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THE ANALYSIS OF PROPERTIES OF PLATERS USED FOR THE STRUCTURAL-BALLISTIC SAFETY SHIELDS IN MARINE VESSELS

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Abstract

Some selected parameters of steel for structural-ballistic shields (OKB) used in the Navy vessels have been presented. The standards for steel to be used for ballistic shields are established by safety standards institutions and committees. There has been made an analysis of steel used for OKB of the vessels. The bullet-proof of the platters has been carried out on the appropriate position. The results of bullet-proof test of selected platters have been presented. The analysis made allowed to select the platters used for the structural-ballistic safety shields in marine vessels and give the direction for further research determined by contemporary threats of both military and terroristic nature. To produce the platters there have been used two types of armoured metal sheet which had been milled to flats made of the basic steel and which can be applied in shipbuilding. The structural-ballistic platters have had the form of flats with the total thickness of 8.5–9.2 mm. The prepared structural-ballistic platters have been technological processed in order to increase the degree of their strength. There have been also presented mechanical and technological properties of platters after heat treatment. The results of the bullet-proof have been presented in graphs form defining the dependence between the hit force and time. The effects of fire of specimen made of platters, by 7.62 mm cal. bullets with the proper speed have been seen on photographs.

Keywords: *ballistics shield, high resistance steel, platters, penetration, perforation*

1. Introduction

More than a hundred-year „bullet struggle with a shield" does not have any solutions of the problem of protection the crew and equipment against the bullets or shrapnel. That problem is still in the public eye of many experts of armed forces of sea countries. It displays in various means of fight connected with development of a new generation of materials designed for construction fighting vessels and bullet-proof apparatus.

The vessel structural materials in a conventional version do not belong to a group of materials being durable on the mechanical penetration i.e. bullet- or shrapnel-proof. A ballistic-proof is defined as a capacity to counteract of the shell plating puncture (target) with a given density ρ_t, with a bullet (metal shrapnel) with a density ρ_p, which moves at the speed of V_u [5, 8].

Materials used for a bullet-proof hull and for the protective shields of various military constructions (armours) should be characterized by two opposing features: high hardness and relatively high plasticity preventing to arise the material cracks and splinters during the bullet hit. Until now studies have not disclosed any of dependences between the mechanical properties of the armoured materials (R_e, R_m, A, Z, K_{IC}) and their crack resistance. It is assumed with a certain approximation that the ballistic resistance of the armoured steel strongly depends on the dynamic limit of its plasticity R_{ed}. The influence of hardness, immediate durability and impact resistance (especially thin metal plates) on the ballistic resistance is often emphasized [5].

The requirements and results of the until studies of high ballistic resistance materials have led to production of homogeneous materials i.e. with constant level of hardness on the whole section and also some heterogeneous materials with changeable hardness (crack resistance and energy-consuming) on the section. The requirements and results have also permitted to analyze some ballistic properties of the existing hull materials with special taking constructive-ballistic platters into consideration.

2. Characteristic of the constructive-ballistic platters

The structural-ballistic platters (PKB) were made of armoured steel of 30GHMNbV and 30GSN4MBV, which were rolled on flats made of steel usually used in vessels construction: non-alloy steel S275JR, microscopic steel of high resistance 15G2ANb – EH460 after heat improvement and bainitic steel 10GHMBA – E620 T, after heat improvement [4, 7, 9]. There were also produced the bi-metal flats with total gauge of 8.5–9.2 mm. The chemical constitutions of platters are presented in Tab. 1.

Tab. 1. The chemical constitution of the armoured steel 30GHMNbV and 30GSN4MBV

Steel	The chemical constitution, %											
	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Nb/B	V	Al	N
30GHMNbV	0.30	1.30	0.70	0.01	0.01	1.30	0.10	0.60	0.10	0.09 Nb	0.20	0.04	0.01
30GSN4MBV	0.30	0.80	1.20	0.01	0.01	1.50	4.00	0.42	0.30	0.003 B	0.10	0.03	–

The mechanical properties of PKB are defined on specimen, which was under tests on the universal testing machine MTS810.12. The results of those tests are showed in Tab. 2.

Tab. 2. The mechanical properties of PKB

Platter KB	Oz	PKB gauge [mm]	Layer thickness [mm]	$R_{0.2}$, [MPa]	R_m, [MPa]	Z, [%]	HV30
30GHMNbV/ 15G2ANb	1	9.2	3.6 5.6	480	850	37	527 141
30GHMNbV/ S275JR	3	8.5	4.0 4.5	570	950	33	560 193
30GHMNbV/ 10GHMBA	4	8.7	4.0 4.7	530	950	37	502 156
30GSN4MBV/ 15G2ANb	6	8.9	3.3 5.6	550	920	28	590 138
30GSN4MBV/ 10GHMBA	7	8.6	4.2 4.4	700	1050	32	434 148
30GSN4MBV/ S275JR	8	8.5	3.9 4.6	630	1170	30	586 183

3. Methodology of the bullet-proof tests

The tests of the bullet-proof of specimen made of the naval steel and the bi-metallic platters (PKB) are carried out on the stand built in the Naval Academy of Gdynia which is the Tool

Ballistic Pendulum (OWB) (Fig. 1 and 2) [7].

That stand enables to measure the outlet velocity of the bullet, the bullet impact force F_u, the energy E_p and also the terminal velocity V_k of the residual part of the bullet together with the plug and plate fragments.

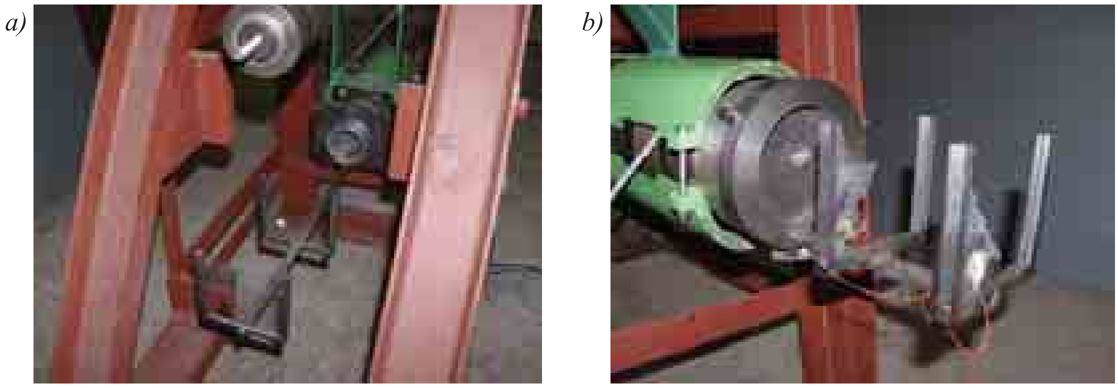

Fig. 1. The view of the pendulum with the installed specimen: a) before firing, b) after firing

All the quantities are converted into adequate electric and recorded signals and then they are analyzed or printed. The construction, the way of specimen chuck and the recording of the tests results are described in detail in [1]. The knowledge of the force F_u and the impact energy E_p enables among other things to estimate the ballistic resistance of the material:

$$O_b = F_u / l_k \, d_p \, . \tag{1}$$

For the used conditions of firing, the shield the value of $l_k d_p$ takes the form [13]:

$$l_k \, d_p = 1.5 \cdot (\rho_p / \rho_t)^{1/3} \cdot (\rho_p V^2 / 2S_t)^{1/3} \tag{2}$$

and the ballistic resistance can be defined as:

$$O_b = F_u / 1.5 \cdot d_p^2 [(\rho_p / \rho_t)^{1/3} \cdot (\rho_p V^2 / 2S_t)^{1/3}]^2 \, , \tag{3}$$

where:

F_u – a force generated by the bullet impact into a shield,
l_k – a depth of shield penetration made by the bullet,
d_p – a diameter (calibre) of the bullet punching the shield,
V – a volume of a crater eroded by the bullet,
ρ_p – a density of the bullet material,
ρ_t – a density of a shield material,
S_t – a constant of shield susceptibility to deformation during the impact.

Testing the naval materials has proved that the ballistic resistance depends on physical mechanical properties of the bullet and the shield [7]. To define the value of the resistance the following dependence has been used [13]:

$$O_b = F_u / d_p [12 \cdot 10^{-9} (E_p / B) \cos^2 \alpha_p]^{1/3} \, , \tag{4}$$

where:

B – Brinell hardness (HB) of the shield the value of which changes together with the material temperature,
α_p – kinetic energy of the bullet.

The impact velocities of the conventional bullets into the shield are approximately $V_u \leq 1000$ m/s. For example the bullet (ŁPS-L) with the mass $m = 9.62$ g and $V_u = 800$ m/s has got the energy $E_p \cong 3000$ Nm.

On the basis of [6, 11] one can conclude that the final effects of the ballistic processes are mostly dependent on the complex of dynamic material properties, that is, as mentioned above *HB*, R_m, *KV*, K_{IC} of both the shield and the bullet as well and also on their geometry, shape or mass efficiency E_m. According to assumption [11] there are obtained the following values:

$$R_{dpT} = 4.2\,HB\,, \tag{5}$$

$$Y = 1.7\,HB\,, \tag{6}$$

$$R = R_{dpT}\,[2/3 + \ln(1.14\,E_t / R_{dt})]\,, \tag{7}$$

where:
R_{dpT} – dynamic limit of plasticity of the bullet material (determined by means of Taylor method [14]),
HB – Brinell hardness,
E_t – Young's modulus,
R_{dt} – dynamic limit of plasticity of the shield material,
Y – dynamic resistance of the bullet,
R – dynamic resistance of the shield.

The experimental research and the computation have proved the increase of the ballistic thickness h_{BL} of the single- and multilayer shields with relation to the penetration depth g obtained during firing of semi-infinite plate made of the constructive steel by the bullet with V_u less then 1000 ms^{-1} [3]. Some results of those tests are showed in Fig. 2.

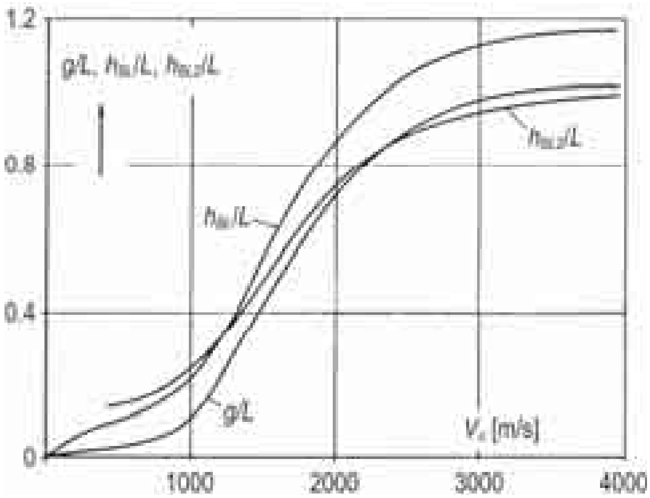

Fig. 2. The dependence between the ballistic thickness of the steel single-layer plates h_{BL}/L, two-layer plates h_{BL2} /L, the relative penetration depth g/L and the fire speed V_u for L/D = 10, where: L, D – length and diameter of the steel (230HB) bullet, g – penetration depth in the semi-infinite plate made of S210JR (180HB) steel

On the basis of the experiments, it is showed that hardness is the basic criterion of steel selection for the armoured shields. However, the dependence between the hardness and the resistance to perforation defined by the ballistic velocity V_{BL} (when the residual bullet speed equals to zero) is not linear [12].

In order to define the ballistic resistance of the shield there is introduced a notion of mass efficiency of multi-layer ballistic shields *M* during firing by the bullets of 7.62 mm calibre, *AP* as a quotient of surface density [9]:

$$M = \frac{(\rho \cdot h_{BL})_{RHA}}{\sum_{i=1}^{k} \rho_i \cdot h_i}\,, \tag{8}$$

where:

$(\rho \cdot h_{BL})_{RHA}$ – surface density and thickness h_{BL} of the homogeneous plate made of RHA steel,
$\rho_i \cdot h_i$ – density and thickness of i-th layer of the ballistic multi-layer shield.

For example for a shield made of RHA steel of 380 HB hardness and the ballistic thickness $h_{BL} = 15$ mm, the mass efficiency is $M = 1$, while for the steel of 550 HB hardness, thickness of $h_{BL} = 13$ mm and surface density $\rho \cdot h_{BL} = 98$ kg/m^2, the mass efficiency is $M = 1.16$ [9]. Moreover the tests proved that the shields which are the platters with double hardness 600HB/400HB enabled to lower the ballistic thickness $h_{BL} = 8$ mm and to raise the surface efficiency factor $M = 1.78$ [11].

Steels used for the naval structural shield show the comparable ballistic resistance but only if the shields are the 2-3 times thicker [3].

4. Results of bullet-proof tests PKB

The specimens for testing the bullet proof of platters were marked by numbers meaning the number of platters and letters as well (Tab. 1.):
P – means fire from the side of the armoured platter layer (steel 30GHMNbV or 30GSN4MBV),
M – means fire from the side of the soft layer (steel 15G2ANb, S275JR, 10GHMBA).

Specimen-shields of KB platters installed on the Tool Pendulum were bombard from the machine gun PK by bullets of calibre 7.62 mm at the speed of 825±25 m/s. The bullets have eroded while penetrating at the speed above the plastic wave velocity. Under those circumstances, the specimens have performed or they have insignificantly plastic deformed. Some examples of graphs of impact forces of specimen-shields with the diameter of 120 mm are presented on Fig. 3 and 4.

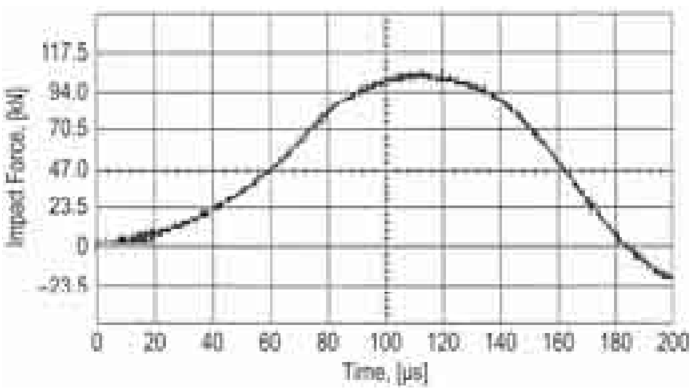

Fig. 3. The graph of the impact force F(t) of the bullet of calibre 7.62 mm from the specimen-shield with diameter of 120 mm made of the platter KB No. 6P, V_u = 825 m/s, F_{max} = 99 kN

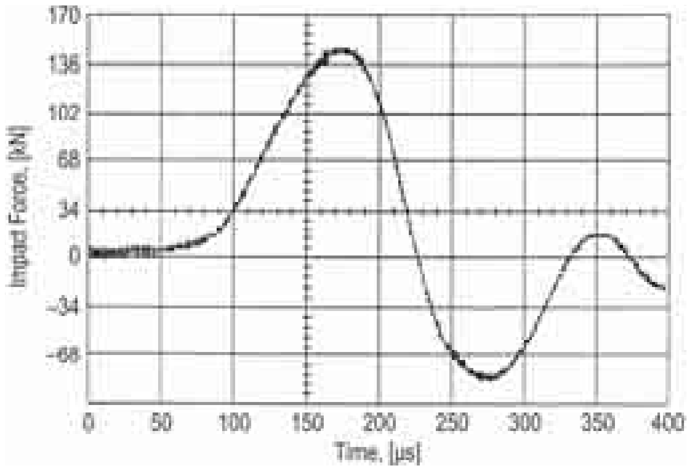

Fig. 4. The graph of the impact force F(t) of the bullet of calibre 7.62 mm from the specimen-shield with diameter of 120 mm made of the platter KB No. 7P, V_u = 825 m/s, F_{max} = 148 kN

The example effects of fire the specimen-shields are presented in Fig. 5.

a)  b) 

Fig. 5. The effect of fire the specimen-shields of platters KB with the diameter 120 mm by the bullets of calibre 7.62 mm at the impact speed of 825 m/s: a) the platter KB No. 3P – the plastic deformation without the plug, F_{max} = 82 kN, b) the platter KB No. 8P – the specimen perforation, F_{max} = 111 kN

5. Analysis of the bullet-proof of platters put to the shooting.

A partial shearing adiabatic of the plug has appeared in the fired specimen made of the platter no 1P. The maximum resisting force from the side of the armoured steel has reached 105 kN, while a total perforation with the resisting force equal to 60 kN has ensued from the side of the soft steel.

The comparison of platters No. 3P and No. 8P points to higher ballistic resistance of the platter No. 3 – Fig. 5a. The specimen-shield of it has given in cavity over 6 mm under the force of 82 kN, while the specimen of the platter No. 8 has given in perforation in spite of the resisting force equal to 111 kN – Fig. 5b. The specimen-shields of the platters No. 4P and 7P have given in perforation. The perforation of platters was also observed in platters No. 4, 7 and 8, while there has existed a partial development of the adiabatic shearing plug in platters No. 1 and 6. Only a plastic cavity has been observed in the point of impact in the platter No. 3.

The realized tests of platters with the thickness 8.5–9.2 mm let to rank them according to bullet-proof of platters No. 3, 1, 6, 7, 4 and 8 in turn. On the basis of those tests it is possible to admit that increasing their thickness up to 10 mm they are resistant to firing from the machine gun PK of 7.62 mm calibre. Both for the single-layer specimen and double-layer specimen made of 10GHMBA steel put firing by steel bullets of 7.62 mm calibre, the thickness for which the specimen is not shot has amounted to 28 mm [2].

6. Conclusions

At present days in Ministry of Defence and in Navy Headquarters there are carried on discussion concerning the incorporation new vessels in place of the withdrawn old ones up to 2013. That is why the problem of using the ballistic-structural shields on the navy vessels is very up-to-date. The tests and the theoretical analysis of the ballistic resistance of the structural-ballistic platters with double hardness have proved their usefulness as the armoured shields for navy vessels. The platters KB combine the advantages of hard steel with a large ballistic resistance with the plastic shield causing absorption of energy of impact impulse.

Introducing some new materials designed for the naval structural-ballistic shields requires many scientific and research problems solutions. The shields have to be characterized by the increased ability of energy with percussive load and energy dissipation through ballistic erosion of the bullet during firing and the layer selection correspondingly. Those requirements are satisfied by the structural-ballistic platters (PKB). The welded steel layers characterize by different effects of bullet-shield interaction. The upper layer causes the bullet erosion and energy dissipation while the lower one meets mainly the role of energy absorber. The upper layer has to be armoured steel while the lower one – the hull steel.

Application of the ballistic shields in the form of double hardness platter plates enables to significantly reduce the ballistic thickness. The specimens of platters KB with the layer of steel 30GHMNbV has showed the greater resistance than The platters PKB with 30GSN4MBV steel. Similarly, the existence of frontal layer over 40% of the platter thickness increases the ballistic resistance (platter No. 3P).

Typical steels for the structural vessel's shields show a comparable ballistic resistance when they are 2-3 times thicker.

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