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Modeling wear mechanism of artillery projectiles rotating band using variable parametars of internal ballistic process

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This study comprises both theoretical and experimental research of wear mechanism on artillery projectile rotating band. The results of the research have been used for better understanding of complex process of wear rotating band in passing projectile through artillery weapons' grooving barrel and for the purpose of defining the material key characteristics primarily influencing the degree of the rotating band wearing. The study presents comparative theoretical and experimental researches performed on 105 mm and 155 mm artillery systems. The experimental results shown have been obtained by shooting function verification and also on the basis of structural-mechanical testing of material samples.

Key words: **rotating band, artillery projectile, 105 mm projectile, 155 mm projectile, wear mechanism, thermal properties, theoretical modelling, experimental research.**

Nomenclature

a_c – thermal diffusivity of bore [m^2/s]
a_p – thermal diffusivity of rotating band [m^2/s]
A_p – contact surface [m^2]
c_p – specific heat of material [J/kgK]
e_z – width of rotating band cog [m]
h – melting thickness of rotating band [m]
h_p – height of rotating band cog [m]
H_p – width of rotating band [m]
k – non-steady coefficient [-]
n – groove number [-]
N – normal force [N]
P – contact pressure [Pa]
$\dot{q}_c$ – heat flux to bore [W/m^2]
$\dot{q}_p$ – heat flux to rotating band [W/m^2]
$\dot{q}_u$ – total heat flux in the contact zone [W/m^2]
$\dot{q}_{u_{sr}}$ – average value of total heat flux in the contact zone [W/m^2]
Q_c – thermal energy to bore [J]
Q_p – thermal energy to rotating band [J]
Q_u – total thermal energy made by friction in the contact zone [J]
r_p – heat of fusion, for the material of the rotating band [J/kg]
t – elapsed time from rotating band contact [s]
t_s – time interval of solid contact condition [s]
t_u – total time interval defined as the sum of solid contact and partial melting contact time [s]
T_0 – initial temperature of the rotating band and bore [K]
T_{mp} – melting point of the rotating band [K]
V – velocity of sliding rotating band, apropos projectile [m/s\
WR – wear rate per time unit [m/s]
λ_c – thermal conductivity of bore [W/mK]
λ_p – thermal conductivity of the rotating band [W/mK]
μ – friction coefficient [-]
μ_s – friction coefficient during contact in solid state [-]
μ_m – friction coefficient during contact in melting state [-]
ρ_p – density of the rotating band [kg/m^3]

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Introduction

THE rotating band of projectile, during the shooting process and passing of the projectile through the barrel of the weapon provide: transmission of rotating movement, tightness, alignment, projectile position equability in the barrel and start pressure of powder gas. Nowadays, modern and powerful artillery weapon systems, with high powder charges are used, resulting in significant increment of projectile muzzle velocity. In the conditions of such extended tension, caused by this artillery projectile's increased muzzle velocities and powder gas working pressure, the rotating band is exposed to considerably harmful using conditions, while at the same time having to fulfil all the above stated requirements.

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increased muzzle velocities and powder gas working pressure, the rotating band is exposed to considerably harmful using conditions, while at the same time having to fulfil all the above stated requirements.

Up to now, the rotating band made of copper was mostly used, which, in such using conditions, could not fully meet the requirements. Rotating band excessive wear, increased disposal copper on the barrel or exposing rotating band to excessive tensile force on the barrel muzzle caused by considerable increment of centrifugal force, due to the projectile high muzzle velocities, require using other materials better suited for such severe operating mode.

Furthermore, it is necessary to take into consideration the influence of increased temperature, which causes degradation of material's mechanical characteristics. The increased temperature of the rotating band is mostly caused by intense friction between the barrel and rotating band, as well as by the influence of hot powder gases. In order to better perceive the rotating band wear, relevant theoretical and experimental research has been performed. The experimental results confirmed the basic theoretical assumption concerning the thermal and mechanical load of the rotating band.

Theoretical analysis

Extremely complex thermodynamic and gas-dynamic processes are going on during firing from artillery weapons, which causes projectile movement through the grooved barrel. Under the powder gas force effect the projectile accelerates, getting rotating-translatory movement (Fig.1). Engraving the rotating band into the barrels groove and by projectile moving through the same, the projectile gets the rotational movement. In case of excessive rotating band wear, usually occurring once the projectile has passed through the barrel, the projectile will not reach the requested rotation level. This causes lower projectile stability and powder gas passing through, finally resulting in the increased projectile dispersion at the target and increased barrel wear due to gas erosion. This is especially conspicuous at high muzzle velocities and if the projectile is passing through longer length barrel. R.S. Montgomery [1], [9] has performed experimental research of the rotating band wear at the sliding high velocities. Using the "pin-disc" device, he has studied the occurrence of material partial melting in thin surface layer and its carrying away from the surface contact at high sliding velocities. Theoretical analysis of the contact state changes between the rotating band and the barrel, when partial melting of the rotating band occurs on the active surface of the contact place, was elaborated by T. Matsuyama [2].

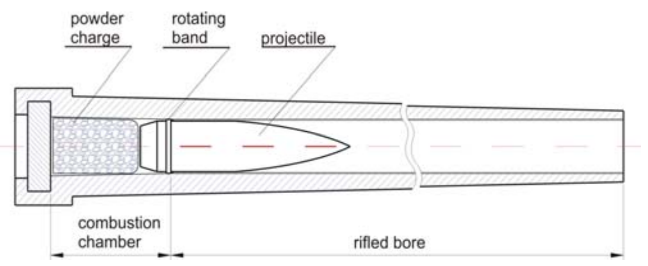

Figure 1. Illustration of a projectile in the weapon's barrel

He found out that the active surface contact of the rotating band is melted even after the projectile has passed a few centimetres at the beginning of its movement, showing that the rotating band wear mostly occurs in partially melted state.

During powder charge combustion, the powder gas pressure and projectile velocity change depending on the trajectory and time.

In this process, the projectile accelerates, obtaining rotational-translatory movement. Looking from the strain aspects, while the projectile passes through the barrel, the sliding speed and contact pressure on the active surface between the rotating band and barrel channel have changed, conditioned by the dynamics of the interior ballistic (IB) process characteristic parameters change.

Description of the rotating band wear mechanism

The theoretical assumption is based on the model which supports the interaction between the rotating band and barrel on the active surface contact, taking into consideration the sliding speed changes (V), contact pressure (P) and friction coefficient (μ) in the time function, when the rotating projectile passes through the weapon's grooved barrel.

At high sliding speed and high contact pressure conditions, a substantial quantity of heating energy is released within the contact zone [3], [8], resulting in the rotating band material partial melting and it being carried away [4]. Dependence of the total heating flux $\left(\dot{q}_u\right)$ released, within the contact zone between the active surface of the rotating band cog and barrel channel is given in eq.(1):

$$\dot{q}_u = \mu \cdot P \cdot V \tag{1}$$

Non-stationary equation of the heating transmission at the constant surface temperature is corrected by multiplying it with non-stationary coefficient (k), which takes into consideration the change of the total heating flux time, and is defined by eq. (2):

$$k = \dot{q}_{u(t)} / \dot{q}_{u_{sr}} \tag{2}$$

Thermal energy transmitted to the rotating band $\left(Q_p\right)$ is calculated as the difference between the total thermal energy released by friction within the contact zone $\left(Q_u\right)$ and the heat transmitted to the barrel $\left(Q_u\right)$. The thermal energy relates to only one rotating band cog. It is calculated by integrating the relevant heating flux in time and multiplying it with the contact surface area (A_p), which is defined by eq.s (3), (4) and (5):

$$Q_c = A_p \left[\int_0^{t_s} \left(\mu_s \cdot P \cdot V - \frac{\lambda_p \cdot (T_{mp} - T_o)}{\sqrt{(\pi \cdot a_p \cdot t}} \right) dt + \int_{t_s}^{t_u} k \cdot \frac{\lambda_c \cdot (T_{mp} - T_o)}{\sqrt{(\pi \cdot a_c \cdot H_p / V}} dt \right] \tag{3}$$

Where the contact surface area is: $A_p = H_p \cdot h_p$.

$$Q_u = A_p \left[\int_0^{t_s} \mu_s \cdot P \cdot V \cdot dt + \int_{t_s}^{t_u} \mu_m \cdot P \cdot V \cdot dt \right] \tag{4}$$

$$Q_p = Q_u - Q_c \tag{5}$$

The time interval (t_s), where the contact condition is solid state, is defined by eq. (6), which corresponds the time of increasing the barrel temperature until rotating band reaches the melting point:

$$t_s = \frac{\pi}{4} \cdot \frac{\lambda_c^2}{a_c} \cdot \left(\frac{T_{mp} - T_0}{\dot{q}_c} \right)^2 \tag{6}$$

Thermal energy transmitted to the rotating band (Q_p) is spent on melting and thin surface layer heating, where the melted layer thickness could be calculated using eq. (7):

$$Q_p = h \cdot A_p \cdot \rho_p \left[r_p + c_p \left(T_{mp} - T_o \right) \right] \tag{7}$$

$$h = \frac{Q_u - Q_c}{A_p \cdot \rho_p \left[r_p + c_p \left(T_{mp} - T_o \right) \right]} \tag{8}$$

The contact pressure force (P) is calculated by dividing the normal force (N) acting on the rotating band cog active side with contact surface area (A_p). In the calculations presented in this paper the friction coefficient, corresponding the value published in [1], [2], [6] has been used, where the influence of material thermal characteristics on the friction coefficient is taken into consideration as given by eq. (9) and concerns high sliding velocities [7]:

$$\mu = \frac{2 \cdot \lambda_p \left(T_{mp} - T_o \right)}{P \cdot V \sqrt{\pi \cdot a_p \cdot H_p / V}} \tag{9}$$

Computation and experimental results

The friction and wear model at high sliding velocities is given through the example of the rotating band, which slides through the grooved barrel, getting rotational-translatory movement, where the partial melting and carrying away of the material in a thin layer occurs.

Table 1. Calculation results of the rotating band cog wear, obtained from alloy CuZn10 (155 mm howitzer Nora B/52, projectile M107)

t	V	μ	P	$\dot{q}_u$	h	WR
ms	m/s	-	Pa	W/m^2	m	m/s
0.000	0.0	0.3000	0.00E+00	0.000E+00	0.000E+00	0.000
1.792	29.0	0.1550	6.84E+07	3.074E+08	9.186E-05	0.051
2.773	58.0	0.1020	1.08E+08	6.417E+08	1.922E-04	0.102
3.320	87.1	0.0880	1.44E+08	1.105E+09	2.850E-04	0.170
3.886	116.1	0.0743	1.75E+08	1.511E+09	4.122E-04	0.225
4.224	145.1	0.0664	2.02E+08	1.948E+09	5.073E-04	0.281
4.922	203.2	0.0561	2.44E+08	2.778E+09	7.525E-04	0.381
5.307	232.2	0.0525	2.59E+08	3.152E+09	9.149E-04	0.422
5.881	290.2	0.0470	2.79E+08	3.798E+09	1.187E-03	0.485
6.424	348.3	0.0429	2.87E+08	4.288E+09	1.469E-03	0.525
6.955	406.3	0.0397	2.86E+08	4.617E+09	1.756E-03	0.542
7.146	435.4	0.0383	2.83E+08	4.724E+09	1.859E-03	0.543
7.690	493.4	0.0360	2.72E+08	4.830E+09	2.152E-03	0.534
8.045	522.4	0.0350	2.64E+08	4.833E+09	2.338E-03	0.524
8.629	580.5	0.0332	2.47E+08	4.758E+09	2.631E-03	0.496
9.196	628.2	0.0319	2.06E+08	4.133E+09	2.875E-03	0.417
9.726	665.9	0.0310	1.76E+08	3.635E+09	3.071E-03	0.358
10.230	696.7	0.0303	1.53E+08	3.234E+09	3.232E-03	0.312
10.873	734.2	0.0295	1.27E+08	2.761E+09	3.409E-03	0.260
11.334	755.0	0.0291	1.14E+08	2.510E+09	3.521E-03	0.233
11.783	773.2	0.0288	1.03E+08	2.300E+09	3.619E-03	0.211
12.222	789.3	0.0285	9.42E+07	2.118E+09	3.706E-03	0.192
12.941	810.6	0.0281	8.29E+07	1.889E+09	3.833E-03	0.169
13.362	823.1	0.0279	7.68E+07	1.762E+09	3.900E-03	0.157
13.905	839.8	0.0276	6.89E+07	1.597E+09	3.979E-03	0.140
14.311	849.9	0.0274	6.44E+07	1.501E+09	4.033E-03	0.131
14.988	863.7	0.0272	5.85E+07	1.376E+09	4.117E-03	0.119
15.110	868.0	0.0272	5.68E+07	1.338E+09	4.131E-03	0.115
15.383	872.1	0.0271	5.51E+07	1.302E+09	4.161E-03	0.112

Calculation results for artillery system 155 mm (howitzer Nora B/52, projectile M107) are given in Table 1.

Table 2. Thermal characteristics of the used materials

mater.	ρ	T_m-T_0	C	C	a	a *	λ	λ *	r
-	kg/m^3	K	J/kgK	J/kgK	10-4 m^2/s	10-4 m^2/s	W/mK	W/mK	KJ/kg
cooper	8960	1063	383	469	1,12	0,84	385	353	209,3
nickel	8800	1435	460	563	0,22	0,12	91	61	305,6
CuZn10	8800	1025	376	461	0,57	0,47	189	173	199,4
steel	7897		452	553	0,20	0,082	73	36	

The values marked with *) given in Table 2 refer to the working temperature of 800°C. The rest of the values are given for 20°C, the ambient temperature.

Figure 2. Illustration of the rotating band 155 mm (left) and 105 mm (right)

The total heating flux generated within the contact zone between the barrel channel and rotating band cog active surface area is calculated by multiplying the friction coefficient, contact pressure and sliding velocity. Using previously given relations the total heating flux $(\dot{q}_u)$ viz. the barrel heating flux $(\dot{q}_c)$ and rotating band heating flux $(\dot{q}_p)$ are calculated. These values are given for the system 155mm in function of contact time duration (Fig.3).

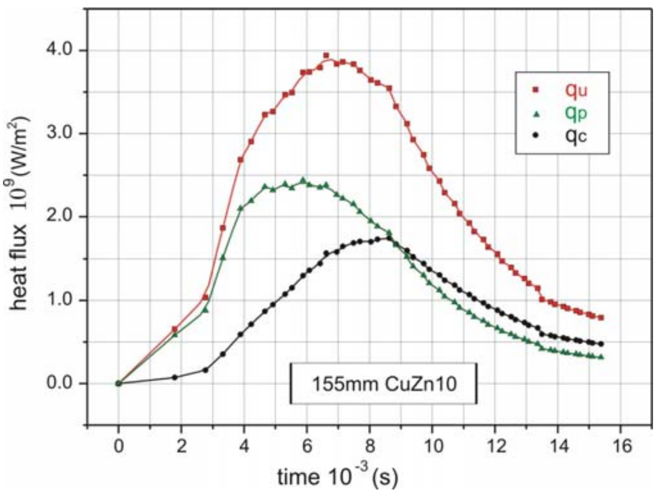

Figure 3. Diagram of the heating flux changes $\dot{q}_u$, $\dot{q}_c$, $\dot{q}_p$ in function of contact time duration

The calculated values of the thickness of the worn layer of the rotating band cog, for 155 mm system and different materials of the rotating band are given in Fig.4.

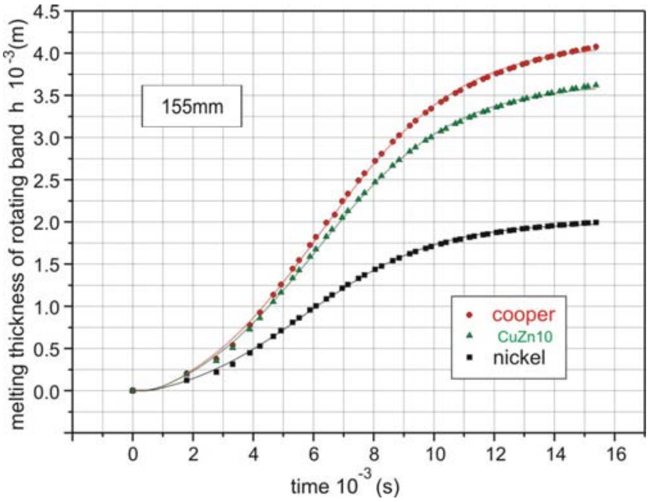

Figure 4. Diagram of changes of thickness *h* of the wear of layers for different materials in function of contact time duration

Comparative diagram of thickness of the wear of layers in function of the contact time duration for 105 mm and 155 mm systems is given in Fig.5.

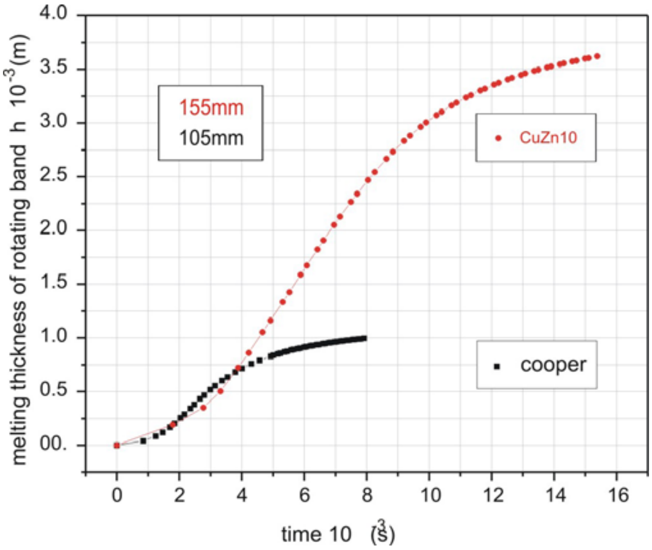

Figure 5. Comparative diagram of changes of the thickness *h* of the wear of layers in function of contact time duration for 105 mm and 155 mm systems

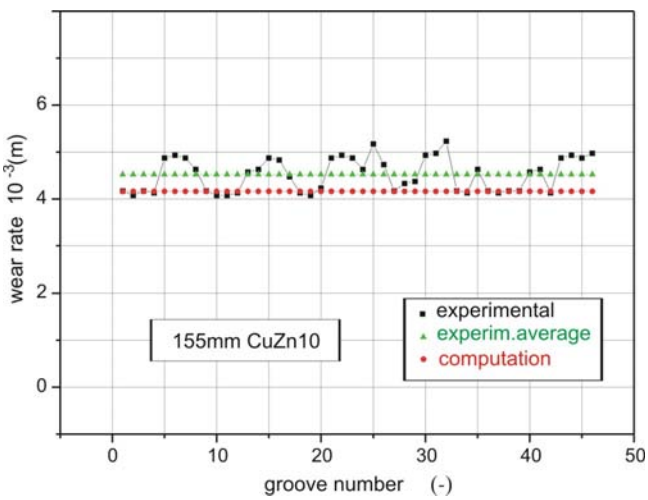

Figure 6. Illustration of rotating band cog wear for projectile 155 mm M107

The Projectile 155 mm M107 was fired from howitzer 155 Nora/52, in conditions of increased powder gas pressure. The characteristic dimensions on the projectile rotating band, manufactured from alloy CuZn10, have been measured after firing. The results speak in favour of the given mathematical model of calculation of the rotating band wear mechanism.

The influence of the contact pressure values on the material wear, while sliding through the grooved barrel, could be clearly seen from the example of 2 (two) projectile 155 mm pieces of the same characteristics with different rotating band widths. The case of projectiles 155 mm M107 (H_p=25.8 mm) and M101 (H_p=51.3 mm) was analyzed, while firing in equal internal ballistic conditions. The rotating band material characteristics (CuZn10) and friction coefficient were identical in both cases.

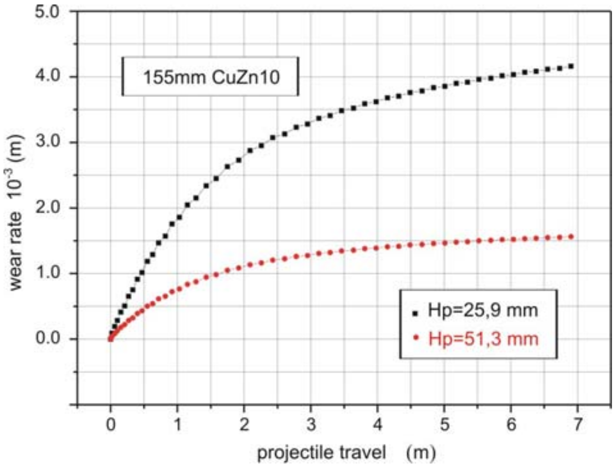

Figure 7. Diagram of rotating band cog wear with different rotating band widths for projectiles 155 mm M107 (H_p=25.9) and M101 (H_p=51.3 mm)

The calculated values of the rotating band wear, for H_p=25.9 mm is h=4.16 mm, while this value for the rotating band width H_p=51.3 mm is significantly smaller and is h=1.56 mm.

Conclusion and suggestions

The theoretical and experimental investigations have been done with the goal to define the mechanism of material wear and the possibilities of applying the materials considered in this paper for the purposes of rotating band manufacturing. The following conclusions have been made:

1. The given theoretical model enables analyzing the rotating artillery projectiles rotating band wear mechanism in function of the following parameters:

- interior ballistic characteristics,
- thermal material characteristics,
- friction coefficient between the rotating band and barrel.

2. Numerical values of the research results, of the wear mechanism model, correspond the experimental values obtained after firing.
3. Better material resistance to wear shows the materials in which high values of the following thermal characteristics are found: specific heat, melting heat and melting temperature.

With better insight into this phenomenon, the primary characteristics of the material are indicated, which predetermine the possibility of its application for rotating band manufacturing purposes. The content of the presented conclusions determine and define the implications for further work in the following fields:

- Analyzing the technological possibilities of copper, nickel and other materials coating on the projectile thin wall cartridge case by introducing the material coating treatment with plasma, welding or similar, where apart from numerous design advantages, better mechanical results are achieved,
- Analyzing the possibilities of manufacturing and fusion of new construction rotating band to the projectile [5], viz. composite material (CFC – carbon fibre-reinforced composite), with copper seal ring.

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Modeliranje mehanizma trošenja vodećeg prstena artiljerijskih projektila korišćenjem promenljivih parametara unutrašnje balističkog procesa

Ovaj rad obuhvata teorijsko i eksperimentalno istraživanje mehanizma trošenja vodećeg prstena artiljerijskih projektila. Rezultati ovih istraživanja su iskorišćeni za bolje sagledavanje složenog procesa trošenja vodećeg prstena u toku prolaska projektila kroz olučenu cev artiljerijskog oruđa i radi definisanja ključnih karakteristika materijala koje primarno utiču na stepen istrošenosti vodećeg prstena. U radu su prikazani rezultati komparativnog teorijskog i eksperimentalnog istraživanja, primenjeni na artiljerijske sisteme 105 mm i 155 mm. Prezentovani eksperimentalni rezultati su dobijeni proverom funkcije - gađanjem.

Ključne reči: **vodeći prsten, artiljerijski projektil, kalibar 105 mm, kalibar 155mm, mehanizam trošenja, toplotne karakteristike, teorijsko modeliranje, eksperimentalno istraživanje.**

Моделирование механизма износа ведущего кольца артиллерийских снарядов пользованием изменчивых параметров внутреннего баллистического процесса

Настоящая работа охватывает теоретическое и экспериментальное исследования механизма износа ведущего кольца артиллерийских снарядов. Результаты этих исследований использованы для лучшего воспринимания сложного процесса износа ведущего кольца в течении прохода снаряда через нарезной ствол артиллерийского орудия и ради определения ключевых характеристик материала, которые в основе влияют на ступень (уровень) износа ведущего кольца. В работе показаны результаты сравнивающих теоретического и экспериментального исследований, применённых на артиллерийских системах 105 мм и 155 мм. Показаные экспериментальные результаты получены верификацией функции - стрельбой, и на основании структурально-механических методов испытывания, проведённых на образцах испытыванных материалов.

Ключевые слова: ведущее кольцо, артиллерийский снаряд, калибр 105 мм, калибр 155 мм, механизм износа, тепловые характеристики, теоретическое моделирование, экспериментальное исследование.

Modélisation du mécanisme de l'usure du guide-bande chez les projectiles d'artillerie au moyen des paramètres variables du procès balistique intérieur

Ce travail comprend les recherches théoriques et expérimentales du mécanisme de l'usure du guide-bande chez les projectiles d'artillerie.Les résultats de ces recherches ont été utilisés pour mieux comprendre le procès complexe de l'usure du guide-bande pendant le passage du projectile à travers l'âme rayée de la pièce d'artillerie et pour définir les caractéristiques principales des matériaux qui influencent primordialement au degré de l'usure du guide-bande.Ce papier présente les résultats des recherches comparées théoriques et expérimentales appliqués aux systèmes de 105 mm et de 155mm.On a exposé les résultats d'essais obtenus par la vérification de la fonction du tir ainsi que les résultats basés sur les méthodes structuro-mécaniques des essais effectués sur les spécimens des matériaux étudiés.

Mots clés: **guide-bande, projectile d'artillerie, calibre de 105mm, calibre de 155mm, mécanisme de l'usure, caractéristiques thérmiques, modélisation théorique, essai expérimental.**