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COMPOSITE SPACE ARMOURS WITH THE BAINITIC-AUSTENITIC AND MARAGING STEEL LAYERS

Abstract: The paper includes results of firing tests of the steel plates with nano-structures, i.e. bainitic NANOS-BA® and maraging of size 50x50x5÷10 mm, 100x100x5÷10 mm and 150x150x5÷10 mm, placed on the armour plate RHA (*Rolled Homogenous Armour*) type Armox 500T or Armox 600T of size 500x500x10 mm, so called "witness plate". There are also presented results of firing tests of the composite space panels CAWA-3+ and CAWA-4 for protection of light armoured vehicles against the anti-tank ammunition type B-32 of 12.7 mm and 14.5 mm calibre. The space panels of size 300x300x17.2÷22 mm and 254x300x17.2÷22 mm were placed at the distance *L*< 150 mm from the protected thin armour RHA type Armox 500T of 8 mm thickness. These panels included, among others, steel plates with nano-structures (of size from 150x150x5÷10 mm to 300x350x7÷8 mm), i.e. bainitic NANOS-BA® and maraging, armoured steel plates and light metal plates. Effective stopping of these projectiles in the tested panels was achieved without any traces of the projectile impact onto the RHA plate of 8 mm thickness.

Keywords: armour panel, space armour, materials engineering, armour plates, nano-crystalline steel / nano-structured steel

KOMPOZYTOWE PANCERZE PRZESTRZENNE Z WARSTWAMI ZE STALI BAINITYCZNO-AUSTENITYCZNEJ I MARAGING

Streszczenie. Artykuł zawiera wyniki badań ostrzałem płyt ze stali nanostrukturalnych, tj. bainitycznych NANOS-BA® i maraging o wymiarach 50x50x5÷10 mm, 100x100x5÷10 mm oraz 150x150x5÷10 mm umieszczonych na płycie pancernej RHA (*Rolled Homogenous Armour*) typu Armox 500T lub Armox 600T o wymiarach 500x500x10 mm, tzw. płycie „świadek". Przedstawiono również wyniki ostrzałów kompozytowych paneli przestrzennych CAWA-3+ i CAWA-4 do ochrony lekko opancerzonych pojazdów przed przebiciem pociskami przeciwpancernymi B-32 kalibru 12,7 mm i 14,5 mm. Panele przestrzenne o wymiarach 300x300x17.2÷22 mm i 254x300x17.2÷22 mm umieszczono w odległości *L* < 150 mm od ochranianego cienkiego pancerza RHA typu Armox 500T o grubości 8 mm. Panele te zawierały między innymi płyty ze stali nanostrukturalnych (o wymiarach od 150x150x6÷10 mm do 300x350x7÷8 mm), tj. bainityczne (NANOS-BA®) i maraging, stalowe płyty pancerne oraz płyty z metali lekkich. Uzyskano skuteczne zatrzymanie tych pocisków w badanych panelach bez śladów uderzenia pocisku na płycie RHA o grubości 8 mm.

Słowa kluczowe: panel pancerny, pancerz przestrzenny, inżynieria materiałowa, płytki pancerza, stal nanokrystaliczna / stal nanostrukturalna

1. Introduction

Light armoured vehicles (wheeled and tracked armoured fighting vehicles - BWP, reconnaissance vehicles, medical and the like) and heavy armoured (tanks) are used on the battle field [1, 2]. Among the light armoured vehicles there are also carriers for persons (VIP) and valuables, etc.

According to STANAG 4569 standard modern light armoured vehicles usually have a composite armour resistant to piercing with the KE projectiles (*kinetic energy* - piercing with their kinetic energy) type AP (*armour piercing*) of caliber 7.62 mm (level 3), 12.7 mm (level 3+) and 14.5 mm (level 4).

The composite armour, particularly of the light armoured vehicle, should be of high E_m (*mass efficiency*) and E_t (*thickness efficiency*). The mass efficiency describes how many times the mass m_{CAWA} of the composite armour CAWA (*composite armour*) is lower than the mass (m_{RHA}) of the steel armour RHA of the same protective capability.

The aim of research was to find such models of protective layers with the smallest mass and thickness, able to stop the AP projectiles. The mass efficiency E_m and the thickness efficiency E_t are the best parameters characterising this type of armours.

2. Measures of protective efficiency of CAWA armour

The mass efficiency E_m determines the mass of RHA armour (m_{RHA}) which ensures the same protection against perforation with the projectile as the tested CAWA armour of m_{CAWA} mass:

$$E_m = \frac{m_{RHA}(h)}{m_{CAWA} + m_{RHA}(h_W)} = \frac{\rho_{RHA} V_{RHA}(h)}{\rho_{CAWA} V_{CAWA} + \rho_{RHA} V_{RHA}(h_W)}, \quad (1)$$

where:

$$m_{CAWA} = \sum_{i=1}^{n} \rho_i V_i , \quad (2)$$

where: ρ_i, V_i - density and volume of the i-layer of the CAWA armour

Thus the E_m is a relation of mass m_{RHA} (h) of the pierced RHA armour (with a projectile of perforation ability h) to the sum of mass m_{CAWA} of the pierced CAWA armour and mass $m_{RHA}(h_W)$ of the RHA armour (protected by the CAWA armour), where the projectile created a crater of depth h_W. In case the CAWA armour stops the projectile completely ($h_W = 0$) the mass efficiency factor takes the form:

$$E_m = \frac{m_{RHA}(h)}{m_{CAWA}} = \frac{\rho_{RHA} V_{RHA}(h)}{\rho_{CAWA} V_{CAWA}}. \quad (3)$$

The thickness efficiency E_t describes how many times the thickness h_{CAWA} of the composite armour CAWA is lower than the thickness h of the steel armour RHA of the same protective capability [1].

$$E_t = \frac{h}{h_{CAWA} + h_W}, \quad (4)$$

where:

$$h_{CAWA} = \sum_{i=1}^{n} h_i \,. \qquad (5)$$

Thus it is a relation of the thickness (h) of the pierced RHA armour (with a projectile of perforation ability h) to sum of thickness (h_{CAWA}) of the pierced CAWA (consisting of n-layers) and thickness (h_W) of the RHA armour base (witness plate), protected by the CAWA, where the projectile created a crater of depth h_W. In case the CAWA armour stops the projectile completely (without any trace of perforation on the RHA plate), then $m_{RHA}(h_W) = h_W=0$ and the thickness efficiency of the CAWA armour takes the form:

$$E_t = h / h_{CAWA}. \qquad (6)$$

The paper includes results of testing of the passive armours PA (*passive armour*) of additional panels type AA (*add on armour*) CAWA-3+ and CAWA-4 for protection of the light armoured vehicles against piercing with the AP incendiary 12.7 mm and 14.5 mm type B-32 projectiles (Table 1). The AA panels can be installed directly on the armour of the protected vehicle or can be placed at some distance from the hull - space panels (SA - *space armour*). The tested panels were placed at the l < 150 mm distance from the protected thin armour type Armox 500T of 8 mm thickness. Nowadays the thickness of hull armour of the light armoured vehicle often amounts to just 8 mm.

The aim of the constructed and tested panels was absorption and entire dissipation of the projectile kinetic energy AP ($m_{RHA}(h_W) = h_W = 0$). In addition the panel's task was to absorb also the thermal energy arrose at the moment of the projectile impact onto the armour, i.e. after ignition of the pyrotechnic mixture of the B-32 type projectile or burst of the explosive of the BZT type projectile (Table 1).

Table 1. Parameters of polish KE projectiles [1]

No.	Projectile caliber, d, mm	Kind of projectile	Mass of projectile m_p, ($m_{p\,m}$), g	Projectile velocity, V_p, ($V_{p\,m}$), m/s	Average kinetic energy of projectile, E_{ev}, J	Thickness of RHA plate and penetration depth (h) [mm] / distance l [m] / $\propto$, °	Comments, probability of penetration (p_p) and inflammation {p_z}, %
1	12.7	B-32	47.4÷49 (48.2)	810÷825 (817.5)	16106	20/200/0°	(90), inflammation of container with petrol behind a target ≠15, L=70 m, {75}
2	14.5	BZT	59.3÷61.3 (60.3)	995÷1015 (1005)	30452	20/100/20° (21.3)	(80), inflammation of container with petrol behind a target ≠20, L = 100 m, {80}
3	14.5	B-32	63÷64.8 (63.9)	980÷995 (987.5)	31156	20/100/20° (21.3)	(80), inflammation of container with petrol behind a target ≠20, L = 100 m, {80}

The tested composite panels included, among others:

- armour nanostructured steel plates, i.e. bainitic NANOS-BA® and maraging,
- armour steel plates,
- light metal plates.

3. Mechanical properties of nanostructured steels

3.1 Bainite – austenite nano – composite NANOS-BA® steel

As a result of laboratory and semi-industrial research carried out on the material of experimental steels a new ultra-high strength steel grade containing 0.55÷0.59% C, 1.95÷2.10% Mn, 1.75÷1.90% Si, 1.20÷1.40% Cr, 0.70÷0.80% Mo and micro-additions of V, Al and Ti was developed in the Institute for Ferrous Metallurgy for application in the composite space armours [4, 5]. Chemical composition and heat treatment of the developed steel grade called NANOS-BA® were submitted by the Institute for Ferrous Metallurgy to the Patent Office of the Republic of Poland for patenting [6, 7]. The developed parameters of thermo-mechanical treatment and heat treatment of NANOS-BA® steel lead to formation of nano-composite structure composed of nanolaths of carbide free bainite of high density of dislocations and nanolaths and nanograins of retained austenite.

By means of the designed technology with application of the equipment constituting the line for semi-industrial simulation of metal products manufacturing (LPS) plates of NANOS-BA® steel were produced, characterized with very high strength and good plasticity: strength (R_m) above 1.8 GPa, yield stress ($R_{0.2}$) above 1.3 GPa and total elongation in static tensile test (*A*) in the range of 12÷16%. Typical hardness of heat treated NANOS-BA® steel plates is shown in Table 2. Such level of mechanical properties enables to use the NANOS-BA steel for construction of space composite armours.

The plates of NANOS-BA® steel manufactured in the LPS were used to cut out specimens for firing tests of 50x50 mm, 100x100 mm and 150x150 mm dimensions, and of 5÷10 mm thickness as well as components for space armours of 250÷300 mm x 250÷300 mm dimensions and of 5 mm to 10 mm thickness. To obtain required mechanical properties two variants of isothermal heat treatment at temperature 225°C and 250°C were carried out.

3.2 Nano – precipitates strengthened maraging steel MS350

Properties of nano-precipitates strengthened steels are achieved owing to heat and/or thermo-mechanical treatment, as a result of which the particles of strengthening phase precipitate from oversaturated matrix. Properties of this type of materials are controlled by selection of the parameters of heat treatment, deciding directly on volume fraction and distribution of size and type of precipitates. Precipitation from oversaturated solution, apart from chemical composition of steel, depends mainly on the temperature and ageing time. Along with the temperature and ageing time increase the mechanical properties improve and plasticity drops until maximum strength is achieved. High-alloy maraging steels, which are applied in most cases following ageing producing maximum hardness (the so called „peak aged state"), are an example of precipitation hardened steel of very high strength and good crack resistance required for structural materials [3÷5].

Experimental material for firing tests and for construction of the space panels which were plates of maraging MS350 steel (18% Ni, 12% Co, 4% Mo and 1.8% Ti) were produced using the line for semi-industrial simulation of metal products manufacturing (LPS). The obtained plates of MS350 steel characterized with the following properties: strength (R_m) above 2.0 GPa, yield stress ($R_{0.2}$) above 1.9 GPa and total elongation in static tensile test (*A*) in the range of 7-8%. Typical hardness of heat treated maraging MS350 steel plates is shown in Table 2.

For the firing tests individual specimens and layers for construction of the space panels of 50x50 mm, 100x100 mm and 150x150 mm dimensions and of 5÷10 mm thickness range were prepared. In order to improve plastic properties short - time ageing at higher temperature than standard ageing temperature was applied.

Table 2. Typical hardness of heat treated nanostructured steels: NANOS-BA® and maraging MS350

No	Steel mark and heat treatment	Plate thickness, mm	Hardness, HV10
1	NANOS-BA®, 225ºC/70h	5÷10	600÷620
2	NANOS-BA®, 250ºC/70h	5÷10	570÷580
3	Maraging MS350, 550º/2÷5min.	6÷10	570÷650

4. Firing tests of the panels with nanostructured steel plates

The nano-structured steel armour plates were made of 50x50x5÷10 mm, 100x100x5÷10 mm and 150x150x5÷10 mm sizes. Initially the nano-structured plates were placed on the RHA "witness" base (Armox 500T and Armox 600T) of 500x500x10 mm size in order to investigate their protective capability and way of cracking while firing with the12.7 mm and 14.5 mm type AP projectiles.

While firing the barrel of the rifle was at the distance of 3.5 m from the RHA armour plate, set in relation to this tested plate for α_{NATO}=0º from the normal to the surface of the RHA plate - a vertical section and a horizontal (90 º horizontal and vertical - Fig. 1).

Fig. 1. Test stand for testing of the protective capability of the steel plates fired with the 12.7 mm armour piercing- incendiary type B-32 projectile

Examples of the bainitic NANOS-BA® plate, RHA armour plate and the maraging MS350 plates after firing with the 12.7 mm armour piercing- incendiary type B-32 projectile are shown in Figs. 2 and 3.

a b c d

Fig. 2. Plate of the bainitic NANOS-BA® steel of 100x100x10 mm size and 50 HRC hardness after firing with the 12.7 mm armour piercing- incendiary type B-32 projectile: a – front of the plate, b - back of the plate, c - front of the RHA plate, d - back of the RHA plate

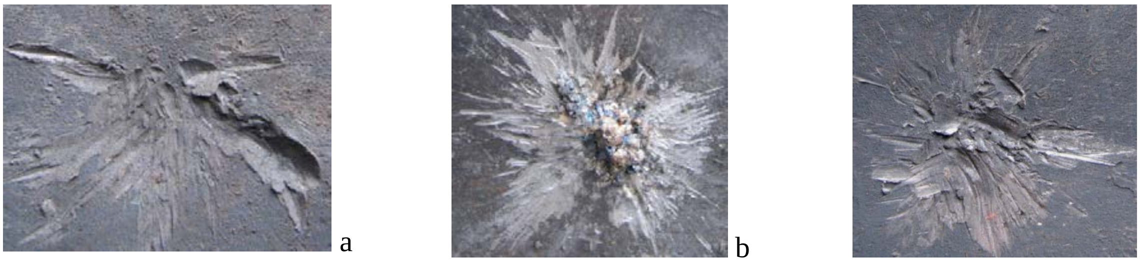


Fig. 3. View of various characteristic traces on the RHA plate after firing the maraging MS350 plates of different hardness after firing with the 12.7 mm armour piercing- incendiary type B-32 projectile: a - HRC=58, b - HRC=61, c - HRC=64

After firing of the nanostructured steel armour plates the characteristic parameters on the RHA plate were measured in places of the investigated plates positions. Figure 4 shows the measured parameters both in case of not perforating of the RHA plate and its perforating.

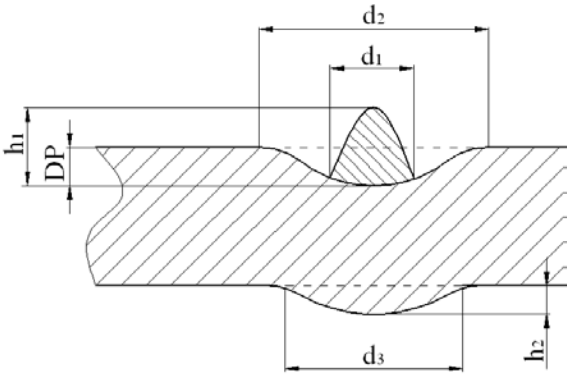


Fig. 4. Parameters of traces on the RHA "witness" plate following experimental steel plate firing: *DP* -depth of penetration, h_1 - height of hill, d_1 - hill diameter, d_2 - dinge diameter, d_3 - bulge diameter on the back surface of RHA, h_2 - bulge height on the back surface of RHA

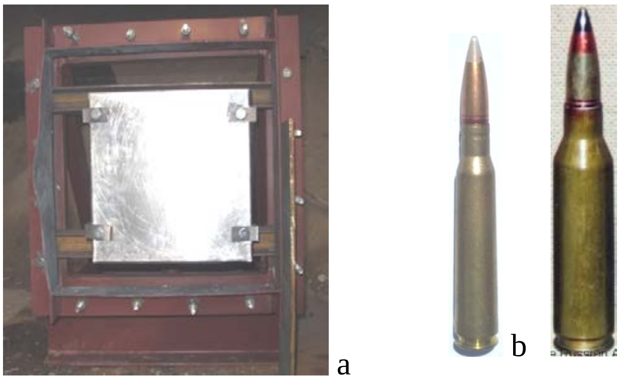
Table 3 shows example of results of firing tests for α_{NATO}=0°, for the investigated nano-structured steel plates, which stopped the 12.7 mm type B-32 projectiles with the minimum depth of penetration (*DP*) of the RHA.

Table 3. Parameters of the RHA (Armox 500T) plate after firing with projectiles B-32 type

Type of plate; dimensions, mm; hardness, HRC	Type of projectile / Depth of RHA penetration	Height of:		Diameter of:	
		hill, h_1, mm	bulge, h_2, mm	dinge, d_2, mm	bulge, d_3, mm
186/550/2/1 100x100x6	12.7 mm AP / 3.5	-	3.3	20.6	28.8
278/510/3/VII 100x100x14	14.5 mm AP / 6.0	1	2.9	30.8	40.8

Next the nano-structured steel plates were placed onto the space panels of 300x300x18÷22 mm and 254x300x18÷22 mm size. The panels included, among others, nanostructured steel plates (of size from 150x150x6÷10 mm to 300x350x7÷8 mm), i.e. bainitic NANOS-BA® and maraging, steel armour plates and light metal plates. The panels were placed at the distance of *L*< 150 mm from the protected thin armour RHA type Armox 500T of 8 mm thickness.

Elements of the test stand for firing tests and applied projectiles are shown in Fig. 5.



a b c

Fig. 5. Test stand and ammunition with the type B-32 projectile:
a - stand with an assembled panel,
b - 12.7 mm cartridge,
c - 14.5 mm cartridge

The 300x300 mm size steel plate with four bushings welded to it was fixed in the frame of the immovable stand. The panel was attached to this plate with the use of four handles and threaded bars, screwed in the bushings. The RHA plate type Armox 500T of 500x150x8 mm size was placed between the support and the panel.

The panels were fired with the 12.7 mm and 14.5 mm type B-32 projectiles (Figs. 5b, c). After each fire the panels and the RHA plate were inspected, and their appearance and destruction of particular layers, were evaluated. The inlet and outlet holes diameter was measured, as well as the height of bulge of the rear side of the panels (Fig. 4).

The results of firing tests of the panels for $\alpha_{NATO}=0^{o}$, which stopped the 12.7 mm and 14.5 type B-32 projectiles are presented in Tables 4 and 5. Destruction of the panels and particular layers of the arrangements after firing are shown in Figs. 6÷9.

Table 4. Results of firing with the 12.7 mm type B-32 projectiles of the panels with maraging MS350 plates

No. of plate	Thickness of the maraging plate, mm	Thickness of the panel, a, mm	Dinge diameter, d_2, mm		Diameter of the outlet hole, mm	Height of bulge, h_2, mm
			max	min		
1/Panel 4	5.5	17.5	17. 6	13.7	-	1.5
1/Panel 5	10	18	14.2	13.7	-	5.8

Table 5. Results of firing with the AP type projectiles of the panels with NANOS-BA® plates

Calibre of the B-32 projectile	No. of panel	Thickness of panel mm	Dinge diameter, d_2, mm		Height of bulge h_2, mm
			max	min	
12.7	1	17.2	13.1	13.5	3.2
	2	17.5	17.6	13.7	1.5
	3	20	16.8	15.3	0.5
	4	22	19.2	14.5	1.1
14.5	5	22	22.3	17.6	7.9

Fig. 6. Front of the panel 4 after firing with the 12.7 mm type B-32 projectile

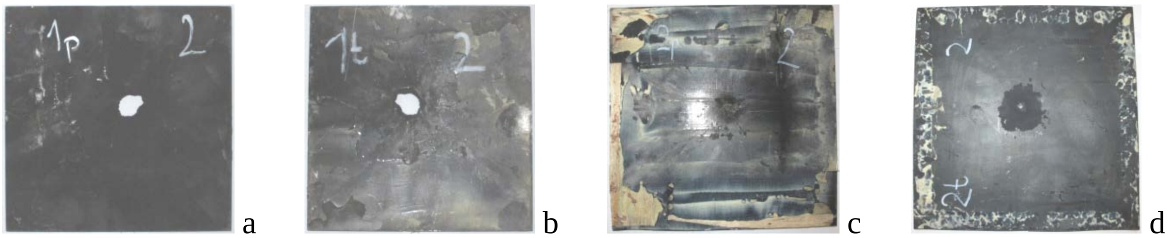


Fig. 7. Specific layers of the panel 4 after firing with the 12.7 mm type B-32 projectile: a - front of the layer 3, b - back of the layer 3, c - front of the layer 4, d - back of the layer 4

Fig. 8. Front of the panel 5 after firing with the 14.5 mm type B-32 projectile

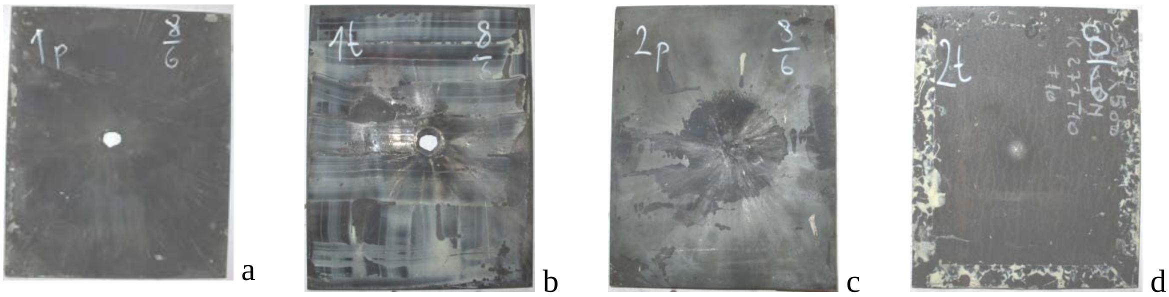


Fig. 9. Specific layers of the panel 5 after firing with the 14.5 mm type B-32 projectile: a - front of the layer 3, b - back of the layer 3, c - front of the layer 4, d - back of the layer 4

5. Conclusions

On the base of investigation of the tested panels which were not pierced the following conclusions can be drawn:

1. After firing the panel with the 12.7 mm type B-32 projectile the smallest bulge of its last layer amounted to 0.5 mm.
2. The smallest surface mass of the panel which stopped the12.7 mm type B-32 projectile amounted to 129 kg/m^2.
3. After firing the panel with the 14.5 mm type B-32 projectile the smallest bulge of its last layer amounted to 7.9 mm.
4. The smallest surface mass of the panel which stopped the 14.5 mm type B-32 projectile amounted to 134 kg/m^2.

References

[1] Wiśniewski A., *Armors, building, designing and testing*. Scientific and Technical Publishing House, Warsaw, 2001. ISBN 83-204-2609-X. (in Polish)

[2] Wiśniewski A., Żurowski W., *Ammunition and armors.* Publishing of Radom University of Technology, Radom, 2001. ISBN 83-88001-58-2. (in Polish)

[3] Marcisz J., Garbarz B., Burian W., Wiśniewski A., New Generation Maraging Steel and High–Carbon Bainitic Steel for Armours, *Proceedings of 26th International Symposium on Ballistics*, Miami, USA, 12÷16.09.2011, pp. 1595.
[4] Garbarz B., Marcisz J., Burian W., Wiśniewski A., Mechanizmy odkształcenia dynamicznego w ultra-wytrzymałych stalach nanostrukturalnych przeznaczonych na pancerze, *Problemy Techniki Uzbrojenia, Biuletyn Naukowy Wojskowego Instytutu Technicznego Uzbrojenia*, Zeszyt 118, nr 2/2011, s. 41.
[5] Garbarz B., Marcisz J., Adamczyk M., Wiśniewski A., Ultrahigh–strength nanostructured steels for armours, *Problemy Mechatroniki, Uzbrojenie, Lotnictwo, Inżynieria Bezpieczeństwa*, *Biuletyn WAT*, 1(3), 2011, pp. 25.
[6] Garbarz B., Burian W., *Bainite-austenite steel and plate manufacturing method of the said steel*, Patent applications by Instytut Metalurgii Żelaza to the Polish Patent Office: No P.394037, 2011.
[7] Garbarz B., Burian W., *Heat treatment method of bainite–austenite steel*, Patent applications by Instytut Metalurgii Żelaza to the Polish Patent Office No P.396431, 2011.

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