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Ballistic Resistance of Steel with the Structure of a Natural Ferrite-Martensitic Composite

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Introduction. For steel armor materials, it is important to reduce the thickness and, consequently, the metal consumption of the protective structure. The previously developed class of materials with the structure of a natural ferrite-martensite composite (NFMC) has characteristics that favor the inhibition of crack development under impact loads and has prospects as an armor material.

Problem Statement. The purpose of this work is to evaluate the possibility of using NFMC materials for armor protection devices based on the results of ballistic resistance tests under a high-power concentrated impact (a projectile flying at a hyper-high speed).

Theoretical Part. The study of ballistic resistance was carried out on samples of steel 14G2 processed according to various modes. The samples had the shape of plates and a square grid on the surface. Simulation tests of the impact of heat-strengthened dowels from a powder-actuated tool and firing of military small arms at the testing site from an SVD sniper rifle and an AK-74 assault rifle with machine loading ammunition were carried out. The results of simulation tests showed a clear advantage of steel with the NFMC structure. The comparison of the results of firing with military small arms has showed that the ballistic resistance of steel with the NFMC structure depends on the ratio of the volume fractions of ferrite and martensite, which cause different thicknesses of the ductile and strong components of the composite. The highest resistance was observed for a sample with an NFMC structure processed according to the regime: quenching 730°C and tempering 180°C.

Conclusions. Steels treated for the NFMC structure can provide effective protection for military personnel with a lower material consumption of armor protection devices, which is due to a special method of braking destruction during a high-power local impact. Thus, the practical application of the developed class of natural composite materials seems promising for obtaining an armor plate with a thinner thickness, which helps to reduce the weight of combat vehicles, increase their mobility and reduce fuel consumption.

Keywords*:* steel, composite, ferrite, martensite, fracture, crack resistance, heat treatment.

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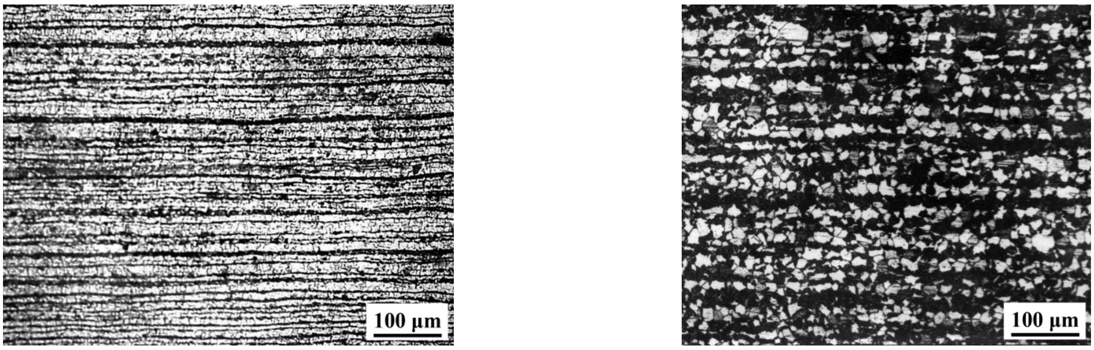
Introduction. Currently, hot-rolled steel sheet is used as a protective material for infantry fighting vehicles, amphibious assault vehicles and armored personnel carriers, which has a ferrite-perlite structure in the condition of supply. Armor made of a sheet with such a structure does not provide the necessary protection in case of high-power local collisions and is easily penetrated by a hand grenade launcher, underbarrel grenade launcher and even small arms with high destructive power — a 7.62 caliber SVD sniper rifle with an armor-piercing cartridge with a tungsten core, a new 12.7 caliber sniper rifle. An increase in the thickness of the armor plate (more than 25 mm) seriously impairs the mobility of combat vehicles on the battlefield, increases the weight and fuel consumption.

In [1, 2], the possibility of creating steel with the structure of a natural ferrite-martensitic composite (NFMC) based on the use of hypoeutectic steels with a lineage ferrite-pearlite structure is substantiated. The hardening of such steel from the intercritical temperature range (A1–A3) makes it possible to obtain a layered structure of a ferrite-martensitic composite (Fig. 1). The study of the properties of the steels under consideration under static tension and shock bending gives reason to believe that such a structure is characterized by a special mechanism of inhibition of crack development [2].



a) *b)*

Fig. 1. Structure of steel grade 14G2: *a* — lineage ferrite-pearlite;
b — after quenching from a temperature of 760 °C

Problem Statement. The aim of this work is to determine the possibility of using steels with the NFMC structure for armor protection devices (individual protection of military personnel, protection of armored personnel carriers, infantry fighting vehicles, armored assault vehicles from damage when firing small arms and grenade launchers). Based on the formulated goal, the task is to obtain data on the ballistic resistance of a steel target with an NFMC structure under a concentrated high-power impact by a projectile flying at hyper-high speed (> 800 m/s).

Research Methodology. The study of ballistic resistance was carried out on 14G2 steel samples processed according to the modes presented in Table 1. The test samples were plates with a size of 150×44×7mm. The surface of the samples was sanded, and then a grid was applied to the surface with a 3 mm pitch in two mutually perpendicular directions.

Table 1

Characteristics of 14G2 steel samples for ballistic resistance tests

Sample No.	Processing mode	Volume ratio ferrite/martensite after quenching	Hardness, HRCэ
1	delivery state	–	< 20
2	quenching 860°C + tempering 400 °C	0/100	38÷40
3	quenching 730°C + tempering 180 °C	65/35	42÷44
4	quenching 760°C + tempering 180 °C	45/55	42÷44

Preliminary simulation tests of target plates were carried out against heat-strengthened dowels (4.5 mm in diameter) using a PTs-8 powder-actuated tool (D-4 muzzle sleeves of maximum power were used).

Further, for the purpose of testing when exposed to a high-power impact (a projectile flying at hyper-high speed), a shooting with combat small arms was carried out at the training ground of one of the military units of the Ministry of Defense of the Russian Federation, stationed in the immediate vicinity of Rostov-on-Don. From the available arsenal, two types of domestic small arms with the highest destructive power were selected: a 7.62 mm SVD sniper rifle and a 5.45 mm AK-74 automatic rifle. Both types were provided with factory-loaded ammunition of two types: a light cartridge with a steel core and an armor-piercing one with a tungsten core in copper shells. The shooting was from a distance of 45 meters, allowing for targeted fire, given the lack of special measures at the training ground to prevent ricochet. The increase in the firing distance, compared with the recommended standards for bullet resistance of a distance of 10 meters, should not significantly affect it when comparing this parameter with reference data, given the high speed of bullets and the assessment of the nature of the damage for these types of weapons: SVD rifle — cartridge 7.62 mm with a bullet LPS and B-32, weight — 9.6-10.4 g, speed — 800÷840 m/s; AK-47 assault rifle — 5.45 mm with a PS and BS bullet, weight — 3.5÷3.8 g, speed — 890÷910 m/s.

Research Results and Discussion. The results of preliminary simulation tests when exposed to the powder-actuated tool dowel are illustrated in Fig. 2. It can be seen that in the state of delivery (Fig. 2 *a*), the plate is shot through to the stop of the dowel. After complete quenching and tempering at a temperature of 400 °C, the plate is shot through, but the dowel does not reach the stop (Fig. 2 *b*). A shot into a plate with an NFMC structure (sample No. 4, Table 1) leads to the destruction of the dowel without significant damage to the plate (Fig. 2 *c*).

a) *b)* *c)*

Fig. 2. Results of simulation tests of target plates made of 14G2 steel when firing a powder-actuated tool:
a — sample No. 1; *b* — sample No. 2; *c* — sample No. 4

The simulation tests carried out showed a clear advantage of steel with the NFMC structure. However, the energy of the dowel delivered to it by the powder charge of the muzzle shell is less than the energy of a concentrated impact of a projectile flying at hyper-high speed. Therefore, samples No. 3 and No. 4 with the NFMC structure (Table 1) were shot using combat small arms. A comparison of the test results showed that the ballistic resistance of steel with the NFMC structure depends on the ratio of the volume fractions of ferrite and martensite, which determine the different thickness of the viscous and durable component of the composite. Thus, sample No. 4 with a small plate thickness of viscous ferrite and low carbon content in the martensitic phase is almost always pierced through with armor-piercing bullets of 7.62 mm and 5.45 mm caliber (Fig. 3). At the same time, sample No. 3, which also has the NFMC structure, but a large thickness of the ferritic phase and the strength of the martensitic layer, is not penetrated through when fired with armor-piercing bullets. The bullet penetrates the metal by 2-3 mm and ricochets. At the same time, a small crack forms on the back side (Fig. 4).

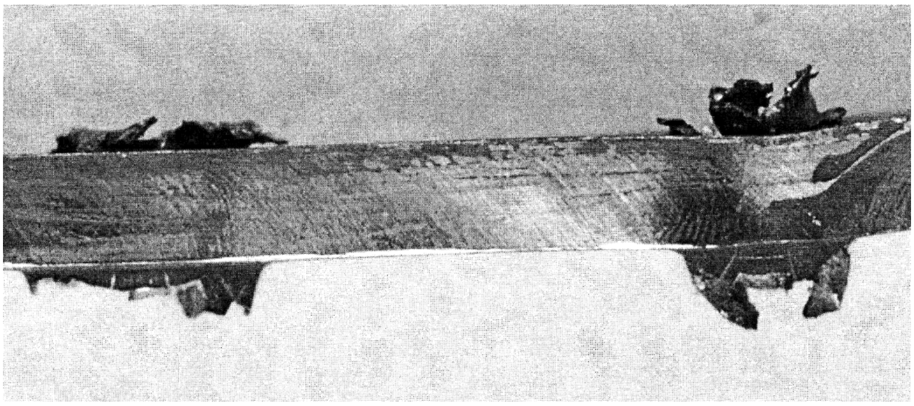
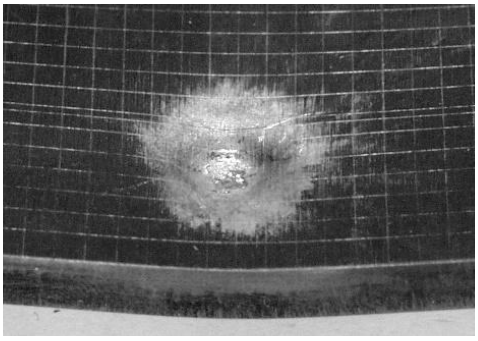
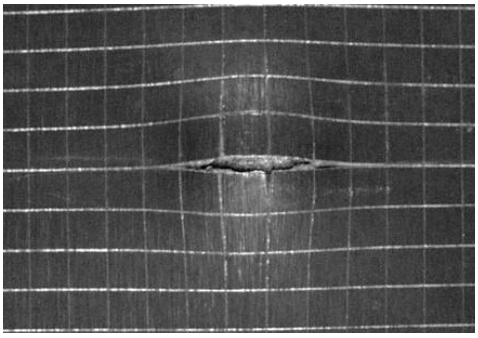


Fig. 3. Through penetration by armor-piercing bullets of 7.62 and 5.45 mm caliber. The remains of the copper shell in the holes. Processing mode: quenching at 760 °C and tempering at 180 °C





a) *b)*

Fig. 4. Absence of penetration, the result of ricocheting: *a* — view from the side of the impact; *b* — view from the back side. Processing mode: quenching from 730 °C and tempering 180 °C

According to the data from the website of the Bureau of Scientific and Technical Information "Equipment for Special Services" [3], the widely used armored steel SPS-43 [4], manufactured according to TU (technical conditions) 0902-005-31041642-95 when fired from an SVD rifle with an LPS cartridge requires a two-layer sheet with a total thickness of 8.3 mm. The natural composite material created by the authors fulfills the task of bullet resistance when hit by this type of weapon with a thickness of 7 mm.

The high ballistic resistance of steel with the NFMC structure is due to a special mechanism of crack movement in steel, the structure of which is organized in the form of parallel layers of ductile, viscous ferrite and durable martensite. When a crack approaches the martensite-ferrite surface, a stratification in ferrite occurs on it (or near it) due to the presence of tensile stresses parallel to the crack plane [5-9]. In this case, part of the energy supplied from the outside is spent on the formation of the stratification surface in ferrite. The exit of the crack into the stratification leads to a change in its trajectory, a stop in its progress and relaxation of tensile stresses at its apex. To destroy the next layer of the composite (martensitic layer), a new crack must form in it, but already under conditions close to the uniaxial stress state, which will require additional energy.

In [6], the condition for the occurrence of the stratification is written as follows:

$$\sigma \geq \frac{K_D}{\varphi\sqrt{c}}, \qquad (1)$$

where K_D — a certain critical value of the stress intensity coefficient; $\varphi = \frac{3+\nu}{1+\nu}$ — constant (ν — Poison's ratio); c — thickness of the breakable layer (martensite).

At the same time, it is shown that for the occurrence of stratification before the martensitic crack (before the destruction of the next breakable layer), it is necessary that $\sigma_p < \sigma < \sigma_{0,2}$ and, consequently, the condition for the occurrence of stratification inhibiting the destruction of the layered sample has the form:

$$K_D \leq \varphi\sqrt{\frac{E\sigma_{0,2}h\upsilon}{\alpha\beta}}, \qquad (2)$$

where h — thickness of the plastic layer (ferrite); υ — thickness of the plastic layer (ferrite); $\alpha = \frac{1+\nu}{3-\nu}$ and $\beta = \frac{4}{3-\nu}$ — constants.

The value $K_D \sim \sqrt{\gamma_s n_s^2}$, then condition (2) will take the following form:

$$\sqrt{\gamma_s n_s^2} < \theta\sqrt{a\upsilon}\,, \tag{3}$$

where γ_s — the ultimate shear strain in the ferrite plate; n_s — the shear hardening index; $\theta = \varphi\sqrt{\frac{E}{\alpha\beta}}$ — constant.

If the thickness of the plastic ferrite layer in a multilayer sample is sufficient to fulfill condition (3), then stratification is formed that prevents further advancement of the main crack. For steel grade 14G2 at values γ_s approximately 1000 MPa and $n_s = 0{,}43$ the stratification occurs at a ratio of $\frac{h}{c} \geq 3$. This ratio occurs when quenching steel grade 14G2 with temperatures from 730 °C to 740 °C of the intercritical interval [10, 11].

Conclusions. Thus, the results of determining the ballistic resistance of steel with the NFMC structure showed that with less material consumption, it could provide effective protection for military personnel, which is due to a special method of braking destruction during a local high-power impact. The practical application of the developed class of natural composite materials seems promising for obtaining armor plate with a smaller thickness, which helps to reduce the weight of combat vehicles, increase their mobility and reduce fuel consumption.

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