T-72 tank barrel bore wear

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***Abstract*—**The paper provides results of an analysis of character of smooth barrel bore wear of the T-72 tank, a combat vehicle that remains in service with a number of armed forces throughout the world. The BG20 MkII Gun Barrel Bore Gauge system purchased from Aeronautical & General Instruments Ltd in the UK was used to take measurement in the barrels of T-72 tank. Three types of the wear of leading part of the barrel bore were documented. There are also, in original way, mathematically formulated conditions of formation of a specific type of wear caused by firing the armour-piercing fin-stabilized discarding sabot 3BM-15 in the paper.

***Keywords*—**Armour-piercing fin-stabilized discarding sabot, Smooth barrel bore wear, BG-20 MkII measurement system.

I. Introduction

THE barrels of guns are strained in complex ways, which result in their fast wear depending on the caliber and power of the gun. Tank cannons rank among the most powerful guns; the 2A46 cannon of the T-72 tank is the most powerful gun of the Czech Armed Forces.

The extent of barrel bore wear depends mainly on the action of gunshot which burdens the barrel mechanically (by force) and thermally (by changes of the material volume and material characteristics). The other degrading factors reducing lifetime of the barrel are chemical impact of the shoot products on barrel bore and erosive impact of hot gases flowing fast through the barrel bore.

The most considerable factor influencing the barrel bore life is high temperature tensions on the thin layer of the inner surface of barrel bore which develop due to dynamic temperature tension during the gunshot. The effect of these factors is complex and the influence of temperature tensions and erosion caused by hot gases act together with mechanical tension and chemical impacts. The last mentioned degrading influence relates mainly to the emission of gases between the projectile and the inner barrel bore surface and, thus, to deformation of the barrel bore due to gas pressure and dilatation caused by heating. In one-piece ammunition there is also gas flowing in front of the projectile at the beginning of its movement, which is a very important source of the barrel bore wear. The above mentioned influences are further discussed e.g. in [1], [3], [10], [19].

The study of barrels lifetime enables to manage practically not only the lifecycle of barrel itself but moreover the whole cannon and also the overall battle tank life cycle.

Available literature, e.g. [1], [10], [11], [12], [26], describes rifled bore wear of cannon barrels in dependence on cannon power and the number of rounds fired. As far as smooth bore wear is concerned, the literature almost does not deal with it. In contrast to rifled barrels, smooth barrels use for shooting rounds of various construction types which cause different character of wear. Basic types of cartridges used in T-72 tank are cartridges with fin stabilized projectiles of the following types: high-explosive anti-tank fin-stabilized with tracer (HEAT-T), high-explosive (HE), armour-piercing fin-stabilized discarding sabot with tracer (APFSDS-T). The aim of this paper is to report on successful measurement and analysis of the character of the process of 2A46 cannon barrel wear of T-72 tank which is still used in several armies [16].

II. Devices for barrel bore measurement

The mechanical instrument PKI-26 (see Fig.1) is determined for the measurement of the barrel bore leading part of the 2A46 tank cannon.

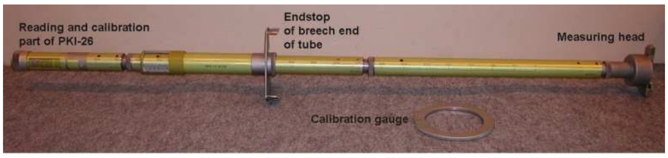

Fig.1 Photo PKI-26 device ready for measurement

According to the Military Directive [29] this device is primarily designed for the measurement of the real diameter of the barrel bore within the distance of 850 mm from the breech end of the tube (10 mm behind the forcing cone). The recorded value must be lower than the allowed diameter of 128.3 mm. Moreover, it is determined that the diameter in another part of the barrel bore must be lower than the allowed diameter of 128.0 mm. This device shall be used for the measurement of copper layer by comparison of barrel bore diameters in the areas with and without the copper layer. The maximal allowed copper layer is 0.15 mm.

With PKI-26 it is possible to carry out the measurement only within the distance of maximally 1050 mm from the breach end of the tube as well as from the muzzle. Based on the knowledge of the principles of wear of tank barrels using sub-calibre projectiles, it is necessary to monitor and evaluate the information on dimensions of the whole barrel bore [30]. For that reason the BG-20 modified system was purchased from Aeronautical & General Instruments Limited (UK). This

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modification was the first application for the barrel with the caliber of 125 mm for which it was necessary to produce a new measurement head, a new calibration gauge, a longer feeder tube in the length of 6 m and other accessories for the caliber of 125 mm. Fig. 2 shows the photograph of BG-20 system prepared for measuring with a 2 m long feeder tube.

Fig. 2 Photo BG-20 MkII with 2 m feeder tube

III. Capability of the PKI-26 and BG-20 Devices

To evaluate the appropriateness of PKI-26 and BG-20 use for the measurement of dimensions of tank cannons barrel bores it is possible to use indexes of the gauge capability C_g and C_{gk} [14], [23].

The index of the gauge capability C_g expresses precision of the gauge in the following relation:

$$C_g = \frac{0.2T_R}{6s_g}, \qquad (1)$$

where T_R is specified tolerance range and s_g is standard deviation of the measurement values.

The index of the gauge capability C_{gk} expresses the accuracy of the gauge in the following relation:

$$C_{gk} = \frac{0.1T_R - \left|\bar{x}_g - x_e\right|}{3s_g}, \qquad (2)$$

where $\bar{x}_g$ is average (mean) measurement value and x_e is standard's true value (etalon).

The value of the caliber dimension of BG-20 (125.999 mm) - see Fig. 3 - was used as standard's true value for both devices.

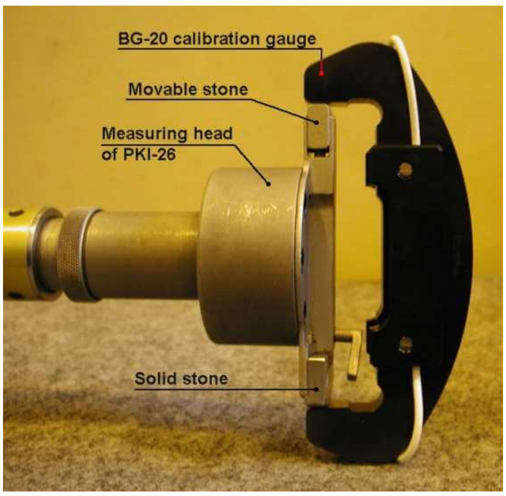

Fig. 3 BG-20 calibration gauge as a standard's true value

The indexes of the gauge capabilities C_g and C_{gk} according to the formulas (1) and (2) determine whether the results of the measurement of particular gauge are located, with the probability of 99.73 %, within the range of tolerance (20%).

There are also other ways to evaluate the capability of gauges in which the range of tolerance is not 20 % (e.g. 15 %) and the probability is not 99.73 % (it may be 99 % or 95 %) [14], [23], [28].

The final evaluation of capabilities of both gauges is illustrated in Table I.

TABLE I
Rules for evaluation of the gauge capability

Index Value	Gauge Evaluation
$C_g, C_{gk} \geq 1.33$	The gauge is capable of measuring the particular dimension
$C_g, C_{gk} \prec 1.33$	The gauge is incapable of measuring the particular dimension

The value of tolerance range was determined by the value of T_R = 0.15 mm in accordance with the production drawing of the barrel: there is a requirement of $125^{+0.15}$ mm for the diameter of the leading part of the barrel, as well as a requirement (0.15 mm) for measurement of the copper layers. Consequently, the value of tolerance range was determined within the value of maximally allowed wear of the leading part of the 2A46 barrel bore – i.e. 3.3 mm (128.30 mm - 125.00 mm).

As standard's true value we used calibration gap gauge of BG-20 which is designed for the caliber of 125 mm the true value of which is x_e =125.999 mm. After calibration, the gauge was measured under standard conditions by both devices fifty times in total. The recorded values are shown in Table II for PKI-26 and Table III for BG-20.

TABLE II
Values in mm recorded with PKI-26 No. 339

x_1	126.025*	x_{18}	126.000	x_{35}	126.100
x_2	126.100	x_{19}	126.000	x_{36}	126.125*
x_3	126.125*	x_{20}	126.000	x_{37}	126.125*
x_4	126.050	x_{21}	126.000	x_{38}	126.025*
x_5	126.025*	x_{22}	126.000	x_{39}	126.075*
x_6	126.000	x_{23}	126.025*	x_{40}	126.000
x_7	126.000	x_{24}	126.000	x_{41}	126.000
x_8	126.025*	x_{25}	126.000	x_{42}	126.000
x_9	126.025*	x_{26}	126.000	x_{43}	125.975*
x_{10}	126.025*	x_{27}	126.000	x_{44}	125.975*
x_{11}	126.025*	x_{28}	126.000	x_{45}	126.000
x_{12}	126.025*	x_{29}	126.025*	x_{46}	126.000
x_{13}	126.050	x_{30}	126.005	x_{47}	126.000
x_{14}	126.075*	x_{31}	126.075*	x_{48}	125.975*
x_{15}	126.000	x_{32}	126.075*	x_{49}	126.000
x_{16}	126.000	x_{33}	126.010	x_{50}	126.000
x_{17}	126.000	x_{34}	126.125*		
Calculation for the tolerance of 0.15 mm					
$C_g = 0.1213$			$C_{gk} = -0.0954$		
Calculation for the tolerance of 3.30 mm					
$C_g = 2.6684$			$C_{gk} = 2.4517$		

Note: The values in Table II marked similarly as 126.025* (value 0.025) point out that the value was estimated with the accuracy of half scale segment (segment = 0.05 mm) of the scale of PKI-26 (see Fig. 4).

Fig. 4 Reading the value of half segment from PKI-26

According to Table II we may conclude that PKI-26 is incapable of measuring the copper layer of the barrel bore since both indexes of capability are significantly lower than 1.33 (see Table I). Based on this fact it can be doubt about the requirement of the Directive [29] to check of extent of copper layer. For the same reason it is not possible to use PKI-26 for the evaluation of production quality.

Based on the calculation of capability indexes C_g and C_{gk} for the tolerance of 3.3 mm, we may conclude that PKI-26 is fully useable for the inspection of barrel bore wear in the area of 10 mm behind the forcing cone (850 mm from the breech end) and the area of barrel muzzle in accordance with the requirements of the Directive [29].

With respect to the construction of this device, we are not able to diagnose more than 3 m of the leading part of the barrel bore.

TABLE III
VALUES IN MM RECORDED WITH BG-20 NO 689

x_1	125.999	x_{18}	125.999	x_{35}	125.997
x_2	125.999	x_{19}	125.997	x_{36}	125.998
x_3	125.997	x_{20}	125.997	x_{37}	125.998
x_4	125.998	x_{21}	125.997	x_{38}	125.998
x_5	125.998	x_{22}	125.997	x_{39}	125.998
x_6	125.997	x_{23}	125.997	x_{40}	125.998
x_7	125.994	x_{24}	125.997	x_{41}	125.995
x_8	125.995	x_{25}	125.995	x_{42}	125.995
x_9	125.996	x_{26}	125.997	x_{43}	125.996
x_{10}	125.999	x_{27}	125.997	x_{44}	125.994
x_{11}	125.999	x_{28}	125.995	x_{45}	125.995
x_{12}	125.996	x_{29}	125.999	x_{46}	125.998
x_{13}	125.994	x_{30}	126.000	x_{47}	125.997
x_{14}	125.995	x_{31}	125.998	x_{48}	125.997
x_{15}	125.998	x_{32}	125.998	x_{49}	125.997
x_{16}	125.998	x_{33}	125.998	x_{50}	125.996
x_{17}	125.999	x_{34}	125.997		
Calculation for the tolerance of 0.15 mm					
$C_g = 3.3892$			$C_{gk} = 2.9509$		
Calculation for the tolerance of 3.30 mm					
$C_g = 74.5630$			$C_{gk} = 74.1247$		

According to Table III and calculated values of capability indexes we may conclude that BG-20 MKII is capable of measuring the leading part of barrel bore of T-72 tank. This gun barrel bore gauge system is fully useable not only for the purpose of technical inspections in accordance with the Directive [29], but also as a standard gauge for the evaluation of quality of barrel bores in full length of their leading parts.

IV. MEASUREMENT OF T-72 TANK BARRELS WITH BG-20 MKII

For simplification we can assume that we have 3 basic construction types of projectile for T-72 tank.

The first type is created by 3BK-14M (high-explosive anti-tank) projectile with tracer and with cumulative effect and 3OF-19 (high- explosive) projectile, that are very similar in design of leading part and round body creates one solid structural unit. Their muzzle velocity is about 850 m/s.

The second type represents 3BM-15 projectile with kinetic energy penetrator (armour-piercing fin-stabilized discarding sabot with tracer) which is guided in barrel by three-piece sabot and by stabilizing fins. Its muzzle velocity is about 1800 m/s.

The third type TAPNA is a new projectile with kinetic energy penetrator and new larger and lighter discarding sabot made from aluminum alloy - see Fig. 5. Its muzzle velocity is also approximately 1800 m/s [13], [16].

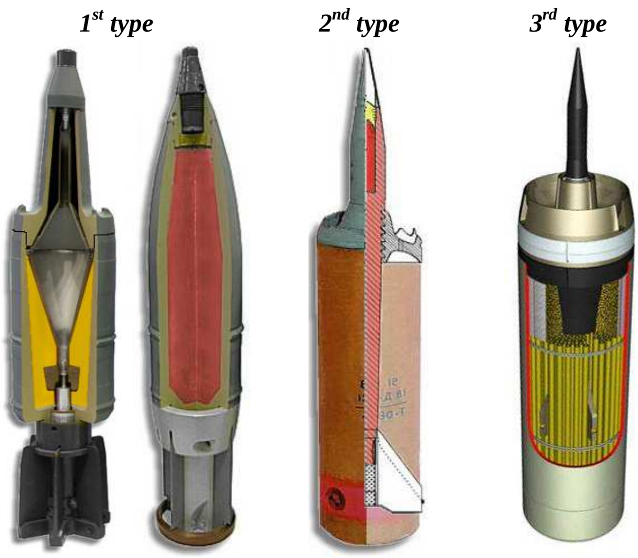

Fig. 5 Construction types of projectile for T-72 tank

To analyze the character of wear process, three 2A46 cannon barrels were selected from which from 222 to 830 different types of projectiles were shot. However, in each of the barrels, the number of one type of projectile prevailed.

A survey of projectiles shot from individual barrels is given in Table IV [16].

TABLE IV
SURVEY OF TYPES AND NUMBERS OF PROJECTILES SHOT

Barrel	Type of projectile	Number	Frequency
B0507	3OF-19 (HE)	761	91.7 %
	3BK-14M (HEAT-T)	69	8.3 %
	Total	830	-
C0164	3BM-15 (APFSDS-T)	188	39.5 %
	3BK-14M (HEAT-T)	70	14.7 %
	3OF-19 (HE)	218	45.8 %
	Total	476	-
D0034	TAPNA (APFSDS-T)	171	77.0 %
	3BM-15 (APFSDS-T)	32	14.4 %
	3OF-19 (HE)	19	8.6 %
	Total	222	-

V. TYPES OF TANK T-72 BARREL WEAR

On the basis of accomplished measurements it is possible to say that three basic types of tank T-72 barrel bore wear exist. The first type of barrel bore wear is caused by 3OF-19 (HE) projectiles mainly, the second by 3BM-15 (APFSDS-T) projectiles and the third by a new type of sub-calibre projectiles TAPNA (APFSDS-T).

The course of measured internal dimensions of barrel No B0507 worn by shooting 3OF-19 projectiles whose number significantly prevails is shown in Fig. 6 (the nominal dimensions of a new barrel bore are shown by the dotted line).

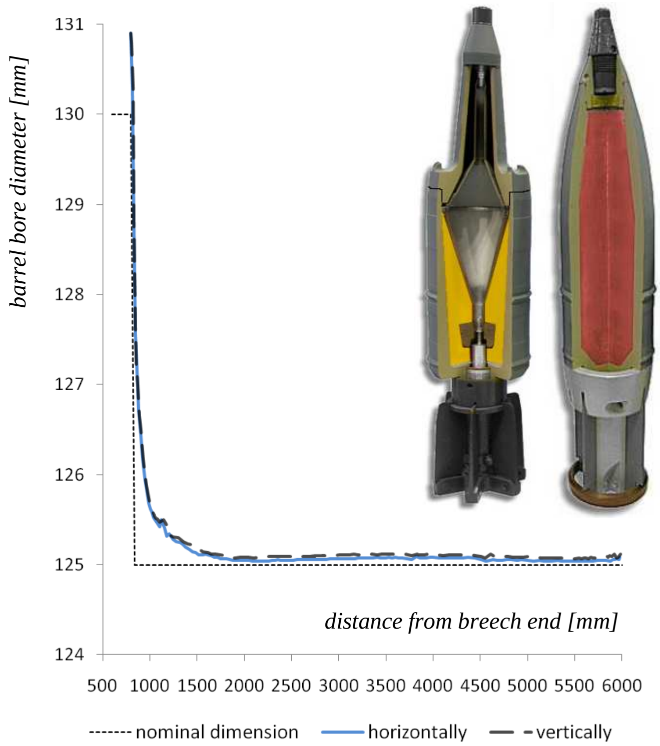

Fig. 6 Barrel No B0507 – wear caused mostly by 3OF-19 projectiles

The course of the measured dimensions of leading part of B0507 barrel bore obviously shows common character of wear of the forcing cone beginning and the part before muzzle. The course of wear is symmetrical in horizontal and vertical plain. Thus, some statements about asymmetric (eccentric) wear of forcing cone and beginning of leading part caused by loading projectiles have not been proven true and thus it is probably not necessary to rotate the barrel when we run out ¼, ½ and ¾ of barrel lifetime. This praxis is implemented for example in UK army and it costs a lot of money.

In comparison with standard courses of wear, there is an atypical increased wear in the second third of the leading part of the barrel.

Taking into account that 3BK-14M projectiles are similar in the design of driving parts to 3OF-19 projectiles; it can be assumed that the character of wear caused by them will be very similar.

The wear caused by shooting 3BM-15 projectiles shown in Fig. 7 is of essentially different character. From the comparison of the wear courses shown in Figs. 6 and 7 it is obvious that a significant wear of forcing cone and of the beginning of the barrel bore leading part is caused by 3BM-15 projectiles. The influence of 3OF-19 projectiles on this kind of wear is, even at high frequency of their shootings, negligible.

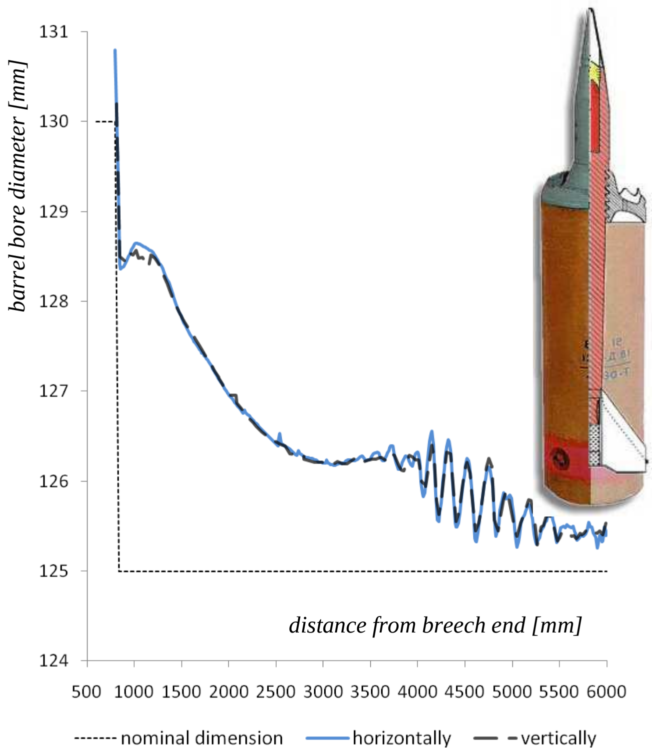

Fig. 7 Barrel No C0164 – wear caused by shooting mostly 3BM-15 projectiles

The position of seal ring in the front part of sabot of 3BM-15 projectile enables their partial spreading out (swinging) with respect to the penetrator by the force from gas pressure. This causes an increase in contact pressure between the barrel wall and sabot. It is demonstrated by a gradual increase in wear approximately in the first and partially in the second third of barrel bore. Thus, also the surface of sabot behind seal ring gets into the contact with the surface of the bore.

Fig. 8 shows the measured course of barrel bore dimensions where the wear is caused predominantly by TAPNA projectiles.

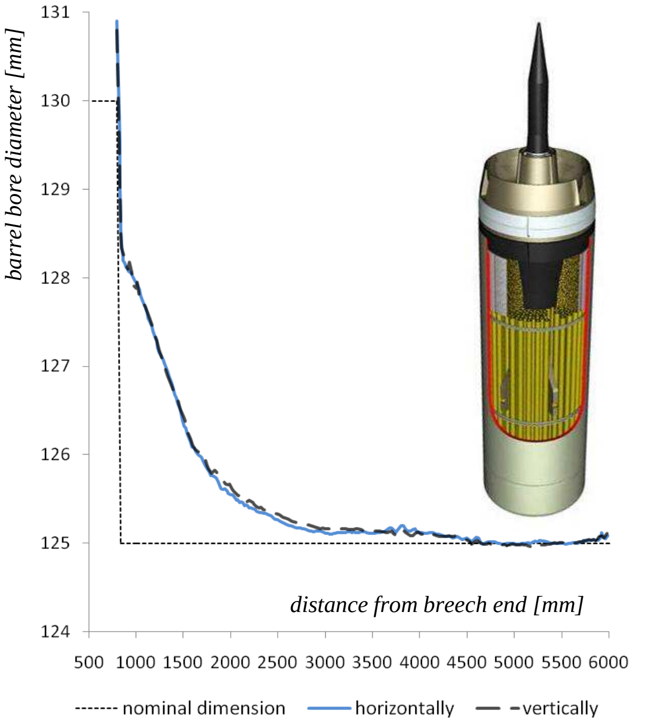

Fig. 8 Barrel No D0034 – wear caused predominantly by TAPNA projectile

Significantly bigger wear caused by 3BM-15 and TAPNA rounds in comparison with 3OF-19 and 3BK-14M projectiles results from sabot.

The distinctive wear of the beginning of the leading part of barrel bore has not been eliminated even by the construction of more appropriate sabots of TAPNA projectile – see Fig. 8. Also in sabots of this projectile, seal ring is located in the front part. That is why the spreading out of sabots by action of power from gas pressure might occur also in this case. The reduction of contact pressure occurs after certain travel of projectile when the spreading out is hindered by fins of sabots.

Reducing the bore diameter in the barrel part in front of muzzle is probably originated by abrasive wear of aluminium fins of sabots.

The next part of the paper will deal with a more detailed description of possible reasons of the wear of the beginning of barrel bore leading part by shooting sub-caliber armour-piercing projectiles of 3BM-15 types which is illustrated in Fig. 7. The causes and more detailed description of the course of wear of other parts of bore will be discussed after measuring wear in more barrels. It is necessary to verify the repeatability of this cyclical wear (see Fig. 7).

VI. Barrel Wear Caused by Sub-Caliber Projectiles

Now we will mathematically formulate the conditions of possible occurrence of increased barrel wear at the beginning of its leading part (see Fig. 7). Forces and load affecting the sabot (3BM-15 projectiles have 3 sabots) and seal ring are drawn in Fig. 9.

The force from the pressure of propellant gases causes moment

$$M_{\mathrm{A}} = F_p \left(y_{VS} + e \right), \qquad (3)$$

where F_p is force of pressure of propellant gases affecting perpendicular projection of surface S_{VS}, y_{VS} is distance of gravity centre of sabot from point A in the direction of axis y and e is eccentricity of point of action F_{p} towards gravity centre of sabot $\mathrm{T_{VS}}$. The force F_{p} is given by the relation $F_{\mathrm{p}} = pS_{\mathrm{VS}}$ and $S_{\mathrm{VS}} = \frac{1}{3}\frac{\pi}{4}\left(d^2 - d_p^2\right)$, where p is momentary pressure of propellant gases, d is caliber and d_{p} is penetrator diameter.

Moment M_{A} tends to swing the sabot around point A. By this, at the place of contact of seal ring with internal surface of barrel bore, the following reaction occurs:

$$N_{\mathrm{VS}} = \frac{M_{\mathrm{A}}}{l_x}, \qquad (4)$$

which increases contact pressure between barrel and seal ring. Against this swinging of sabot around point A, circumferential forces N_{TOt} take effect. They are a reaction of seal ring to its extension by the influence of force N_{VS}. Against this swinging affects also moment of friction force T.

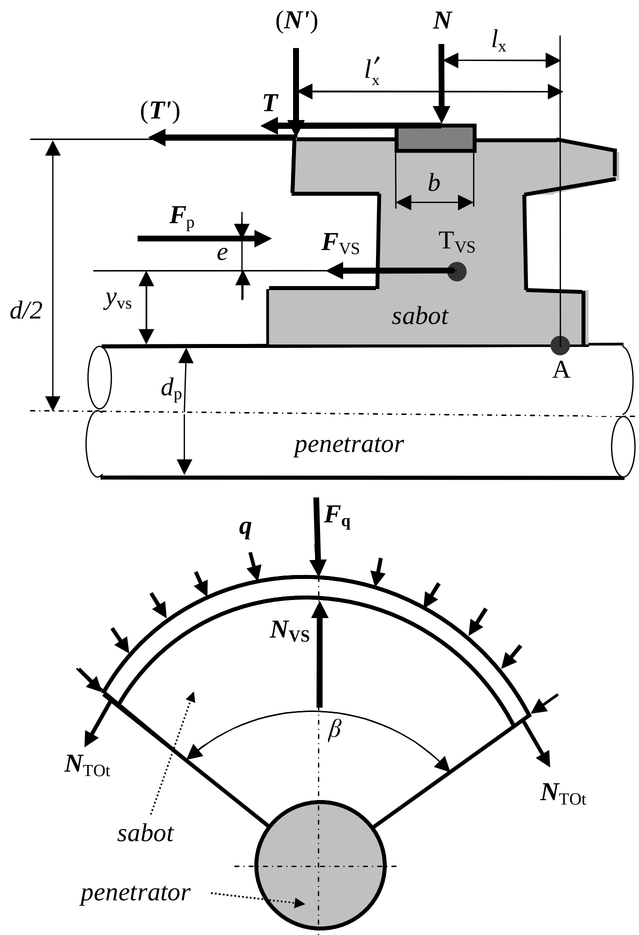

Fig. 9 Forces affecting sabot of 3BM-15 projectiles

Force N_{VS} causes the highest pressure $p_{N,\max}$ in the direction of its activity. In the direction diverted by angle β, it will interact by the following pressure: $p_N = p_{N,\max}\cos\beta$.

The elementary circumferential surface of seal ring of the width b and size $\mathrm{d}S = \frac{bd}{2}\mathrm{d}\beta$ will be affected by corresponding part of reaction $\mathrm{d}N_{\mathrm{VS}}$ for which it is valid that:

$$\mathrm{d}N_{\mathrm{VS}} = p_{\mathrm{N}}\mathrm{d}S = p_{\mathrm{N,max}}\cos\beta\frac{bd}{2}\mathrm{d}\beta . \quad (5)$$

By the integration of the equation (5), we will get the relation between force N_{VS} and internal pressure reacting with the seal ring of the shape as follows:

$$N_{\mathrm{VS}} = \frac{bd}{2}p_{\mathrm{N,max}}\int_{-\frac{\pi}{3}}^{\frac{\pi}{3}}\cos\beta\mathrm{d}\beta =$$

$$= \frac{bd}{2}p_{\mathrm{N,max}}\left[\sin\beta\right]_{-\frac{\pi}{3}}^{+\frac{\pi}{3}} = 0.866bdp_{\mathrm{N,max}},$$

from which the internal pressure is expressed as

$$p_{\mathrm{N,max}} = \frac{N_{\mathrm{VS}}}{0.866bd} . \quad (6)$$

For force N_{VS} and pressure $p_{\mathrm{N,max}}$ it is still valid that $\mathrm{d}N_{\mathrm{VS}} = p_{\mathrm{N,max}}\frac{bd}{2}\mathrm{d}\beta$ and at the same time $\mathrm{d}N_{\mathrm{VS}} = N_{\mathrm{TOt}}\mathrm{d}\beta$, from which we will get

$$N_{\mathrm{TOt}} = p_{\mathrm{N,max}}\frac{bd}{2} . \quad (7)$$

After substituting $p_{\mathrm{N,max}}$ from the relation (6) we will get

$$N_{\mathrm{TOt}} = \frac{N_{\mathrm{VS}}}{0.866bd}\frac{bd}{2} = \frac{N_{\mathrm{VS}}}{1.732} . \quad (8)$$

The increase in contact pressure between the barrel wall and seal ring will result from force

$$N = N_{\mathrm{VS}} - 2N_{\mathrm{TOt}}\cos\frac{\beta}{2} = N_{\mathrm{VS}} - N_{\mathrm{TOt}} = = N_{\mathrm{VS}} - \frac{N_{\mathrm{VS}}}{1.732} = 0.423N_{\mathrm{VS}} . \quad (9)$$

Using Fig. 9, we can now express the condition of balance of moments of forces affecting point A as follows

$$Nl_{\mathrm{x}} + F_{\mathrm{VS}}y_{\mathrm{VS}} + T\left(\frac{d}{2} - \frac{d_p}{2}\right) - M_{\mathrm{A}} = 0 , \quad (10)$$

where l_{x} is the distance of point of action N from point A in the direction of axis x, F_{VS} is inertial force affecting sabot and given by the relation: $F_{\mathrm{VS}} = m_{\mathrm{VS}}\ddot{x}$, m_{VS} is the weight of one sabot, $\ddot{x}$ is acceleration of translation motion of sabot (identical with projectile acceleration).

Acceleration $\ddot{x}$ can be expressed from motion equation of projectile by the following relation $\ddot{x} = \frac{\pi d^2}{4m_{\mathrm{q}}}p$, where m_{q} is weight of the whole projectile ($m_{\mathrm{q}} = m_{\mathrm{p}} + 3m_{\mathrm{VS}}$) and m_{p} is weight of penetrator.

After substitution to relation (10) and arrangements, we will get the relation for determination of force N_{VS} increasing contact pressure between barrel wall and seal ring as follows:

$$N_{\mathrm{VS}} = \frac{\frac{\pi d^2}{4}p\left[\frac{1}{3}\left(y_{\mathrm{VS}} + e\right)\left(1 - \frac{d_p^2}{d^2}\right) - \frac{m_{VS}}{m_{\mathrm{q}}}y_{\mathrm{VS}}\right]}{0.423l_x + 0.5f_{\mathrm{TO}}\left(d - d_{\mathrm{p}}\right)} , \quad (11)$$

where f_{TO} is friction coefficient between seal ring and barrel wall.

The magnitude of reaction N_{VS} is, according to relation (11), proportional to the pressure of propellant gases; thus, the maximum is reached in the place of maximal pressure. In case of 2A46 cannon and 3BM-15 projectile, the maximal pressure $p_{\mathrm{N,max}}$ is reached in the distance of 0.53 m from the beginning of forcing cone. The maximum measured wear of the beginning of barrel bore is according to Fig. 7 caused in the distance of approximately 0.25 m. This difference can be explained by the fact that we do not know the real course of gases' pressure (measured course of pressure at shooting by 3BM-15 projectile is not available), and that as a result of high surface pressure and its rapid increase, significant compression of seal ring occurs already at the beginning of projectile movement. By this, also the back edge of sabot gets into contact with the surface of barrel.

Initial reaction q achieves its maximum at the moment of full compression of seal ring by barrel wall, i.e. on the trajectory of 0.40 m maximum. Providing that the material of seal ring behaves as ideally elastic and plastic material, $q_{\max}$ will equal yield value (in case of seal ring made of annealed copper, yield value is about 60 MPa). Thus, it is apparent that the rear part of the surface of sabots will get into contact with internal surface of barrel bore even before the place of maximal pressure $p_{\mathrm{N,max}}$. Significant wear is partly caused by friction resulting from friction force T' (see Fig. 9).

Let us assume that against force N_{VS}, force F_{q} interacts from the reaction q of seal ring, given by the relation

$$F_{\mathrm{q}} = q\frac{bd}{2}\int_{-\frac{\pi}{3}}^{+\frac{\pi}{3}}\mathrm{d}\beta = q\frac{\pi bd}{3} . \quad (12)$$

For the known force N_{VS}, we will now formulate the condition of moments balance

$$N'l_{\mathrm{x}}' + F_{\mathrm{q}}l_{\mathrm{x}} + \left(T_{\mathrm{q}} + T'\right)\left(\frac{d}{2} - \frac{d_p}{2}\right) - N_{\mathrm{VS}}l_{\mathrm{x}} = 0 ,$$

from which after substitution and operations we will get

$$N' = \frac{N_{\mathrm{VS}}l_{\mathrm{x}} - F_{\mathrm{q}}\left[l_{\mathrm{x}} + 0.5f_{\mathrm{TO}}\left(d - d_{\mathrm{p}}\right)\right]}{l_x' + 0.5f\left(d - d_{\mathrm{p}}\right)} ,$$

where l'_x is distance of point of action N' from point A in the direction of axis x and f is friction coefficient between sabot and barrel wall.

This force results in contact pressure at the edge of sabot

$$p'_{N,max} = \frac{N'}{0.866bd} \,. \tag{13}$$

Force N', or better to say pressure $p'_{N,max}$, thus will cause high contact load of internal barrel surface which is just the reason of big wear of this part of bore.

As a conclusion and for better judging the effect of sabots swinging on the wear of barrel bore we will depict pressure caused by force N_{VS} using the relations (6) and (13). The both dependence of pressure $p_{N,max}$ between the barrel wall and seal ring and also pressure $p'_{N,max}$ between the barrel wall and edge of the sabot on the travel of projectile, or let us say travel of seal ring, are shown in Fig. 10.

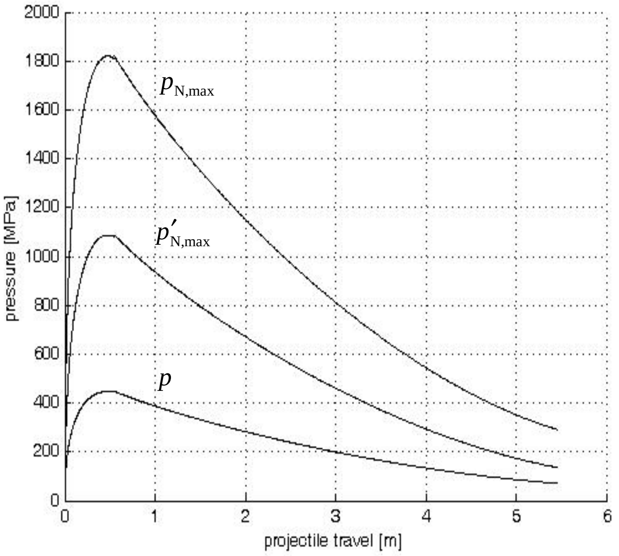

Fig. 10 Course of pressure of gases p, pressures $p_{N,max}$ and $p'_{N,max}$ in dependence on travel of seal ring in barrel [16]

The pressure of gases p in the Fig. 10 was computed using "Russian" system of interior ballistics equations (14) presented e.g. in [17], [19], [26], [27]:

$$p = \frac{f\omega\psi - \dfrac{\theta\varphi m_q v^2}{2}}{s\left(l_\psi + l\right)} \,,\ \psi = \kappa z + \kappa\lambda z^2 + \kappa\mu z^3 \,,$$

$$\frac{dz}{dt} = \frac{p}{I_k} \,,\ \varphi m_q \frac{dv}{dt} = sp \,,\ \frac{dl}{dt} = v \,, \tag{14}$$

$$l_\psi = l_0\left[1 - \frac{\Delta}{\delta} - \Delta\psi\left(\alpha - \frac{1}{\delta}\right)\right],\ \Delta = \frac{\omega}{c_0} \,,\ l_0 = \frac{c_0}{s} \,,$$

where f is specific energy of propellant, ω is mass of propellant charge, ψ is relative burnt propellant mass, θ is parameter of propellant gases expansion, φ is coefficient of fictivity, m_q is mass of projectile, v is velocity of projectile, s is bore area, l_ψ is reduced length of free volume of combustion chamber, l is travel of projectile, κ, λ and μ are form function coefficients, z is relative burnt thickness of propellant grain, I_k is total impulse of pressure of propellant gases, δ is propellant density, α is covolume of propellant gases, c_0 is initial combustion volume and t is time.

System of equations (14) contains seven variables $\left(\psi, z, p, v, l, t, l_\psi\right)$. It is a closed system of equations and has only a single solution – course of interior ballistic characteristics *p*, *v*, *l* in dependence on time *t*.

VII. Conclusion

The gun barrel is one of the most important parts of gun and it determines both gun power and gun lifetime. Contemporary theories of barrel lifetime match the wider theory of the propellant gases erosion and limit states of barrel material.

The study of barrels lifetime enables to manage practically not only the lifecycle of barrel itself but moreover the whole gun. Therefore the very wide range of theoretical and practical tasks of the evaluation of the technical conditions of barrels during its service has to be solved.

According to capability indexes it can be concluded that PKI-26 device is incapable of carrying out the evaluation of copper layer of the barrel bore since both indexes of capability are significantly lower than 1.33. PKI-26 is suitable for the inspection of barrel bore wear in the area of 10 mm behind the forcing cone (850 mm from the breech end) and the area of barrel muzzle in accordance with the requirements of the Directive [29]. With respect to the construction of this device, we are not able to diagnose more than 3 m of the leading part of the barrel bore.

The contribution shows the suitability of the use of BG-20 MKII Gun Barrel Bore Gauge System (Aeronautical & General Instruments Limited production) for the measurement of wear of smooth barrels bore. Measured courses of wear, or let's say the changes in the diameter of leading part of barrel bore caused by shooting of various types of projectiles and then also demonstrate the suitability of used constructions of projectile sabots.

There can be stated that three basic types of tank T-72 barrel bore wear exist. The first type of barrel bore wear is caused by 3OF-19 (HE) projectiles mainly, the second by 3BM-15 (APFSDS-T) projectiles and the third by a new type of sub-calibre projectiles TAPNA (APFSDS-T).

From the point of view of bore wear it seems obvious that sabots of 3BM-15 and TAPNA projectiles are inappropriately designed.

For comprehensive description of causes of wear resulted from 3BM-15 projectiles, it is necessary to conduct measurements on more barrels and consequently to analyze the causes of occurrence of cyclical wear in the last third of barrel bore. On the basis of this analysis it is recommended to determine the dependence of amplitude and period of wear on construction characteristics of sabots and barrel.

A new sub-calibre projectile of APFSDS type with a longer driving part of sabots and seal ring located on rear driving band has been introduced in the Czech Armed Forces recently. In this construction of projectile it is possible to assume significantly lower wear in both forcing cone and beginning of barrel leading part. The assessment of wear caused by shooting these projectiles will be dealt with in the future.

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