# TESTING 10GHMBA STEEL FOR VESSEL BALLISTIC SHIELDS

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***Abstract***

*This paper presents the methods of testing the materials subjected to static and dynamic tensile tests, presented for 10GHMBA – E620 bainitic steel. The tests were conducted on the MTS 810.12 universal strength testing machine, a rotary hammer, a station especially designed for the conditions required for the Taylor test, an equipped ballistic pendulum and high-speed digital camera Phantom v12. The data collected in the tests are necessary for strength calculations of these constructions. The calculations are performed with the use of numerical methods and computing techniques, including constitutive equations for the performance description of a given material. Specific parameters and material constant values for the missile and the shield are accounted for in the equations. The parameters and constant values are either determined in experiments or 'selected', which is a significant issue in the case of high deformation speed. The final section presents examples of numerical simulations which enable the analysis of quick change processes which occur when a construction is subjected to strains due to strike with an object moving at a high speed, such as a 12.7 mm calibre missile moving at approx. 1000 ms$^{-1}$. The knowledge of mechanical properties of materials is crucial in designing constructions exposed to direct fire and other dynamic effects. The results are presented in the form of charts and graphs.*

***Keywords**: bainitic steel, static properties, dynamic properties, high deformation speed, impact testing machine, Taylor test, equipped ballistic pendulum, computer simulations*

## 1. Introduction

Due to significant threat of terrorist attacks on vessels, it is necessary to develop vessel ballistic shields. It mainly applies to vessels with steel plank hull. They are designed for protecting the key elements of vessels, such as commanding positions, storage spaces for hazardous cargo, crew accommodation, and for ensuring immunity to gun fire and shrapnels. Encountering fire attack should not lead to losing the integrity and functionality of the protected construction of the vessel. It is especially vital in the case of the vessel crew protected with the shield against missile attack, shrapnels of the falling remains of shot down missiles, armoured missiles or the effects of small calibre shellfire.

The vessels of the Polish Navy were not equipped with the above kind of shields, although such constructions are widely used in NATO countries. In rifle gun fire with bullet speed at approx. 1000 ms$^{-1}$ deformation speed is within the range of $10^4$ - $10^7$, in addition the performance description of the materials is rather complex, while determining the material properties is difficult and costly.

Computing techniques and numerical methods enable simulating the penetration process of a given material or a construction element by a missile moving at a particular speed. The only way to perform numerical simulations is by 'selecting' the required parameters, material properties, and the accuracy of selection can only by verified in experiments. In order to verify dynamic characteristics of the tested materials used in ballistic shields, it is necessary to prepare an adequate testing station.

The study objective is presenting the performance of the materials, in this case - 10GHMBA steel - at high deformation speed values, and the dynamic properties of the subject-matter steel used in anti-terrorist ballistic shields. The knowledge of mechanical properties of materials is crucial in designing constructions exposed to direct fire and other dynamic effects.

## 2. Scope of research

The issue of vessel ballistic shields which protect special accommodation and areas in the vessel against missiles and shrapnels is still the subject of extensive development.

When a missile strikes an obstacle, it usually induces local adiabatic cutting (HSIC - High-Speed-Impact-Cutting) and ballistic erosion, leading to local defragmentation (usually connected with partial melting of the shield and/or missile), as well as penetration or perforation of the shield. The hole (or crater) in the shield has a specific diameter and depth. Fragmented remains (shrapnels) of tempered steel missiles (diminishing at ballistic penetration) may show more plasticity than the 'sharp' and hard missiles (Fig. 1), as well as the blunt and brittle ones [5].

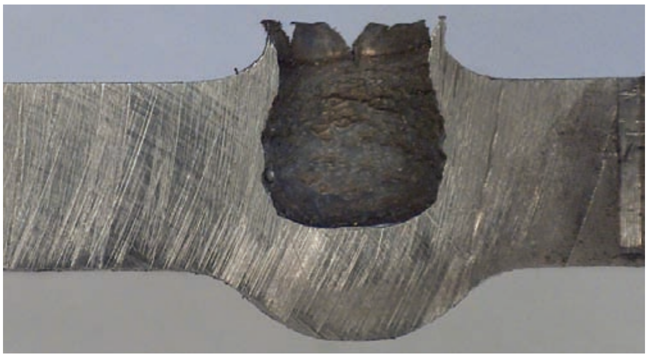


*Fig. 1. Macroscopic images of a crater filled with the remains of a fragmented and eroded bullet showing signs of HSIC in the steel shield cut*

Perforation mechanisms and ballistic effects usually vary – especially in metal shields of varying thickness, ductility and hardness – even in similar values of kinetic energy of missiles [5].

Strength calculations for these constructions are performed with the use of numerical methods and computing techniques including constitutive equations for the performance description of a given material. Specific parameters and material constant values for the missile and the shield are accounted for in the equations. They are either determined in experiments or 'selected', which is a significant issue in the case of high deformation speed. In order to verify dynamic characteristics of the tested materials used in ballistic shields, it is necessary to prepare an adequate testing station, sufficiently equipped to enable determining material properties at high deformation speed. The study results will enable practical verification of numerical calculations and, as a result, the assessment of penetration power of the tested materials. Therefore, a special testing station with an adequately equipped ballistic pendulum is used. This station is used for determining material properties at high deformation speed as induced in 7.62 and 12.7 mm calibre missile fire.

Determining the dynamic characteristics used for anti-terrorist shields at high deformation speed as induced in 7.62 and 12.7 mm calibre missile fire was preceded with static and dynamic trials up to the speed of 50 ms-1.

## 3. Static and dynamic tests of steel

The chosen testing material is 10GHMBA – E620T steel. It is bainitic steel of high hardness which can be used for ballistic shields. The chemical composition of steel is presented in Tab. 1.

The basic properties of 10GHMBA E620T steel were obtained in a tensile test conducted on an electro-hydrodynamic strength testing machine, type MTS 810.12. Samples were subjected to a dynamic tensile test performed on a rotary hammer at deformation speed of 40 m/s. Thanks to the measurement system applied it was possible to simultaneously measure the tensile force and deformation speed, and register the data on a digital oscilloscope.

*Tab. 1. Chemical composition of 10GHMBA E620Tsteel*

| Sheet thickness [mm] | Chemical composition [%] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 | C | Mn | Si | $P_{max}$ | S | Cr | Ni | Cu | Mo | V | Nb | Ti | Al | $N_2$ | B |
| | max .10 | .60 1.00 | .15 .35 | max .015 | max .010 | 1.00 1.40 | .40 .60 | .25 .45 | .40 .60 | - - | .015 .035 | .010 .030 | .02 .06 | max .009 | .025 .045 |

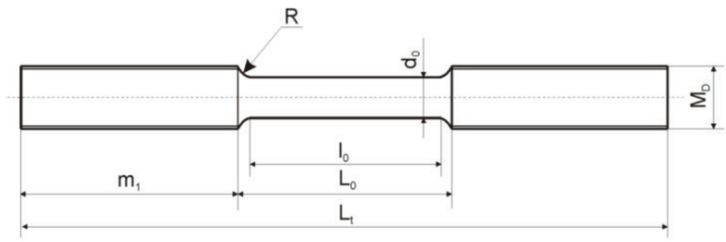



*Fig. 2. The shape and measurements of samples for testing the dynamic properties of 10GHMBA steel*

The shape and measurement of samples tested on a rotary hammer are presented in Fig. 2. Static tensile tests made it possible to determine:

- Young modulus $E$ = 209.073 GPa,
- limit for the application of Hooke's law $R_H$ = 518.5 MPa,
- yield strength $R_{0.2}$ = 695 MPa,
- tensile strength $R_m$ = 758.5 MPa.

Deformation speed: (2.6 E-5 - 5.1E-4) 1/s.

With the use of a rotary hammer with adequate accessories, dynamic properties of the tested steel for the deformation speed of 20 - 40 $ms^{-1}$ were determined.

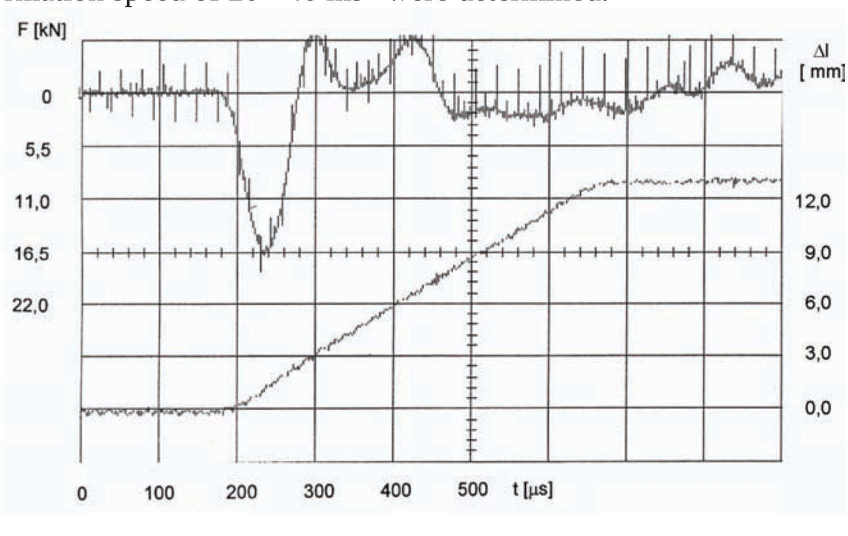



*Fig. 3. Relation between force F(t) and deformation Δl(t), and duration of the dynamic tensile test of a sample of 10GHMBA-E620T-U steel, subjected to strain at the speed of v = 30$ms^{-1}$ on a rotary hammer*

Figure 3 presents exemplary graphs of force and traverse dislocation for the dynamic tensile test performed on steel samples on a rotary hammer.

Figure 4 presents a collective graph of stress and deformation for 10GHMBA-E620T steel relative to deformation speed. In the case of the tested vessel steel, an increase in deformation speed up to 20 $ms^{-1}$ induces a considerable increase in mechanical properties, and in the range of 20 - 40 $ms^{-1}$ a slight increase in dynamic mechanical properties is observed in comparison to static tension.

Chart 2 presents the relation between the dynamic values of yield strength $R_{0.2d}$ and dynamic strength $R_{md}$, and appropriate static limit $R_{0.2}$ and $R_m$ values of the tested steel.

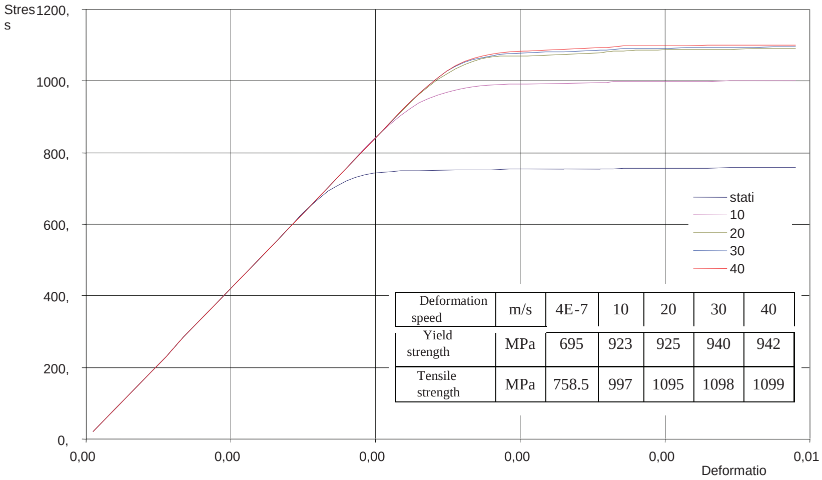
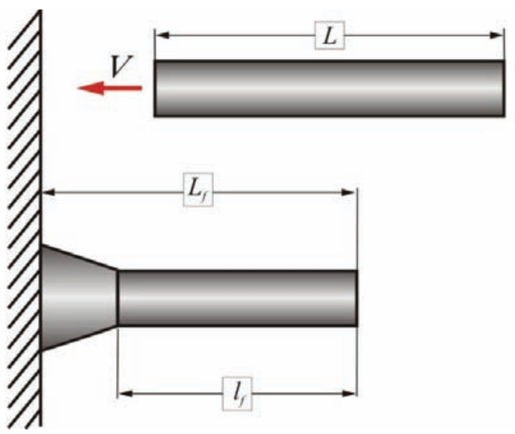



*Fig. 4. Graph: stress-deformation for 10GHMBA-E620T steel relative to deformation speed*

*Tab. 2. Relation between the maximum dynamic value of yield strength $R_{0.2d}$ and dynamic strength $R_{md}$ (for v = 40m/s), and appropriate static $R_{0.2}$ and $R_m$ values for 10GHMBA-E620T steel*

| 10GHMBA-E620 | Diameter | $R_{md}$ / $R_m$ | $R_{ed}$ / $R_{0.2}$ |
|---|---|---|---|
| | 5.0 | 1.37 | 1.37 |

Determining the mechanical properties of materials at crosshead speed above 100 $ms^{-1}$ is a rather complex process which requires appropriate equipment and description model. The model is based on the theorem developed by G. Taylor [1, 6]. The application of the theorem enables determining the dynamic yield strength of materials solely on the grounds of the results of geometrical measurements of a cylindrical sample (following a collision with a hard undeformable sheet) and the density of the sample material and speed of impact with the sheet [2]. The pattern illustrating the methods and the equation for estimating the dynamic yield strength $Y$ is presented in Fig. 5. The tests were conducted in Military University of Technology in Poland, in its Institute of Armament Technology on an especially prepared testing station [7].




$$Y = \frac{\frac{1}{2}\rho V^2\left(1-\frac{l_f}{L}\right)}{\left(1-\frac{L_f}{L}\right)\ln\left(\frac{L}{l_f}\right)}.$$

*Fig. 5. A pattern illustrating the Taylor method and equation for estimating the dynamic yield strength Y, where: $\rho$ - material density of cylindrical sample; V – impact speed; L – length of sample prior to impact; $L_f$ – total length of sample following impact; $l_f$ – length of the undeformed sample*

A cylindrical sample, whose measurements are presented in Fig. 6, was placed in a cartridge case, into which a weighed amount of powder had already been placed. By using a range of weighed powder amounts, a range of propulsion conditions (impact speed values) could be achieved.

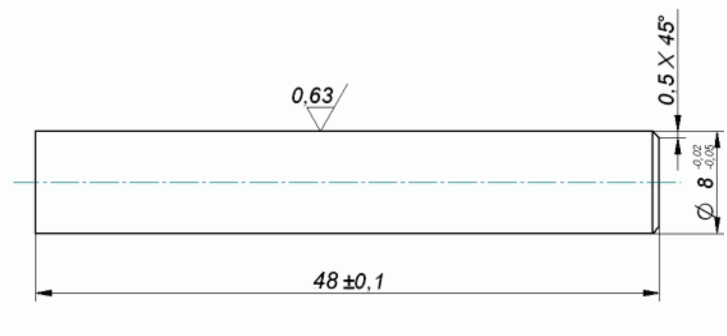



*Fig. 6. Measurements of the tested sample and the view of the sample placed in a case*

In order to determine the impact speed, a high-speed digital camera Phantom v12 capable of 2 $10^5$ fps was used. The speed of propulsion, mass and geometry of samples before and after the test, as well as the results of calculations for dynamic values of yield strength for an exemplary sample are presented in chart 3. Steel density of 7850 kg/$m^3$ was used in the calculations.

| Sample name | Diameter [mm] | Initial length $L$ [mm] | Mass [g] | Speed V [m/s] | Final length $L_f$ [mm] | Distance $l_f$[mm] | Dynamic yield strength $Y$ [MPa] | Comments |
|---|---|---|---|---|---|---|---|---|
| nr 3 | 7.953 | 47.978 | 18.633 | 212.98 | 41.626 | 19.5 | 1290 | |

*Tab. 3. A chart presenting the results of measurements and calculations for 10GHMBa steel samples*

10GHMBA steel was dynamically deformed in the propulsion range of 132 - 280 ms-1. For this range of deformation speed the mean value of yield strength Y was 1289 MPa, with standard deviation of 16 MPa.

In order to test the materials at crosshead speed of approx. 1000 ms-1 a special testing station was used - it was an adequately equipped ballistic pendulum.

Figure 7 shows a sample before and after being shot through on a ballistic pendulum. The photographs show samples which have been shot through. The samples have been photographed from the front, back and side and appropriate parameters were registered.

*Fig. 7. Shot through sample; front, back and side view*

Table 4 presents exemplary results of measurements of 10GHMBA steel samples for a range of thickness values.

*Tab. 4. Results of measurements in penetration power tests of 10 GHMBA steel sample*

| sample thickness | force registered on dynamometer | missile speed in front of the sample | missile speed behind the sample | the angle of pendulum inclination |
|---|---|---|---|---|
| *mm* | *kN* | *m/s* | *m/s* | *°* |
| | none | 818.0 | none | 14.20 |
| *32* | 730.6 | 826.0 | none | 14.23 |
| | 725.6 | 830.0 | none | 14.30 |

The process of material perforation by the bullet consists in transforming the energy carried by the bullet into the energy of sample deformation, generated heat, works of pendulum, etc. The thicker the sample, the stronger the force impulse registered by the dynamometer in the pendulum when a sample is thick enough to stop a bullet, force reaches maximum values. Increasing the sample thickness, above this value, results in a minor increase in force as registered by the dynamometer. This change in force impulse relative to thickness is similar to the relation between the angle of pendulum inclination and thickness. When thickness value is larger than the value at which a missile is stopped, the angle value increases slightly. The conducted tests show that in the case of 10GHMBA – E620 steel, minimum thickness of plating which stops a 12.7 calibre missile is approx. 32 mm.

## 4. Simulation trials

Numerical simulations were conducted with the use of commercial software, which enables the analysis of quick change processes which occur when a construction is subjected to strains due to impact of an object moving at a high speed. For the purposes of the simulations, spatial geometry of the sample and missile was illustrated, and discretization of the missile along with the sample was performed. Preliminary simulation was performed to assess the results of the sample thickness measurements against calculation results. Computer software for calculating quick change processes enable following movement parameters, stress level, deformation, displacement, internal forces and other factors as the process progresses.

Figures 8 and 9 below show exemplary results of numerical calculations for a tested 32 mm thick sample made of 10GHMBA steel subjected to perforation with a stiff 12.7mm calibre missile.

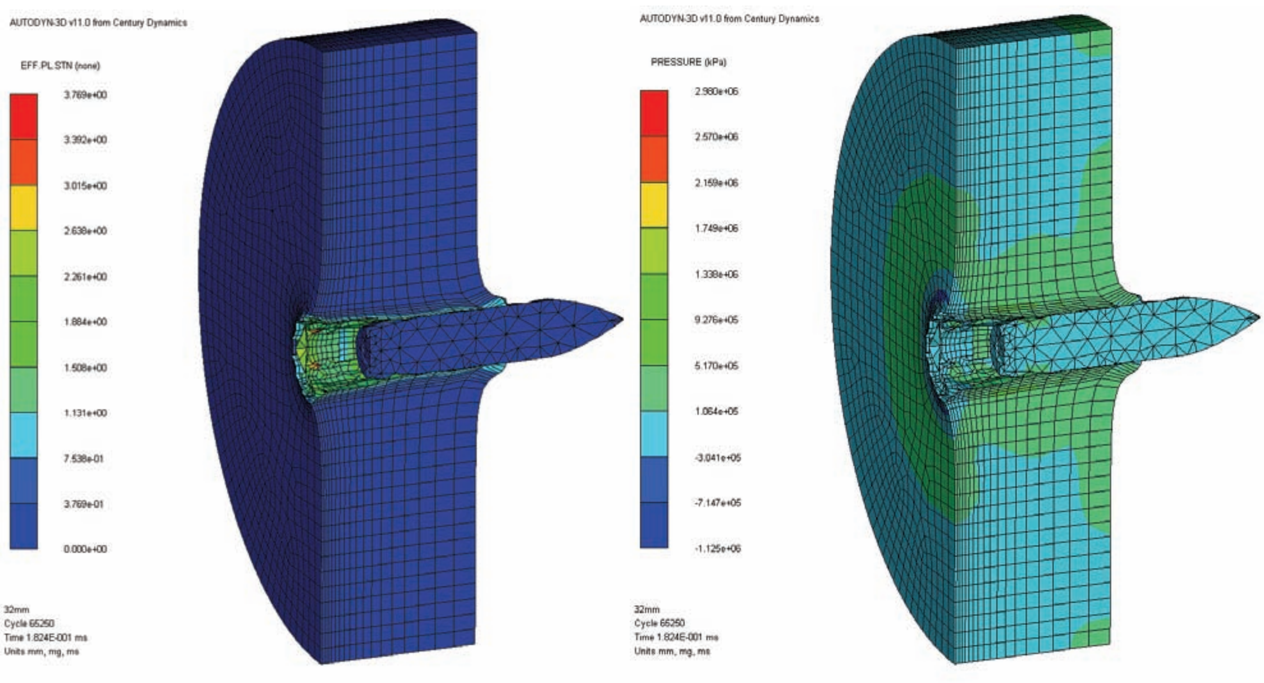



*Fig. 8. Plastic deformations and distribution of pressure while perforating a 32 mm thick 10GHMBA steel sample*

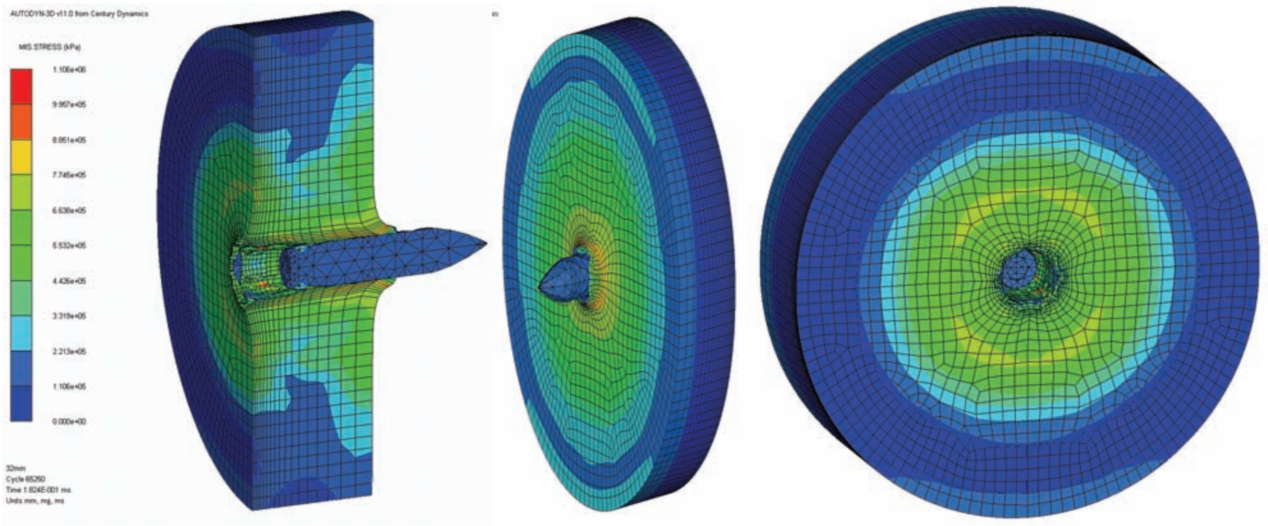


*Fig. 9. Distribution of stress while perforating a 32 mm thick 10GHMBA steel sample*

## 5. Conclusions

The verification of dynamic characteristics of the tested steel used for ballistic shields was possible thanks to preparing adequate testing stations equipped in appropriate measurement tools to ensure the measuring of appropriate physical values. As the physical values became known, it was subsequently possible to compare them with the values calculated in the numerical simulation. As a result, the obtained calculation results enabled the assessment of the quality of the numerical simulation in terms of the coefficient values used in calculations.

The calculation results indicate that for 10GHMBA – E620 steel the minimum shield thickness which stops a 12.7 calibre missile is approx. 27 mm, whereas the measurements indicate the thickness of 32 mm. In the calculating model the precise shape of a missile was not accounted for, which resulted in the 15% error. The simulation enabled illustrating the distribution of extreme reduced stress which occurred on the sample. The simulation result of perforating steel plating with a missile moving at a high speed is described, inter alia, by constitutive models of Huber-Misses and Johnson-Cook [1-4].

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