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SELECTED ISSUES OF INCREASING THE FIRE EFFECTIVENESS OF COMBAT VEHICLES
Wybrane problemy zwiększenia efektywności ogniowej wozów bojowych

Abstract: *The research paper reviews selected issues associated with the current state of the armoured (tanks) and infantry fighting vehicle technology, with particular emphasis on the operating effectiveness of elongated sub-calibre projectiles fired from tank guns, which enable full perforation of ca. 500 mm thick armour steel plates. Their efficiency is comparable with the impact of shaped heads with armour steel penetration capabilities, and amounts from 6 to 8 calibres – warhead diameters. Furthermore, the paper discusses a numerical analysis, which shows the velocities of elongated projectiles (of tungsten matrix sinters) required to achieve a determined armour steel penetration depth. In addition, it also presents the performance characteristics of two 100 mm calibre shaped warheads, with copper inserts and apex angles of 51º and 60º.*

Keywords: armament, sub-calibre projectiles, terminal ballistics, shaped charges

Streszczenie: *W artykule przedstawiono wybrane problemy dotyczące aktualnego stanu techniki pancernej (czołgów) oraz wozów bojowych piechoty, ze szczególnym uwzględnieniem skuteczności działania wydłużonych pocisków podkalibrowych wystrzeliwanych z armat czołgowych, umożliwiających pełną perforację płyt ze stali pancernej o grubościach około 500 mm. Ich skuteczność porównywalna jest z oddziaływaniem głowic kumulacyjnych o zdolności penetracji stali pancernej, wynoszącej od 6 do 8 kalibrów-średnic głowicy. W pracy ponadto przedstawiono analizę numeryczną, pokazującą jakie są wymagane prędkości pocisków wydłużonych (ze spieków na osnowie wolframowej) dla uzyskania określonej głębokości penetracji w stali pancernej. Ponadto zaprezentowano charakterystyki działania dwóch głowic kumulacyjnych o kalibrze 100 mm z wkładkami z miedzi o kątach wierzchołkowych 51º i 60º.*

Słowa kluczowe: uzbrojenie, pocisku podkalibrowe, balistyka końcowa, ładunki kumulacyjne

1. Introduction

The theory of operational activities and the experience gained during armed conflicts worldwide indicate that contemporary combat is of airborne and land nature. Such operations entail new threats for combat vehicles from assault aircraft and helicopters, armed with anti-tank measures, primarily with smart ammunition and mining systems. An air strike is possible at any time of the day and at any place. This is enabled by satellite and air reconnaissance systems. A feature of modern combat operations is the high dynamics of situation changes and the manoeuvring nature of military activities.

Given the fact that in the light of the new political circumstances, the Polish Land Forces should be prepared to execute tasks as part of potential operations domestically, as well as abroad, within allied and multinational groups, which is why the armament of combat vehicles ought to provide effective operation of sub-units in all conditions. This is why, given previous analyses, the development of these weapons needs to be focused primarily on:

- increasing target detection abilities, especially at night and in adverse weather conditions, over significant distances,
- increasing the probability of hitting a target with the first projectile over significant distances,
- improving the effectiveness of inflicting damage on a target, using new ammunition types,
- gaining the ability to effectively combat air targets.

There are two basic methods to modernize armament (including combat vehicles) in practice – through the purchase and utilization of own defence industry capabilities. It seems that importing ready-made armoured technology would be pointless, mainly due to economic and social reasons, as well as owned production facilities. This aspect is extremely important, since by deciding to manufacture armoured technology domestically, local defence industry is given a chance to be maintained, e.g. by creating job vacancies for thousands of workers and specialists.

Another issue is the funding of research work on new armament systems for combat vehicles. The worldwide development of armoured technology follows two primary tracks, namely, work commissioned by states (Germany, Great Britain, USA) and work conducted by individual companies (France, Italy). Due to the fact that the financial situation of our armament companies, solely state-owned, does not give them an opportunity to individually undertake tasks for economic reasons, the scheme involving the construction of modern armoured technology should be a government program.

The further section of this publication (cl. 2) discusses the issues regarding the current state of the armoured (tanks) and infantry fighting vehicle technology. Clause 3 presents an analysis, based on numerical simulations, which shows the velocities of sub-calibre elongated projectiles required to achieve a specific armour steel penetration depth. In addition, it also presents the performance characteristics of two 100 mm calibre shaped warheads, with copper inserts and apex angles of 51º and 60º.

2. Domestic modernization of armament systems for combat vehicles

The armament quality in combat vehicles owned by the Polish Armed Forces does not fully correspond to the anticipated tasks and falls far from global standards. In particular, this applies to T-72 tanks and BWP-1 infantry fighting vehicles. There are no sufficient funds to purchase or construct completely new tanks and infantry fighting vehicles. Hence the need to undertake tasks increasing the combat effectiveness of tanks, infantry fighting vehicles and armoured personnel carriers, mainly through their modernization.

2.1. Modernization of tanks

The previously conducted analyses clearly show that the modernization of T-72 tanks, combined with replacing the tank gun with a 120 mm cal. one is unprofitable, and the achieved results will be of questionable quality due to the need to adopt numerous compromises associated with joining solutions developed in different periods, under the influence of varying approaches towards the tank engineering process. Furthermore, as indicated by the results of work on the modernization of T-72 tanks (mainly in Russia) [14], the disadvantages of the 125 mm gun can be largely mitigated – it mainly concerns the ammunition used. The effectiveness of new ammunition with 125 mm high-explosive and armour-piercing shells is comparable to 120 cal. ammo [11].

For the T-72M/M1 and PT-91 tanks to be able to effectively combat third-gen tanks, they should be equipped with sub-calibre shells, capable of penetrating 500 mm thick armour (approximate, reduced armour thickness of third-gen tanks). These requirements are satisfied by the new APFSDS-T sub-calibre shell for a 125 mm tank gun, developed by the Military Institute of Armament Technology (MIAT) and implemented for manufactured by Mesko S.A. Introducing this shell into a fire unit will increase the firepower of T-72 and PT-91 tanks against heavily armed targets [15].

MIAT also constructed and Mesko S.A. implemented 125 mm blank cartridges, which involves sub-calibre, shaped and high-explosive shells. Using this ammunition will enable training in conditions fully reflecting the nature of a battlefield. The training process is one of the most important factors impacting combat efficiency in peacetime. The ability to train soldiers in conditions as close to war as possible, enables reaching their high combat prowess. The application of, among others, specialized blank cartridges provides a possibility to reflect battlefield conditions during field training [17].

Over the recent years, Polish Army units introduced Leopard-2 tank equipped with the Rh120L44 120 mm smoothbore gun, which had previously been using shells combined with the APFSDS-T armour-piercing sub-calibre shells and HEAT shaped shells, treated as multi-purpose cartridges. However, according to current views, multi-purpose shells are not effective against anti-tank armour-piercing weapon stations, armoured carriers, as well as infantry, especially at long distances and with the targets behind vertical obstacles or building walls. The LEOPARD-2 tanks introduced for use by the Polish Army are equipped with a complete set of ammunition, which will be gradually consumed as they are operated, therefore, it will need to be supplemented. This will particularly apply to bullets with blank cartridges, which are used in greater amounts, than combat cartridges, during peacetime. Therefore, there was a need to simultaneously develop shells with a combat and blank cartridge.

It was developed under the supervision of MIAT, and comprises a new family of 120 mm cartridge for Leopard-2A4 tanks. They are high-explosive and sub-calibre cartridges, both blank and combat. The introduction of new sub-calibre ammunition significantly increases the firepower of the Leopard-2 tank against heavily-armoured targets, through improving ammunition parameters – enhanced armour penetration up to 500 mm. Whereas the introduction of high-explosive shells to a fire unit expands the fire capacity of this tank in terms of combating fortified points of resistance in cities, as well as mountainous and forested areas. It should also be mentioned that the modernization of the Leopard-2A4 tank used by the Polish Army to 2PL version (fig. 1) has already commenced, and its scope involves, among others:

- modernizing observation and targeting devices of the commander and gunner,
- additional ballistic shielding of the turret,
- replacing the hydraulic stabilization of the gun and turret drive with electric,
- installation of a fire-fighting and anti-explosion system,
- application of a new control and monitoring system for the commander,
- installation of an additional APU unit,
- equipping the tank with additional baskets for extra equipment and adapting the towing and evacuation equipment to the increased mass of the tank,
- modernizing the gun along with adapting to the use of new ammunition types,
- application of the day and night reversing camera for the driver.

Fig. 1. The Leopard-2A4 used by the Polish Army

The contemporary battlefield requires tanks to increase the scope of executed tasks. They include defending against combat helicopters and combating hidden targets. Current combat helicopters can effectively attack combat vehicles from a distance of 6÷7 km. Tanks are able to respond efficiently from a distance of 2÷3 km. These are values highly unfavourable for tanks. Hence the use of high-explosive shells, and ultimately, special type with delay-action fuses programmable prior to firing, can significantly improve the firepower of T-72, PT-91 and Leopard-2 tanks, while maintaining the current driving dynamics, i.e., without increasing the mass of the tank. Such a solution has been proposed by the Military Institute of Armament Technology, and it comprises a tank anti-helicopter artillery system [6].

An important direction in terms of the modernization of Polish tanks is increasing the firepower by improving and expanding fire control systems (SKOs), particularly applicable to the T-72 tank, which in practice almost does not have it. The introduction of a new SKO would have to be based on solutions applied within the Polish-made PT-91 tank (fig. 2), taking into account the results of successive work conducted at the Przemysłowe Centrum Optyki S.A. involving periscopes and gunsights [5].

Fig. 2. The Polish PT-91 tank

The Przemysłowe Centrum Optyki S.A. suggests modernizing the observation and targeting devices of T-72M/M1 vehicles in two variants of the optoelectronic equipment.

The first variant involves modernizing the TKN-3/3B commander’s observation device and the TPN-1-49-23 gunsight, and the replacement of the mechanic-driver's observation device with a next-gen PNK-72 (fig 3) – already fitted, among others, in PT-91 tanks, WZT-3 technical support vehicles and the BRDM-2 recon vehicles).

The second variant involves replacing the commander’s observation device with a next-gen POD-72 Liswarta (fig. 4) - fitted in, among others, PT-91 tanks, WZT-3 technical support vehicles and BRDM-2 recon vehicles), replacing the mechanic-driver’s observation device with the PNK-72, and modernizing the TPN-1-49-23 gunsight.

Fig. 3. PNK-72 next-gen mechanic-driver's observation device

Fig. 4. POD-72 Liswarta next-gen commander's observation device

Modernization variant selection depends on the technical condition of active devices intended for modernization. Modernization enables increasing the range of sight and effective fire in night-time conditions thanks to the retrofitted night-vision sight of the gunner from 800 to 2000 m. Whereas respective ranges, using the TKN-3Z tank commander's observation device or the new POD-72 Liswarta were increased from 400 to 1200 m. The application of the new PNK-72 Radomka driver's night-vision sight increased his/her vision range from 100 to 300 m. Tank unmasking was eliminated by removing infrared illuminators.

Therefore, it should be stated that the aforementioned retrofitting proposals would increase the fire effectiveness of tanks used by the Polish Army. They would improve the primary armament efficiency and enhance the possibilities of firing at night and in adverse weather conditions [4].

2.2. Modernization of infantry fighting vehicles

Infantry fighting vehicles (IFVs) are armed and armoured combat vehicles, mostly crawlers (and/or wheeled vehicles similar to armoured personal carriers, if armed with a gun of at least 20 mm cal.), intended for carrying and providing fire support for mechanized infantry soldiers on the battlefield. The best known, and also one of the oldest infantry fighting vehicles in the Polish Armed Forces is the BWP-1 (fig. 5).

Fig. 5. BWP-1 infantry fighting vehicle

It is of Russian design and exhibits numerous advantages required of a modern combat measure, especially in terms of manoeuvrability, as well as overcoming water and terrain obstacles. However, its combat value is rather law, which mainly results from the fitted weapons. The smoothbore, unstabilized 73 mm gun enables firing only with armour-piercing and frag bullets. Its effectiveness at distances exceeding 900 m does not allow for engaging in even combat with the IFVs of other countries, armed with 25-40 mm guns, able to destroy IFVs and armoured carried over distances of up to 2500 m [3]. Due to these drawbacks, the most important aspect of their modernization is the turret system. Developing and constructing such a system in domestic conditions is quite unrealistic. Therefore, a feasible solution is to purchase a turret system abroad. Conducted analyses indicated that this could be the HITFIST 30 turret system by OTO MELARA, which is fitted, among others, in the Polish ROSOMAK armoured personnel carrier. Such an approach has several pros, such as lowering the retrofitting costs, if only because the 30x173 mm Nammo ammunition is currently manufactured in Poland [10].

Another element of the BWP-1 modernization is replacing the ATGM Malutka with a next-gen ATGM, such as, e.g. the ATGM Spike offered by a Polish manufacturer (ZM MESKO), the performance parameters of which enable combating heavily-armoured targets at distance from 200 to 4000 m [12].

It is also rather important to install an automatic grenade launcher on the BWP-1, which is fitted on combat vehicles by almost all major armies of the world. Automatic 40 mm grenade launchers are manufactured in Poland by ZM Tarnów. They utilize shells developed by ZM Dezamet S.A. Works in this regard are ongoing and equipping BWP-1 with these grenade launchers in the future would significantly expand their fire capabilities with combating infantry and hidden targets at close ranges.

The AMV Rosomak wheeled armoured personnel carriers are the most modern combat vehicles used by the Polish Armed Forces (fig. 6).

Fig. 6. AMV Rosomak wheeled armoured personnel carrier

They are equipped with state-of-the-art weapons, which satisfy the requirements of a contemporary battlefield. Their armament enables combating lightly armoured vehicles and combat helicopters. The fire guidance system enables firing while the vehicle is moving, day and night, and in adverse weather conditions. One of the upgrade options (offered by the Polish industry) for the WAMC Rosomak can be the introduction of a new ammunition type. Such as, e.g. the multi-purpose Ahead offered by Radwar S.A., under participation of MIAT. This system can be adapted to the BWP-1, which would enable expanding the fire capabilities of these vehicles with more effective combating of attack helicopters, anti-tank missiles and hidden targets.

3. Evaluating the operational effectiveness of selected elongated sub-calibre projectile designs and shaped warheads

The evaluation was based on conducted numerical simulations involving the penetration of elongated projectiles into armour steel plates. It involved analysing six projectile-plate system variants, which differed in terms of impact velocities and the strength properties of armour steel. A 530 mm long projectile, 23 mm in diameter, made of tungsten matrix sinter (with an approximately 7% addition of iron and nickel), with a density of 17.3 g/cm^3 was selected. Plate dimensions: thickness 700 mm and diameter 475 mm were chosen to model penetration into the semi-space. The calculations were conducted for initial velocities of the projectiles of: 1250; 1550 and 1800 m/s (variants 1, 2 and 3, respectively) when hitting an armour plate steel, variant 1, and 1000; 1250 and 1550 m/s (variants 4, 5 and 6, respectively) when hitting an armour plate steel, variant 2.

The calculations were conducted using the numerical method of free points [7], adapted in particular to solving 2D, non-stationary problems of elasto-plastic movement of solids (metals, ceramics), exposed to high dynamic loads and subject to strong strains. This method, apart from the four basic conservation (mass, momentum and inner energy) equations and four partial differential equations for the components of the stress tensor deviator, is expanded with material state equations, a model describing the strength properties of the elasto-plastic body in Jonhson-Cook form and the condition of material plastic flow (Mises), as well as the gap formation model.

An elasto-plastic body model was used to describe the behaviour of metals under strong, dynamics loads appearing upon armour penetration by a projectile. This model was presented in this section of the paper in its full, compact form.

Designations of values used in the equations: t – time, ρ – density, w – mass velocity vector along the r and z coordinates, respectively; p – pressure, e – inner energy, T – temperature, ρs – solid phase density, $\hat{\sigma}$ – stress tensor, S_{ik} – stress tensor deviator components, $\overset{\nabla}{S}_{ik}$ – Jaumann derivative, Y – bar material dynamic yield stress, μ – shear modulus, ε^p_{ik} – plastic strain tensor components, ε^p – equivalent plastic strain, $\dot{\varepsilon}^p$ – equivalent plastic strain change rate, V_c – gap specific volume, $T_* = (T - T_0)/(T_m - T_0)$, T_0, and T_m – initial temperature and melting point, respectively.

The values present in the equations (3.1-3.23): k_1, k_2, k_3, e_{00}, e_{01}, e_{02}, e_{03}, e_{04}, γ, ρ_0, ρ_{S1}, ρ_{S2}, n, m, A, B, C, μ_0, σ_{00}, Y_0, Y_{max}, T_m, V_{c1}, V_{c0}, ψ– constant coefficients.

The equation system expressing the laws of momentum, mass and energy conservation (axial symmetry) is of the following form [8,16,18,20]:

$$\frac{d\rho}{dt} + \rho\nabla \cdot \vec{w} = 0 \tag{3.1}$$

$$\rho\frac{d\vec{w}}{dt} = \nabla \cdot \hat{\sigma} \tag{3.2}$$

$$\rho\frac{de}{dt} = \hat{\sigma} \cdot \nabla\vec{w} \tag{3.3}$$

$$\overset{\nabla}{S}_{ik} = 2\mu\left(\dot{\varepsilon}_{ik} - \frac{1}{3}\dot{\varepsilon}_{ii}\delta_{ik}\right) \tag{3.4}$$

The plastic flow condition for metals was adopted in the Mises form:

$$S_{ij}S_{ij} \le \frac{2}{3}Y^2 \tag{3.5}$$

Equation of state for metals was adopted as:

$$p = k_1 x + k_2 x^2 + k_3 x^3 + \gamma \rho e \tag{3.6}$$

$$x = 1 - \frac{\rho_0}{\rho_S}\ , \quad k_2 = 0 \quad \text{dla} \quad x < 0 \tag{3.7}$$

Metal temperature can be determined from the relationship:

$$T = 300 \frac{e_0 - e}{e_{00}} \tag{3.8}$$

$$e_0 = e_{00} + e_{01} x + e_{02} x^2 + e_{03} x^3 + e_{04} x^4 \tag{3.9}$$

A modified model utilizing elements of the Steinberg – Guinan and Johnson – Cook models was used to describe the strength properties and had the following form:

$$Y = \left[A + B \cdot \left(\varepsilon^p \right)^n \right] \cdot \left(1 + C \ln \dot{\varepsilon}_*^{\,p} \right) \cdot \left(1 - T_*^{\,m} \right) \cdot F\left(\rho_S \right) \tag{3.10}$$

$$\left[A + B \cdot \left(\varepsilon^p \right)^n \right] \le Y_{max} \tag{3.11}$$

$$Y = 0 \quad \text{dla} \quad T > T_m \tag{3.12}$$

$$\mu = \mu_0 \left(1 - T_*^{\,m} \right) \cdot F\left(\rho_S \right) \tag{3.13}$$

$$\varepsilon^p = \frac{\sqrt{2}}{3} \left[\left(\varepsilon_{rr}^p - \varepsilon_{zz}^p \right)^2 + \left(\varepsilon_{rr}^p - \varepsilon_{\varphi\varphi}^p \right)^2 + \left(\varepsilon_{zz}^p - \varepsilon_{\varphi\varphi}^p \right)^2 + \frac{3}{2} \left(\varepsilon_{rz}^p \right)^2 \right]^{1/2} \tag{3.14}$$

$$F\left(\rho_S \right) = \begin{cases} 1 & \text{dla} \quad \rho_S \ge \rho_{S1} \\ \dfrac{\rho_S - \rho_{S2}}{\rho_{S1} - \rho_{S2}} & \text{dla} \quad \rho_{S2} \le \rho_S < \rho_{S1} \\ 0 & \text{dla} \quad \rho_S < \rho_{S2} \end{cases} \tag{3.15}$$

The limitation of strength properties by emerging gaps were modelled by multiplying Y μ and k_1, k_2 and k_3 by a respective $G(V_c)$ function:

$$Y^T = Y \cdot G(V_c), \qquad \mu^T = \mu \cdot G(V_c), \qquad (k_1, k_2, k_3)^T = (k_1, k_2, k_3) \cdot G(V_c) \quad (3.16)$$

The $G(V_c)$ function was taken in the form

$$G(V_c) = 1 - \rho V_c \quad (3.17)$$

Equation system describing the gap volume growth dynamics, taken as in the modified Fortow model [1,9,19]:

$$\frac{dV_c}{dt} = -k\,\mathrm{sign}(p) \cdot \left[|p| - \sigma_0 \right] (V_c + V_{c0}) \quad \text{for} \quad |p| \geq \sigma_0 \quad (3.18)$$

$$\frac{dV_c}{dt} = 0 \quad \text{for} \quad |p| < \sigma_0 \quad (3.19)$$

$$\frac{1}{\rho} = V_c + \frac{1}{\rho_s} \quad (3.20)$$

where:

$$\sigma_0 = \sigma_{00} \cdot F(\rho_S) \cdot H(\varepsilon^p) \cdot (1 - T_*^m)\, G_1(V_c) \quad (3.21)$$

$$G_1(V_c) = \frac{V_{c1}}{V_{c1} + V_c} \quad (3.22)$$

$$H(\varepsilon^p) = \exp(-\psi\, \varepsilon^p) \quad (3.23)$$

The coefficient values are given in the table below (γ constants are 2.17 and 1.54 for steel and tungsten, respectively).

Table 1

Values of the coefficients present in the equation of state, gap formation model and Johnson-Cook model for steel (Steel, Steel 1, Steel 2) and the tungsten matrix sinter (Tungsten).

Material	ρ_0	k_1	k_2	k_3	e_{00}	e_{01}	e_{02}	e_{03}	e_{04}
	$\frac{g}{cm^3}$	GPa	GPa	GPa	$\frac{J}{10^2 \cdot g}$	$\frac{J}{10^2 \cdot g}$	$\frac{J}{10^4 \cdot g}$	$\frac{J}{10^4 \cdot g}$	$\frac{J}{10^4 \cdot g}$
Steel	7.9	164.8	312.4	564.9	-1.34	-2.908	1.012	2.051	2.901
Tungsten	17.3	285.0	484.0	762.0	-0.407	-0.627	0.8068	1.336	1.604

Material	A	B	C	m	n	Y_{max}	T_{m0}	ρ_{S1}	ρ_{S2}
	GPa	GPa	-	-	-	GPa	K	$\frac{g}{cm^3}$	$\frac{g}{cm^3}$
Steel 1	0.600	0.312	0.006	1.0	0.37	2.0	1.793	6.87	5.84
Steel 2	0.792	0.510	0.012	1.0	0.26	2.0	1.793	6.87	5.84
Tungsten	1.506	0.177	0.016	1.0	0.12	4.0	1.723	15.0	0.0

3.1. Characteristics of the process of an elongated projectile penetrating an armour steel plate

The aforementioned numerical calculation method enables generating calculation results in the form of text files for selected times. For a given moment it provides quantitative information, which determines the values of all interesting physical quantities in space (r, z). Instantaneous positions of projectile or plate elements (R, Z) and the physical quantities (velocities (Uz- axial, Ur - radial), pressure, density, temperature, equivalent plastic strain) are assigned to the initial (t = 0) position of these elements. These elements can be freely selected. This can be a single element resulting from the numerical, initial division of the calculated space or a group of such individual elements. Within the case under consideration, it is justified to isolate radial elements determined with the values of their initial axial positions (z_0=Z(0)=const) and longitudinal elements for fixed initial values of their radius (r_0=R(0)=const). This way, it is possible to observe instantaneous strains of such specified elements in space (r, z) and corresponding physical quantity distributions along these elements.

Figure 7 and fig. 8 show a sample, instantaneous (t = 300 μs) crater image (axial half-section) and strain geometries for selected elements in the plate and projectile, respectively. The initial positions of these elements are given in the description of the figures. It can be seen that the crater consists of two layers, with deformed and pushed plate elements (plate material) in the outer layer, and arranged projectile elements, gradually flowing out of the penetration zone in the inner layer. Crater envelopes – the outer envelope is formed by a longitudinal plate element with an initial radius of $r_0 = 1.15$ cm, which corresponds to the projectile edge, whereas the inner one is formed by the longitudinal projectile element (with the exact same radius, as above). The division boundary is generated by the longitudinal plate element, initially within the axis of symmetry. The maximum value of the radial coordinate of this plate element can be adopted as the crater diameter - R_{kr}. For a given moment, the crater face axial position is determined as the maximum axial coordinate value for a radial element of a projectile, located at the face of the projectile just before radial outflow (in fig. 8 this element has an initial coordinate of z_0=-18.8 cm, and a current coordinate of $z_{cz} = Z\,(z_{0,}300) = 21.43$ cm).

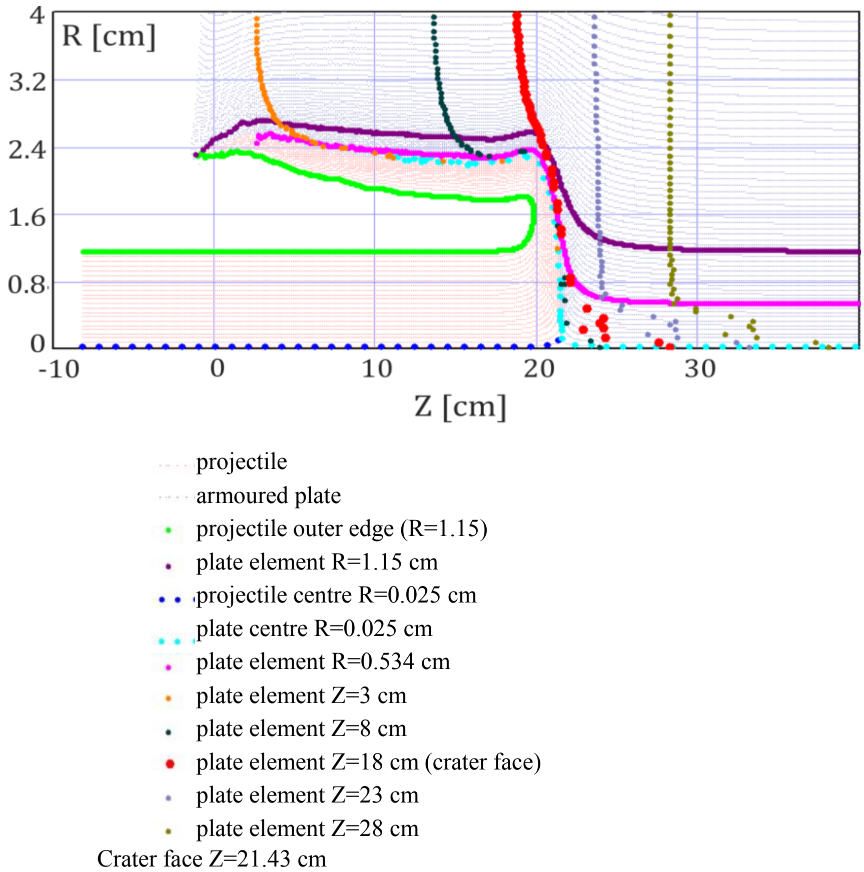


Fig. 7. Illustration showing the strain and position of selected armour plate elements at the moment of penetration within a plane (R, Z), at 300 µs

This coordinate determines the instantaneous projectile penetration depth - L_{kr} (z_0 =0 – plate edge). The difference $L_p = L_{kr} - Z(-L_0, t)$ is the instantaneous projectile length (where L_0 – its initial length). The crater face position change over time determines the projectile penetration velocity (U):

$$\frac{d}{dt}L_{kr} = U \tag{3.24}$$

The instantaneous projectile velocity (V) is determined similarly:

$$\frac{d}{dt}Z\left(-L_0, t\right) = V \tag{3.25}$$

The kinematics show that the shortening of the projectile over a time unit will amount to:

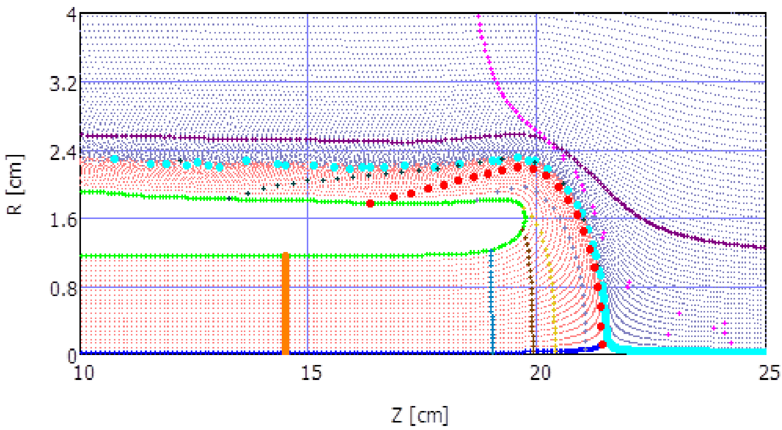
$$\frac{d}{dt}L_p = -\left(V - U\right) \tag{3.26}$$

The penetration efficiency can be determined as the ration between the instantaneous increase in the crater depth and the instantaneous projectile consumption (shortening), namely:

$$dPdl = \frac{\frac{d}{dt}L_{kr}}{\frac{d}{dt}L_p} = \frac{U}{-\left(V - U\right)} \tag{3.27}$$

Successive fig. 9 and fig. 10 compare the waveforms of *U, V,* L_p, L_{kr} in the penetration time function for variants 3 and 4, whereas fig. 11 compares corresponding penetration efficiencies in the function of relative penetration depth. The initial projectile velocity, over a period of approximately 100 μs, is equal to the initial value, and after the strain wave reaches from the penetration zone to the projectile free edge, it decreases almost linearly over time, to 600 μs in the case of a projectile penetrating Steel 1 and to 500 μs for Steel 2, which has higher strength. The penetration velocities, also in approximation, decrease linearly over time. After these periods, the projectile shortens by 80%, and the relative penetration depths are 0.8 and ca. 0.65, respectively. Ultimate, relative penetration depths are 0.94 and 0.72, respectively. These results are the outcome of the difference in penetration efficiencies (fig. 11), resulting from the strength of armour plates. The projectile is almost entirely consumed in both cases.

The illustration shows 3 longitudinal elements, determined by the initial radial positions (R = 0.025, 5.34 and 1.15 cm) and 6 radial elements (their initial axial positions are given in the description of the figure). The longitudinal elements, central and the one corresponding to the projectile outer edge (R = 0.025 and 1.15 cm) are strongly strained and displaced in the radial direction, creating a crater outer periphery envelope, with successively inflowing parts (limited by the initial radius R = 1.15 cm) of plate radial elements. The outer periphery of the crater is filled with the projectile material.



projectile
armoured plate
projectile outer edge (R=1.15 cm)
plate element R=1.15 cm
projectile centre R=0.025 cm
plate centre R=0.025 cm
plate element Z=18 cm (crater face)
projectile element Z=-30.3 cm
projectile element Z=-14.8 cm
projectile element Z=-18.8 cm (crater face)
projectile element Z=-21.9 cm
projectile element Z=-23.8 cm
projectile element Z=-24.6 cm
projectile element Z=-25.7 cm

Crater face Z=21.43 cm

Fig. 8. Figure showing the strain and position of selected projectile elements within the penetration zone in plane (R, Z), at 300 µs

The description of the figure contains the initial positions of these elements. The successively enter the penetration zone, flow out of it and stack up on the outer periphery of the crater. The longitudinal peripheral element of the projectile (R = 1.15 cm) constitutes the outer envelope of this periphery.

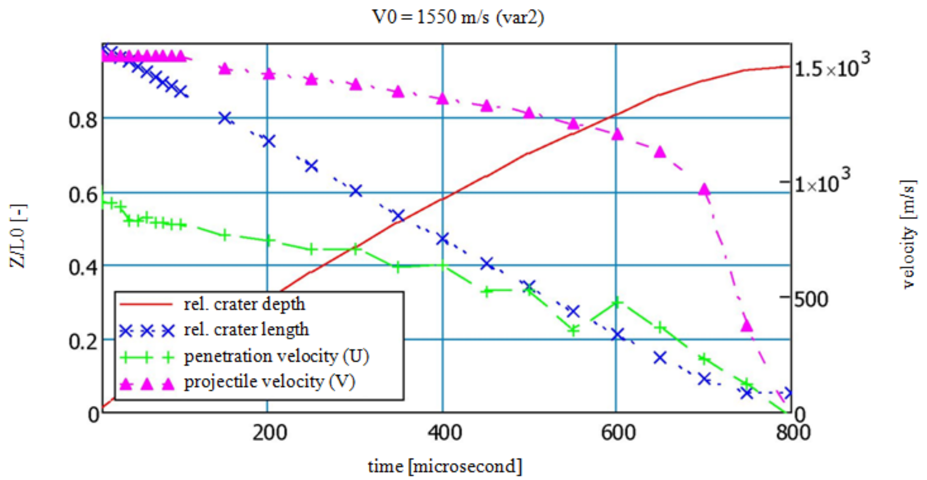


Fig. 9. Waveforms of a projectile penetrating armour steel 1: relative crater depth; relative projectile length and penetration velocity (U), as well as current projectile velocity (V) in the time function

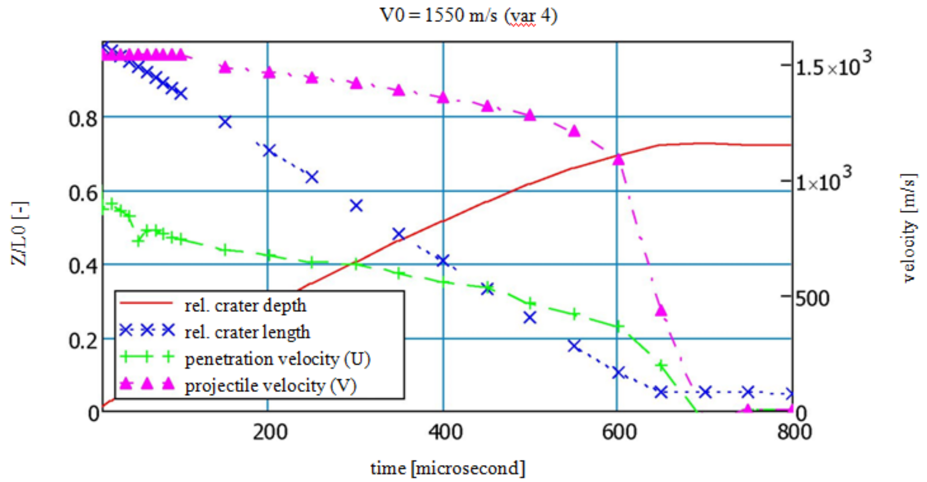


Fig. 10. Waveforms of a projectile penetrating armour steel 2: relative crater depth; relative projectile length and penetration velocity (U), as well as current projectile velocity (V) in the time function

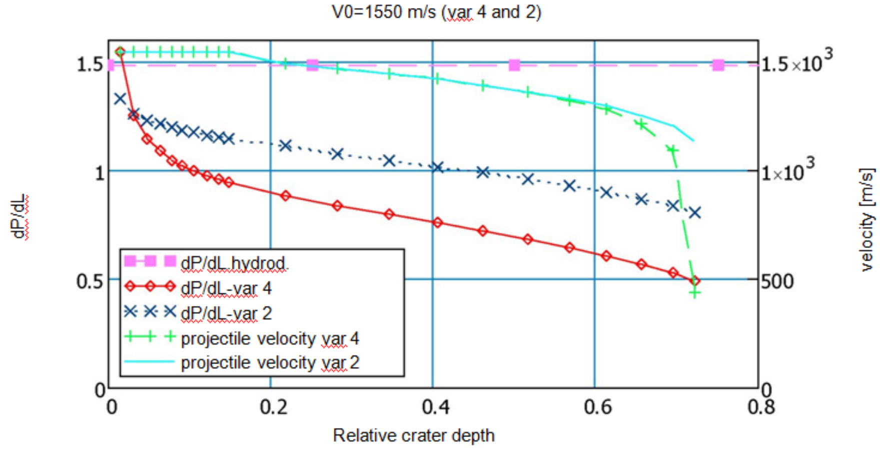


Fig. 11. Compared penetration efficiency for a projectile with an initial velocity of 1550 m/s, into steel 1 and armour steel 2 with greater strength

The corresponding projectile velocity waveforms were also illustrated for these cases. It is apparent that the penetration efficiency depends on the projectile velocity and decreases significantly together with decreasing velocity.

The calculations (variant 5 - V_0 = 1000 m/s and variant 6 - V_0 = 1250 m/s, penetration into an armour plate made of steel 2 in both cases) indicate that the penetration process ends for the projectile velocity value of approximately 800 m/s, with the velocity and efficiency tending to zero and the projectile kinetic energy converted into its radial strain. By the time the penetration was completed, the projectiles were consumed, at a value of 0.68 and 0.83 for V_0 = 1000 m/s and V_0 = 1250 m/s, respectively. Relative penetration depths are 0.18 and 0.38, respectively for the above variants. Because in the aforementioned case, for V_0 = 1550 m/s (fig. 10), the penetration process ends when at a projectile velocity of approximately 1250 m/s, with the projectile almost entirely consumed, it can be concluded that it is possible to increase the relative penetration depth for this variant by 0.38, at the cost of almost twofold initial projectile elongation (1+0.83)*L0. In such a case, the relative armoured steel penetration depth would amount to (0.72+0.38)/(1+0.83) = 0.60 (absolute (0.72+0.38)*53cm = 58.3 cm) .

3.2. Final evaluation of elongated projective operational effectiveness

Two quantities out of the ones discussed in the section above and illustrated by examples of numerical solutions were selected for evaluation. These were the relative penetrations depths (related to the initial projectile length) and the penetration efficiencies in the impact velocity function. These relationships are compared in the next two figures (fig. 12 and fig. 13), for penetration into steel 1 and steel 2 with greater strength, respectively. These examples of numerical solutions point to a strong increase in the penetration efficiency with increasing initial velocity of the projectiles. The penetration depth and penetration effectiveness also increase.

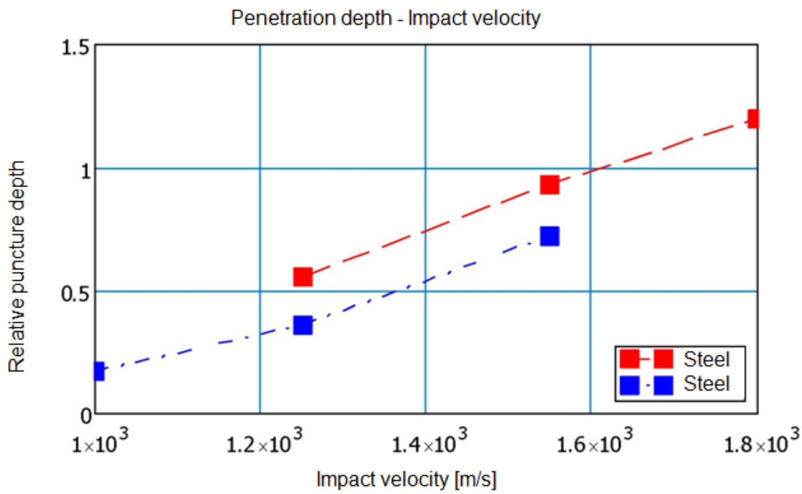


Fig. 12. Comparison of relative depths of elongated projectiles penetrating armour steel of various strength properties

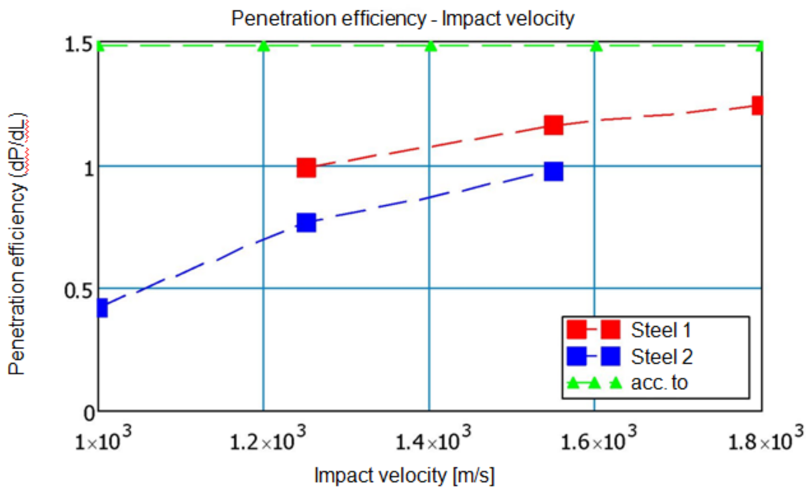


Fig. 13. Comparison of relative depths of elongated projectiles penetrating armour steel of various strength properties, for case 2 tends to zero at a velocity of 800 m/s

It shows marked maximum efficiency, resulting from the hydrodynamic approximation for high impact velocities [13].

3.3. Evaluation of shaped warhead operational effectiveness

In this case, the results of numerical calculations conducted for shaped warheads, applied in practice, with copper inserts, 100 mm cal. and apex angles of 51° and 60° were also used for the evaluation. The final assessments of the relative maximum depths of penetration into armour steel (related to cone calibre) are shown in fig. 14 and fig. 15[1], respectively for these warheads. The obtained penetration depths and the corresponding penetration times for shaped streams increase along with increasing distance between the warhead and the armoured plate. The penetration depths for armour steel are within 8 calibres for the distances above, which amount to 6 calibres (standard distances for the so-called tandem warheads) [2].

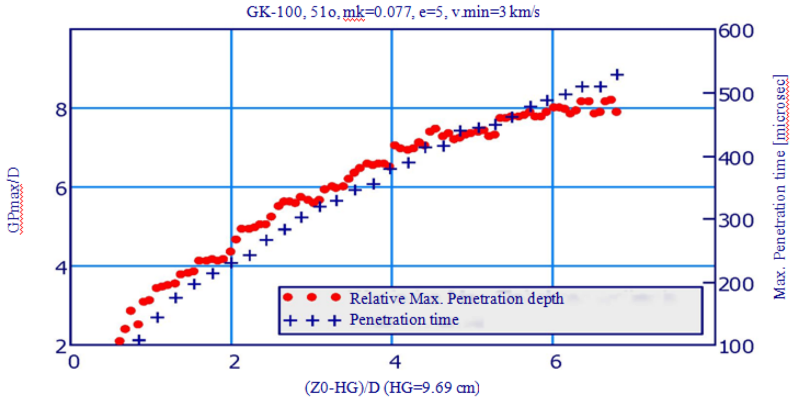


Fig. 14. Operational efficiency of a warhead with a shaped insert and an apex angle of 51°

[1] mk = geometric parameter of the shaped cone (numerically equal to the ratio between the disc thickness and the cone base radius (D/2) with a mass equal to the cone mass); e - relative elongation of shaped stream element, which results in its fragmentation if exceeded; v.min – minimum velocity of the shaped stream element, which can still effectively cause penetration (so-called cut-off speed); HG - shaped cone height

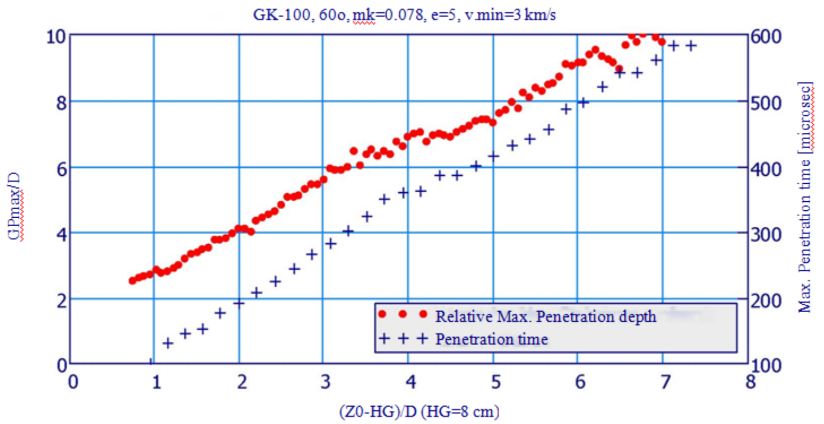


Fig. 15. Operational efficiency of a warhead with a shaped insert and an apex angle of 60º

4. Summary and conclusions

The development of combat means and command systems, as well as the scientific and technical progress determine the needs of the contemporary battlefield. The nature and specificity of modern armed conflicts changes, but combat vehicles still remain the basic weapon for land forces. It is only them that combine the mobility and firepower necessary to occupy and hold terrain. The conducted analyses confirmed the need to modernize combat vehicles, which will increase their firepower. For these reasons, the scope of modernizations determines the primary needs in terms of weapon system development. The basic retrofitting element stems from the need to combat attack helicopters, anti-tank missiles and hidden targets. Digital control systems, coupled with observation and targeting devices, and an external reconnaissance system enable more rapid and precise fire response. New ammunition types increase the fire coverage and effectiveness. In order to indicate and emphasize the needs and requirements in this regard, this research paper involves conducted numerical tests of the armour steel penetration process for selected projectiles.

The results of numerical tests showed that there was a possibility to achieve high operational effectiveness of elongated sub-calibre projectiles used for destroying armoured targets. The depth of penetration into armour steel, equal to or higher than the initial projectile length, can be achieved by ensuring sufficiently high impact velocities in the range of 1600 to 2000 m/s, depending on the steel strength. This requirement arises from the fact of decreased penetration efficiency along with decreasing projectile speed, which is always the case within the penetration process and impacts in ultimate puncture depth. Lower impact velocities, in the range of 1000 to 1500 m/s, exhibit lower initial penetration efficiency, which decreases naturally in the course of penetration and results in the achieved penetration depths being lower than the initial projectile length.

In the case of shaped streams with large velocities from 3000 to 10000 m/s, the penetration efficiency is constant, and the penetration depth depends on the stream element lengths and the workmanship quality of the shaped warhead. The achieved maximum, relative armour steel penetration depths amount to 8 calibres, at a distance from the plate of about 6 calibres.

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