THE ANALYSIS OF THE PARAMETERS OF THE MATERIALS USED FOR ANTITERRORIST SAFETY SHIELDS IN MARINE VESSELS

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Abstract

Selected parameters of steel for constructional ballistic shields 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. The analysis has been made upon currently available national and international steel types. The analysis made allowed to select the types of steel with the best parameters to be used for ballistic safety shields in marine vessels and give the direction for further research determined by contemporary threats of both military and terroristic nature.

The paper presents inter alia: macroscopic images of a crater filled with the remains of grinded and eroded rifle missile with traces of adiabatic shear in the cut of steel disc, the diagram of a vessel of special purpose equipped with shields made of metal plates the Polish Register of Marine Vessels requirements for mechanical parameters of mild-alloy steel and welded joints of high resistance, the stress – strain diagram for steel 10GHMBA-E620T in speed of movement function, chemical constitution and resistance properties of representative steels used for ballistic shields on American and Japanese naval ships, chemical constitution of selected Swedish steels of high resistance applied for ballistic shields.

Keywords: *ballistic shields, high resistance steel, dynamic characteristics, analysis, penetration, perforation*

1. Introduction

The materials used in navy industry for ship hulls which provide buoyancy, stability as well as other operation parameters must be accurately and optimally chosen depending on the purpose of a floating unit. As far as war vessels are concerned one of the most important parts of the ship hull constitutes its external armour plating which apart from its resistance to typical maritime factors must also have bullet-proof capability as well as resistance to explosives – like in case of antiterrorist shields. The influence of marine environment is also of crucial importance, taking the fragility of steel to be commonly caused by the following factors: constructional, the conditions and ways of loading as well as the metallurgic processes of manufacturing (e.g. chemistry). Of the most significant importance in our case are the first two factors defining/ depicting multi – pivot tension state, concentration of strain rates, enhanced/increased rate of deformation and temperature – in marine environment the greatest danger is posed by fragility in low temperatures. [8] Furthermore the most significant feature of ballistic shields is its resistance to perforation i.e. ballistic resistance (protection capacity). A missile should have as high kinetic energy as possible in order to penetrate armour-plated shields. Taking into consideration the variety of artillery missiles, a hull plate is made of upgraded resistance steel. More and more durable and resistant ballistic shields are being continually developed to protect against striking power of a missile or shrapnel. That is why the thickness of a shield depends on the type of steel in order that the resistance of the shield to striking has become optimally perforation - proof when under shellfire. [2, 3]

Missiles might be divided into:

- Small-calibre,
- Medium-calibre,
- Large-calibre,

- Full-calibre,
- Sub-calibre,
- Cumulative (containing explosives),
- Ordinary,
- Armour-piercing,
- Shrapnel – striking,
- Perforating and firing,
- Grenade launched and others.

Each type of a missile has its own characteristic parameters and specifications which determine perforation and/or destruction of particular protection armour. The method and striking power depend on the calibre, speed, energy, the type of the missile as well as its perforation capacity of monolithic steel armour. The striking of a missile on an obstacle/handicap/impediment usually causes partial adiabatic shear as well as ballistic erosion leading to partial defragmentation (commonly combined with melting of a disc and/or a missile) as well as penetration and perforation of the casing of (the shield) (Fig. 1). During the perforation of ballistic shields the release of lethal shrapnel often occurs. The aperture or crater of a given diameter d_t, and depth l_t appears in the disc. The remnants (shrapnel) of missiles of tempered steel (with a speed decreasing at ballistic penetration l_t and V) might indicate enhanced ductility than “sharp”, hard or “blunt” missiles or those indicating fragility.

Fig. 1. Macroscopic images of a crater filled with the remains of grinded and eroded rifle missile with traces of adiabatic shear in the cut of steel disc

The other terms, apart from ballistic resistance, describing the protection capacity of a shield are: bullet proof resistance, shrapnel- proof resistance, resistance to air shockwave [9].The research of ballistic resistance of steel vessel construction-ballistic shields are conducted on relevant normalized samples. The ballistic speed is determined then with regard to the residual velocity of a missile V_r = 0 m/s as well as ballistic at 50% probability of perforation – V_{BL} for residual speed of a missile and estimating bullet – proof resistance by verifying analytical – numeric simulation at a marine range. A standard attempt of verifying resistance consists in perforating steel samples of rifle missiles cal. 7.62mm. Verification of upgraded resistance is carried out by using missiles cal. 12.7 and cal. 14.5 for perforation. The research of shields is conducted in accordance with the DIN 52290 standards and EUROPEAN STANDARD “CEN”. Finally vessel shields are constantly supervised by important institutions including the Headquarters of Marine Technology at Ministry of National Defence as well as the Polish Register of Marine Vessels.

2. Steel requirements used for ballistic plating and shields

At present contemporary protection structures constitute a crucial element of floating units, military and public facilities and others. Their purpose is to enfeeble terroristic acts with the use of explosives or missiles within specified areas. The knowledge of the functioning of explosives at high strain rate is of great significance for designing ballistic shields. Current ship hull plating of contemporary marine vessels do not meet the requirements of antiterrorist ballistic shields antiterrorist when faced with the firing form low calibre weapons as well as rocket or missile shrapnel. It poses a significant problem as regards the protection of a marine vessel in the face of terrorist attack threats. That is why ballistic shields should be installed on the external and internal ship hull to protect crucial spaces and action stations – Fig. 2.

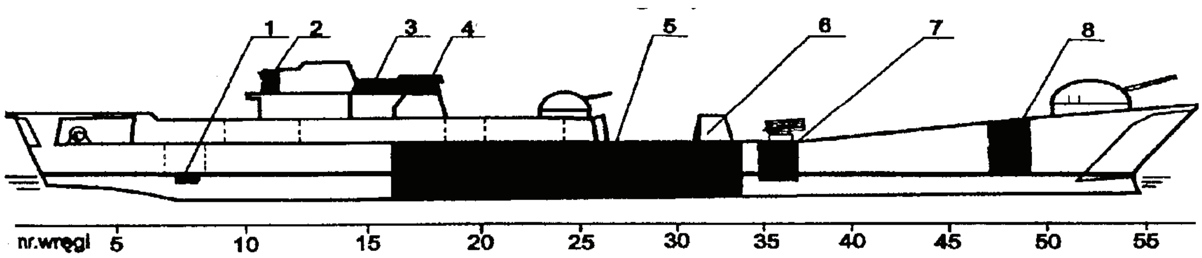

Fig. 2. The diagram of a vessel of special purpose equipped with shields made of metal plates with hardness of 500 HB in the following places: 1, 2 – ammunition store, 3 operational room, 4 the main command post, 5 marine troops, 6-8 – missiles and ammunition

The requirements for vessel ballistic shields to provide:

- resistance to firing of missiles of particular type,
- stable functioning of a shield and a ship hull before and after the firing,
- minimal surface density of a shield,
- relevant mechanical parameters, proper welding of shields.

Providing resistance to firing of particular missiles results from the function of the shield protecting the most significant places on a vessel like those in Fig. 2. The shields must be resistant to firing of rifle missiles cal. 7.62 mm with a steel penetrating core. The trials of ballistic resistance are conducted with bullets cal. 7.62mm – type B-32, cal. 12.7 mm and cal. 14.5 mm – type B-32 and BZT. The process of firing cannot cause any damage of functionality of both the shield and the hull next to the shield. The shields are to protect the crew hidden behind it. Moreover, the purpose of the shield is to protect against shrapnel of a missile remnants or of downed armour as well as against the effects of firing of small – calibre missiles. The requirements concerning minimal surface density of ballistic shields refer to the elements of plating and extensions and the influence of their substance and height to the stability of a vessel. As regards the provision of relevant mechanical parameters, good welding – they result from the requirements posed to steel constructions by classification vessel committees. Ballistic shields may constitute an integral part of a hull or a part of vessel equipment which can be separated from the hull's plating. However, in order that the function of a shield may be accomplished they must be manufactured from materials meeting the requirements of both ballistic protection and a constructional vessel shield. The materials to be used at steel vessel constructional shields are under supervision of classification vessel committees as well as military institutions. The institutions include: The Headquarters of Marine Technology at Ministry of National Defence and the Polish Registry of Vessels. According to those institutions the selection of materials for constructional shields should refer to the dynamic parameters of materials and the conditions of dynamic loading. The institutions introduce certain recommendations concerning the construction process of a vessel as well as determine minimal parameters for steel and welding connectors designed for marine constructions: KV crack energy of Charpy samples at sample temperatures, the plasticity limits Re, casual durability for tension Rm as well as elongation of fivefold sample A5. In the process of selection of steel classification committees take into consideration its resistance to cracking, minimal design temperature, quality criteria of welding connectors. Low-carbon steel of ordinary resistance of Re = 235 MPa, Rm = (400 – 500) should be used after hot laminating or normalizing with a reduced carbon content up to 0.21% (plasticity variety D) and 0.18% carbon for E variety at hallmark temperatures of -20 and -40. It is equivalent for plasticity varieties of steel with regard to the energy of cracking samples $KV_p = 20$ J, $KV_w = 27$ J at hallmark temperatures of $0^0C(B)$, $-20^0C(D)$ and $-40^0C(E)$. It is recommended to normalize or heat treatment with plastic forming for E plasticity variety. The normalizing process (N) might be replaceabled for regulated laminating (CR) or heat treatment with plastic forming (TMCP) and fast cooling after laminating. (OLAC). Low-carbon and mild-alloy steel: C-Mn or C-Mn-Nb (V, Ti) with fine-grained structure and resistance category: Remin =(315, 355, 390) MPa and plasticity variety A, D, E, F (for example: 15GA-EH32 and 15G2Anb-EH36 are ranked as upgraded resistance steel. It is also recommended to use mild-alloy weldable and high-strength alloy steel after hardening and tempering with possibility of heat treatment with plastic forming (TMCP). They are selected into six categories of strength and four plasticity varieties according to the Polish Register of Marine Vessels (Tab. 1) [14] - using the categories of strength, it is able to form an opinion about function during expected the militant-defensive and naval situations.

This is particularly important for naval vessels, which shields are made of weldable steels of high resistance due to their special duty purposes. Apart from this, fracture toughness,

minimum operating temperature and figure of merit of welded joints are to be considered. Applied heat treatment methods make the other factors which always must be taken into account during manufacturing process. Appropriate material heat treatment method allows adequate parameters e.g. these relating to resistance to perforation (ballistic resistance) to be obtained [2, 3, 9].

Increased steel ballistic resistance was characterized by following parameters:
R_{ed} = min 720 MPa, R_{md} = min 850 MPa, A_{5d} = min 16% [4].

Steels for armoured anti-terrorist shields must meet a number of classification requirements so that they could fulfil its successfully prolonged protective function on a naval vessel.

Tab. 1. The Polish Register of Marine Vessels requirements for mechanical parameters of mild-alloy steel and welded joints of high resistance

A category of steel	Tensile test			Charpy test V			Bend test of welded joint	
	R_e/Y_z MPa, min.	R_m/R_{mz} MPa, min.	A_5 % min.	Temp. of sample °C	KV_{min} L/L_z, J	KV_{min} T J	An angle bend (degrees)	Diameter/, thickness D/t
1	2	3	4	5	6	7	8	9
A420 D420 E420 F420	420/Y42	530-680/ 530	18	0 -20 -40 -60	42/47	28	120	4
A460 D460 E460 F460	460/Y46	570-720/ 570	17	0 -20 -40 -60	46/47	31	120	4
A500 D500 E500 F500	500/Y50	610-770/ 610	16	0 -20 -40 -60	50/50	33	120	4
A550 D550 E550 F550	550/Y55	670-830/ 670	16	0 -20 -40 -60	55/55	37	120	5
A620 D620 E620 F620	620/Y62	720-890/ 720	15	0 -20 -40 -60	62/62	41	120	5
A690 D690 E690 F690	690/Y69	770-940/ 770	14	0 -20 -40 -60	69/69	46	120	5
Y_Z – symbol of welded joint category, R_{mz} – joint resistance, L – longitudinal sample, L_z – sample from welded joint, T – lateral sample, KV – bend energy of Charpy sample V, D – diameter of bending rod, t – thickness of sample, R_e – plasticity limits, R_m – durability for tension, A_5 – elongation of fivefold sample.								

3. Weldable steels of high resistance for ballistic ship shields application

Nowadays, both foreign and domestic shipbuilding industry offers armoured steel of increasingly better quality. Polish weldable bainitic steel of high resistance (SSWW), grade **10GHMBA** which is the subject of research, can be successfully applied for the ship shields.

Its main advantage consists in resistance to iterative perforation with missiles calibre 7.62 and 12.7 mm and their shrapnels. Appropriately selected heat treatment method and the chemical constitution : 0.11% C, 0.59% Mn, 0.33% Si, 0.02% P, 0.03% S, 1.40% Cr, 0.05% Ni, 0.51% Mo, 0.41% Cu, 0.0004% B, 0.03% Ti, 0.04% Nb, 0.046% Al, 0.011% N2 influence its functional properties and resistance to gunfire perforation [4].

Due to noticeably low content of pollutants like sulphur and phosphorus, i.e. high metallurgical purity and high constitution homogeneity, the steel under research shows good welding properties.

Gas shielded MAG welding method provides welding joints which preserve a native material category. However, Shielded Metal Arc Welding (shielded electrode) proves to be a good method as well [18].

Optimal selection of individual constituents in a material together with an appropriate heat treatment method application, allowed high static and dynamic mechanical properties to be obtained. Increase in speed of movement causes distinct increase of yield point at dynamic tension in relation to static tension. Fig. 3 demonstrates the stress – strain diagram for steel

10GHMBA-E620T in speed of movement function [1, 17]. Noticeably, the above mentioned steel exceeds considerably minimum boundary values of increased ballistic resistance. The heat treatment which was applied consisted in heat toughening (hardening at temp. T_h = 930ºC in water, then air-cooling tempering T_{odp} = 525 ºC).

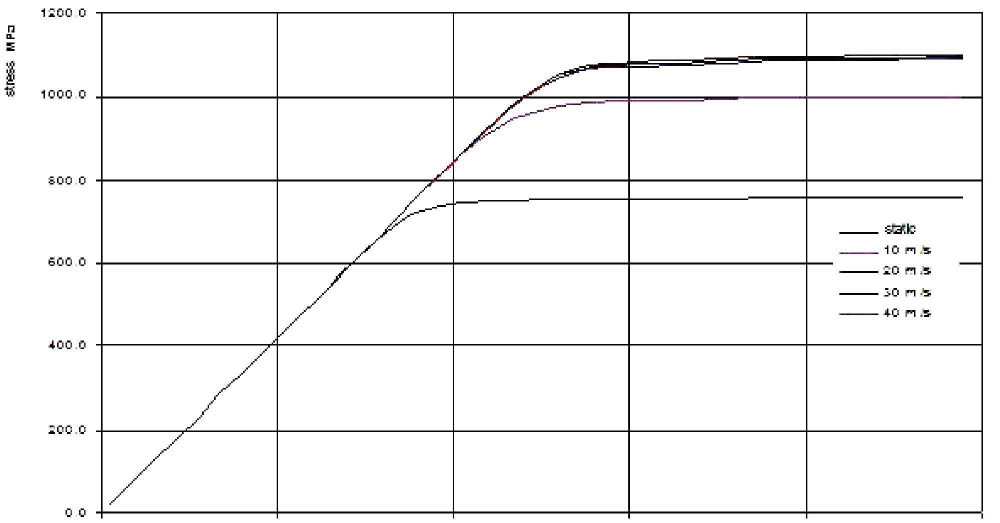

Fig. 3. The stress – strain diagram for steel 10GHMBA-E620T in speed of movement function

Weldable steel of high resistance manufactured in Poland, which resembles closely steel 10GHMBA in terms of its constitution and properties , and ensures the similar ballistic resistance is steel of grade **11GHNMBA**.

The content of chemical constituents for this steel is shown below [4] :

0.12% C, 1.00% Mn, 0.31% Si, 0.011% P, 0.016% S, 1.03% Cr, 0.96% Ni, 0.53% Mo, 0.21% Cu, 0.0052% B, 0.05% Ti, 0.037% Nb, 0.062% Al, 0.016% N2.

After application of steel toughening similar to as for 10GHMBA, the values obtained are as follows:

$$R_e = 953 \text{ MPa},\ R_m = 1032 \text{ MPa},\ A_5 = 11.4\%,\ Z < 57\%,$$
$$R_{ed} = 991 \text{ MPa},\ R_{md} = 1115 \text{ MPa}.$$

It can be observed that the requirements referring to increased ballistic resistance have been met, although to a slightly less extent in relation to steel 10GHMBA.

Another example of Polish made steel SSWW of a good ballistic resistance is **12GHN2BA**, which is comparable to steel 10GHMBA, which has the following chemical constitution [4]:
0.13% C, 1.08% Mn, 0.55% Si, 0.018% P, 0.028% S, 0.88% Cr, 2.67% Ni, 0.17% Mo, 0.12% Cu, 0.0045% B, 0.03% Ti, 0.014% Nb, 0.060% Al, 0.013% N2.

As for previously listed steels, heat toughening was applied which resulted in the following mechanical properties [4]:

R_e = 826 MPa, R_m = 904 MPa, A_5 = 11.0%, Z < 34%, R_{ed} = 942 MPa, R_{md} = 1012 MPa.

Although increased ballistic resistance was also preserved, a distinct and adverse difference in distinctive resistance values is present.

Considering similarly low sulphur and phosphorus content, both steels preserve good welding properties. The optimal welding method in both cases is gas shielded MAG welding.

A few most commonly used naval steels in America and Japan like T1, HY – 80, HSLA – 80 and HT – 80, HT – 100 have been selected as representative of Western production materials for general comparison with presented above steels manufactured in Poland for ship ballistic shields application. The chemical constitution and properties are shown in Tab. 2 [4]. These are weldable high resistance steels SSWW of comparable properties and parameters, which are also subjected to appropriate heat treatment in order to obtain increased ballistic resistance.

Tab. 2. Chemical constitution and resistance properties of representative steels used for ballistic shields on American and Japanese naval ships

Steel	Chemical constitution	R_e MPa min
T1	0.10-0.20% C, 0.15-0.35% Si, 0.60-1.00% Mn, max 0.035% P, max 0.040% S, 0.40-0.80% Cr, 0.70-1.00% Ni, 0.40-0.60 % Mo, 0.15-0.50% Cu, 0.03-0.10% V, 0.02-0.06% B	690
HY – 80	0.10-0.20% C, 0.12-0.38% Si, 0.10-0.45% Mn, max 0.020% P, max 0.020% S, 1.29-1.86% Cr, 2.43-3.32% Ni, 0.27-0.63 % Mo, max 0.25% Cu, max 0.03% V, max 0.02% Ti	550
HSLA – 80	max 0.07% C, max 0.40% Si, 0.40-0.70% Mn, max 0.025% P, max 0.010% S, 0.60-0.90% Cr, 0.70-1.00% Ni, 0.15-0.25 % Mo, 1.00-1.30% Cu, 0.02-0.06% Nb	550
HT – 80	0.05% C, 0.20% Si, 1.30% Mn, max 0.003% P, max 0.001% S, 1.50% Ni, 1.10% Cu, 0.015%Ti	690
HT – 100	0.11% C, 0.25% Si, 0.90% Mn, max 0.003% P, max 0.001% S, 0.56% Cr, 1.00% Ni, 0.45%Mo, 0.25% Cu, 0.05% V, 0.002% B	900

Steels T1 and HY – 80 were subjected to conventional heat toughening (through repeated heating to hardening).

Steels HSLA – 80 and HT – 80 were subjected to solution heat treatment and quench ageing.

Yield point Re = min. 550MPa – the minimum numerical value is identical in relation to steel HY – 80, however for this case, solution heat treatment and quench ageing were applied due to a distinctly different chemical constitution.

For steel HT – 100, line of rollers heat treatment toughening was applied.

Steels such as RHA (e.g. Armox 370S), AISI 4340 (e.g. Armox 560S) or AISI 4330 (e.g. Armox 46100, Armox 500, Armox 500S) can represent totally different steels used for ballistic shields. However, steels RHA are manufactured mainly for combat vehicles purposes, which operate in mainland environment so are not exposed to such difficult conditions as at sea. Nevertheless, their military application and resistance properties make them fall into a category of wider range use.

For comparison, Tab. 3 shows chemical constitution of selected Swedish steels of high resistance applied for ballistic shields.

Tab. 3. Chemical constitution of selected Swedish steels of high resistance applied for ballistic shields

Steel	Chemical constitution
Armox 560S	max 0.37% C, 0.10-0.40% Si, max 1.20% Mn, max 0.015% P, max 0.010% S, max 1.50% Cr, max 3.50% Ni, max 0.70% Mo, max 0.005%B
Armox 46100	max 0.32% C, 0.10-0.40% Si, max 1.20% Mn, max 0.015% P, max 0.010% S, max 1.50% Cr, max 1.80% Ni, max 0.70% Mo, max 0.005%B
Armox 500S	max 0.30% C, 0.10-0.40% Si, max 1.20% Mn, max 0.015% P, max 0.010% S, max 1.00% Cr, max 1.30% Ni, max 0.70% Mo, max 0.005%B
Armox 500	0.25% C, 0.50% Si, 1.20% Mn, max 0.015% P, max 0.010% S, 0.50% Cr, 0.20% Mo, max 0.002%B

For the listed steels Armox, the maximum value of resistance ranges from 1650 do 2450 MPa depending on tempering temperatures i.e. from 150^0 C to 200^0 C [19].

4. Summary

It's commonly known that welding low-alloyed steel of high resistance is characterized by high resistance properties i.e. R = 420 – 900 MPa, good malleability (plasticity, impact strength) and welding. Such properties might be obtained thanks to the fact that in metallurgy and thermal treatment more modern technologies have been used such as obtaining steel of high purity, constant steel founding, thermal – plastic treatment and accelerated cooling, modification of chemistry. [6] This developing tendency of making steel for vessel ballistic shields has been directing towards improving resistance parameters, enhanced resistance to perforation without increasing e.g. the thickness of a shield which could unnecessarily enlarge the mass of the whole vessel. In spite of more and more popular and available materials used for military purposes other than steel (e.g. ceramic gradient materials) it must be emphasized that in vessel industry the development of special types of steel is absolutely crucial, all the more, that modern welding steel meet the requirements of the most rigorous resistance norms. Discrepancies in thermal treatment might be observed, depending on chemistry so that the best parameters of steel might be obtained. In spite of visible discrepancies especially with regard to key chemistry at national and overseas vessel armour steels, the most important mechanical properties stay very close, which also reflect the need for further development of steel vessel shields.

References

[1] Kyzioł, L., Charchalis, A., *Testing 10GHMBA steel for vessel ballistic shields*, International Scientific Congress on Powertrain and Transport Means, Journal of KONES (in print).

[2] Sperski, M., *Model obliczeniowy do oszacowania odporności balistycznej pancerzy stalowych*, Zeszyty Naukowe Akademii Marynarki Wojennej, Nr 4, 2009.

[3] Świątek, K., Szturomski, B., *Zastosowanie zmodernizowanego wahadła balistycznego do prób przebicia pociskiem kalibru 12,7 mm materiałów stosowanych na osłony antyterrorystyczne*, Zeszyty Naukowe Akademii Marynarki Wojennej, Nr 2, 2009.

[4] Fila, J., Zatorski, Z., Zaczek, Z., *Własności technologiczno – użytkowe i balistyczne okrętowej SSPW gatunku 10GHMBA-E620T*, Referaty sympozjum, Nowoczesne materiały w okrętownictwie, Politechnika Gdańska, Gdańsk 1995.

[5] Bugłacki, H., *Wpływ składu chemicznego i obróbki cieplnej na właściwości mechaniczne okrętowych stali spawalnych wysokiej wytrzymałości*, Referaty sympozjum, Nowoczesne materiały w okrętownictwie, Politechnika Gdańska, Gdańsk 1995.

[6] Ćwiek, J., Łabanowski, J., *Stale wysokiej wytrzymałości na konstrukcje morskie*, Referaty sympozjum, Nowoczesne materiały w okrętownictwie, Politechnika Gdańska, Gdańsk 1995.
[7] Dobrzański, L., *Podstawy nauki o materiałach i metaloznawstwo: materiały inżynierskie z podstawami projektowania materiałowego*, Wydawnictwa Naukowo-Techniczne, Warszawa 2002.
[8] Butnicki, S., *Stale i żeliwa dla przemysłu okrętowego*, Wydawnictwo Morskie, Gdańsk 1971.
[9] Wiśniewski, A., *Pancerze, budowa, projektowanie i badanie*, Wydawnictwa Naukowo-Techniczne, Warszawa 2001.
[10] Klepaczko, J. R., *An experimental technique for shear testing at high and very strain rates.* The case of mild steal, International Journal of Impact Engineering, 15, 1, pp. 25-39, 1994.
[11] Klepaczko, J. R., *Advanced experimental techniques in materials tastings*, New experimental methods in material dynamics and impact, Series: Trends in mechanics of materials, Eds. W. K. Nowacki, J. R. Klepaczko, pp. 223-266, 2001.
[12] Goldsmith, S., Finnegan, A., *Normal and oblique impact of cylindro-conical and cylindrical projectiles on metallic plates*, International Journal of Impact Engineering, 4, 2, pp. 83-105, 1986.
[13] Zukas, J., *High velocity impact dynamics*, John Willey & Sons Inc. U. K. 1990.
[14] *Polski Rejestr Statków: Przepisy klasyfikacji I budowy statków morskich,* Zmiany Nr 1/1998 do części IX, Materiały i spawanie, Gdańsk 1995.
[15] Baujat, V., Cousquer, J., Laurian, J., Quinchon, Gillard, F., Rotrubin, J. L., *Submarine pressure hull construction in 100 HLES steel*, pp. 81-101, 1990.
[16] Blicharski, M., *Wpływ węgla i siarki na własności stali o dużej udarności utwardzonej miedzią*, Proc. 14th Int. Sci. Conf. Advanced Materials and Technologies, AMT, 1995.
[17] Jurczak, W., Kyzioł, L., *Dynamic properties of 7000- series aluminium alloys at large strain rates*, Polish Maritime Research, (w druku).
[18] 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 (monografia) Nr 128 A, AMW, Gdynia 1996.
[19] Seaglitz, M., Krauss, G., *Deformation, fracture and mechanical properties of low – temperature – tempered martensite in SAE 43XX steels*, Metallurgical and Materials Transactions, 28, 2, 377-387, 1997.