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IMPACT RESISTANCE OF ALUMINIUM SHIP STRUCTURES

ABSTRACT

In the article there are summarized author's results of research carried out in the Department of Basics of Marine Engineering of Polish Naval Academy for the last years. The results of those tests are listed in the selected publications that generally describe the improving impact resistance of the marine aluminium alloys.

Using the ballistic dividers, sharing in the same thickness or applying the ceramics state the main methods to increase the impact resistance of the tested alloys. The interlayer aluminium structures are super effective. Their impact strength in relation to the monolithic material rise 3-times. This significantly improves their resistance to piercing by the 7.62 mm missile and the fragmentation (making shrapnel) decreases during the explosion. Each aluminium alloys are protected by the ballistic ceramics of 5 mm thickness with the fire caused by the missile of E = 3kJ. The Armox 500S steel can provide an effective protection for aluminium alloys as a ballistic divider during the fire by the 7,62 mm B32 missile.

Key words:
aluminium alloys, impact resistance, ship constructions.

INTRODUCTION

Ship construction load on a wave, with the state of sea above 3°B moving with a high velocity (V_{max} ~ 50 kn that is about 93 km/h) is an example of impact resistance, which a ship constructor must take into account. The skeleton construction of ship structures as a system of longitudinal and transverse bindings (frame floor,

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frames, beams, hull and superstructure reinforcements) when connected to the sheet planking constitutes the main factor determining durability and deformation resistance of the deck and superstructure. This phenomena touches the hull and the superstructure and there is no matter what material they are made of aluminium alloy or hull steel. Increasing the safety of the crew in operational and fighting conditions demands using engineering material of the best quality and innovative solutions aimed at constant improvement of existing materials as well as a prospective construction and technology solutions.

Over the centuries, the choice of material of the highest quality for building ships in relation to the means of combating measures guarantees 'combat viability' of the ship. Taking into consideration the relation between 'a missile and the armour' guarantees a capability of lasting in case of armed conflicts. A bullet of a defined mass (from a few grams to several kilograms) moving with high speed (over 600 m/s), which have an impact on a small area will cause its puncture with a high density of energy, and the resistance that the material poses is often called ballistic resistance.

Works on impact and ballistic materials resistance to non-contact explosions are related to optimization of frequently opposite material properties, for example high quality and resistance to puncture by bullets and their fragments as well as non-contact underwater blasts with good indicators of ductility (R_e, A_5, KV), weldability and operating cracking resistance. It causes major problems in construction in relation to the choice of the material.

Currently, not only armed ships, but standard ships as well require the use of material of higher ballistic resistance in their structures and high-tech warfare agents in the view of terroristic activity or pirates.

Protection in the scope of ballistic ships is frequently limited to shielding vital compartments of its structure e.g. ammunition chambers, superstructure, the main command station, the engine room, fuel containers. For example, the shields used on 'Oliver Hazard Perry' frigates (e.g. 'Pułaski' ship of the Polish Navy) are Kevlar slabs of 19 mm thickness used to protect electronic systems and 19 mm slabs of aluminium alloys used to protect ammunition chambers, and the engine room central is protected by the bullet proof steel slab. For construction of ships materials of good chemical properties are used, especially materials resistant to cold cracking at low temperatures, impact resistant, and resistant to corrosion in sea water and atmosphere. Aluminium alloys have such properties, especially high-strength alloys of 7xxx series without Cu.

Unfortunately, those materials, which are more and more widely used in ship-building and were used to build a ship, show insufficient puncture resistance for the standard calibre of 7.62 mm.

A constructor must aim at combining good operating properties of materials with mechanical properties. It is often very hard to implement. It is obvious that passive protection measure should be resistant to bullet to the biggest extent. They should be an efficient element of responsible military constructions, which protect equipment and crews. Currently, light armour of vital ship departments should protect a unit to such extent that if it gets hit by a bullet, it could implement the mission that was assigned to it and safety come back to the port. Due to technical and economic restrictions, it is not always possible to implement.

The aluminium alloy is recognized and frequently used material in constructions of armour of military equipment. The alloys are capable of protecting combat vehicles and their crew from bullets of a smaller calibre. Their low mass efficiency (E_m) against armour piercing bullets of 7.62 mm calibre may be compensated by their favourable structural characteristics, which decreases the total mass of lightly armoured vehicles, which is vital. E_m is defined as a real density G_p [kg/m^2] of a rolled homogeneous steel armour of HB = 320–380 hardness and a real density of the studied armour ratio, when the armours provide the same level of protection in the same conditions of combat threat. Aluminium alloys are frequently used as the internal layer in a form of plated slabs, in which the external layer may be made of a steel armour slab of high hardness — in that case the mass efficiency of those alloys against AP bullets of 7.62 mm calibre is significantly increased. Those data from the literature were verified in polygon tests, and their results were published by reversing the task in which the protected material is high-strength 7020 aluminium alloy and its 7020M modification.

THE RESULTS OF TESTS

The most important research results and research methods have been shown on selected articles for last few years. A synthetic description of achievements in the scope of forecasting impact resistance of ship structures made of aluminium alloys in operating conditions.

In the single-field cycle of publications there were described issues related to operation of ship structures made of aluminium alloys in relation to impact resistance:

- methods of increasing impact resistance, taking into consideration: the alloy type, the rate of deformation, the notch type;

- methods of increasing resistance to puncture (ballistic resistance) with a steel bullet of 7.62, taking into consideration: the type of structure (solid, split), the type of separators/protective layers, the bullet type;
- methods of increasing resistance to explosions taking into consideration the influence of the type of structure (solid, split).

The puncture and explosion resistance studies were limited to 7020M alloy as studies on its impact resistance showed its superiority over 7020 alloy.

Dynamic properties of 7xxx series aluminium alloys at large strain rates [3]

Scientific problems solved

Under the influence of a dynamic load, there is an increase in durability indicators of high-strength naval aluminium alloys in relation to values obtained in the static tensile test. When mounting sheets of the notch made of metal sheet of 7xxx alloy on a ship structure, it is necessary to take into consideration the direction of rolling of those sheets. The direction should be parallel to the ship axis. Each type of a surface defect of aluminium sheets of 7xxx series alloy has a significant influence on its dynamic properties. The lowest vulnerability to dynamic loads, and thereby to deformation ratio, occurs in case of defects, which were described in the study as samples with the ‘V’ notch. Samples with the ‘V’ notch of both 7020 and 7020M alloy had a higher increase in durability properties than smooth samples and samples with ‘U’ notch at increasing rate of deformation. Results from the static and dynamic studies may constitute a basis for dynamic modelling of aluminium alloys deformations as a tensile/viscoelastic material.

Impact and ballistic resistance of high-strength aluminium alloys intended for ship constructions [1]

Scientific problems solved

Results of impact tests conducted with the use of a drop forge for solid and split samples of new 7020M alloy with the use of Abaqus computer simulation were described. Verification of laboratory tests was done also on a basis of polygon tests. The essence of the division was based on substituting the aforementioned elements with at least two thinner elements of the same material and of a thickness not exceeding the original one, which are not bounded on the surface. Those elements absorbed much more energy in case of deformation, without losing their cohesion (cracks), thanks to which they represent much higher impact resistance.

In the article, calculations of absorbed impact and deformation energy for solid and split samples of the same thickness were made. The favourable results of the increase in impact resistance of the new alloys results from comparison of σ maximal stress and ϕ maximal energy of resilient deformation of a double pivot beam of thickness, loaded in the centre by a static lateral force — F under maximal stress and maximal energy of resilient deformation of similarly loaded by one F force two beams of ½ h thickness each, which amount to 2σ and 4ϕ. It means that in case of the same weight and thickness of one-layer shield and multi-layer shield, the maximum stress under load increases much slower with the number of layers, than the energy absorbed.

For the chosen energy of the drop forge and split samples of 7020M alloy (tab. 1), deformation values were shown (marked as *b*) as well as reduced stress values — σ_{HMH} accompanying it that were obtained in tests with the use of the drop forge and verified with the use of a computer simulation. The comparison of data in table 1 and values for the same parameters but for solid samples shown in table 2 of a given alloy shows that the values are smaller in comparison to split samples and the difference obtained in the simulation made with the Abaqus application was about 10% in an extreme case.

Tab. 1. Parameters of the split sample of the same thickness of 7020M alloy [1]

Drop height of the striker m	Striker velocity m/s	Kinetic energy N·m	Stress σ_{HMH} MPa	Deformation *b* mm		Difference %
				simulation	*experiment*	
0.4	2.80	109.76	250.5	34.77	34.23	1.58
0.6	3.43	164.81	279.0	46.82	44.21	5.90
0.8	3.96	219.54	330.0	54.37	52.0	4.55

Tab. 2. Parameters of the solid layer of 7020M alloy [1]

Drop height of the striker m	Striker velocity m/s	Kinetic energy N·m	Stress σ_{HMH} MPa	Deformation *b* mm		Difference %
				simulation	*experiment*	
0.4	2.80	109.76	252	27.8	32.8	8.5
0.6	3.43	164.81	265	31.6	35.2	10.3
0.8	3.96	219.54	273	41.2	43.6	5.5

In the polygon conditions, results of laboratory studies of 7020M alloy were verified.

The effects of detonation of explosive payload of 1.5 kg TNT were conducted in accordance with the normalized sample for solid and splits samples of 7020M alloy shown in figure 1.

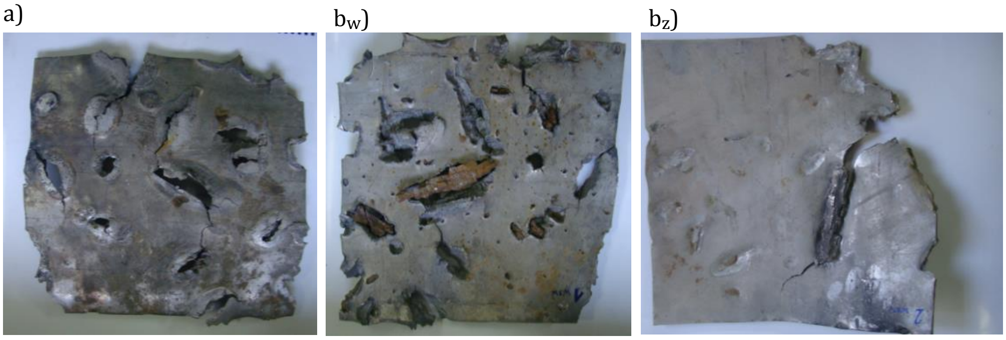

Fig. 1. Effects of sheet metal perforation (dimensions: 300 x 3000) of 7020M alloy: a) solid density — 12mm b) split ($_w$ — internal, $_z$ — external side from the source of explosion) of the same thickness (d = 2 x 6 mm) after detonation of a high explosive fragmentation missile of 100 mm calibre OF412 of 1.4 kg TNT from the distance of 0.6 m [1]

Test of impact and ballistic resistance were conducted on a new, alternative 7020M alloy (improved In comparison to 7020 alloy), which is supposed to increase operating security of naval constructions made of it in conditions of firing or explosion danger.

The dynamic load of 7020M alloy results an increase of the strength in relation to the statistic static strength in the scope dependant on the deformation ratio. Splitting of a structure made of 7020M alloy of the same thickness (g = 12 mm ⇔ g = 2 x 6 mm) increases the impact resistance by 3 times. The heterogeneous studied alloy show low resistance to puncture, however, the use of ballistic ceramics (Al_2O_3) of 6 mm thickness fully protected the material from puncture with 7.62 mm ŁPS missiles of 3kJ energy. The split construction of the studied alloy of the same thickness allowed the better protection from explosive fragments at 1.4 kg TNT detonation than the solid structure.

The current superstructure of ship 620 should be made of aluminium split metal sheets, if technological and construction conditions allow for that. An alternative solution is to use of ballistic ceramics glued on the exterior of plating with epoxy resin to the solid plating material.

Multi-layer ballistic shields for naval and offshore structures of means of combat transport [2]

Scientific problems solved

Puncture resistance studies of the new 7020M alloy (AlZn5Mg2CrZr) and A-category hull steel protected with Armox steel in naval 500S and land 500T versions with the use of n split layers of the same thickness in various separators systems gave positive results for this alloy. Armox steel as a protective material of the thickness of above 7 mm effectively protects the studied materials from a shell of 7.62 mm ŁPS calibre or B32 of 3–3,5 kJ energy. Using additional layers made of vulnerable elements, such as rubber compound or bonding of divided samples, does not significantly influence on puncture resistance of studied materials. Splitting Armox and hull steel worsens their resistance to puncture. When combining the use of ballistic separators, the rule that the hardest materials should be placed on the side of firing should be applied, which additionally protects the structure from the impact of fragments of shells.

CONCLUSIONS

The use of a division of the studied alloys of the same thickness gives better protection from impact forces, including those of high energy density. The use of spacers between those layers does not change the energy of a shell penetration, however filling the space with bulk material (crushed toughened glass) or filling containers with water significantly increases puncture resistance (bulletproof). The use of spacers between the layers of alloys made of various materials: rubber compound, polyester and glass laminate and ballistic ceramics in various configurations increases the protection efficiency and in case of ceramics of thickness of 8 mm, it stops a bullet of energy up to 3 kJ. It is a rule that the hardest spacer should be placed from the side of firing in the spacers configurations. Due to high density of ceramics (and the need to use it on big surfaces, which increases its weight and limits the mobility of a ship), increasing puncture resistance in case of a spacer protection of 7020 and 7020M alloys may be obtained by using combined solutions, without using ceramic. An intermediate material (e.g. polyester and glass laminate) of good mechanical properties may be placed between the layer of the alloy protected, relatively — hermetical containers with water, which additionally will in be an element that decreases fire risk when fired with B32 (incendiary missiles) or it is possible to use both: the material and containers.

Using reinforced rubber compound (produced by Wolbram) does not increase puncture resistance of the studied alloys.

To protect high-strength alloys of 7xxx series, Armox500S steel (S — the marine version) which thickness is 7 mm fully protects aluminium alloys of 6 mm against ŁPS missiles (3.3 kJ), just like ceramics of 8 mm thickness do.

Division in any configuration of hull, construction or Armox steel decreases the efficiency, in contrast to aluminium alloys, against piercing with a missile of E ~ 3 kJ. Light aluminium structures may be protected with steel with the use of combined materials in a steel/Al/aluminium alloy configuration, as in case of the hull of the 620 ship.

The majority of aluminium structures (e.g. superstructure) is above the water line, that is why in the polygon tests, the impact of explosions on dispersal of a pressure pulse of a shock wave is on air the same as a non-contact explosion. In the initial polygon tests 75 g of TNT were used (in a closed cylinder) to create pressure of about 50–60 MPa, and then to produce p = 250–500 MPa (which destroys ships) on a free surface — a damaging missile of 150 mm containing 1.5 kg of TNT. Armour piercing fin stabilized discretion sabot missiles, HEAT (high explosive anti-tank) *cumulative* missiles and also the EFP bombs contain such amount of TNT. The bombs EFP may penetrate the HRA armour of thickness (h) from 550 to 1300 mm with energy of explosive cumulative stream. Solid and split samples (of the same thickness) on new alloy 7020M of an increased size (ϕ 570 mm) were tested over an explosion in a cylinder and 250 x 250 mm slabs for 1.5 kg TNT detonation. Effectiveness of protection of the influence of TNT detonation under the explosive load of an alloy was better for split samples, even though there was penetration with some fragments of internal layer (from the side of explosion), which maintained the continuity of external slabs.

Author has also participated, to a limited extent, in a research project concerning impact resistance of ship structures of polyester and glass laminate exposed to a submarine explosion. For example, due to an explosion of 500–1000 kg load, on a ship traverse and causing pressure of ~ 250–500 MPa on its notch, the ship may sink or there might be a permanent damage of its construction. It requires searching for new high-strength products and efficient construction solutions, especially of strained elements of the hull of vessels, so that its use fully prevented various catastrophic or combat damages and sinking of all ships. Non-metallic materials, such as polyester and glass laminate, comply with those requirements better than metallic ones. Simulation studies conducted for the model hull structure of 207 ship project, which was made of polyester and glass laminate, were compared with the estimated distribution of pressures and stresses (deformations) on the hull studies at TNT detonation in the amount of 200 g to 37.5 kg in an intermediate explosion from the depth of 42 m and the distance of 420 m. The deformations of hull registered show that the ship maintains the desired stability, which guarantees appropriate operation of the ship. The anisotropic properties of the laminate demand verification of material characteristics of laminate and conduction of studies on a real object (ship 207P).

REFERENCES

[1] Jurczak W., *Impact and ballistic resistance of high-strength aluminium alloys intended for ship constructions*, 'Polish Maritime Research', 2015, No. 1, pp. 11–16.

[2] Jurczak W., Józwiak S., Świątek K., *Wielowarstwowe osłony balistyczne dla morskich i lądowych środków transportu bojowego*, 'Logistyka', 2010, No. 3, pp. 1683–1693 [*Multi-layer ballistic shields for naval and offshore structures of means of combat transport* — available in Polish].

[3] Jurczak W., Kyzioł L., *Dynamic properties of 7xxx series aluminium alloys at large strain rates*, 'Polish Maritime Research', 2012, No. 1, pp. 38–44.

ODPORNOŚĆ UDAROWA ALUMINIOWYCH KONSTRUKCJI OKRĘTOWYCH

STRESZCZENIE

W artykule podsumowano wyniki badań prowadzonych przez autora w ostatnich latach w Zakładzie Podstaw Budowy Maszyn Okrętowych Akademii Marynarki Wojennej. Wykorzystano do tego wybrane publikacje, w których opisano dokonania w zakresie podnoszenia odporności udarowej okrętowych stopów aluminium.

Stosowanie przekładek balistycznych, dzielenie w tej samej grubości czy stosowanie ceramiki to główne metody zwiększania odporności udarowej badanych stopów. Rewelacyjną skuteczność wykazują przekładkowe konstrukcje aluminiowe, których udarność w stosunku do litego materiału rośnie trzykrotnie. Tym samym znacznie polepsza się odporność na przebijanie pociskiem 7,62 mm i maleje defragmentacja (odłamkowość) podczas wybuchu. Każdy rodzaj okrętowego stopu aluminium chroni ceramika balistyczna o grubości 5 mm przy ostrzale pociskiem o E = 3 kJ. Stal Armox 500S może stanowić skuteczną ochronę stopów aluminium jako przekładka balistyczna podczas ostrzału 7,62 mm pociskiem B32.

Słowa kluczowe:

stopy aluminium, odporność udarowa, konstrukcje okrętowe.