Evaluation of projectile ramming process in new and worn smooth barrels of guns

Jiri Balla, Stanislav Prochazka, Van Yen Duong

***Abstract*—**This article deals with the influence of barrel wear and barrel thermal deformation of tank cannon on the ramming process. Barrel wear was used as input data from measuring on 125 mm smooth tank cannon barrels. Barrel thermal deformation and the ramming process of APFSDS (Armor-Piercing Fin-Stabilized Discarding Sabot) projectiles were calculated using ANSYS Workbench software utilizing the Finite Element Method (FEM). The ramming process calculation was done for two case scenarios: the first case was for a new barrel deformed by barrel thermal effects from firing; the second case was for a worn barrel influenced by the same thermal effects. The reaction force as the most important standardized factor used to evaluate the effect and safety of the ramming process is verified by experiment performed on the above mentioned 125 mm weapon system. The calculated results are reasonably compatible with the experimental results. The research results also provide a background for the state-of-the-art knowledge to upgrade the Czech Defense Standards (COS) for the ramming device of artillery weapons and tanks.

***Keywords*—** Barrel thermal deformation, barrel wear, forcing cone, ramming process, tank cannon loading

I. INTRODUCTION

IT IS known that the combat efficiency of artillery, especially self-propelled howitzers and tanks depends on many tactical and technical factors, see [15], [16], [30], and [35]. One of the most important technical factors is the rapidity of fire and the safety of projectile ramming during unstable motion of fighting vehicles on the battlefield. A very important factor is the safety of projectile ramming while a fighting vehicle in the battlefield is moving fast and over bad terrain or bad road conditions when a heavy projectile must not fall down from the cartridge chamber, see [1], [4], and [7].

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J. Balla is with the University of Defense, Kounicova 65, 662 10 Brno, Czech Republic (corresponding author to provide phone: 00 420 973 44 5013; e-mail: jiri.balla@unob.cz) and Alexander Dubcek University of Trenčín, Studentska 2, 911 50 Trencin, Slovakia; email: jiri.balla@tnuni.sk.

V. Y. Duong is with the University of Defense, Kounicova 65, 662 10 Brno, Czech Republic; e-mail: yen.duongvan@gmail.com).

S. Prochazka is with the University of Defence, Kounicova 65, 662 10 Brno, Czech Republic (corresponding author to provide phone: 00 420 973 44 5268; fax: 00 420 973 44 5011; e-mail: stanislav.prochazka@ unob.cz).

Therefore, both the rapidity and safety of ramming depend on the quality of the ramming device which is a very important part of the loading device. Firstly, the ramming device secures the projectile in the barrel while the projectile is engraved into the barrel forcing cone, thus preventing the risk of projectile fallback, see [2], [3], [26] and [27]. Secondly, the ramming process creates a deformation field between the driving band and the forcing cone to seal the air-gap between the powder chamber and the guidance section of the barrel, ensuring the powder gas does not leak through this air-gap when firing, see [6], [9], and [36]. Thirdly, the accurate position of the projectile in the chamber after ramming gives a steady movement to the projectile in the barrel and decreases vibration of the projectile which, together with all the above mentioned factors, increases firing accuracy, see [21], [25], and [27]. Generally it is mentioned in [26] with respect to the ramming devices and rammed projectiles. The interface configuration between the chamber, the forcing cone and ammunition shall ensure that no projectile falls back out of its seating, at any angle of elevation, between the action of loading and exiting the barrel by firing. To reduce the risk of fall back to a minimum, the following shall be taken into account during design and development. Besides the coincidence of the rammer axis with the bore axis, the rammer head must remain in firm with the base of projectile as it drives the projectile into its seating. When hand ramming is in operation (as back up of a motor drive), with or without the use of a stave, contact between hands and the equipment should be prevented when ramming at any elevation angle and traverse.

As, potentially, fall back can cause premature explosion in the bore, trials are required to establish the degree of risk involved both power ramming, in follow-through and flick modes, and hand ramming. In these trials, the force required to eject a projectile which has been correctly rammed is measured by a load cell or other device.

According to [26] the ejection force is assumed to be same as the retention force holding the projectile in the rammed, seated, position. Flick rammed projectile subjected to too high velocity of ram may sustain filling, cargo, sub-components or fuse damage. Trials to establish the margin of safety (upper threshold) are required. Other trials are necessary to ensure that rammed, correctly seated projectiles do not become dislodged during laying drills, movement (in case of tanks when loaded in readiness for engagement) or as a result of any operational vibration.

The test procedure is described very shortly. A series of not less than 20 projectiles is to be rammed and ejected with the ejection force being measured for each projectile in the series. After ejection, each round should be examined, and if found to be satisfactory, rammed again and fired. Ramming is to be carried out at the maximum permissible loading elevation and at any lower elevations considered critical.

The several of data are recorded. There are several of them: the velocity of the ramming, the depth of ram and finally the ejection force.

The standard [26] assumes that the rifled bore is used. The different problem occurs when barrel is smooth as it is in the modern tank cannons. One example is illustrated in Fig. 1 where the chamber length of 800 mm is followed with the short forcing cone having the length for the new barrel only 40 mm. Then the leading part follows (only its beginning is in Fig. 1) with the diameter which corresponds to the weapon caliber *d*. During barrel life after series of fires the forcing cone is shifted more and more into the leading part of the barrel and the projectile is caught deeply after its ramming. The distance l_p is lengthened, see Fig. 2.

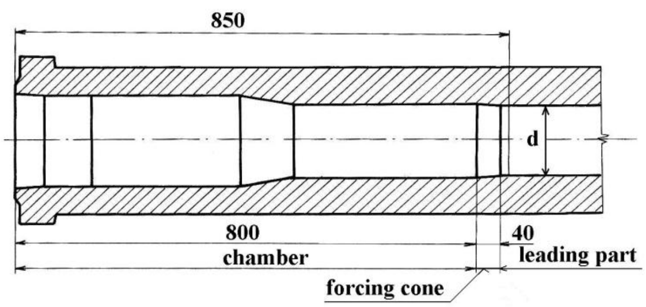

Fig.1 Smooth barrel

The position of the APFSDS projectile in barrel is illustrated in Fig. 1, see [9], [17], [18], and [20].

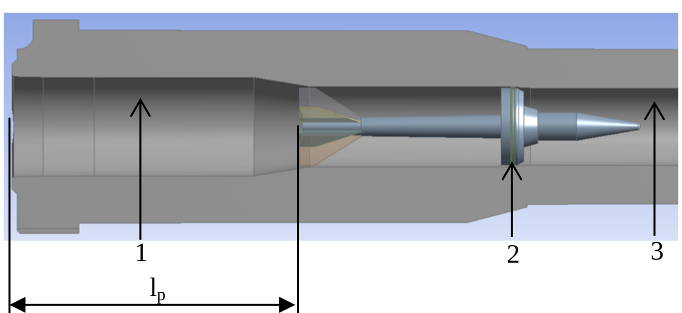

Fig.2 Position of the APFSDS projectile in the barrel after ramming: 1- chamber; 2- contact area between the forcing cone and the driving band; 3- leading part

The main ramming characteristics are the ramming velocity at the end of the ramming process, when the projectile engraves into the forcing cone, and the ramming force that secures the projectile in the barrel before firing, see [5], [32], and [37]. The ramming velocity for howitzers and tank cannon has been discussed in [2], [3], [5], and [25], but the determination of any forces in course of ramming and the projectile engraving is very difficult due to the nonlinear plastic-elastic problem making the determination of many factors hard. The standard [26] deals with the value determination of the force necessary to hold the projectile in the barrel. However, it only defines the opposite force (which must be the same), known as the retention force, when the tested projectile is extracted from the barrel using a special arrangement. The first calculated force results have been published in [7] for the 152 mm howitzer system with rifled barrels. But the 125 mm tank cannons use the different smooth barrels. The rammer velocities at the end of the operation obtained from measuring are about 2.9 $m \cdot s^{-1}$ for the 125 mm tank cannons and 1 $m \cdot s^{-1}$ for 152 − 155 mm howitzer systems. Barrel wear and thermal deformation influence the ramming process intensively [9] [19], [36], and [37]. In the following section a ramming process with respect to barrel bore wear and the thermal deformation caused by the effects of a firing cycle will be calculated using ANSYS software.

II. Barrel Thermal Deformation

One of the most important side-effects of a shot is barrel heating. Very often it becomes a barrier to the power growth of the weapon. The heat is transferred from the inner surface to the outer surface of the barrel wall. The created uneven thermal field causes on one hand a thermal deformation field and on the other hand thermal expansions due to the temperature rise. The resultant deformation that results from the stress is significantly smaller than the bore expansion, as the thermal expansion is only 10% of the total deformation once the required stabilized temperature state is reached [11], [36], and [37]. The radial deformation changes in the barrel along the barrel axis are very important input data for the ramming problem, especially the diameter change of the forcing cone and of the beginning of the leading part (the first third of the forcing cone). The changes in the inner diameter influence the interaction process between the projectile driving band and the forcing cone during ramming.

In order to calculate the thermal deformation field in the barrel wall the Steady-State Thermal component of the ANSYS Workbench software has been used, see [12], [22], [23], [29], and [40] primarily. It is assumed that temperature distribution in the barrel wall is dependent on the radius according to the Fourier-Kirchhoff partial differential equation, see [35], and [36] for example, describing thermal transmission in the radius direction at a steady temperature mode.

$$T(r) = T_1 - \Delta T \frac{\ln \frac{r}{r_1}}{\ln \frac{r_2}{r_1}}, \qquad (1)$$

Where

T_1 –temperature at the barrel bore,

T_2 – temperature gradient in the barrel (radius direction),

r_1, r_2 – barrel internal and external radius.

The results of the calculations are the heat fields in the barrel wall. These heat fields are used as input data for using the Static Structural component of the ANSYS Workbench software to calculate the thermal deformation fields.

The FEM model for the tank cannon barrel during all loading projectile process was worked out using [8], [10], [13], [14], [24], [28], [31], [33], [34], [39], and [40] and is shown in Fig. 3. The circle indicated as a represents the forcing cone area.

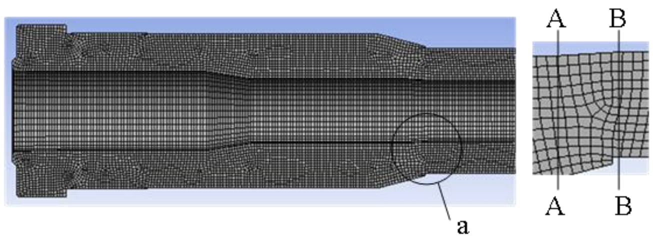

Fig.3 Model of a 125 mm tank cannon barrel

The results of calculations have been tested by way of comparison with the analytical solution of the heavy-walled barrel. The boundary conditions at the end of the calculated area were set from the conditions of non-deformation area in the axial direction outside of the calculated area.

The interactions between the projectile driving band and the forcing cone occur in the A-A and B-B cross-sections.

Temperature distribution from the inner surface to the outer surface is shown in Fig. 4. The temperature on the inner surface is, from experience, set at 350°C taking into account the requirement not to exceed the maximum recommended temperature on this surface. The temperature decreases in the radial direction from the inner to the outer surface. The temperature gradient, at the steady temperature state, reaches 150° – 200°C for heavy gun barrels, see [19], and [36]. In this case the temperature on the outer surface was calculated as 200°C. The calculated temperature fields – see Fig. 4 – create the input data for the barrel deformation problem.

The calculation results of barrel thermal deformation are shown in Fig. 5.

After each shot, the shape of the barrel forcing cone is changed due to the barrel thermal deformation. This change forms a new shape in the barrel forcing cone. The calculation results of the radial thermal deformation of the inner surface along the barrel length are approximately 0.3 mm (see Fig. 6).

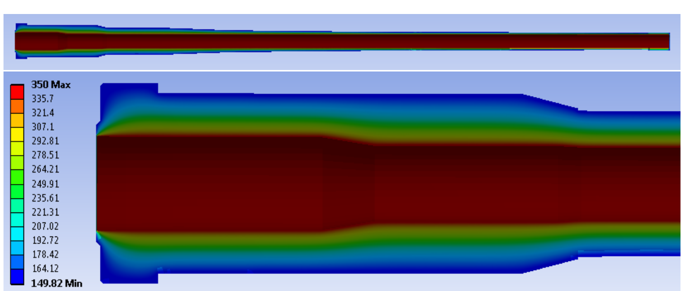

Fig.4 Temperature field in barrel wall

The maximum values are around the forcing cone of the barrel. Those are the danger areas for securing the projectile in the barrel post-ramming, see [7], [17], and [36].

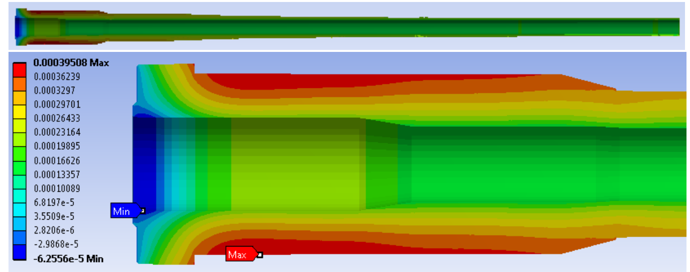

Fig.5 Radial thermal deformation field (m) of barrel wall

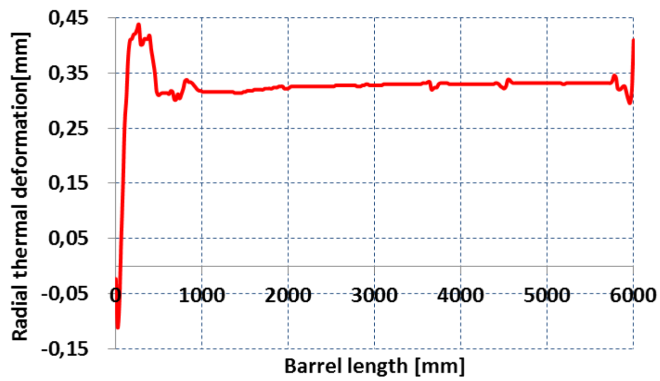

Fig.6 Barrel radial thermal deformation of the inner surface along the barrel length

III. Barrel wear

The ramming process is influenced not only by barrel thermal deformation, but also by barrel wear that influences projectile ramming more intensively than barrel thermal deformations. This can be explained by the main reason that rapidity of fire of self-propelled howitzers as well as tank cannons is quite low (6 to 8 rounds/min). The time from previous firing cycle to the next firing cycle is quite long with respect to the duration of barrel temperature drop. The barrel temperature drops and the elastic thermal deformations of the barrel disappear or reduce to zero before the next firing cycle is performed. However, in order to satisfy the safety requirements of any weapon system operation, the ramming process with simultaneous influences of barrel thermal deformations and barrel wear will be researched.

Measurement results for the 125 mm worn cannon barrels performed by the Department of Weapons and Ammunition are shown in Fig. 7, Fig. 8, and Fig. 9, [17], [18], [19], and [20]. The measured value is the inner barrel bore diameter. The inner diameter of the new cannon barrel bore is $125^{+0.15}$ mm. The limited diameter of barrel behind the forcing cone (850 mm from bottom) is 128.3 mm. The projectile manufacturing tolerance of diameter is $129^{-0.4}$ mm.

Then it can be 128.6 mm. It is reason why the occurrence of the initial barrel chamber volume increasing when new projectile is rammed into the worn barrel – projectile does not stop as in the new barrel, but deeply. In all these mentioned figures the barrel length starts from 800 mm. It is the beginning of the forcing cone followed by the leading part of the barrel bore, see Fig. 1 as well. According to [17] it is known that APFSDS projectiles cause different character of

wear unlike HEAT (high explosive anti-tank) and HE (high explosive) projectiles.
Usually the barrel wear firing APFSDS projectile is more than eight times greater than barrel wear using HEAT and HE projectiles.

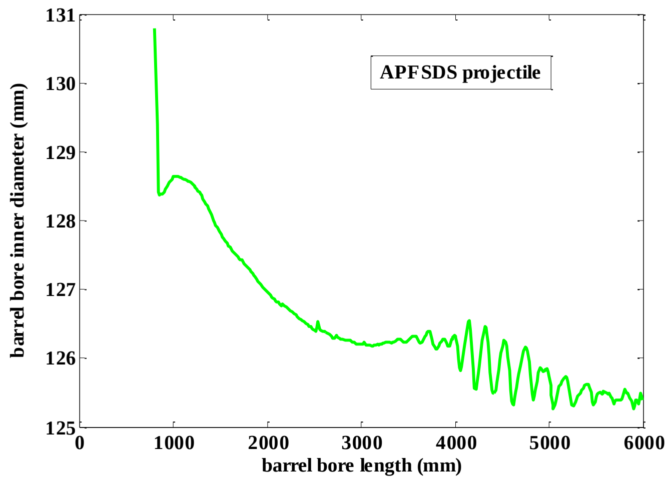

Fig.7 Wear of cannon barrel bore firing mainly APFSDS projectiles with ferrous sabot

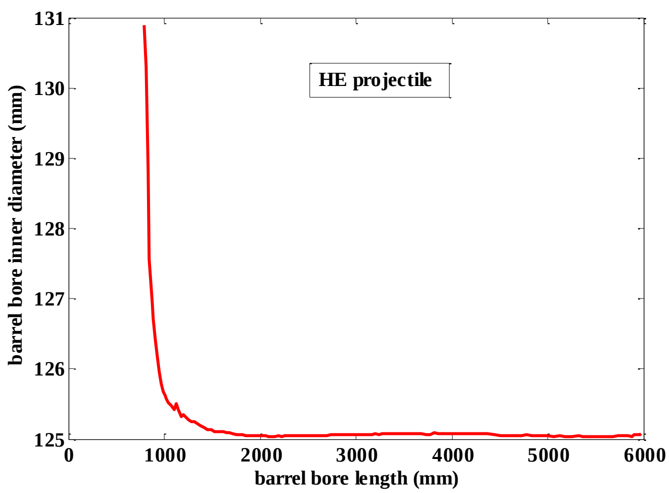

Fig.8 Wear of cannon barrel bore firing HE projectiles

The growth of the wear behind the forcing cone in the Fig.7 has been discussed in [17], [19], and [20].
The differences of driving band shape between APFSDS and HE (high explosive) projectiles, quantity of fired rounds etc. cause that the barrels wear to be in the different range of values. The barrel firing mainly APFSDS projectiles with ferrous sabots is worn out more intensively than the barrel firing new APFSDS projectiles using the nonferrous sabots.
Evidently, barrel wear occurs more intensively at the region of the forcing cone and at the beginning of the leading part of the barrel bore (the first third of the forcing cone). Wear of the forcing cone and the leading part can be generally specified by increasing of the diameter at a point between the forcing cone and the leading part, see Fig. 1.

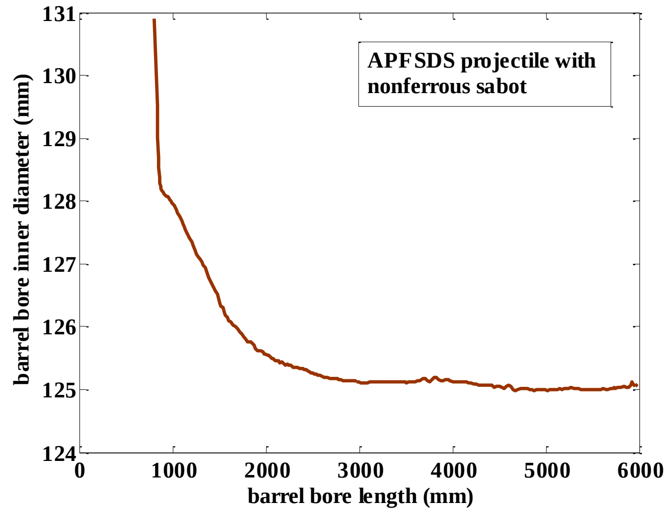

Fig.9 Wear of cannon barrel bore firing mainly APFSDS projectiles with nonferrous sabot

IV. Influences of Barrel Thermal Deformation and Barrel Wear on Projectile Engraving

As it is mentioned in last sections the barrel wear influences the engraving of the projectile at the end of the ramming process as it is explained in Fig. 10 where are three cases – new barrel, worn barrel, and worn and heated barrel. The case with thermal deformation from heating is exaggerated due to clear explanation of the research object. The main results are that the projectile is rammed deeply into the barrel and it can cause serious problems in service as it is represented by the l_p length in Fig. 10.

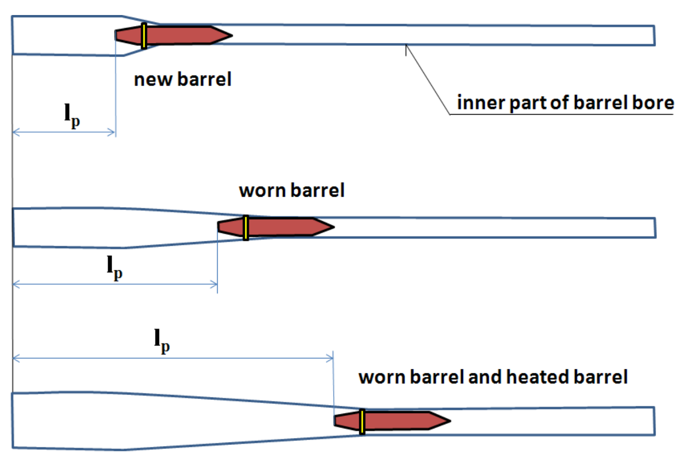

Fig.10 Explanation of projectile position in different barrels

The calculation and simulation have been carried out for two cases with helping of The Transient Structural component of the ANSYS Workbench software.

The position of the projectile before and after ramming, where it is engraved is shown in Fig. 11 for the new barrel. The place of the driving band is marked by the red circle.

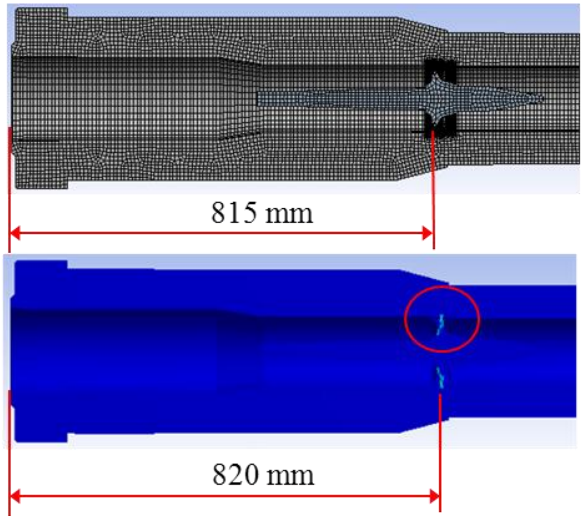

Fig.11 Projectile position before and after ramming – new barrel

The FEM model of the ramming problem is shown in Fig. 12 after magnification. The boundary conditions are set for the problem, including fixed position of the barrel at the barrel bottom and the initial ramming velocity of the projectile. The projectile velocity the rammer velocity at its end position, where the ramming device stops but the projectile moves continuously in the direction of the barrel axis with an initial velocity of 2.9 $m \cdot s^{-1}$, see Fig. 14, and Fig. 20.

The first case describes the geometry of a new barrel with the thermal deformations determined in ANSYS Workbench using FEM. The ramming process of the APFSDS projectile was simulated and calculated on this model base.

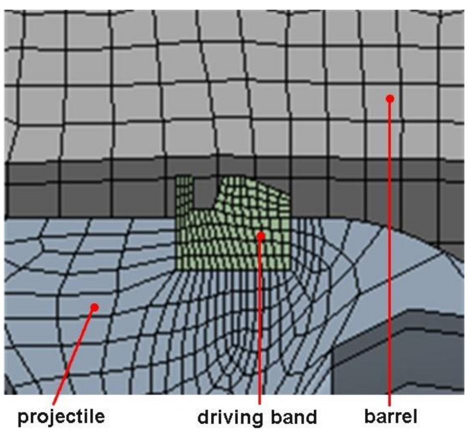

Fig.12 FEM model of driving band engraving

The equivalent stress (Von-Misses) with the thermal deformation effect in the new barrel is 212 MPa. The calculated reaction engraving force achieved at the process beginning is more than 20 kN, see Fig. 13, and the projectile velocity drops after 2 ms approximately, see Fig. 14. The measurement of this force is very difficult. The validity of the FEM model has been performed indirectly using the unique measuring device designed at Weapons and ammunition department of University of Defence in Brno during research works on the project Delo (this word means Cannon in English) as other works [17], [18], [19], [20], and [37].

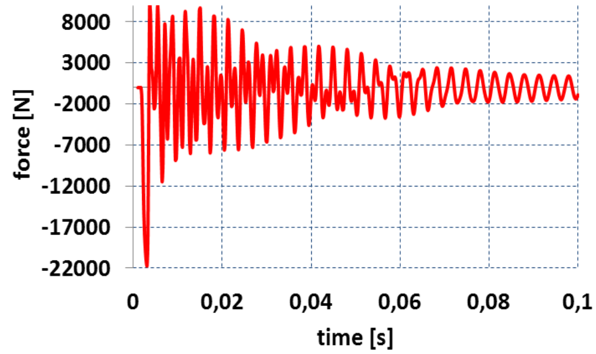

Fig.13 Reaction force in a new barrel

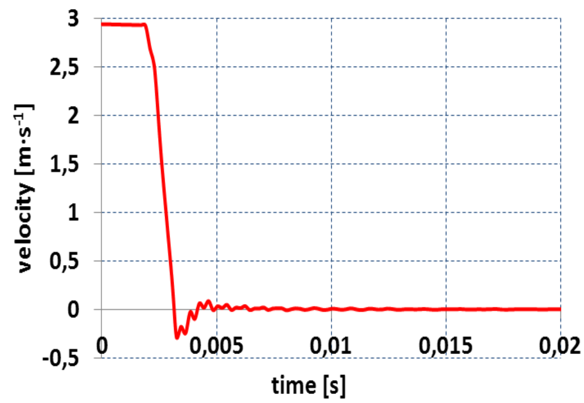

Fig.14 Projectile velocity in a new barrel

The measuring equipment is depicted in Fig. 15.

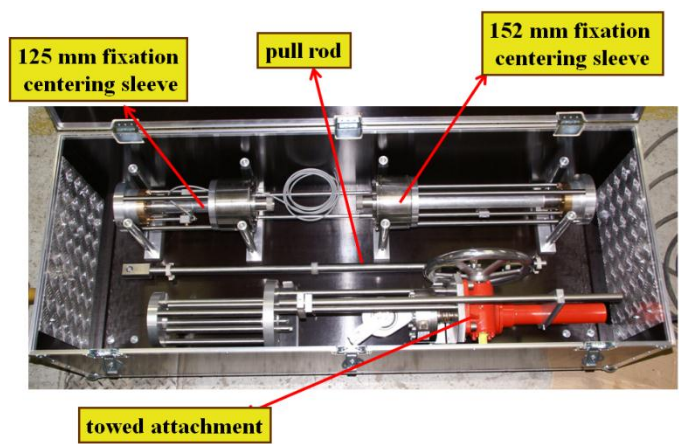

Fig.15 Force measurement device

The device is able to determine the extraction force from the barrel at 125 mm tank cannon and 152 mm howitzer. This force equals to the retention force according to the standard [26]. The two fixation centering sleeves are used for it.

The fixation centering sleeve having the HBM displacement gauge inserts into the barrel and fixes to the barrel chamber and it have to touch-down on the barrel bottom. After sleeve centering this is fixed by means of the eight threads.

The initial position of the displacement gauge is set and ensured with the pull rod and the screw. The pull rod is connected with the extracted projectile via the tie tube having the bayonet joint. The hook-type towing attachment is put together with the fixation centering sleeve and the pull rod is united with the HBM force gauge through the coupling pin. By means of the hand wheel is the projectile pulled out of the barrel. The second prototype will use the DC electric motor due to the extraction force should be independent on the crew. Special measuring arrangement enables the record both the extraction force and the projectile displacement (and additionally time as well). The evaluation software is in disposition with additional export data into ASCII format enabling other analyses. The Fig. 16 shows the main electric parts of the measuring device as they are connected together.

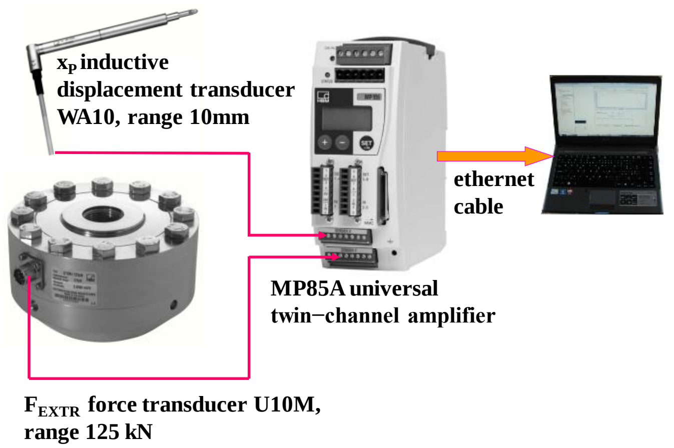

Fig.16 Scheme of measuring device

One example of 125 mm projectiles extraction forces comparing the measured (red color) and calculated (blue color) data is portrayed in Fig. 17.

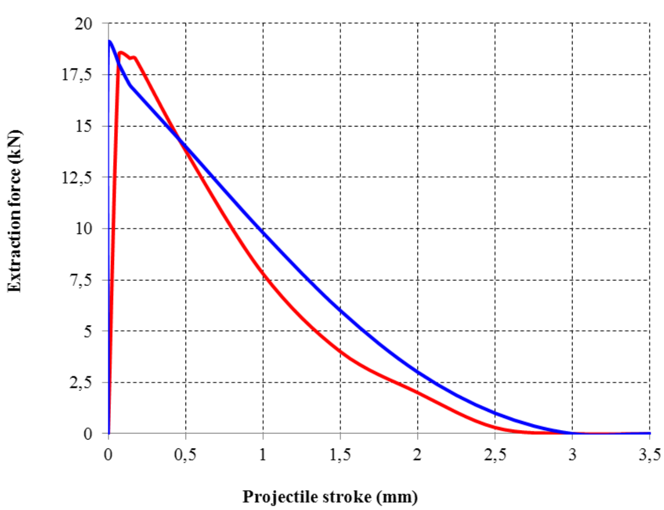

Fig.17 Comparison of measured and calculated data

The extraction force varies from 15 kN to 20 kN (motor drive ramming). The ramming force and ramming velocity change on the real properties of the drive where the input circuits and voltages can take different values in every particular case. To evaluate the appropriateness of measuring device U10M uses for the measurement of extraction force of tank cannons barrel bores it is possible to use index of ramming process capability C_{RD}. Let us define the term ramming process capability as its ability to reach a continual fail-proof engraving of projectiles into the forcing cone. An adoption of this new term enables to build up an unambiguous criterion for an assessment of the ramming projectiles process and thereby the evaluation of the complete loading cycle.

The assessment of the test follows now.

Let us assume that the fallback occurrence probability takes place if the extraction force F_E is less than 5 times the force of gravity of the projectile ($5G_P$):

$$F_E < 5G_P . \tag{2}$$

The $5G_P$ retention force provides sufficient safety to preclude potential dislodgement of the projectile. It would be become as a result of opening or closing the breech and normal operating drills when the ordnance is loaded or laid. This criterion is in accordance with standard COS 109 002, [26].

The index of ramming process capability is defined in the form, see [6]:

$$C_{RD} = \frac{\bar{F}_E - 5G_P}{3s_{F_E}} , \tag{3}$$

where s_{F_E} s is the standard deviation.

According to (3) it is possible to define three examples of capability of the projectile ramming process. If $C_{RD} > 1$ then the ramming process is fully capable, when $C_{RD} = 1$ the process is conditionally capable and in the case $C_{RD} < 1$ the process is incapable.

The explanation of the C_{RD} values is following. The probability of the projectile fallback is at the value $C_{RD} = 1$ theoretically 0.0013. It means that one of 1000 rammed projectile can fallback. This level of the ramming capability is from security risks point of view poor at the amount rammed projectiles 103 ÷ 104 during the service.

The acceptable security risk during a life of service is considered the probability of fallback only one of one million (1 000 000) rammed projectiles. This probability level matches to the value of the capability index $C_{RD} \geq 1.583 \cong 1.6$.

Ramming device is considered fully capable when capability index (determines from 25 ÷ 30 projectile ramming cases) achieves a value greater than 1.583 (practically greater than 1.6). This value of capability index ensures stable and safety ramming projectile process.

According to [6] is possible to determine the index capability from the 25 measurements as it is set in the Table I.

The mean value was calculated according to the formula (n = 25):

$$\bar{F}_E = \frac{\sum_{i=1}^{n} F_{E_i}}{n} \tag{4}$$

The standard deviation is determined from following formula:

$$s_{F_E} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(F_{E_i} - \bar{F}_E\right)^2}\,. \qquad (5)$$

TABLE I
INPUT VALUES DETERMINING INDEX CAPABILITY

test No.	F_{Ei} (kN)	test No.	F_{Ei} (kN)	test No.	F_{Ei} (kN)
test 1	17.2	test 10	19.1	test 19	16.6
test 2	15.5	test 11	17.8	test 20	18.8
test 3	19.1	test 12	18.7	test 21	19.5
test 4	20.1	test 13	18.9	test 22	15.3
test 5	18.0	test 14	16.7	test 23	19.7
test 6	16.6	test 15	18.4	test 24	17.9
test 7	15.8	test 16	16.8	test 25	18.3
test 8	19.9	test 17	17.5		
test 9	15.5	test 18	19.5		

Let us assume that the values of extraction force have a normal distribution (on the basis of Kolmogorov – Smirnov goodness of Ht test, this hypothesis has not been rejected). Both the mean value and standard deviation of normal distribution were stated N(17.9; 1.5) from the Table 1 and (4), (5). Thus, according to the data of Table I and (5), the index of ramming process capability $C_{RD} = 3.86$. Then the ramming process is fully capable.

The second case is represented by the worn barrel and influence of thermal deformations, where the projectile is rammed deeply, see Fig. 18.

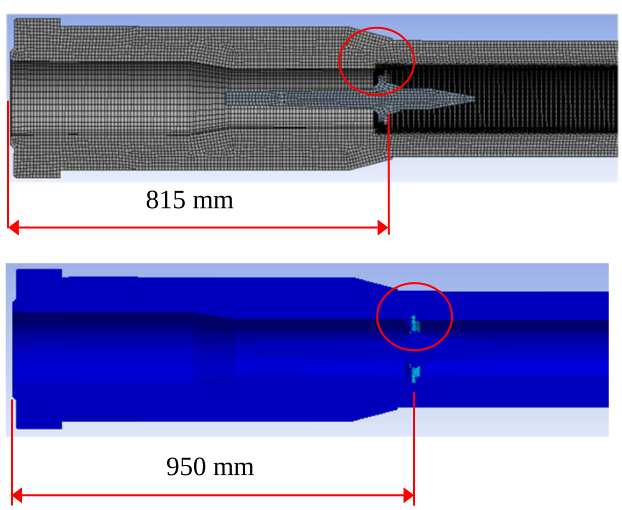

Fig.18 Projectile position – worn and heated barrel

The calculated maximum equivalent stress in a worn barrel is 98 MPa and that is twice as low as in a new barrel.

The reaction force and the projectile velocity in the engraving process are shown in Fig. 19 and Fig. 20

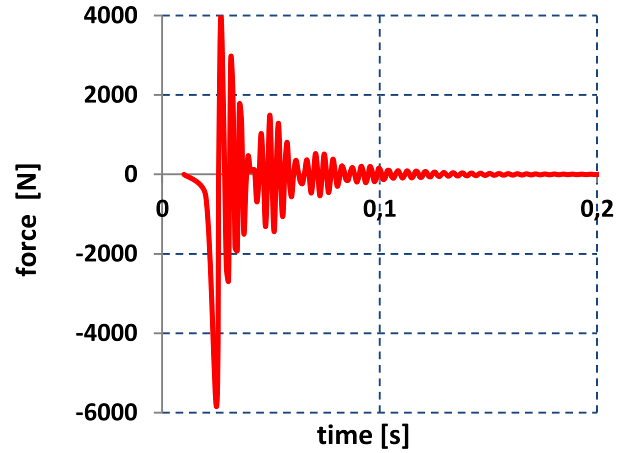

Fig.19 Reaction force in a worn barrel

The reaction force, securing the projectile in the barrel, is lowered to a similar ratio as the equivalent stress.

Comparing Fig. 13, and Fig. 14 with Fig. 19 and Fig. 20 the engraving process for the worn barrel with thermal deformation effect in the course of a single shot can be evaluated. At the beginning of the engraving period (approximately 0.015 s), the projectile moves without resistance forces as the worn barrel diameter is greater than the driving band diameter. In this stage the projectile velocity slowly decreases from 2.9 $m{\cdot}s^{-1}$ to 2.5 $m{\cdot}s^{-1}$, see Fig. 20, as a consequence of action friction forces.

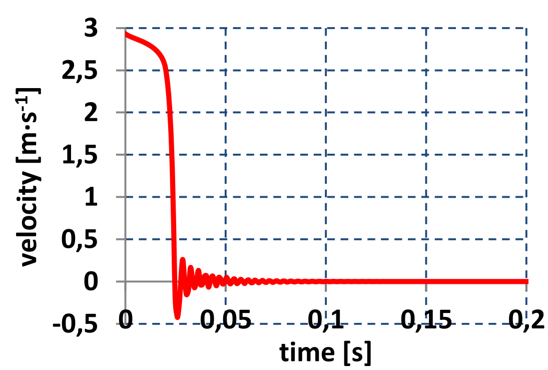

Fig.20 Projectile velocity in a worn barrel

The resistance force caused by the interaction between the driving band and the inner surface of the barrel – engraving the projectile into the forcing cone – occurs at the point where the barrel diameter is smaller than the driving band diameter. Due to the resistance force the projectile velocity decreases dramatically to zero. Simultaneously, owing to the driving band dynamic impact to the inner surface of the barrel, both of resistance force and the barrel velocity have vibration forms, see Fig. 10, Fig. 11, Fig. 13, and Fig. 14, as it was confirmed in [27] for 155 mm projectiles.

But the beginning and the end of periods have to be improved to obtain the more accurate results.

V. CONCLUSION

For a new barrel, where the barrel dimensions are given in the technical documentation, the distance between the initial projectile position where the impact starts and stops, was 3 – 5 mm. The distance in the worn barrel, as represented in Fig. 18, was much greater than for the new barrel reaching up to 150 mm, see Fig. 12. The prolongation of the ramming displacement leads to a rise in the volume of the barrel chamber causing a change in the development of barrel gas pressure. The place of the maximum value of the gas pressure in the barrel shifts to the place where the barrel thickness is smaller. This phenomenon can cause the risk of barrel chamber elongation. A permanent elongation can occur when the barrel wear is greater than the value specified in the technical documentation of the Czech Defence Standards, see [26] for requirements of the loading process. Then barrel explosion can occur. This problem is very important for APFSDS projectiles whose velocities go beyond 1500 $m \cdot s^{-1}$.

The increase in resistance forces, caused by the driving band engraving, happens in the region where the worn barrel diameter is smaller than the driving band diameter. In such a case the projectile is rammed deeper than in an unworn barrel and projectile velocity at the beginning of the engraving is lower as a consequence of the projectile movement by inertia. In a new barrel the rammer is designed to stop its movement at the start of the projectile driving band in the forcing cone. If the rammer stroke was greater rammer deformation could occur. For this reason the rammer velocity was increased up to 3 $m \cdot s^{-1}$. This measure ensured that the projectile would also be held in a worn barrel at any elevation angle when loading on the move where significant inertia forces strongly influence the loading system.

The impact and the interaction between the driving band and the inner barrel surface are non-linear dynamic processes and the velocities and the reaction forces have their typical oscillating movement known as the ping-pong effect, see [27].

In the future, the measuring of reaction forces using the new HBM measuring device with electric drive instead of hand one and specification of the input data for FEM shall be conducted.

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Jiri Balla born in Poprad (Czechoslovakia), 6th June 1954. MSc degree in mechanical engineering at Military academy in Brno 1978. PhD degree in field weapons and protection against them at Military academy in Brno 1986. Assoc Prof of Military academy in Brno 1998 in field military technology, weapons and ammunition. Professor of Defense University in Brno 2006 in same field as Assoc Prof. Current the author’s major field of study is dynamics of weapon barrel systems. He worked in military units as ordnance officer. After PhD studies he was a teacher as lecturer and associate professor. He was visiting fellow at Royal Military College and Science (RMCS) in Shrivenham (UK) 1996, 1997, 1998. Currently he is a professor at University of Defense in Brno at Weapons and ammunition department and a professor at Alexander Dubček University of Trenčín, Študentská 2, 911 50 Trenčín, Slovakia.

The main books:

1. D. F .Allsop, J. Balla, V. Cech, L. Popelinsky, S. Prochazka, J. Rosicky, Brassey´s Essential Guide to MILITARY SMALL ARMS. London, Washington. Brassey´s, 1997.
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Prof. Balla is member of Czech Association of Mechanical Engineers (CzAME).

Van Yen Duong Van Yen Duong born in Vinh Phuc (Vietnam), 22nd February 1974. Eng degree in field of weapons and ammunition at Military Technical Academy in Hanoi 1996. MSc degree in mechanical engineering at Military Technical Academy was obtained in Hanoi 2004. After university graduation, he is an officer in Vietnamese Army and has worked as a researcher at Institute of Weapons and Ammunition in Hanoi for ten years in field of designing weapon and ammunition systems. In 2012 he finished post-gradual program in University of Defense in Brno, Czech Republic and got Ph.D title in field of weapons and protection against them. Currently, he continuously works in Institute of Weapons and Ammunition as a researcher.

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Stanislav Prochazka born in Havlickuv Brod (Czech Republic), 15th March 1952. MSc degree in weapons and munition at Military academy in Brno 1975, PhD degree in the field of weapons and munition at University of Defence 1983, Associate professor 1990. Currently he works as a lecturer at University of Defence in Brno at Department of Weapons and ammunition. His main areas of interest are small arms, barrels and breech mechanisms.

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