures) leads to a serrated shape of the grain boundaries, which can be one of the ways to reduce temper brittleness (irreversible and reversible) and increase the level of impact toughness. Therefore, in order to obtain a high-strength state in steels containing strong carbide-forming elements (CFE), it is advisable to use double austenitization modes for critical products to transfer the maximum amount of carbon and CFE into a solid solution during the first austenitization and fix the supersaturated state of the matrix during quenching, and when implementing the second austenitization (with a traditional heating temperature for a particular steel), to grind the austenite grain and obtain a through-hard martensitic structure after quenching, and with subsequent tempering (single or multiple) to achieve the separation of secondary phase particles of optimal size and number [25–30].

The results of the studies showed that for many steels listed in Table (with vanadium), such a temperature of the first austenitization is ≈ 1050…1100 °C. Industrial testing of high-temperature austenitization at the stage of preliminary heat treatment (which included PFO) showed that even a heating temperature of 960…980 °C provides such steels with a level of strength significantly exceeding the level of the yield or proportionality limit after traditional austenitization temperatures (850…8800 °C). And for steels additionally microalloyed, for example, with niobium and boron, complete dissolution of secondary phase particles can be achieved at temperatures of ≈ 1250 °C.

Studies by various scientists [31, 15] have also established that slow (2…300 °C/min) or intensive heating of the metal for final hardening (after the first high-temperature austenitization) leads to the restoration of coarse-grained austenite. The grinding of austenite grains occurs at medium metal heating rates

(≈ 200…1000 °C/min) to traditional austenitization temperatures.

Therefore, to eliminate structural heredity (restoration of large austenite grain size) during subsequent (after high-temperature treatment) hardening and grain structure refinement of the treated steel of type 0KhN3MFA (for example, steels 71; 88Sh; 42 and others – see Table), in well-known works (for example, R.V. Televycha, S.V. Prikhodko [32, 33] it is recommended to adhere to the following main parameters of technological operations:

– after high-temperature hardening, carry out tempering (single or multiple), the temperature-time parameters of which can significantly change the dislocation substructure of the package martensite and the state of the α-solid solution (i.e. > 3500 °C with holding time ≥ 1 h), i.e. in order to eliminate structural factors that do not allow creating conditions for the restoration of fine austenite grains during finish hardening from traditional temperatures. It is advisable only after such tempering to carry out heating to the finish hardening;

– heating for final (after high-temperature treatment) hardening should be carried out at a rate of less than 500 °C/s.

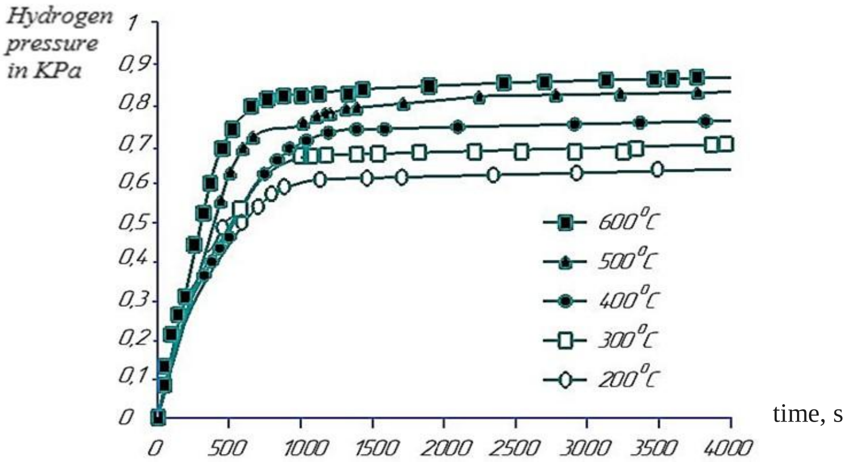
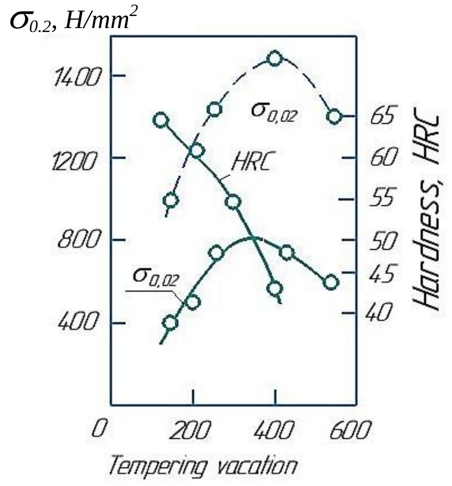


Fig. 2. Dependence of the pressure change in the reaction tube (reflects the change in the concentration of diffusion-mobile hydrogen in 40KhGM steel, which was previously saturated with hydrogen) upon heating to different temperatures and isothermal holding [17]

At the same time, depending on the alloying level of steels after hardening, low, medium (see Fig. 3), or high (Fig. 4) tempering can be used, which, respectively, ensure high strength indicators (proportionality, elasticity or yield strength) due to dispersion or secondary hardening of the metal [33].

When designing metal products for critical purposes, standardized levels of the yield, elasticity or proportionality limit are introduced as a strength criterion. In a number of regulatory documents regulating the level of mechanical characteristics of the metal of various products, such a parameter as the ratio of the absolute values of the yield strength and the tensile strength (σt/σv) is introduced. It is believed that the difference in the absolute values of the tensile strength and yield strength determines the plasticity reserve of the metal of the product.

For low-alloy steels that are hardened in the rolling mill stream (hardening from rolling heat, with possible self-tempering or after separate low tempering), after performing the strengthening heat treatment of rolled sheet, it is prohibited to subject such metal to any temperature effect above ≈ 250 °C, since it can lead to complete or partial loss of operational properties [9].



Chemical composition of the studied steels:
▬ – carbon steel with 0.75…0.8% C;
—◦— – carbon alloy steel (C = 0.5…0.6%; Si = 0.8…1.1%; Mn = 0.15…0.4%; Cr = 0.9…1.2%; W = 1.8…2.2%; V = 0.15…0.3%)

Fig. 3. Dependence of the values of the elastic limit and hardness of hardened carbon steels on the temperature of the next tempering [21]

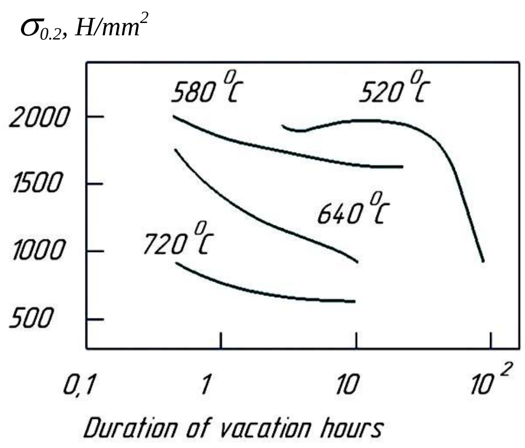


Fig. 4. Effect of tempering temperature and duration on the yield strength of alloy steel 30WCrV17-2 [21]

It is known that to obtain rolled sheet with a high level of structural strength of the metal when operating under local shock conditions [15, 24–26] the main factors are:

– solid-solution strengthening of the matrix with alloying elements that increase the lattice friction stresses and the resistance to the movement of dislocations, which also increase the resistance of the steel to tempering;

– strengthening by martensitic transformation with subsequent tempering (or tempering), which creates an optimal substructure and implements dispersion or secondary hardening of steel (depending on the level of alloying of steel);

– reducing the grain size of austenite (and, accordingly, the secondary structure);

– obtaining dispersed particles of the secondary phase and their uniform distribution in the matrix;

– reducing the level of internal stresses and providing the metal with compressive stresses;

– using modern combined treatments to increase the level of structural strength by creating a superhard outer coating layer in the process of chemical-thermal treatment of sheet metal plates or using new deformation treatment schemes or heat treatment to obtain a nanostructured state in the metal and other modern technologies that can provide steel plates with a level of strength (temporary resistance) ≥ 2000 MPa, which is practically impossible to obtain by traditional processing methods.

When implementing any of the listed strengthening mechanisms, the ultimate strength (especially for the elastic and proportional limits) will be higher, the less non-martensitic structural components are in the steel structure, the lower the level of microdeformations (residual stresses) with the maximum number of dispersed particles of the secondary phase, evenly distributed in the matrix.

Taking into account the above provisions that affect the processes of structure formation in dual-use steels, stepwise heating regimes were developed to high-temperature austenitization, hardening (with obtaining through-hardening martensitic) and intermediate tempering before finishing austenitization, which ensured obtaining a safe level of diffusion-mobile hydrogen in the metal and grinding of austenite grains in the metal during finishing heating and hardening, which together with subsequent tempering made it possible to obtain the hardness of plates (in cross section) from 0KhN3MF steel at the level of 53-55 HRC.

RESULTS OF TESTS OF THE EXPERIMENTAL PLATE FOR PENETRATION

The results of the penetration tests of the experimental plate measuring ≈220x220 mm with a thickness of 6.8 mm made of 0KHN3MF steel (No. 2, 3) for compliance with the basic levels of protection (type 1) – 4 or 5 protection class according to DSTU 8782:2018 (see clause 5.2.1, Table) or their fragments after ballistic tests are shown in Figs. 5–7.

The experimental plate passed ballistic tests for the ability to stop 7.62x54 mm (7.62x54R) LPS rifle bullets with a non-heat-strengthened core in a steel (bimetallic) casing with a rifle cartridge and for the ability to stop 5.45x39 mm PP (7N10) machine gun bullets with a heat-strengthened core in a steel (bimetallic) casing with a machine gun cartridge (see Fig. 5,a,b) – for compliance with the basic level of protection for externally worn body armor (type 1) – 4th protection class according to DSTU 8782:2018, clause 5.2.1, Table.

Ballistic tests of the No. 1 plate were conducted using a light LPS bullet with a steel non-heat-strengthened core in a steel (bimetallic) jacket 7.62x54 mm (7.62x54R) LPS (57-N-323s) with a rifle cartridge (see Fig. 6,a,b) according to the standards for ballistic testing (see Table, DSTU 8782-2018) for level 5 protection (a Bulgarian-made MG-1M light machine gun was used, the barrel was made by the American company Remington). Ballistic tests were also conducted for level 5 protection using the FMJ RN US bullet (see Fig. 7) with an all-metal copper alloy jacket with a hemispherical nose part of 7.62x51 mm (FMJ-U.S. Military designation M80 according to the classification of body armor for resistance to US weapons (corresponds to protection class III) – Appendix A, see Table, DSTU 8782:2018, NIJ 0101.06, NIJ 0101.04) with a lead bullet and a rifle cartridge (a Czech-made sniper rifle was used, the barrel of the American company Remington – model “700 ADL Tactical FDE 20” cal.308).

To determine the structural strength reserve of the experimental armor plate, a penetration test was conducted using a B3 7.62x54 mm (7.62x54R) armor-piercing incendiary bullet with a heat-strengthened core in a steel (bimetallic) jacket (57-B3-231) with a rifle cartridge (see Fig. 7) – a standard for ballistic testing (see Table, DSTU 8782-2018) for the 6th level of protection (a Bulgarian-made MG-1M light machine gun was used, with a barrel from the American company Remington);

Thus, when testing armor plate No. 1 made of 0KhN3MF steel for penetration in accordance with the requirements of DSTU 8782:2018 under normal climatic conditions (temperature 270 °C, humidity 78%)

at a firing distance of 10 m using various ammunition, the following results were obtained:

1 – when testing a plate measuring ≈ 220x220 mm and 6.8 mm thick made of 0KhN3MF steel (see Fig. 5,a,b), for compliance with the 4th protection class according to DSTU 8782:2018 (see clause 5.2.1, Table) for external body armor (type 1), rifle bullets 7.62x54 mm (7.62x54R) LPS with a non-heat-strengthened core in a steel (bimetallic) shell with a rifle cartridge (see Fig. 5,a) and 5.45x39 mm PP (7N10) machine gun bullets with a heat-strengthened core in a steel (bimetallic) jacket with a machine gun cartridge (see Fig. 5,b). The metal of the plate withstood the collision with the bullets of the specified ammunition without through holes, cracking of the metal in the collision zone, and only on the outer surface are visible imprints from the bullets 1…1.5 mm deep;

2 – ballistic testing of the plate for compliance with the 5th protection class according to DSTU 8782:2018 (see clause 5.2.1, Table) for externally worn body armor (type 1) used rifle bullets LPS 7.62x54 mm (7.62x54R) LPS (57-N-323S) with a non-heat-strengthened core in a steel jacket with a rifle cartridge (the places of contact of the metal with the bullet are marked with the No. 2). At the same time, the plate withstood the impact and received minor damage – a deepening of up to 1…1.5 mm (see Fig. 5,a). Bullets with a solid metal jacket made of copper alloy with a hemispherical nose part 7.62x51 mm with a rifle cartridge were also used. According to Appendix A, see Table, DSTU 8782:2018, NIJ 0101.06, NIJ 0101.04; FMJ-U.S. Military designation M80) the used bullet FMJ RN US according to the test methods is the standard for testing armor plates of protection level Ш according to the classification of body armor for resistance to the action of US means of destruction (which is similar to the 5th protection class according to DSTU 8782:2018). The metal of the plate withstood the impact from the collision with the bullet (the place of contact of the metal with the bullet is marked with the No. 3) without through holes, cracking of the metal in the collision zone, and only an imprint (indentation) with a depth of ≈ 1 mm is visible on the outer surface of the plate;

3 – to determine the structural strength reserve of the metal of the experimental plate, it was decided to conduct a test for compliance with the 6th protection class according to DSTU 8782:2018 (see clause 5.2.1, Table) for externally worn body armor (type 1) using an armor-piercing incendiary bullet 7.62x54 mm (7.62x54R) with a heat-strengthened core in a steel jacket (B32 7-B3-323) with a rifle cartridge. The metal of the plate received a through shot and from the dynamic action of the bullet, the plate in the contact zone split into parts (see Fig. 7, the place of contact of the metal with the bullet is marked with the No. 1). In this case, the hole in the metal of the plate is practically equal to the diameter of the bullet.

The test results showed that the experimental armor plate No. 1 made of 0KhN3MF steel with a size of ≈ 220x220 mm and a thickness of 6.8 mm did not withstand the additional test for compliance with the basic level of protection of class 6 according to DSTU 8782:2018 (see clause 5.2.1, Table) for externally worn body armor (type 1).

Photos of the experimental plate No. 1 after ballistics tests for different levels of protection according to DSTU 8782:2018 are shown in Figs. 5–7.

CONCLUSIONS

During the research, an analysis of the chemical composition of dual-purpose steels known in open sources of information, which are used by various countries for the manufacture of light armor and products from it, was performed (see Table). Taking into account the presence of carbide- and nitride-forming elements in the composition of the steels listed in Table, which have a high dissociation temperature (from 1050 to 12600 °C and higher), it is necessary to use high-temperature heating to implement homogenization annealing of the billet or forging and austenitization temperature for hardening, after which it is necessary to use hardening from traditional temperatures, which able to ensure grinding of austenite grain in the case of using a rational mode of tempering after high-temperature hardening. The presence of a high concentration of nickel in the composition of steels increases their flocking sensitivity. For the use of such steels in the manufacture of high-strength products of responsible purpose, it is advisable to use thermal anti-flocculation treatment in the technological scheme of metal processing with the achievement of a safe level of diffusible-mobile hydrogen in the metal, taking into account the existing concentration of sulfur in a specific metal melt and data on its effect on the safe level of hydrogen in the metal.

In order to obtain armor plates from homogeneous metal, which are able to provide protection levels of classes 4 and 5 according to DSTU 8782:2018, it is advisable to use sheet metal with a hardness level of 550…650 HB, which is produced according to the technology of regulated rolling with the implementation of the hardening regime in the state line (from rolling heating) with subsequent self-tempering or low tempering (< 250 °C) with separate heating. In the absence of such an opportunity to obtain sheet metal after thermomechanical treatment with annealing in the state line, it is possible to use a hot-rolled sheet of dual-use steels for the manufacture of armor plates for the 4th and 5th class of protection after carrying out effective modes of double hardening and tempering from separate heating.

ACKNOWLEDGEMENTS

The research results were obtained with the financial support of the National Research Foundation of Ukraine within the framework of the project (registration number 2025.06/0084).

a *b*

Fig. 5. Photo of a test plate for a bulletproof vest after being fired with ammunition from AK-47, AK-74 assault rifles at level 4 protection according to DSTU 8782:2018 (a);
Photo of a fragment of an experimental steel plate measuring 220x220 mm and 6.8 mm thick made of 0KhN3MF steel (front plane – the place of contact of bullets with the metal of the plate) (b)

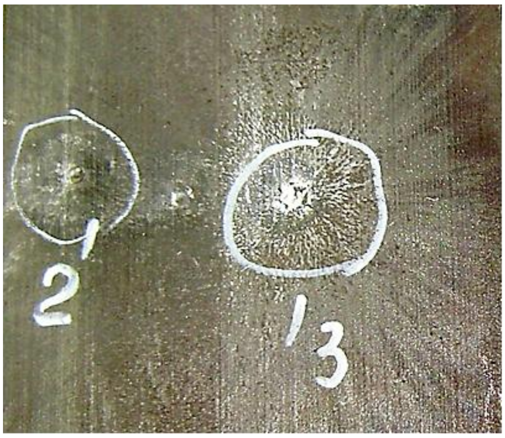


Fig. 6. Photo of a fragment of a test steel plate measuring 220x220 mm and 6.8 mm thick made of 0KhN3MF steel (front plane – the place of contact of bullets with the metal of the plate) after shooting according to DSTU 8782:2018 for compliance with class 5 protection with a rifle bullet LPS 7.62x54 mm (7.62x54R) LPS (57-N-323S) with a non-heat-strengthened core in a steel shell with a rifle cartridge (the place of contact of metal with the bullet is marked with the number No. 2) and a bullet with an all-metal shell made of copper alloy with a nose part of a hemispherical shape 7.62x51 mm with a rifle cartridge (the place of contact of metal with the bullet is marked with the number No. 3)

Fig. 7. Photo of a fragment from experimental plate No. 1 measuring ≈220x220 mm and 6.8 mm thick made of 38KhN3MFA steel after testing with an armor-piercing incendiary bullet 7.62x54 mm (7.62x54R) with a heat-strengthened core in a steel jacket (B32 7-B3-323) with a rifle cartridge for compliance with protection class 6 according to DSTU 8782:2018 (see clause 5.2.1, Table) for externally worn body armor (type 1)

REFERENCES

1. *Materials and technologies. Armored metal materials*. Volume 2, Book 1 (A-O). Kyiv: IPM; Scientific opinion, 2008, p. 174-178.

2. Класифікація бронежилетів за ДСТУ 8782:2018, NIJ 0101.06. URL: https://velmet.ua/klasifikatsiya-bronejiletiv-standart-dstu-8782-2018-nij-0101-6.html (date of application 12.01.2025).

3. U. Radostina. *Body armor protection class. DSTU and NATO standards.* URL: https://arp. co.ua/klas-zakhystu-bronezhyleta.standarty-dstu-i-nato (access date 12.01.2025).

4. *Armored steel "SPS-43"* / Bureau of scientific and technical information "Technology for special services": [site]. - URL: http://www.bnti.ru/des.asp?itm=2390&tbl=08.02.05.&ysclid=l5mi3koutt157231786 (access date: 10.06.2022).

5. L.M. Deineko, P.I. Loboda, A.O. Andreev, V.O. Pole. Development of the parameters of the

complex processing technology of the main rigid elements of bulletproof vests *// Scientific and information journal "Metalology and heat treatment of metals"*. Dnipro, 2019, N 3(86), p. 37-43.

6. Materials and technologies. Armored ceramic materials. Volume 2, Book 1 (A-O). Kyiv: IPM; "Scientific opinion", 2008, p. 171-174.

7. O.S. Marchenko. Prospects for the development of means of individual armor protection // *Modern special equipment*. 2010, N 3(38), p. 99-106.

8. S. Bobrova, L. Sergienko, L. Galavska, T. Shatylo. *Analysis of national and international standards regulating requirements for individual armor protection*. URL: http://journals.khnu.km.ua/vestnik/wp-content/uploads/2024/01/329-ts2023-n6-64-69.pdf (accessed on January 12, 2025).

9. "41-General Product Information Strenx, Hardox, Armox and Toolox-UK", www.ssab.com

10. J. Speera, D.K. Matlocka, B.C. De Coomanb, J.G. Schrothc. Carbon partitioning into austenite after martensite transformation // *Acta Materialia*. 2003, v. 51, issue 9, p. 2611-2622.

11. D.V. Edmondsa, K. Hea, F.C. Rizzob, B.C. De Coomanc. Quenching and partitioning martensite – a novel heat treatment // *Materials Science and Engineering-A*. 2006, v. 438-440, p. 25-34.

12. A.J. Clarke, J.G. Speer, D.K. Matlock, F.C. Rizzo, D.V. Edmonds. Influence of carbon partitioning kinetics on final austenite fraction during quenching and partitioning // *Scripta Materialia*. 2009, v. 61. p. 149-152.

13. V.I. Zurnadzhi, V.G. Efremenko, V.G. Gavrilova, and others. Formation of a heterophase structure in low-alloy steel using the innovative technology of heat treatment "Quenching and Partitioning" // *Metallophysics and New Technologies*. 2018, N 40 (12), p. 1603-1624.

14. V.F. Zakey, E.P. Parker. Successes in the development of iron-based alloys // *Problems of development of structural alloys /* Ed. Jaffe. New York, 1977: Trans. with English. M.: "Metallurgy", 1980, p. 86-112.

15. L.M. Deineko. *Development of scientific foundations of strengthening heat treatment of connecting parts of oil and gas pipelines and special purpose products*: Diss. for obtaining sciences. stupa doctor of Technical Sciences, Dnipropetrovsk, 2000.

16. N.I. Vorobyev, O.K. Tokovoy, A.V. Mokrinsky, et al. Effect of sulfur content and non-metallic inclusions in steel on floc formation in large forgings // *Bulletins of higher educational institutions. Black Metallurgy*. 2003, N 2, p. 18-20.

17. A.D. Shaburov. *Theoretical and technological aspects of energy-saving anti-flake treatment of forgings with the use of non-heated slow cooling in thermoses taking into account the effect of trapping the water pipe with traps:* Diss. abstract. on the application form. candidate degree technical Sciences 15.16.01. Chelyabinsk, 2014.

18. R.I. Jaffee and B.A. Wilcox. *Fundamental aspects of structural alloy design:* Battelle institute materials science symposium, 1975.

19. Yu.Ya. Meshkov. *Physical foundations of destruction of steel structures*. Kyiv: "Naukova dumka", 1981, 238 p.

20. Yu.Ya. Meshkov. Physics of the destruction of steel and topical issues of structural strength // *The structure of real metals*. Kyiv: "Scientific Opinion", 1988, p. 235-255.

21. Yu.Ya. Meshkov. Problems of viscosity and energy-intensive destruction of structural steels in modern materials science // *Metalology and heat treatment of metals*. 1999, N 3, p. 34-40.

22. Yu.Ya. Meshkov, G.A. Pakharenko. *Metal structure and brittleness of steel parts*. Kyiv: "Naukova dumka", 1989, 160 p.

23. Yu. Meshkov, T.N. Serditova. Ductile fracture criterion for uniaxial tension of low-carbon steels // *Physics of Metals*. 1985, v. 5(6), p. 1180-1188.

24. L.I. Tushinsky. *Theory and technology of hardening of metallic alloys*. Novosibirsk: "Nauka, Siberian Department", 1990, 306 p.

25. I. Artinger. *Tool steels and their heat treatment:* Directory. Translated from Hungarian / Ed. by L.S. Kremneva. M.: "Metallurgy", 1982.

26. K. Firth, K.R. Harwood. Fractography and fracture toughness of high-strength 5% Cr-Mo-V steel // *The fracture toughness of high-strength materials* / Translated from English Ed. Bersteina M.L. M.: "Metallurgy", 1973, p. 136-151.

27. R.I. Jaffee and B.A. Wilcox. *Fundamental aspects of structural alloy design*: Battelle institute materials science symposium, 1975.

28. E. Goodremon. *Special steel* / 2nd ed.: Trans. with German. M.: "Metallurgy", 1966, v. 2, p. 1049-1076.

29. M.V. Prydantsev, L.N. Davydova, I.A. Tamarina. *Structural steels*: Directory. M.: "Metallurgy", 1980, 288 p.

30. V.P. Ilyina. The effect of preliminary heat treatment on the microstructure and resistance to brittle fracture of high-strength steels // *Metal Science and Heat Treatment*. 1998, N 8, p. 5.

31. V.D. Sadovsky. *Structural heredity in steel*. M.: "Metallurgy", 1973, 208 p.

32. R.V. Televych, S.V. Prikhodko, O.V. Kocherga. Crystalography of γ-α transformations in tempered structural steel. The influence of the degree of preliminary tempering of martensite on structural heredity during rapid heating // *Metallophysics*. 1993, v. 15, N 10, p. 81-89.

33. R.V. Televych, S.V. Prykhodko. Crystalography of γ-α transformations in tempered structural steel. Influence of the degree of preliminary tempering of martensite on the crystallography of fine-grained austenite complex // *Metallophysics*. 1993, v. 15, N 12, p. 35-41.

Article received 27.02.2026

СУЧАСНІ ТЕХНОЛОГІЇ ЗМІЦНЕННЯ СТАЛЕЙ ДЛЯ ВИГОТОВЛЕННЯ ЗАХИСНИХ ЕЛЕМЕНТІВ БРОНЕЖИЛЕТІВ

Частина 1

Л.М. Дейнеко, В.Л. Пінчук, А.В. Панченко

В умовах повномасштабної війни, яка триває в Україні, питання захисту життя та здоров’я громадян набуло особливого значення. Надійні засоби індивідуального захисту, зокрема засоби індивідуальної безпеки (ЗІБ) – бронежилети, є життєво необхідними для збереження життя та мінімізації ризиків отримання травм та поранень не тільки від куль, а в більшій мірі від уламків. Ключова вимога до матеріалу бронепластини – здатність витримувати дію боєприпасів певного виду без пробиття та поразки людини осколками, які можуть відшаруватися з протилежної площини бронепластини. Броньовим сталям таку балістичну стійкість забезпечують високоміцні низьколеговані або леговані марки та структурний стан металу, який забезпечують попередня та фінішна термічна (або комбінована) обробки. Конкретний рівень властивостей металу бронепластин залежить від класу захисту (для якого вони плануються), хімічного складу та параметрів обробки металу. Метою даної статті є дослідження впливу хімічного складу сталей та режимів термічної (для гомогенного стану) і хіміко-термічної обробок (для отримання гетерогенного стану) на властивості обраних для дослідження сталей і обрання раціонального складу сталей для виготовлення захисних листів бронеодежи та розроблення сучасних режимів обробки для забезпечення 4–5 класу захисту згідно ДСТУ 8782:2018, який є одним із ключових в Україні за цим напрямом. На основі результатів теоретичних і експериментальних досліджень запропоновано параметри технології термічної обробки з об’ємним зміцненням захисних елементів бронежилетів із використанням у якості прикладу хромо-нікель-молібден-ванадієвої сталі для отримання протикульової дії до 5 класу захисту в умовах експлуатації бронежилетів.