ZESZYTY NAUKOWE AKADEMII MARYNARKI WOJENNEJ
SCIENTIFIC JOURNAL OF POLISH NAVAL ACADEMY

2016 (LVII) 3 (206)

DOI: 10.5604/0860889X.1224755

Zdzisław Zatorski*

SPECIAL MARINE STEELS AND CONSTRUCTIONAL-BALLISTIC SHIELDS DESIGNED PNA

ABSTRACT

In order to increase security of the country in the field of new materials and technologies and research methods were developed, patented and implemented: austenitic steel X02CrNiMoMnN21-16-5-4 with electrodes for welding of steel and high-strength bainitic steel 10GHMBA-E620T. The author developed a theoretical and technological basis for the design of marine constructional-ballistic shields, which has implemented a pilot scale and technical support. In addition, he developed an original method for testing ballistic shields and unified position to the research, which studied and co-patented.

Key words:
austenitic stainless steel, cast steel, electrode welding, bainitic steel, constructional and ballistic shields.

SPECIAL MARINE STEEL AND CONSTRUCTIONAL-BALLISTIC SHIELDS

The adoption of these topics can justify the author's work since 1983 in the Department of Materials Science and Metal Technology in the Polish Naval Academy PNA. The author participated actively in the implementation of a number of scientific research in the field of new materials and technologies under the direction of Commander Dr. Eng. Joseph Fila. Therefore, the significant part of the works and articles from this period is signed as a joint.

* Polish Naval Academy, Faculty of Mechanical and Electrical Engineering, Śmidowicza 69 Str., 81-127 Gdynia, Poland; e-mail: z.zatorski@amw.gdynia.pl

Austenitic steel X02CrNiMoMnN 21-16-5-4

Research has largely been dictated by the development and proper implementation of elements of the paramagnetic steel and cast steel intended for use in sea water for manufactured laminate naval mine project 207 [2, 8, 13]. These studies carried out in part in the Central Research and Development Program CPBR 2.4 and statutory works [5]. Thanks to the co-authorship's technology has been developed, patented and comprehensively implemented high-strength austenitic steel reduced below 0.03% carbon content, and increased to 0.3% nitrogen content. To obtain such a low carbon content applied secondary metallurgical vacuum treatment processes VOD and VAD.

After the introduction of nitrogen in nitrides increased yield strength steel almost doubled in relation to the steel AISI 304 and the stability of the austenite after cold-deformation, at the same time reducing the sensitizing effect of carbon. Structural studies of systems has shown that properly processed austenitic stainless steel products to be supersaturated in water from 1080°C to 1150°C.

In principle, it is necessary for long-term traversing austenitic steels at temperatures between 500°C to 900°C, associated with the precipitation of carbide and brittle intermetallic phases. Recommendations supersaturation investigated steel need not be maintained at the cooling of wire and thin sheet metal, and a very thick degree shaped article of hot and cold deformation. The effects of supersaturation are effective to produce a homogeneous fine-grained austenite having an average grain 13 μm. The mechanical properties of austenitic stainless steel X02CrNiMoMnN21-16-5-4 the cold rolling and supersaturation after deformation given in the table 1 [2].

Table 1. Mechanical properties of austenitic steel X02CrNiMoMnN21-16-5-4 [own work]

Heat treatment	YS [MPa]	TS [MPa]	$A5_{min}$ [%]	HBN	KV_{min} [J]
Supersaturation	420	700	35	185	175
Cold rolling	600	1000	35	300	70

Developed Material Conditions Technical forgings and sheet thicknesses from 3 mm to 40 mm [13]. Based on these requirements of the elements produced forged, rolled and drawn after the supersaturation from 1100°C and cold-deformed and annealed at 450°C wire. This was possible thanks to the functioning steel mills and processing factory. Huta Baildon produced ingots, rods and shafts, in Huta Batory forgings and plates, and in Stalowa Wola sheets. However, in Huta Baildon blank prepared for welding wires and ropes and HZWD Mikrohuta — welding wires diameter 1.6–1.8 mm and 0.36 mm diameter wire to wire trawl and sailing. The Plant Marine Equipment SEZAMOR in Slupsk implemented on request SMW in 1987 paramagnetic anchor chains caliber 17,5 mm category 3a according to PRS. Production of paramagnetic anchor chain, line elements of the shaft, rudder, Kort nozzle and a number of other applications allowed to break the existing lock technology [mm]. Development of the technology exchange plating trawl acoustic conducted necessary tests weldability and fatigue tests, and provided new materials and conducted supervision Naval Shipyard [6]. Obtained constantly paramagnetic characterized by a coefficient of permeability below the required 1.01 and at the same time high resistance to corrosion in seawater. Resistance to pitting and crevice corrosion test method potentiokinetic in artificial sea water at 20°C showed the potential of pitting and crevice 1100 mV and 1050 mV. It should be added that in Germany built the fleet of units to detect and combat min entirely made of steel with similar physico-chemical characteristics [2].

Electrodes for welding austenitic stainless steel X02CrNiMoMnN 21-16-5-4

Electrodes in the form of wire Sp03H21AN16G5M4Nb MIG and TIG welding as well as ES21-16-5-4B coated electrodes for welding of austenitic stainless steel X02CrNiMoMnN 21-16-5-4. GMAW method has been developed and patented and implemented in cooperation with Huta Baildon and the Naval Shipyard SMW [2, 4]. Noteworthy is the introduction of coated electrodes ES21-16-5-4B components improve corrosion resistance. Thus retains the characteristics of the parent material. Joints showed no welding defects, especially prone to hot cracking, and with less than 1% share of secondary phases (mainly sigma). Mechanical properties of selected weldments in SMW sheets 10 mm thick are given in the table 2.

Table 2. Mechanical properties of welded joints of austenitic stainless steel X02CrNiMoMnN 21-16-5-4 sheet thickness 10 mm [13]

Welding electrode	YS [MPa]	TS [MPa]	KV [J]
Sp03H21AN16G5M4Nb	509	882	91
ES21-16-5-4B	475	765	102

Fatigue tests of welded joints resulted in computer and experimental evaluation of the effect of welding notches on low cycle fatigue steel X02CrNiMoMnN21--16-5-4 [35].

Austenitic cast steel L05H21N20G2M3Nb

Austenitic cast steel L05H21N20G2M3Nb originally developed and manufactured in Huta Małapanew-Ozimek was patented by Dr. Commander Eng. Joseph Fila [1]. Cast steel for poured-welded structural components cantilever drive shaft 207 ships of the project showed the mechanical properties given in the table 3.

Cast steel can be welded above the electrodes Sp03H21AN16G5M4Nb MIG and TIG and electrode welding ES21-16-5-4B [2].

Table 3. Mechanical properties austenitic cast steel L05H21N20G2M3Nb [2]

YS [MPa]	TS [MPa]	$A5_{min}$ [%]	RA [%]	KV_{min} [J]
235	480	35	50	115

L03H21AN16G5M4Nb and L08H21AN16G5M4Nb cast steels were tested materials together. Primarily, they were designed to be identical except to the carbon content. The higher Ni, Mn and Cr contents were added in order to increase the nitrogen content exceeding the solubility limit for normal atmosphere, from 0.25% to 0.50% N [10].

Mechanical properties of the L03H21AN16G5M4Nb cast steel with contents of 0.25%N and 0.025% C are listed in the table 4 [10].

Table 4. Mechanical properties of the L03H21AN16G5M4Nb cast steel with 0.25%N and 0.025% C [own work]

YS [MPa]	TS [MPa]	$A5_{min}$ [%]	RA [%]
311	581	27,9	32,3

The effect of nitrogen and chemical compositials austenitic cast steels on their mechanical properties and low cycle behavior has been investigated [13, 36]. These results gave optimal selection of cast steel [9].

Bainitic high-strength steel 10GHMBA-E620T

Since national high strength steels did not meet the requirements for marine applications so this topic was taken. As a result of studies conducted material characteristics, microstructural simulation of heat treatment and welding and literature study prepared and investigated the usefulness of original developed 10GHMBA-E620T steel welded marine structures [18]. The study was conducted on a steel thickness of 12 mm and 25 mm flats made in pilot scale in Mikrohuta-Strzemieszyce. Weldability test was performed in accordance with the requirements of the PRS. Welding was carried out two recommended methods of low energy: coated electrode EB1.70 MAG and electrode SpG1SN2pr — 1,2sz-pa shielded mixture of Ar + 20% CO_2 [18]. As a result, MAG welding preserves category NVE690 when welding electrode coated steel decreased category to NVD620. Selected mechanical properties of the steel grade 10GHMBA-E620T are given in the table 5.

Table 5. Mechanical properties of bainitic steel 10GHMBA-E620T [7, 12]

Products	YS [MPa]	TS [MPa]	$A5_{min}$ [%]	RA [%]	$KVp_{(-40C)}$ [J]
Flats	792	894	19,2	68,7	33
Sheets	690–733	738–763	16,6–19,0	–	33–42

On the basis of the developed composition and technology prepared TWT-WSMW/02.01.85 [12] made industrial smelting in an electric furnace Huta Baildon involving refining VOD/VAD. Then obtained ingots rolled and heat-treated in Huta Czestochowa steel sheets 8 mm, 12 mm and 25 mm. For these sheets the weldability test was performed in accordance with the requirements of the Polish Register of Ships PRS. Welding was carried out two recommended methods of low energy: coated electrode type OK 75-75-110-18 1 ESAB MAG and electrode SpG1SN2pr — 1,2sz-pa shielded mixture of Ar + 20% CO_2.

The result is a new bainitic steel 10GHMBA-E620T fulfilling the requirements of Det norske Veritas NVD620 who obtained the patent PL [3] and approved Polish Register of Ships [12] intended for heavy duty structural components of ships. A characteristic feature of the steel 10GHMBA-E620T against other steels in this category is the lack of heating before welding in order to avoid cold cracking. Furthermore, it showed increased ballistic resistance, and resistance to reheat cracking during operation at elevated temperatures [14, 16, 40].

Marine constructional-ballistic shields

For several years in PNA researched ballistic shields, especially as applied to shipbuilding. Team of Commander Dr. Fila developed in 1994–1996 for the Polish Navy and Committee Research KBN Report on increasing ballistic hulls and ship structures [5, 33]. The work was completed implementation of industrial plater two- and three-layer, explosively welded and rolled in the steelworks conditions. Then Zatorski developed theoretical and technological basis for development of the design marine constructional and ballistic shields. This is a new class of ship multi-functional materials. This solution is based on the model of the shield type of de-structor-energy absorber, developed in the monograph [41], and other works [34, 39]. Previously accepted the task: the development plate as a shock absorber [27, 38], modelling of energy absorbed under firing [31, 32], research methodology, using the unified position for testing bullet-proof shields [33, 34, 39], design methodology ballistic shields multilayer [22, 25, 31], the behavior of the shield material after firing [19], resistance shield fire at an angle [21], assessment of resistance to tearing of welded joints shields constructional-ballistic [28, 37]. In a series of works of diag-nostic and verification of firing process [23, 24, 25] showing the versatility of the method used for the experimental verification of numerical simulation [29]. Shields used on selected sections of the hulls of the required high resistance to fire bullets cal. 7.62 mm, at the same time characterized by adequate ductility and weldability [6]. So avoid entering inside the hull of additional armor plates, less effective (fig. 1).

a) b)

Fig. 1. The effect of firing constructional-ballistic shield 30GHMVNb/15G2ANb
on the front side a) the destructor, V_{BL} = 820 m/s and on the rear side b) absorber, V_{BL} = 700 m/s,
bullet cal. 7,62 mm [41]

The constructional-ballistic steel ship shields should comply the require-ments for assurance a good weldability and plasticity as well as the integrality and functionality of the shield and the construction of the hull under a firing.

BALLISTIC RESISTANCE OF MATERIALS

Experimental verification of numerical simulation of projectile motion on cons-tructional shields has been developed. The experiments were performed on unified test stand to investigate ballistic resistance of materials in field conditions (fig. 2).

The test stand was developed at the Polish Naval Academy in Gdynia and then patented [11]. The design of this test stand is based on construction of ballistic pendulum. The measurement: *F(t)* — impact force, χ — the turn angle of the ballistic pendulum, V_p, V_r — impact velocity and residual velocity of the projectile has been developed. All the measurement data are transmitted to a digital oscilloscope and a personal computer.

The ballistic velocities as $V_{BL[Z]}$ and $V_{BL[Z1]}$ are determined according to the author's method and take the form

$$V_{BL[Z]} = [\frac{I}{m_p^2}(2m_p \cdot V_p - I)]^{1/2} \; [\mathrm{m\,s^{-1}}], \tag{1}$$

without measurement of residual velocity V_r,
where:

$m_r \cong m_p \cong m_{BL}$ — residual, initial and ballistic masses of the projectile [kg];

I — impulse of force transmitted to the dynamometer of the ballistic pendulum [Ns].

Ballistic velocity $V_{BL[Z1]}$ takes the form

$$V_{BL[Z1]} = [V_p^2 - \frac{V_r}{m_p}(m_p \cdot V_p - I)]^{1/2} \; [\mathrm{m\,s^{-1}}], \tag{2}$$

without measurement of residual mass m_r, where: $m_p \cong m_{BL}$, $m_s << M_{ew}$ [41].

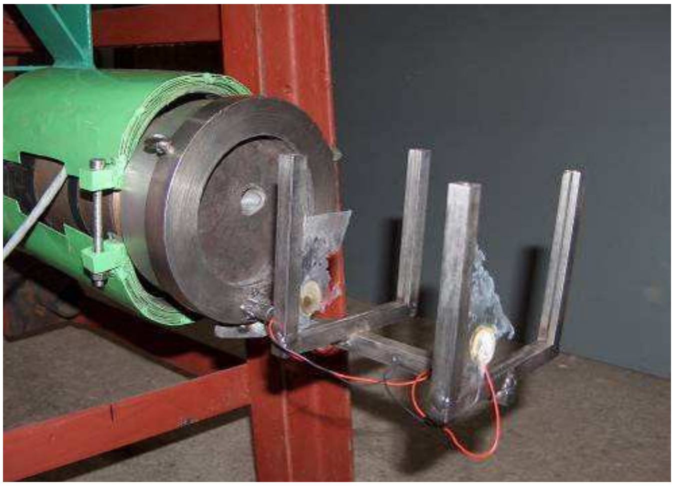

Fig. 2. The unified test stand for investigation of the materials ballistic resistance
Polish Naval Academy [from the PNA archive]

The ballistic velocity $V_{BL[RI]}$ according to Recht's and Ipson's method takes the form

$$V_{BL[R]} = [V_p^2 - V_r^2]^{1/2} \ [\mathrm{ms^{-1}}], \tag{3}$$

Verification of numerically simulated ballistic velocity VRO versus the before-mentioned velocity was carried out. The 10GHMBA-E620T steel shields have been impacted by type B-32 projectiles cal. 12.7 mm.

The effect of strain and strain rate on yield stress of 10GHMBA-E620T steel and failure strain has been considered for the material constitutive model Johnson--Cook [15]. Steel sample-target has been impacted by RB-Rigid Body projectile [30]. All analyses were carried out with the analysis code LS-DYNA AUTODYN-3D. Validation of numerical modelling includes a comprehensive hexagonal mesh convergence study. Ballistic velocity V_{BL} = VBO of 10GHMBA-E620T steel plates has been computed using the validated numerical procedure and experimental tests. Comparison of experimentally determined ballistic velocities: $V_{BL[Z1]}$, $V_{BL[Z]}$ and $V_{BL[RI]}$ with numerically simulated ballistic velocity *VRO* for the 10GHMBA-E620T steel shield impacted by the projectiles type B-32 is shown for example in figure 3.

The experimental results of the determination ballistic resistance of the shields indicate that proper energy absorbed by the shield $V_{BL[R]}^2$ according to Recht's and Ipson's method is less accurate (coefficient R = 0,9510) in comparison to $V_{BL[Z]}^2$ and $V_{BL[Z1]}^2$ according to the author's method [29].

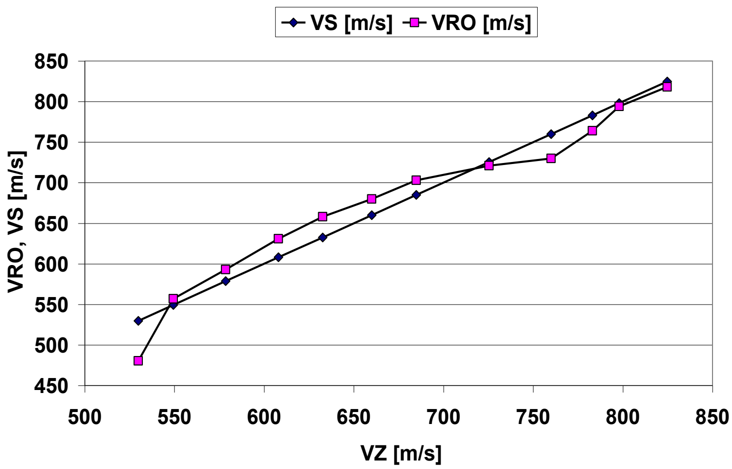

Fig. 3. The experimentally determined ballistic velocity $V_{BL[Z]}$ ($VZ = VS$) are compared with the numerically simulated ballistic velocity *VRO* of the 10GHMBA-E620T steel shield impacted by the projectiles type B-32 cal. 12.7 mm (coefficient R = 0,9734) [29]

The applied diagnostic method can be used to determine ballistic thickness h_{BL} and ballistic velocity V_{BL} for both homogeneous plates as well as multi-layered constructional shields [4, 10, 11]. Ballistic velocities: $V_{BL[Z1]}$, $V_{BL[Z]}$, $V_{BL[RI]}$ — obtained from experiments and numerically simulated ballistic velocity *VRO* are verificated against plate thickness in figure 4.

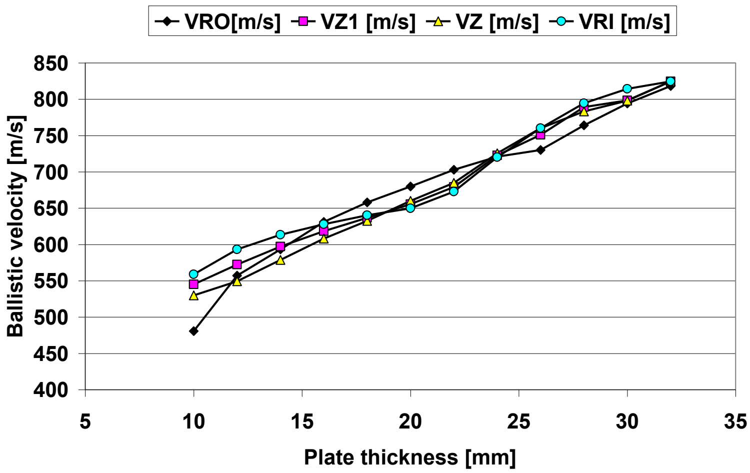

Fig. 4. The experimentally determined ballistic velocity $V_{BL[Z]}$, $V_{BL[RI]}$, $V_{BL[Z1]}$ and numerically simulated ballistic velocity *VRO* against of the 10GHMBA-E620T steel plate thickness impacted by the projectiles type B-32 cal. 12.7 mm [29]

The 10GHMBA-E620T steel shield of ballistic thickness 32 mm impacted by the projectile type B-32 cal. 12.7 mm is tested at the ballistic velocity of V_B = 824,0 ms^{-1} and the kinetic energy of 17 kJ. The effect of fire simulations and Ansys LS Dyna process of penetration of the projectile in a plate with a thickness ballistic h_{BL} is shown in figure 5 [17, 29].

Verified specific energy at the same time creating a crater through the energy of the creation of a imprint expressed in units of Brinell hardness number [20, 26, 30].

The experimental verification numerical simulation of projectile impact on ballistic shields is basic advantage of the method and presented unified test stand. For a number of cases that with a proper choice of contact algorithm, computed projectile ballistic velocities can match closely with corresponding test-based values.

a) b)

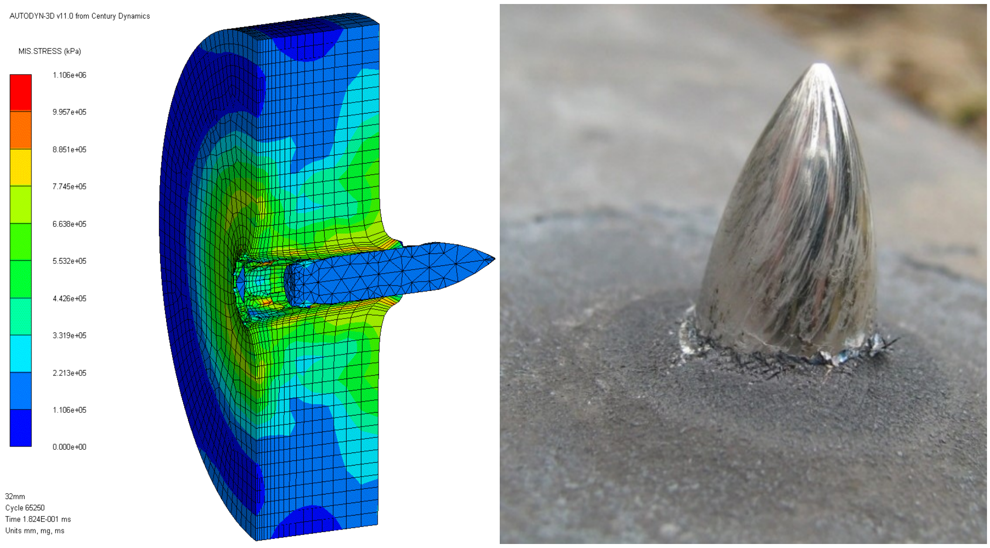

Fig. 5: a) simulation Ansys LS Dyna; b) the effect of fire of ballistic steel 10GHMBA panels with a thickness h_{BL} = 32mm bullet B-32 cal. 12.7mm [17, 29]

Single and multilayer ballistic shields carried out on the floating shield after shelling on the training ground sea (fig. 6 and 7) [5].

Fig. 6. Floating shield after shelling on the training ground sea
[from the author's archive]

Fig. 7. Back 'to shield floating' Commander Joseph Fila and author of the shelling on the training ground sea [from the author's archive]

CONCLUSIONS

In order to increase security of the country in the field of new materials and technologies and research methods were developed, patented and implemented: austenitic steel X02CrNiMoMnN21-16-5-4 with electrodes for welding of steel and high-strength bainitic steel 10GHMBA-E620T. Currently in the country they are built ships, whose hulls are made entirely of imported austenitic steel in this category. In addition, the author developed an original method for testing ballistic shields and unified position to the research, which studied and co-patented. The modelling guidelines developed in this paper can thus be useful in efficient creating of new design solutions, what can otherwise consume considerable time and resources if they are determined by physical testing. An improvement of ballistic resistance of multilayered shields is possible together with an introduction of the energy efficiency of production.

REFERENCES

[1] Fila J., *Staliwo austenityczne, zwłaszcza okrętowe nierdzewne*, patent PL 159766, WUP 01/1993 [*Austenitic cast steel, especially stainless steel ships* — available in Polish].

[2] Fila J., *Wpływ azotu i czynników technologicznych na mikrostrukturę i własności użytkowe elementów okrętowych z amagnetycznych stopów Fe-Cr-Ni-Mn-Mo-Nb-N*, 'Zeszyty Naukowe Akademii Marynarki Wojennej', 1996, No. 128A [*The influence of nitrogen and technological factors on the microstructure and functional properties of marine elements from paramagnetic alloys Fe-Cr-Ni-Mn-Mo-Nb-N* — available in Polish].

[3] Fila J., Zaczek Z., Zatorski Z., *Stal bainityczna, zwłaszcza na konstrukcje okrętowe i hydrotechniczne morskie*, patent PL 166545, 1995 [*Bainitic steel, especially in the construction, marine and hydro marine* — available in Polish].

[4] Fila J., Zatorski Z. et al., *Elektroda otulona, zwłaszcza do spawania stali okrętowych paramagnetycznych wysokiej wytrzymałości*, patent PL P313232, WUP 03/1996 [*The electrode wrapped, especially for welding of high strength marine paramagnetic steels* — available in Polish].

[5] Fila J., Zatorski Z., *Podwyższanie odporności balistycznej kadłubów i konstrukcji okrętowych*, report No. 1-3/1994–1996/IPBMO/'Powłoka'/AMW-KBN (unpublished) [*Raising of resistance ballistic hulls and constructions ship* — available in Polish].

[6] Fila J., Zatorski Z., *Rola czynników strukturalnych i charakteru obciążeń w procesach pękania złączy zgrzewanych okrętowych łańcuchów kotwicznych z nowej amagnetycznej stali 00H21AN16GSM4Nb*, 'Zeszyty Naukowe Politechniki Świętokrzyskiej. Mechanika', 1992, Vol. 48, pp. 85–92 [*The role of structural factors and the nature of the load in the process of cracking of welded joints ship anchor chains from new paramagnetic steel 00H21AN16GSM4Nb* — available in Polish].

[7] Fila J., Zatorski Z., *Skład chemiczny i struktura a spawalność nowej SSWW gatunku 10GHMBA-E620T o podwyższonej odporności balistycznej*, 'Marine Technology Transactions', 1992, Vol. 3, pp. 65–86 [*The chemical composition and structure and weldability of a new species HSS 10GHMBA-E620T with increased ballistic resistance* — available in Polish].

[8] Fila J., Zatorski Z. et al., *Stal austenityczna, zwłaszcza okrętowa nierdzewna*, patent PL159768, WUP 01/1993 [*Austenitic stainless steel, especially steel for Shipbuilding* — available in Polish].

[9] Fila J., Zatorski Z., *The effect of nitrogen on behaviour of Cr-Ni-Mn-Mo-Nb — austenitic stainless cast steels in torsion*, Proc. 15th Conf. on Material Testing in Metallurgy 11th Congress on Materials Testing EUROMAT '94, 1994, 2, pp. 545–549.

[10] Fila J., Zatorski, *The effect of nitrogen on low cycle fatigue mechanisms of austenitic stainless cast steels*, 'Journal of Theoretical and Applied Mechanics', 1994, Vol. 32, No. 1, pp. 249–260.

[11] Fila J., Zatorski Z., *Zunifikowane stanowisko do badania odporności balistycznej materiałów, zwłaszcza okrętowych, konstrukcyjno-osłonowych i pancernych*, patent P313233, WUP03/1996 [*Unified stand for testing ballistic materials, particularly marine, construction and shielding and armor* — available in Polish].

[12] Fila J., Zatorski Z., Zaczek Z., *Własności technologiczno użytkowe i balistyczne okrętowej SSWW gatunku 10GHMBA-E620T*, Mat. Conf. 'Nowoczesne materiały w okrętownictwie' [*'Modern materials in shipbuilding'*], 25.09.1995, Politechnika Gdańska, Gdańsk 1995, pp. 47–57 [*The properties of technological utility and ballistic HSS marine species 10GHMBA-E620T* — available in Polish].

[13] Fila J., *Zoptymalizowane własności nierdzewnych i wysokowytrzymałych okrętowych stali, staliw i spoiw amagnetycznych*, 'Marine Technology Transactions', 1992, Vol. 8, pp. 25–64 [*Optimized properties of stainless steel and high-strength marine steels, cast steels and paramagnetic adhesives* — available in Polish].

[14] Flis L., Sperski M., *Badania odporności balistycznej pancerzy ze stali 10GHMBA na ostrzał pociskami 12,7 mm*, 'Zeszyty Naukowe Akademii Marynarki Wojennej', 2011, No. 3, pp. 27–42 [*Research ballistic armor of steel 10GHMBA in firing bullets 12.7 mm* — available in Polish].

[15] Johnson G. R., Cook W. H., *A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures*, Proceedings of the 7th International Symposium on Ballistics, The Hague, The Netherlands, 1983, pp. 541–547.

[16] Szturomski B., *Badania odporności na ostrzał pociskami kalibru 12,7 mm stali 10GHMBA z wykorzystaniem wahadła balistycznego*, 'Biuletyn WAT', 2010, No. 4, pp. 411–422 [*Tests of resistance to fire bullets caliber 12.7 mm of steel 10GHMBA using ballistic pendulum* — available in Polish].

[17] Szturomski B., *Charakterystyki dynamiczne do symulacji numerycznej materiałów stosowanych na osłony antyterrorystyczne na jednostkach pływających*, AMW, Gdynia 2009 (unpublished) [*Dynamic characteristics of the numerical simulation of materials used for anti-terrorist guards on vessels* — available in Polish].

[18] Zatorski Z., *Badania nowo opracowanej stali 10GHMBA-E620T na spawane konstrukcje morskie*, PhD thesis, Politechnika Gdańska, Gdańsk 1988 [*Research newly developed steel 10GHMBA-E620T welded marine structures* — available in Polish].

[19] Zatorski Z., *Ballistic penetration response of high strength bainitic steel*, 'Journal de Physique', France, 2000, IV, Vol. 10, pp. 571–576.

[20] Zatorski Z., Biernat R., *Energetyczny pomiar twardości Brinella* [*Energy-based determination of Brinell hardness*], 'Zeszyty Naukowe Akademii Marynarki Wojennej', 2014, No. 4, pp. 103–116.

[21] Zatorski Z., *Dependence of Impact Obliquity Angle Versus Hardness and Thickness of Steel Plates*, 'Polish Journal of Environmental Studies', 2007, Vol. 16, 3C, pp. 134–138.

[22] Zatorski Z., *Design of ballistic multi-layered steel shields*, 'Marine Technology Transactions', 2006, Vol. 17, pp. 189–199.

[23] Zatorski Z., *Diagnostics of ballistic resistance of constructional shields and experimental verification*, 'Journal de Physique', France, 2006, IV, Vol. 134, pp. 1131–1136.

[24] Zatorski Z., *Diagnostics of ballistic resistance multi-layered shields*, 'The Archive of Mechanical Engineering', 2007, No. 3, pp. 205–218.

[25] Zatorski Z., *Diagnostics of ballistic resistance of multi-layered shields and fracture mechanisms*, Multi-phase and multi-component materials under dynamic loading, 10th European Mechanics of Materials Conference (EMMC10), Kazimierz Dolny, Poland, June 11–14, 2007, Eds. W. K. Nowacki and Han Zhao, IFTR PAS, Warsaw and LMT Cachan, 2007, pp. 441–450.

[26] Zatorski Z., *Energetyczna weryfikacja ostrzału i twardości Brinella*, 'Logistyka', 2014, Vol. 5, pp. 1719–1724 [*Energy verification of fire and Brinell hardness* — available in Polish].

[27] Zatorski Z., *Energy-absorbing capacity of impact loaded plate*, 'Marine Technology Transactions', 2006, Vol. 17, pp. 201–212.

[28] Zatorski Z., *Evaluation of steel clad plate weldability using ram tensile test method*, Engineering Transactions, 55, 3, 2007, 1-10.

[29] Zatorski Z., *Experimental verification of numerical simulation of projectile impact on ballistic shields*, 'Archive of Mechanical Engineering', 2013, No.4, pp. 545–555.

[30] Zatorski Z., Flis L., *Energetyczna weryfikacja i symulacja efektów ostrzału*, 'Logistyka', 2014, Vol. 5, pp. 1725–1733 [*Energy verification and simulation of the effects of fire* — available in Polish].

[31] Zatorski Z., *Modelling and experimental verifications of energy density absorbed by constructional shields under firing*, 'Archive of Mechanical Engineering', 2007, No. 1, pp. 17–25.

[32] Zatorski Z., *Modelling of energy absorbed under firing of homogenous plates*, 'Marine Technology Transactions', 2005, Vol. 16, pp. 317–328.

[33] Zatorski Z., *Odporność na przebijanie pakietów i platerów konstrukcyjno-balistycznych*, Mat. 2nd Conf. Science-Techn. 'Odporność udarowa konstrukcji' [*'Shock resistance design'*], Rynia, 9–11.12.1998, pp. 353–360 [*Resistance to punching packages and constructional-ballistic plate* — available in Polish].

[34] Zatorski Z., *Odporność na ostrzał laminatów z osłonami ceramicznymi*, 'Zeszyty Naukowe Akademii Marynarki Wojennej', 2005, No. 2, pp. 139–149 [*Resistance to fire laminates with ceramic protection* — available in Polish].

[35] Zatorski Z., Fila J., *Komputerowa i doświadczalna ocena wpływu karbów spawalniczych na małocyklową trwałość zmęczeniową stali OOH21AN16G5M4Nb*, 'Zeszyty Naukowe Politechniki Świętokrzyskiej. Mechanika', 1989, Vol. 45, pp. 207–213 [*Computer and experimental evaluation of the effect of notches welding on low-cycle fatigue life of steel OOH21AN16G5M4Nb* — available in Polish].

[36] Zatorski Z., Fila J., *Wpływ składu chemicznego na charakterystyki niskocyklowego zmęczenia austenitycznych staliw wysokoazotowych*, 'Zeszyty Naukowe Politechniki Świętokrzyskiej. Mechanika', 1995, Vol. 57, pp. 285–293 [*Effect of chemical composition on the characteristics of the low-cycle fatigue austenitic cast steels with high nitrogen content* — available in Polish].

[37] Zatorski Z., *Ocena jakości połączeń zgrzewanych przez rozrywanie platerów stalowych*, 'Zeszyty Naukowe Politechniki Świętokrzyskiej. Mechanika', 2001, Vol. 73, pp. 103–110 [*Evaluation of quality of welded joints by tearing steel clad plate* — available in Polish].

[38] Zatorski Z., *Odpowiedź plastyczna i perforacja płyt uderzanych przez pręt*, Mat. 2nd Conf. Science-Techn. 'Odporność udarowa konstrukcji' [*'Shock resistance design'*], Rynia, 9–11.12.1998, pp. 353–360 [*Answer plastic and perforated plates impacted by the rod* — available in Polish].

[39] Zatorski Z., *Odporność na ostrzał kompozytów ceramika-guma-stal*, 'Zeszyty Naukowe Akademii Marynarki Wojennej', 2005, No. 1, pp. 219–227 [*Resistance to fire ceramic-rubber-steel composites* — available in Polish].

[40] Zatorski Z., *Struktura a spawalność i odporność balistyczna nowej SSWW gatunku 10GHMBA-E620T*, Mat. National Conference 'Dobór i eksploatacja materiałów inżynierskich', ['The selection and operation engineering materials'], Jurata 1997, pp. 501–506 [*Structure and weldability and ballistic resistance HSS new species 10GHMBA-E620T* — available in Polish].

[41] Zatorski Z., *Teoretyczne i technologiczne podstawy projektowania okrętowych osłon balistycznych*, 'Zeszyty Naukowe Akademii Marynarki Wojennej', 2009, No. 177A [*Theoretical and technological basis for the design of ship ballistic shields* — available in Polish].

OKRĘTOWE STALE SPECJALNE I OSŁONY KONSTRUKCYJNO-BALISTYCZNE OPRACOWANE W AMW

STRESZCZENIE

Dla wzrostu bezpieczeństwa kraju w zakresie nowych materiałów i technologii oraz metod badawczych opracowano, opatentowano i wdrożono: stal austenityczną X02CrNiMoMnN21-16-5-4 wraz z elektrodami do spawania tej stali oraz wysokowytrzymałą stal bainityczną gat. 10GHMBA-E620T. Autor opracował teoretyczne i technologiczne podstawy projektowania okrętowych osłon konstrukcyjno-balistycznych, które wdrożył w skali półtechnicznej i technicznej. Ponadto opracował oryginalną metodę badania odporności balistycznej osłon oraz zunifikowane stanowisko do badań, które przebadał i współopatentował.

Słowa kluczowe:
stal austenityczna, staliwo, elektroda do spawania, stal bainityczna, osłony konstrukcyjno-balistyczne.