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.

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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 seawater 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 13μm. 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>
<thead>
<tr>
<th>Heat treatment</th>
<th>YS [MPa]</th>
<th>TS [MPa]</th>
<th>A5_min [%]</th>
<th>HBN</th>
<th>KV_min [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supersaturation</td>
<td>420</td>
<td>700</td>
<td>35</td>
<td>185</td>
<td>175</td>
</tr>
<tr>
<td>Cold rolling</td>
<td>600</td>
<td>1000</td>
<td>35</td>
<td>300</td>
<td>70</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Welding electrode</th>
<th>YS [MPa]</th>
<th>TS [MPa]</th>
<th>KV [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp03H21AN16G5M4Nb</td>
<td>509</td>
<td>882</td>
<td>91</td>
</tr>
<tr>
<td>ES21-16-5-4B</td>
<td>475</td>
<td>765</td>
<td>102</td>
</tr>
</tbody>
</table>

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]

<table>
<thead>
<tr>
<th>YS [MPa]</th>
<th>TS [MPa]</th>
<th>A5min [%]</th>
<th>RA [%]</th>
<th>KVmin [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>235</td>
<td>480</td>
<td>35</td>
<td>50</td>
<td>115</td>
</tr>
</tbody>
</table>

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]

<table>
<thead>
<tr>
<th>YS [MPa]</th>
<th>TS [MPa]</th>
<th>A5min [%]</th>
<th>RA [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>311</td>
<td>581</td>
<td>27,9</td>
<td>32,3</td>
</tr>
</tbody>
</table>

The effect of nitrogen and chemical composititals 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 require-
ments 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% CO₂ [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]

<table>
<thead>
<tr>
<th>Products</th>
<th>YS [MPa]</th>
<th>TS [MPa]</th>
<th>A5min [%]</th>
<th>RA [%]</th>
<th>KVp (-40°C) [J]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flats</td>
<td>792</td>
<td>894</td>
<td>19,2</td>
<td>68,7</td>
<td>33</td>
</tr>
<tr>
<td>Sheets</td>
<td>690–733</td>
<td>738–763</td>
<td>16,6–19,0</td>
<td>–</td>
<td>33–42</td>
</tr>
</tbody>
</table>

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% CO₂.

The result is a new bainitic steel 10GHMBA-E620T fulfilling the require-
ments of Det norske Veritas NVD620 who obtained the patent PL [3] and approved
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. Fur-
thermore, 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 multifunctional materials. This solution is based on the model of the shield type of destructor-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 diagnostic 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).

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

The constructional-ballistic steel ship shields should comply the requirements 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 constructional 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, $\chi$ — 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 $V_{BL[1]}$ and $V_{BL[1]}$ are determined according to the author’s method and take the form

$$V_{BL[1]} = \left[\frac{I}{m_p^2} (2m_p \cdot V_p - I)\right]^{1/2} [\text{m s}^{-1}],$$  

(1)

without measurement of residual velocity $V_r$.

where:

$m, p, r, m$ — residual, initial and ballistic masses of the projectile [kg];

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

Ballistic velocity $V_{BL[1]}$ takes the form

$$V_{BL[1]} = \left[\frac{V_p^2}{m_p} - \frac{V_r}{m_p} (m_p \cdot V_p - I)\right]^{1/2} [\text{m s}^{-1}],$$  

(2)

without measurement of residual mass $m_r$, where: $m_p \approx m_{BL}, m_s \ll M_{ew}$ [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

$$V_{BL[RI]} = \left[V_p^2 - V_c^2\right]^{1/2}, \quad [\text{ms}^{-1}]$$

(3)

Verification of numerically simulated ballistic velocity $V_{RO}$ 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 $V_{BL} = V_{BO}$ of 10GHMBA-E620T steel plates has been computed using the validated numerical procedure and experimental tests. Comparison of experimentally determined ballistic velocities: $V_{BL[Z]}$, $V_{BL[Z]}$ and $V_{BL[RI]}$ with numerically simulated ballistic velocity $V_{RO}$ 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 $V_{BL[RI]}^2$ according to Recht’s and Ipson’s method is less accurate (coefficient $R = 0.9510$) in comparison to $V_{BL[Z]}^2$ and $V_{BL[Z]}^2$ according to the author's method [29].

![Graph](image_url)

Fig. 3. The experimentally determined ballistic velocity $V_{BL[Z]}$ ($V_Z = VS$) are compared with the numerically simulated ballistic velocity $V_{RO}$ 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: $V_{BL[Z1]}$, $V_{BL[Z2]}$, $V_{BL[RI]}$ — obtained from experiments and numerically simulated ballistic velocity $V_{RO}$ are verified against plate thickness in figure 4.

![Graph showing ballistic velocity vs plate thickness](image)

Fig. 4. The experimentally determined ballistic velocity $V_{BL[Z1]}$, $V_{BL[Z2]}$, $V_{BL[RI]}$ and numerically simulated ballistic velocity $V_{RO}$ 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 $V_B = 824,0 \, \text{ms}^{-1}$ 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 an 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.
Fig. 5: a) simulation Ansys LS Dyna; b) the effect of fire of ballistic steel 10GHMB panels with a thickness $h_{BL} = 32$mm 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]
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.

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Special marine steels and constructional-ballistic shields designed PNA


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OKRĘTOWE STAŁE 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 współpatentował.

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