Scientific Technical Review, 2010, Vol.60,No.2,pp.70-75

UDK: 629.762:623.56
COSATI: 19-01

Jacketed Long-Rod Penetrators: Problems and Perspectives

Sebastian Baloš[1)]
Milutin Nikačević[2)]
Predrag Ristić[2)]
Leposava Šiđanin[1)]

This paper reviews problems and perspectives of jacketed long-rod penetrators. The present status of their developement is shown, while a special attention is given to the influence of jacket material on the occurence of bending vibrations during the acceleration and free flight. A special consideration is given to the design of load transferring jacket/core joints, which is a significant technological problem. Finally, the effectiveness of jacketed long-rod projectiles on different targets - vertical, oblique and spaced ones - is also analyzed. It has been shown that nowadays the most effective jacket material is maraging steel. The efectiveness of jacketed long-rod penetrators is lagrely influenced by impact velocity and a nose shape, which, if optimized correctly, may result in a notable increase penetration of jacketed long-rods compared to conventional monoblock long-rods, even against multilayered targets.

Key words: **projectile, long-rod penetrators, jacket, projectile construction, poduction technology.**

Introdiction

SINCE the appearance of tanks, a need for anti-tank and later anti-armour weapons was recognized. A special and arguably the most effective type of anti-armour weapons are kinetic projectiles fired from tank guns. The first such projectiles were developed from ship – anti ship ammunition, with projectile bodies were made of steel. However, by the developement of more effective armour protection, mainly sloped armour and the need for making the projectiles more lethal at extended ranges, antiricochet and ballistic caps were introduced. The next step was the application of alternative alloys, based on tungsten, which formed projectile sub-calibre cores. Thus, upon impact, the core posessed an equal or higher kinetic energy, concentrated on a smaller area, to increase penetration. Finaly, at the end of the Second World War, armour piercing discarding sabot projectiles (APDS) emerged, with sub-projectiles that could separate from the sabot at some distance from the gun muzzle. The velocity drop at range was thus lower, by decreasing the frontal area of the projectile and the subsequent lower drag, retaining relatively high penetration at longer ranges. However, these projectiles could not be made with a higher length to diameter ratio higher than around five, due to their spin stabilisation. The answer was fin stabilization, which was used at APFSDS ammunition (armour piercing fin stabilized discarding sabot). The first tank that used such ammunition was the Soviet T-62 tank.

The first APFSDS penetrators were made of steel, but at a later stage, more efficient tungsten-carbide was introduced. As this material was relatively brittle, it was placed in a steel sleeve, or jacket. Furthermore, by the developement of tungsten-nickel-iron-cobalt, as well as depleted uranium-titanium alloys with higher ductility, the steel sleeve was dropped as unnecessary, leading to monoblock APFSDS projectiles [1-8].

According to Andersons equation [9,10], the penetration depends on a muzzle velocity, an L/D ratio (length to diameter ratio) and a projectile length (Eq.1).

$$P = L\left(0.212 + 1.044v - 0.194\ln\frac{L}{D}\right) \qquad (1)$$

where, P is the penetration, L is the long-rod length, v is the impact velocity and D is the long rod diameter.

By analyzing equation (1), it can be seen that the penetration is proportional to the length of the penetrator which is the dominant parameter. This means that there is a need for increasing the length of the penetrator. However, to achieve an optimal muzzle velocity and to stay within the gun design limitations, projectiles (roughly penetrator + sabot) have to have a constant weight. To increase penetrator weight and therefore length, a sabot has to be made as light as possible. Therefore, the traditional materials such as steel and aluminium alloys are starting to be replaced by composite materials, as is the case with the latest US M829A2 and M829A3 APFSDS ammunition. On the other hand, the projectiles, to achieve higher lengths, need to have the diameter as small as possible, having a very slender shape, with a relatively high L/D ratio. Today, the L/D ratio reached around 30. Beyond this value, with present materials, a number of failures may occur, in an interior ballistic, flight ballistic and terminal ballistic phase. During the interior and flight ballistic phases, structural integrity and stability problems such as flexure, buckling

---

1) University of Novi Sad, Faculty of Technical Sciences,Trg Dositeja Obradovića 6, 21000 Novi Sad, SERBIA
2) Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA

and/or bending vibrations may occur [11]. These may cause yaw and consequently significantly lower terminal ballistic performance [12-14].

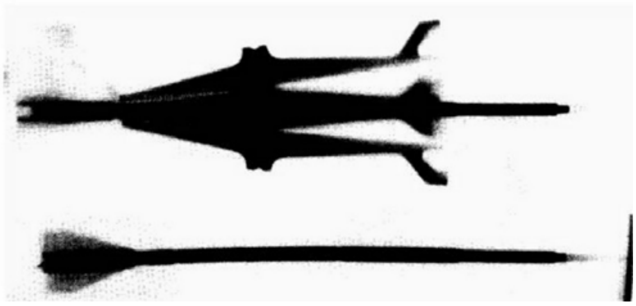

Figure 1. Bending of an APFSDS projectile ($D = 6$mm, $L/D = 40$, $v = 1710$ m/s)[15].

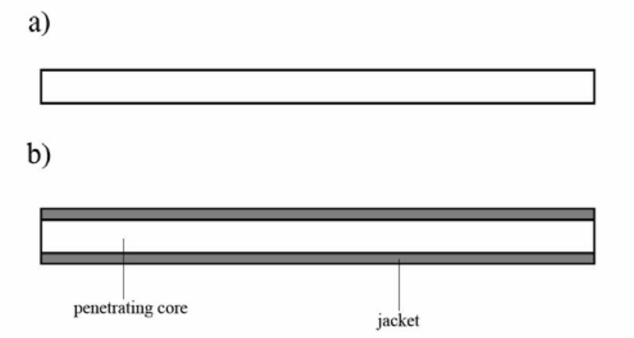

Figure 2. Monoblock (a) and a jacketed long-rod penetrator (b).

There are, however, several problems regarding designing and using jacketed APFSDS projectiles: jacket material, its thickness and the method of joining the jacket and the penetrator. Although the penetration against simple, vertical, rolled homogenous armour (RHA steel) may be expected to improve, an even more slender projectile compared to monoblock projectiles with L/D>30, may have a different effectiveness against sloped and/or spaced armour types. Furthermore, spaced and sloped targets proved to be the most difficult targets made of ductile materials for slender long-rods, which may cause significant efficiency drop for jacketed projectiles as well. Finally, it is of great importance to find if the jacket adds to penetration directly, or indirectly, through providing ability of firing a longer projectile.

This paper reviews the most important problems and possible solutions in the area of jacketed long-rod projectiles.

Jacket materials

Hypothetically, the optimal material should provide the lowest weight of the jacket and at the same time the highest Young modulus of elasticity. The highest weight should be thus left for the penetrating core and, at the same time, the stiffness in flight should be the highest. The most suitable material that fulfills both requirements is composite materials, especially fibre reinforced composites, such as carbon or glass reinforces plastics. However, jackets made from fibre reinforced composites may have a relatively high thickness, increasing the projectile diameter and therefore increase drag, leading to a more significant velocity drop at range. Accordingly, metallic alloys, such as steel and titanium alloys should be considered as well. Therefore, a careful optimization should be done, as shown in [10].

Table 1 Modelling results for projectiles with and without the jacket of various properties [15].

		A	B	C	D	E
projectile type		monoblock	monoblock	jacketed	jacketed	jacketed
diameter D [mm]		15	25	15/25	15/25	15/25
length to diameter L/D		40	24	40	40	40
relative density of the jacket		0	0	0.240	0.091	0.254
relative Young's modulus of the jacket		0	0	0.329	0.786	1.429
relative maximal deflection		1	0.360	0.445	0.185	0.137
relative bending stress	jacket	0	0	0.244	0.243	0.326
	core	1	0.6	0.445	0.185	0.137
relative total mass		1	2.78	1.427	1.162	1.453
relative muzzle velocity		1	0.865	0.962	0.982	0.960
relative velocity at 2 km		1	0.817	0.843	0.837	0.843

Table 1 shows the results obtained for monoblock and jacketed projectiles with two different jacket materials (different densities) and three Young's modulus values. Projectiles C, D and E are clearly based on projectile A, with a core diameter of 15 mm, but with different jackets applied, with a projectile diameter of 25 mm. This means that the ratio between the diameter of the projectile and the penetrating core is 0.667, for projectiles C, D and E. The jacket density and the Young's modulus are varied at three levels. Projectile B has the diameter of projectiles C, D and E, but is of the monoblock design, which means thet its mass is the highest. Furthermore, relative velues of maximum deflection, bending stress, mass, muzzle velocity and velocity at 2 km are given. These values are given as relative to the corresponding values of projectile A.

According to the results shown in Table 1, by applying jackets, a lower maximum deflection is obtained, as well as bending stress by a factor of two to seven. By applying medium density – highest Young's modulus jacket (projectile E), relative maximum deflection and bending stress in the core are the lowest. This is clearly the most effective jacket out of three considered. If the core material is tungsten alloy (heavy metal, density of 17.3 g/cm^3), a relative density of 0.254 means that the density of the projectile E core is 4.4 g/cm^3, clearly closely corresponding to a titanium alloy [15].

Joining jacket and core

Joining jacket and core should provide an effective load transfer between these elements. Acceleration forces and shear loads at the penetrator may detach the jacket from the core. By applying equation (2), the required minimum shear stress between the jacket and the core may be calculated:

$$\tau = \frac{1}{4} Cal^2 P \frac{m_p}{d_p l m_g} \qquad (2)$$

where: τ - the required minimum shear stress between the jacket and the core, Cal - calibre, P - pressure at projectile base, m_p - penetrator mass, m_g - projectile mass (penetrator and sabot), l - jacket length (shear length) and d_p - diameter of tungsten ally core.

The joint between the jacket and the core should withstand at least a shear stress of over 60 MPa, for a maximum pressure inside the barrel of 6000 bar, Fig.3. Three different technologies were considered: bonding/shrinking, cold radial forging and build-up welding [16].

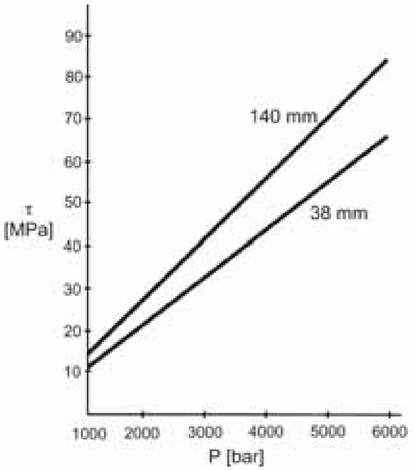

Figure 3. Required minimum shear stress plotted against pressure at projectile base, for a range of gun calibres – 38 mm to 140 mm [16]

Bonding/shrinking

Structural bonding by using adhesives may provide shear stresses of about 25 MPa, which is clearly insufficient for a main battle tank gun APFSDS projectiles. However, by combining the adhesives with shrinking, when the application of shaft/hub assembly is considered, shear stress might be increased to 45 bar [17]. By applying this joining tehnology at a 38 mm test-gun and ammunition (maraging steel jacket and tungsten alloy core), a shear stress of 30 MPa was obtained, providing structural integrity of the jacketed projectile up to 2200 bar maximum pressure. The difference between this experiment and the values obtained for a shaft/hub assembly of 15 MPa, may be the result of a different geometry (a relative longer joint) and lower athesion to the tungsten alloy surface.

Cold radial forging

Cold radial forging of maraging steel to tungsten alloy core resulted in shear stresses between 50 and 61 MPa, which enabled the structural integrity of the jacketed projectile of 4500 to 5000 bar barrel pressure. These pressures are not equal to modern main battle tenk guns, though, but rather to 30 – 35 mm automatic cannons. After cold radial forging and machining the outer part of the jacket, heat treatment in form of ageing at 480^{o}C during 3 h is neccessary to achieve ultra – high strength of the jacket.

Build-up welding

Maraging steel may be applied to the core by build-up welding, by using maraging electrodes [18]. After ageing, the jacket/core bond could be maintained for over 5000 bar barrel pressures. This corresponds to over 55 MPa shear stress. These values are sufficient for a medium calibre cannon, but not a 120/140 main battle tank gun.

The presented results have shown that cold radial forging and build-up welding are the most promising techniques. However, in future work, other technologies may be considered. One notable example is the pouring of zinc-alloy into the gap between the core and the jacket, in combination with threaded surfaces. Furthermore, by combining adhesive bonding with threaded contact surfaces, composite materials may be used as an alternative jacket material.

Penetration of long rods

Monoblock projectiles of a high L/D ratio are prone to bending and fracture when penetrating sloped and especially sloped and spaced armour arrays. For this reason, it is understandable that long rods of a L/D>30 may be even more sensitive to such targets. To address the issue of penetration of jacketed long rods, their effectiveness against vertical RHA (rolled homogenous armour steel) will be presented, then sloped RHA and finally, their effectiveness against different materials, primarily ceramics and composite materials.

Vertical RHA

In the excellent work by Lehr et al. [15], long rods with a length of 180 mm and diameters of 3 and 4 mm were tested against vertical RHA having UTS of 1200 MPa. This corresponds to L/D of 45 and 60. Both projectiles were jacketed, with a jacket made of carbon fibre reinforced plastics (CFRP), with a jacket thickness to core diameter ratio (T/C) of 0.625 and 0.833 respectively. The penetration results were compared to a monoblock projectile of the same length and a diameter of 4 mm (L/D=30). The nose shape of all tested projectiles was sharp – conical. The key parameter that describes the effectiveness of the projectile is its penetration to length ratio (P/L).P/L values are given in Table 2. It should be noted that upon impact, the projectile with L/D=45 left a clean passage, Fig.4, while the one with L/D=60 broke, Fig.5. The reason for core fracture may be the interaction between the core and jacket material upon impact, which induces stresses in the core. A thinner core has a smaller cross sectional area and is therefore more sensitive to fracture.

When rods were fired at an elevated muzzle velocity of well over 2000 m/s, the difference between the monoblock L/D=30 and jacketed L/D=46 is only 2%, Table 2. No core fracture was noticed.

Table 2 P/L ratios of various experiments with jacketed long rods against vertical RHA [15]

L/D	jacket material	T/C	nose shape	muzzle velocity [m/s]	core fracture	P/L
30	-	-	conical	2000	yes	1.10
45	CFRP	0.625	conical	1937	no	0.90
60	CFRP	0.833	conical	2020	no	0.65
30	-	-	conical	2420	no	1.28
45	CFRP	0.625	conical	2340	no	1.25

In all these experiments, two coaxial craters were notices for jacketed long rods. The wider crater was notices only at the face of RHA plate and is the result of the CFRP jacket, which relatively quickly became eliminated, while the narrower and longer crater is the result of the core. Although the jacket contributes to over 40% of the projectile weight, it does not contribute to penetration, or it has a negative effect causing core fracture in case of longer and smaller diameter cores (L/D=60).

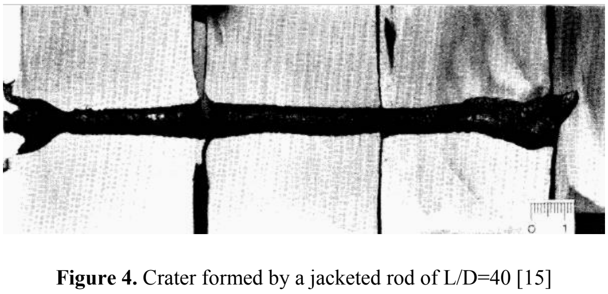

Figure 4. Crater formed by a jacketed rod of L/D=40 [15]

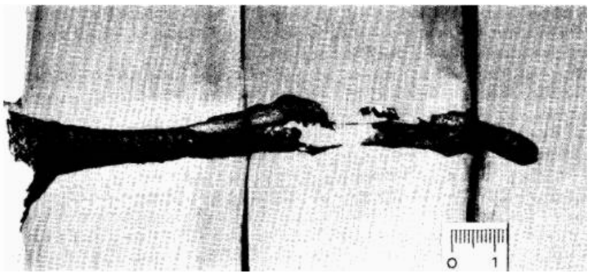

Figure 5. Crater formed by a jacketed rod of L/D=60 [15]

Sloped and spaced RHA

The paper [15] also addresses the problem of sloped RHA. Projectiles, as in the previous case, were monoblock and CFRP jacketed, both with a length of 120 mm and a diameter of 3 mm (jacketed, L/D=40) and 4 mm (monoblock, L/D=30). The target was spaced and sloped at 60° from the vertical. It consisted of a 5 mm RHA plate (UTS=1200 MPa), two RHA plates 9 mm thick (UTS=500 MPa) and a 5 mm RHA plate (UTS=1200 MPa). Looking at the line of sight, between each of these plates there was a distance of 100 mm. According to the results shown in Table 3, it can be seen that the very sensitive jacketed penetrator fractured and achieved only P/L of 0.5, compared to the reference monoblock projectile with L/D=30. Also, this reference projectile achieved P/L of only 0.9, which is notably lower than that against vertical RHA (1.28) at a similar muzzle velocity.

Table 3 P/L ratios of various experiments with jacketed long rods against spaced and sloped RHA at 60° [15]

L/D	jacket material	T/C	nose shape	muzzle velocity [m/s]	core fracture	P/L
30	-	-	conical	2451	no	0.96
40	CFRP	0.625	conical	2386	yes	0.50

On the other hand, Leonard [19] and Rosenberg and Deckel [20] in their respective works concluded that conical nosed long-rods do not possess sufficient efficiency against sloped targets. Against such targets, a blunt nose is much more effective, providing a shorter penetration path through the sloped armour.

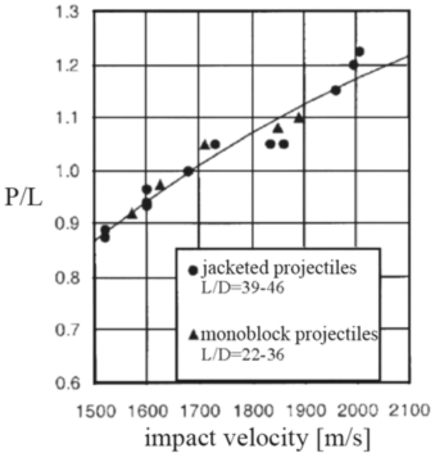

Figure 6. Penetration to length ratio (P/L) in relation to the impact velocity for jacketed and monoblock projectiles against sloped RHA of 260 HB [1].

Lanz et al. [1] tested blunt nosed jacketed full – size long rods against sloped steel targets with 260 BHN. According to the results presented in Fig.6, there is no major difference of P/L between monoblock (L/D=22 - 36) and jacketed projectiles (steel jacket). Similar results have been reported by Lehr et al. [15], who tested jacketed long-rods, 850 mm long, with a diameter of tungsten-alloy core of 21 mm and steel jacket. A steel jacket external diameter was 27 mm, which means that the T/D is 0.143. The impact velocity was 1510 m/s. By analyzing the dimensions and weight of the projectile, as well as its impact velocity, it is clear that the authors intended to model a full-sized 120 mm APFSDS projectile, at an impact distance of 2000 m. The penetration into a 300 BHN RHA target was 380 mm at an angle of 60° from the vertical. This may roughly be twice the thickness of a 760 mm RHA plate of the same hardness. Therefore, P/L is 0.9, well within the values presented by Lanz et al. [1], Fig.6.

Conclusions

According to the results presented in this review, some conclusions may be drawn:

- From the point of view of added mass, bending deflection and stress in the core, the optimal material for jackets are fibre reinforced composites.
- Technologically speaking, the optimal jacket material is maraging steel. It can be joined to the penetrating core by cold radial forging and build-up welding, the most promising methods from the point of view of shear stress between the jacket and the penetrating core. An alternative joining method may be the pouring zinc-alloy into the gap between the core and the jacket, in combination with threaded surfaces.
- Conical nose of jacketed long-rods may be effective only against vertical armour, at higher impact velocities, where P/L of jacketed and monoblock projectiles are almost identical.
- Against sloped armour, a blunt nose is more effective, as with slender monoblock projectiles. Jacketed projectiles with a blunt nose have the same P/L as slender long-rods. This is experimentally proven for size and impact velocities of full-scale long-rod projectiles with L/D up to 46.
- Jacketed long-rods are one of the alternative ways of improving the performance of APFSDS ammunition. By applying jackets, the penetration of present tank guns may increase by a considerable margin, prolonging their operational lives and making them effective against present-day and future armour types.

References

[1] LANZ,W., ODERMATT,W., WEINRAUCH,G.: *Kinetic energy projectiles: Development history, state of the art*, Proc. of 19th International Symposium of Ballistics, Interlaken, Switzerland, May 2001, pp.1191-1198

[2] OGORKIEWICZ,R.: *Technology of tanks*, Jane's Information Group Limited, Coulsdon 1991., pp.76-83

[3] HILMES,R.: *Main Battle Tanks – Developements in Design since 1945*, Brassey's Defence Publishers, London, 1987., pp.37-41

[4] KATAVIĆ,B., NIKACEVIĆ,M.: *Properties of the cold swaged and strain aged PM 91W–6Ni–3Co heavy alloy*, Second International Conference on: Deformation Processing and Structure of Materials, Belgrade, May 26–28, 2005, pp.135–140

[5] KATAVIĆ,B., NIKAČEVIĆ,M., ODANOVIĆ,Z.: *Effect of cold switching and heat treatment on properties of PM 91W-6Ni-3Co heavy alloy*, Science of Sintering, 2008., Vol.40, pp.319-331

[6] NIKAČEVIĆ,M., RADOVIĆ,LJ., RISTIĆ,P.: *Uticaj sastava šipki W-legure teškog metala na probojnost potkalibarnog projektila 100*

mm, 3. Naučno-stručni skup iz odrambenih tehnologija OTEH–2009, Vojnotehnički institut Belgrade.

[7] NIKAČEVIĆ,M, RADOVIĆ,LJ., RISTIĆ,P.: *Uporedna analiza osobina tela potkalibarnog projektilaod W-legure domaćeg i stranog porekla*, Tehnički izveštaj VTI 03-01-0570, Belgrade, 2009.

[8] NIKAČEVIĆ,M., RADOVIĆ,LJ., RISTIĆ,P.: *Uticaj tehnologije izrade šipki teškog metala na funkcionalne karakteristike potkalibarnog projektila*, Tehnički izveštaj VTI 04-01-01540, Belgrade, 2008.

[9] ANDERSON,C, WALKER,J., BLESS,S, SHARRON,T.: *On the velocity dependenceof the L/D effect for long-rod penetrators*, Int. J. Impact Eng., 1999, Vol.17, pp.13-24

[10] LEEMING,W, RIGBY,M.: *An analysis of the penetration performance of long-rod projectiles with various sleeving materials*, 20th International Symposium on Ballistics, Orlando, 2002, pp.142h

[11] ERNST,H.J., LANZ,W., WOLF,T.: *Penetration comparison of L/D=20 and 30 mono – block penetrators with L/D=40 jacketed penetrators in different materials*, Proc. of 19th International Symposium of Ballistics, Interlaken, Switzerland, May 2001., pp.1151-1158

[12] GEE,D., LITTLEFIELD,D.: *Yaw impact of rod projectiles*, International Journal of Impact Engineering, 2001, Vol. 26, pp.211-220.

[13] BLESS,S., GEE,D., PEDERSEN,B.:, *Yaw degradation of hypervelocity long rods striking space-containing steel targets*, Int. J. Impact Eng., 2003, Vol. 29, pp.117-126

[14] BLESS S., SATAPATHY S., NORMANDIA M.:, *Transverse loads on a yawed projectile*, International Journal of Impact Engineering, 1999, Vol.23, pp.77-86

[15] LEHR,H., WOELLMAN,F., KOERBER,G.: *Experiments with jacketed rods*. Int. J. Impact Eng., 1996, Vol.17, pp.517-526

[16] FANG,H., HÖLZLE,J., KNOBEL,R., LANZ,W.: *Joining jacket and core for jacketed steel/tungsten penetrators*, Proc. of 19th International Symposium of Ballistics, Interlaken, Switzerland, May 2001, pp.363-372

[17] MUSCHARD,W.: *Festigkeitsverhalten und Gestaltung geklebter und schrumpfgeklebter Wellen-Naben-Verbindungen*, Paderborn, 1983., pp.120

[18] KLINGAUF,S., SEIFERT,K.: *Erfahrungen beim Schweissen eines martensitaushärtbaren Stahls*, Bundesministerium der Verteidigung – Forschungsbericht aus der Wehrtechnik BMVg-FBWT 78–17, 1978., pp.254

[19] LEONARD,W.: *The Effect of nose shape on Depleted Uranium (DU) long – rod penetrators*, Army Reasearch Laboratory, Aberdeen Proving Ground, September 1997

[20] ROSENBERG,Z., DEKEL,E.: *On the role of nose profile in long-rod penetration*, International Journal of Impact Engineering, 1999., Vol. 22, pp.551–557

Received: 08.04.2010.

Potkalibarni projektili sa košuljicom: Problemi i perspektive

U radu su analizirani problemi i perspektive vezane za potkalibarne projektile sa košuljicom. Prikazan je trenutni status istraživanja, sa posebnim osvrtom na uticaj materijala košuljice na pojavu savojnih vibracija tokom ubrzanja i leta projektila. Posebna pažnja posvećena je tehnologijama spajanja košuljice i probojnog jezgra, što predstavlja jedan od problema pri praktičnoj primeni ovog tipa projektila. Konačno, analizirana je efikasnost potkalibarnih projektila sa košuljicom protiv vertikalnog, zakošenog i razmaknutog oklopa. Pokazano je da je trenutno, najefikasniji materijal za izradu košuljice, martenzitno-stareni čelik. Velik uticaj na probojnost potkalibarnog projektila ima brzina udara i oblik vrha, koji, ako se izvrši pažljiva optimizacija, može da rezultuje značajnim poboljšanjima u odnosu na konvencionalne monoblok projektile, čak i protiv višeslojnih oklopa.

Ključne reči: **projektil, potkalibarni projektil, košuljica, konstrukcija projektila, tehnologija proizvodnje.**

Подкалиберные снаряды с оболочкой – проблемы и перспективы

В настоящей работе анализированы проблемы и перспективы связаны с подкалиберными снарядами с оболочкой. Здесь показано текущее состояние исследований, с особым упоминанием влияния материала оболочки на появление сгибающих вибраций в течение ускорения и полёта снаряда. Особое внимание уделено технологиям соединения оболочки и пробивного сердечника, что является одной из проблем при практическом применении этого типа снаряда. Наконец, анализирована эффективность подкалиберных снарядов с оболочкой в пробивании вертикальных, скошенных и разомкнутых бронь. Здесь показано, что в данный момент самым эффективным материалом для выработки оболочек является мартенсит – сталь (плав железа и углерода). Большое влияние на пробиваемость подкалиберного снаряда оказывает скорость удара и форма вершины, которое, если проведётся аккуратная оптимизация, может привести к значительным улучшениям по сравнению с установившимися одноблочными снарядами, даже и против многослоистых бронь.

Kly~evwe slova: **снаряд, подкалиберный снаряд, оболочка, конструкция снаряда, технология производства.**

Les projectiles à calibre réduit à l’enveloppe: problèmes et perspectives

Les problèmes et les perspectives concernant les projectiles à calibre réduit sont analysés dans ce travail. On a présenté l’état actuel des recherches et l’attention particulière est donnée à m’influence du matériel de l’enveloppe sur l’apparition des vibrations courbées pendant l’accélération et le vol du projectile. L’attention spéciale est également prêtée aux technologies de jointure de l’enveloppe et du noyau, ce qui représente un des problèmes lors de l’application pratique de ce type de projectile. On a analysé à la fin l’efficacité des projectiles à calibre réduit à l’enveloppe contre le blindé vertical, oblique ou espacé. On a démontré que le matériel le plus efficace pour la fabrication de l’enveloppe est, à présent, l’acier martensitique. Une grande influence à la pénétration chez les projectiles à calibre réduit ont la vitesse de l’impact et la forme du nez qui, si on réalise bien l’optimisation peut produire des améliorations signifiantes par rapport aux projectiles conventionnels mono block et même contre les blindés à plusieurs couches.

Mots clés: **projectile, projectile à calibre réduit, enveloppe, construction de projectile, technologie de production.**