KAUNAS UNIVERSITY OF TECHNOLOGY

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RESEARCH AND SIMULATION OF BALLISTICS PROCESSES OF SMALL ARMS AMMUNITION BULLETS

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

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MAŽO KALIBRO KULKŲ BALISTINIŲ PROCESŲ MODELIAVIMAS IR TYRIMAS

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INTRODUCTION

Ballistics began to develop very fast when fire arms were invented. The focal attention was paid to the artillery as to the main force in the battlefield. Many famous scientists of the past worked in this field.

Common opinion on ballistics is that many problems are frequently solved and there is no need for research in this field any more. However, from the perspective of the applications of classic ballistics in the artillery, these problems are experimentally thoroughly investigated as well as theoretically. Nevertheless, modern ballistics presents a wide area of new engineering problems. Classic ballistics deals mainly with processes in cannons and the flight of projectiles in the air. Nowadays all processes related to the projectile motion, including the projectile-target interaction, are being considered as ballistics. On the other hand, terminal ballistics finds application areas in aircraft, automotive industries, space vehicle engineering, and etc. Interior ballistics of small arms ammunition is frequently investigated experimentally and empirically. Exterior and terminal ballistics (which for biological targets is called wound ballistics) of small arms ammunition are investigated by using simplified analytical models. For terminal ballistics applications reliable universal analytical models currently do not exist. For such tasks it is very important to estimate the properties of the material properly and the behavior during very short duration loads that are common in high velocity impact dynamics. Ballistic processes are accompanied by thermal softening, failure, erosion of the material and other complex phenomena and provide a wide range of modern research problems.

The research object is to develop, verify and validate computational models of small arms ammunition bullets (calibre up to 12.7mm) and bullet-target interaction. Applying the developed computational models, the ballistic processes of small arms ammunition bullets have to be investigated and the main dynamic properties of such processes need to be obtained.

The following problems are solved:

- The determination of the motion law of a bullet in a barrel and the estimation of the extraction force of the bullet from the case. This enables to improve the relationships used in order to obtain the motion law of the bullet.
- The experimental investigation of the exterior ballistics of a bullet, obtaining the velocity versus displacement relation and the determination of the velocity of the bullet just before its interaction with a target.
- The estimation of the dynamic properties of the material in terms of material constants on the basis of a rod-plate terminal ballistics computational model by comparing computed residual velocity values against experimental ones.

- The development finite element models of a textile target and the estimation of dynamic properties of its interaction against the deformable bullet.

Research methods. Theoretical and analytical methods were employed while conducting this research. The theoretical methods are based on solid mechanics, fluid dynamics and high velocity impact dynamics theories. The experimental investigations in the field of exterior and interior ballistics were performed by measuring the powder gas pressure in the barrel and bullet’s velocity at two points of a trajectory. Terminal effects of bullet-target interaction were evaluated by measuring bullet’s channel in the target.

Finite element software LS-DYNA, ANSYS and MSC. SUPER FORGE were used in this work. A mathematical software MATLAB was used for performing data acquisition and numerical mathematic tasks. Finite element meshes were generated by using TRUEGRID and SOLIDWORKS was employed to build some geometrical models.

Scientific novelty. The main points of scientific novelty of this work are:

- A new computational model for determining the resistance force of the motion of a bullet in a barrel, developed by introducing the concept of a smooth barrel equivalent to the rifled one.
- By applying this model, the equation of bullet’s motion in the barrel was supplemented with terms, estimating the extraction force from the case.
- Newly estimated dynamic properties of the material by comparing experimental and computational results of the rod-plate interaction.
- A new computational model of textile targets developed in LS-DYNA.

Practical application. By applying the proposed model for determining the resistance force in the barrel, the displacement-time and powder gas pressure-bullet displacement relationships at first stages of the bullet motion were established. Estimated relations provide information about bullet and powder charge that is very common for engineering applications during ammunition design and development.

Newly estimated material dynamic constants for engineering application of the solid textile fabrics involve the research and development of the bullet-target process investigation and simulation in real time scale.

Validated computational models developed in ANSYS and LS-DYNA software provide tools for engineering comparative analysis of the existing designs and development of the new ones.

The items presented for defence:

- The computational model of the resistance force in the barrel.

- Estimated dynamic properties of the material obtained on the basis of the comparison of computed and experimental results of residual velocity of the projectile after perforation of the target.
- The computational mezzo-mechanical model of textiles presented as a woven structure of yarns approximated as shell elements.

Approbation. Materials presented in this dissertation were published in 2 articles in scientific journals and 2 articles in scientific conference proceedings. The results of the research were discussed in 3 scientific conferences.

Structure and volume of the work. The dissertation consists of an introduction, four chapters, conclusions, a list of references and author's publications concerning the dissertation and appendixes. The total volume of the dissertation is 141 pages, 75 pictures and 35 tables.

1 LITERATURE REVIEW

The first chapter overviews ballistics processes, ballistics objects and experimental methods and describes the main ballistic tasks. The multi-physic task of interior ballistics deals with a process taking place inside the barrel when a round is fired. In practical application this is frequently solved using an experimental method. For large and medium calibre systems a great amount of various analytical models is proposed but all of them are simplified and, to provide solutions, some experiments for the empirical constants determination in the interior ballistics equation system need to be arranged. Small arms ammunition interior ballistics tasks for practical applications are solved using empirical and tabular methods. Exterior ballistics, examining the influence on the projectile during its flight from a muzzle to the target, is the oldest and most formalized of all the types of ballistic tasks. Similarly to exterior ballistics, many analytical models are proposed to interior ballistics. In large and medium calibre systems and for small arms ammunition these methods are used in a simplified form. For common and standard projectile types, tabular and empirical methods, based on large quantity experiments, including matching statistics and meteorological conditions, are used. Small arms ammunition exterior ballistics tasks frequently are solved employing ballistic coefficient theory. The equation of motion estimating the air drag force is not commonly solved for all types of calibres. It is mainly used for new designs or aerodynamic researches when it is not possible to use ballistic coefficient. Terminal ballistics, describing the effect the projectile causes when hitting the target as well as the counter effect produced on the projectile, is the newest and the most developing field of the ballistics applications. Here are two main directions: terminal ballistics, which deals with material targets such us military vehicles, aircrafts, lightweight armour systems and other and wound ballistics, which deals with biological (human body) targets. Terminal and wound ballistics are often investigated as the projectile's terminal effect on the target, designated as the terminal ballistics.

Terminal ballistics is mainly regarded as an experimental field of the research. Analytical models for the ricochet, penetration and perforation, of solids are built. Still for practical purposes they need a large amount of experiments for the determination of constants and can not be used when tasks are completely changed even in those cases when the same material is used. This chapter places great attention on solution methods of terminal ballistics. Analytical (empirical) methods Tate ricochet and Lambert projectile residual velocity are presented. Finite element explicit analysis software and some specifics according short duration loading simulation were overviewed.

This chapter introduces some material models capable to estimate dynamic processes in the materials. For terminal ballistics simulation, elastic-plastic with kinematic hardening material model was chosen. This material model is suitable to simulate isotropic and kinematic or their combination hardening plasticity and allows to include strain rate, failure and erosion. Dynamic effects of strain rates are accounted by scaling static yield stress with the factor (Cowper-Symonds relation):

$$\frac{\sigma_{d_y}}{\sigma_y} = 1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{1/p} \qquad (1)$$

here: σ_{d_y} – dynamic yield stress; σ_y – static yield stress; $\dot{\varepsilon}$ – strain rate; C, p – constants (constants of Cowper-Symonds relation (ratio).

In this models dynamic yield stress, describing kinematic, isotropic or their combination hardening, is expressed as follows:

$$\sigma_{d_y} = \left[1 + \left(\frac{\dot{\varepsilon}}{C} \right)^{1/p} \right] \left(\sigma_y + \beta E_p \varepsilon_{ef}^p \right) \qquad (2)$$

here: β – kinematic, isotropic or their combination can be specified. Then β=0 – kinematic hardening, β =1 – isotropic hardening, 0<β<1 their combination; $E_p = \frac{E_t E}{E - E_t}$ – plastic hardening modulus; E – elastic modulus; E_t – tangential modulus; ε_{ef}^p – effective plastic strain.

The chapter deals with the most common experimental techniques for interior, exterior and terminal ballistics.

Because of the summation and some demands in small arms ammunition projectile's (bullet) ballistics, dissertation integrates these tasks: 1) The determination of the bullet's motion law in the barrel and the estimation of bullet's extraction force from the case in to the bullet's motion law in the barrel, by which bullet's motion law in the barrel is corrected; 2) The experimental investigation of the bullet's exterior ballistics, the estimation of the relation of the bullet's velocity versus bullet's displacement and the calculation of bullet's velocity just before the interaction with the target; 3) The estimation of the dynamic properties of the material in terms of material constants, using rod-plate terminal ballistics computational model and comparing computational rod's residual velocity results against experimental one; 4) The development of the textile fabrics target's finite element computational model and the estimation of dynamics properties of the deformable bullet and textile fabrics interaction.

2 INTERIOR AND EXTERIOR BALLISTICS INVESTIGATION OF SMALL ARMS AMMUNITION BULLETS, THE ESTIMATION OF THE LAW OF BULLET MOTION

This chapter deals with experimental interior and exterior analysis, where applying integrated experimental and computational method, the motion law of bullet's interior ballistics was calculated. For the exterior ballistics bullet's velocity-displacement curve an experimental and analytical model, employing ballistic coefficient, was used.

In small arms ammunition interior ballistics analysis it is important to know the parameters of interior ballistics. For a product or its component, a comparative analysis of pressure-space (displacement), bullet velocity-space and other curves were frequently employed. During the experimental research (using standard test equipment) pressure-time curve is usually obtained. In this particular case, for small calibres, the quickest way to determinate those curves is to use integrated experimental-analytical analysis method, which contains these steps: 1) The experimental determination of powder gas pressure-time curve ($p=f(t)$) and bullet's velocity at the muzzle (V_Z); 2) The calculation of the bullet drag (F_{bd}) in the barrel using finite element (FE) method; 3) The numerical integration of non-linear differential equation of bullet's motion in the barrel.

The experimental analysis of bullet's interior and exterior ballistics

Interior ballistics experimental analysis was conducted using test barrel with the pressure measurement vents in chamber position, while for exterior ballistics two velocities at some distances (4.5 and 24 m) from the muzzle were measured.

The obtained results are presented in table 1. For the calculation of interior ballistics time and the determination of interior ballistics pressure-time curve, data acquisition software, composed on the MATLAB was used.

Table 1

Interior and exterior ballistics test results

Values	t_{vamzd}, μs	$V_{4.5}$, $\frac{m}{s}$	V_{24}, $\frac{m}{s}$	V_Z, $\frac{m}{s}$	P_{max}, *Bar*	Ballistic coefficient (*B.C.*)
Average	1528,4	860,48	843,54	864,28	3628,8	0,134530
Maximum	1571,0	866,51	850,51	870,20	3706,7	0,142458
Minimum	1489,5	853,99	836,76	857,90	3522,9	0,120483
Range	81,5	12,52	13,75	12,30	183,8	0,021975
Standard deviation	38,9	5,57	5,81	5,63	95,0	0,008964
Confidence interval, 95%	14,5	2,08	2,17	2,11	35,47	0,003347

For interior ballistics bullet's motion equation solution the average pressure-time curve was estimated (Fig. 1).

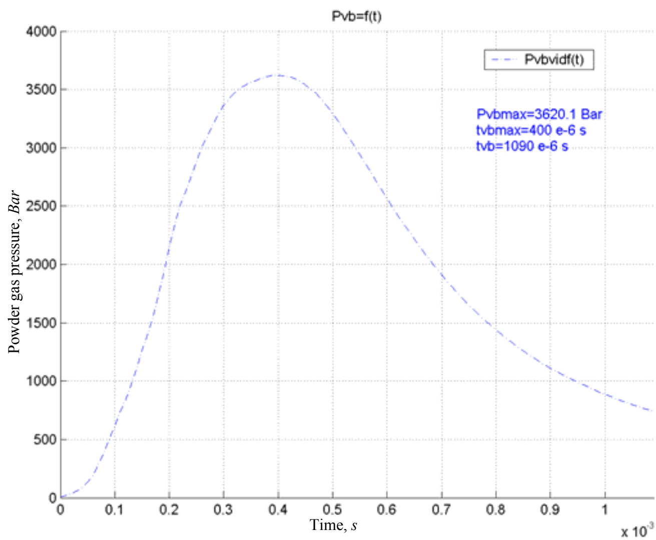


Fig. 1 Average powder gas pressure-time curve

Exterior ballistics characteristic, which will be used for terminal ballistics simulation, and the relation of bullet's velocity with bullet's displacement are presented in table 2. This relation is calculated according to ballistic coefficient methodology. For obtaining exterior ballistics calculations, BALEXT software, integrated into the experimental equipment, was used.

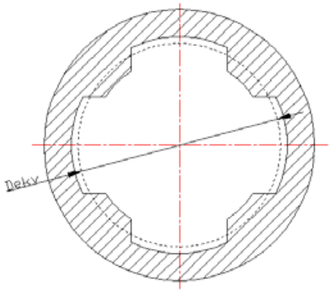
Table 2

Bullet velocity-displacement relation

Displacement, m	100	200	300	400	500	550
Velocity, *m/s*	777,7	692,5	615,0	539,6	469,9	437,2

The calculation of interior ballistics characteristics

For exterior ballistics analysis powder gas pressure relation against bullet displacement and bullet velocity relations with bullet displacement are often used. During the experiment, powder gas pressure relation with time (pressure-time curve) was obtained. For the calculation of characteristics mentioned before, the equation of the bullet's motion in the barrel needs to be solved. In order to calculate the bullet's drag in the barrel, axis-symmetric FE model was built. The direct construction of the model is not correct in that case when barrel's (gun, test and etc.) internal surface is not smooth. Rifled barrel is conversed to the smooth surface using an equivalent diameter, which is calculated through the internal space cross-section area of the needed barrel (Fig. 2). The friction force was calculated as a product of the normal force and friction coefficient. The normal force was calculated in axis-symmetric FE model, using reaction force action, when bullet's external cylindrical surface is loaded by radial displacement, which is difference between bullet's and equivalent smooth barrel radiuses. For the conversion from the rifled to smooth barrel, numerical testing is performed by a constructed 3D model, using MSC.SUPERFORGE software. The comparative analysis between calculated drag forces, using 3D FE model and axis-symmetric FE model was implemented. Some specifics of this system requires to build bullet's computational model as a continuous body from one material and mechanical properties for that bullet's jacket (tombac) were used.



Parameter	Unit	Value
Area of rifled barrel cross-section	mm^2	47,426
Diameter of equivalent smooth barrel	*mm*	7,771
External bullet diameter	*in*	.308
	mm	7,823
Tightness:		
for diameter;	*mm*	0,052
for radius.	*mm*	0,026

Fig. 2 Cross-section of 4 rifles barrel and diameter of equivalent smooth barrel.

MSC.SUPERFORGE software requires the description of the specific elements for forming purposes lake punch, die and billet (Fig. 3). For static load imitation, low velocity (0.5 *mm/s*) on to the punch was assigned. The friction coefficient between bullet and barrel was assumed to be f=0.02.

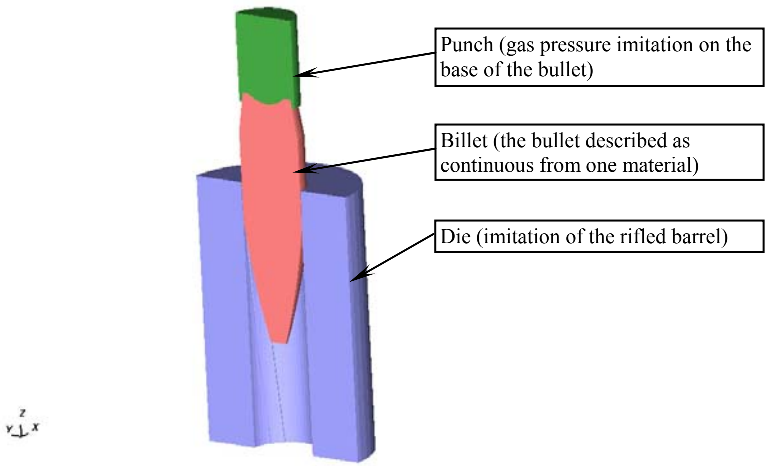


Fig. 3 3D computational model

Axis-symmetric FE model was built in ANSYS, using PLANE82 finite elements. The convergence of the model was verified and the optimal size of the mesh was found when node number in the model was 7167 and elements 2284. In both cases the drag force was calculated (for axis-symmetric model drag was calculated as a friction force). The difference between these models for engineering tasks is negligible and axis-symmetric model can be used for drag in the barrel calculation. The results are presented in table 3.

Table 3

The drag in the barrel calculated by both methods

Bullet's drag calculation method	**Value F_{pvs}, N**
Axis-symmetric FE model	440
3D FE model	425
Difference between 3D and axis-symmetric model	3,4 %

In the analyzed case, the bullet consists of two parts: jacket (tombac) and core (lead). The bullet is loaded by high powder gas pressure. Due to this load, the bullet is additionally deformed and the normal force depends on the pressure. According to this estimation, axis-symmetric model from the continuous bullet was changed into the lead core, jacketed by the tombac and pressure load on the base of the bullet (Fig. 4).

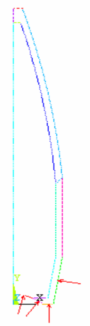


Fig. 4 Axis-symmetric FE model with pressure load

Powder gas pressure was gradually loaded in 100, 500, 1000, …, 3500, 4000 *Bar*. This model was solved using dynamic equilibrium. The resistance force, as the drag, was loaded on the external cylindrical surface of the bullet imitating the friction force. This force was calculated as the normal force from the previous step multiplied by the friction coefficient. The relation between powder pressure gas and the normal force was calculated and approximated by the linear equation (Eq. 3).

$$F_N = a_1 p + a_0, \qquad (3)$$

here: F_N – the normal force; a_1, a_0 – line's equation coefficients (a_1=8.342 10^{-5}, a_0=7.303 10^3); p – powder gas pressure.

Then drag can be estimated in the non-linear equation of the bullet motion (Eq. 4, 5) and is expressed in a form for numerical integration. The equation estimates kinematic operators where the normal force is calculated in the same way as in equation 3.

$$m_k \ddot{x} = A_{vsk} p_{vb}(t) - F_p, \qquad (4)$$

$$F_p = \begin{cases} F_k, x \le x_{kis}, \\ fF_N, x > x_v, \end{cases} \qquad (5)$$

here: m_k – bullet mass; A_{vsk} – barrel's cross-section area (internal space area, (Fig. 2); $p_{vb}(t)$ – experimentally obtained powder gas pressure (Fig. 1); F_p – the drag force; F_k – bullet's extraction effort (force) from the case mouth; F_N – the normal force; f – the friction coefficient; x – bullet's displacement in the barrel; x_{kis} – bullet's displacement when bullet's extraction from the case mouth force is active; x_v – bullet's displacement from which the drag force in the barrel starts acting (for a smooth barrel it is calculated as a friction force).

$$m_k \ddot{x} = A_{vsk} p_{vb}(t) - I_{kis} F_k - I_v f(a_1 p(t) + a_0), \qquad (6)$$

here: I_{kis} – bullet's extraction force from the case mouth, depends on two conditions 0 or 1. 1 is then when the condition $x \le x_{kis}$ is satisfied, and in the other case is 0; I_v – the friction force operator is impacted by two conditions 0 or 1. This force starts acting when the bullet comes into the barrel's rifled part, 1 is then when the condition $x > x_v$ is satisfied, and in the other case is 0.

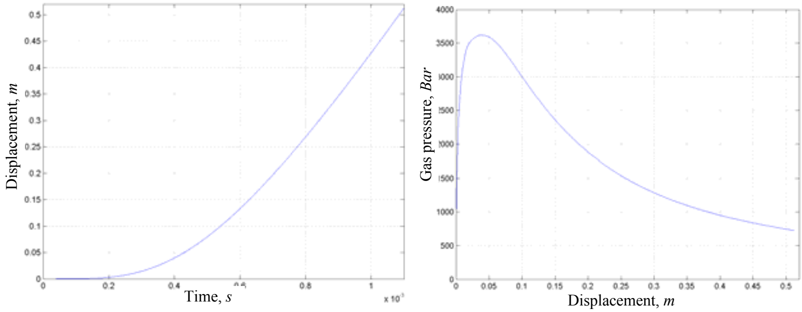
Equation 6 was solved with different friction ratio f values and a good correlation with experimental results was indicated when f=0.075. The results are presented in table 4.

Table 4

The comparison of Experimental and Computational results

Estimation method	**Bullet displacement, l_k, mm**	**Bullet velocity at the muzzle of the barrel, $V_{\check{z}}$, m/s**
Experimental	511	864,28
Calculated value, after numerical integration of equation 4 with friction ratio f = 0,075	511,9	863,91
Difference between experimental and computational results	0,18 %	0,043 %

When bullet motion equation (Eq. 6) was solved, the main interior ballistics characteristics $x=f(t)$, $V=f(t)$, $V=f(x)$, $p_{vb}=f(t)$ could be estimated. These characteristics is used for ammunition and ammunition load (propellant) computational analysis, presented in figure 6, which displays bullet displacement-time and powder gas pressure-bullet displacement curves.



a) b)

Fig. 6 Interior ballistics characteristics: a) bullet displacement (space)-time curve ($x=f(t)$); gas pressure-bullet displacement (space) curve ($p_{vb}=f(t)$)

The main results

In this chapter a few practical interior and exterior ballistics tasks were solved. The computational model of the bullet's resistance force in the barrel calculation, which allowed estimating bullets extraction force from the case into the equation of the bullet motion, was presented in this part.

Through the numerical integration of the bullet motion equation and experimentally estimated powder gas pressure-time curve, the main exterior ballistics curves, related to the bullet's displacement in the barrel, were calculated. Using this model, bullets velocity at the muzzle was calculated with the accuracy of 0.05%.

During the experimental-analytical analysis exterior ballistics – bullet's velocity versus bullets displacement relation was obtained. They form initial conditions for the bullet-target interaction.

Developed computational models and estimated interior and exterior ballistics relation can be used for comparative analysis and engineering applications of ammunition and ammunition components.

3 RESEARCH AND SIMULATION OF TERMINAL BALLISTICS

Material dynamic properties, applying terminal ballistics experimental and computational investigation techniques are presented in the chapter. The comparative analysis, paralleling experimental and computational projectile's (rod) velocity after target's perforation, was performed. Static material properties, using elastic-plastic material model, are estimated. Dynamic properties, employing Cowper-Symonds relation (Eq. 2), are applied. The computational terminal ballistics model is estimated in accordance with the equation:

$$[M]\{\ddot{U}\} = \{P\} - \{I\} \qquad (7)$$

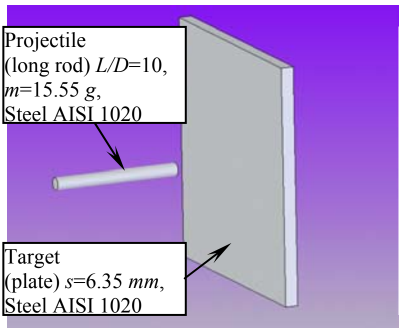
here: $[M]$ – system mass matrix, in the explicit analysis is used as diagonal mass matrix; $\{\ddot{U}\}$ – system acceleration vector; $\{P\}$ – external forces vector; $\{I\}$ – internal forces vector.

The equation (Eq. 7) is solved using explicit dynamics analysis code LS-Dyna.

Terminal ballistics computational model

For terminal ballistics analysis and computational model building, simple models, which consist from two parts: long steel rod (projectile) and steel plate (target), were chosen. The model was validated by applying experimental results. The computational model and experimental results are presented in figure 7.

The computational model consists of two parts which are from the same material: steel AISI 1020. In the first phase friction in the contact, when a simple model of a cylinder shape is used and the contact surface is perpendicular to the motion direction, is assumed to be negligible. This assumption will be reviewed later. Experimental information for material dynamic properties and validation is enough.



Test results

Initial projectile's velocity, *m/s*	Residual projectile's velocity, *m/s*
738	543
1290	1226

m – projectile (rod) mass; L – projectile length; D – projectile diameter; s – target (plate) thickness.

Fig. 7 Terminal ballistics model

Computational FE model was built in ANSYS using APDL language and with keyword EDWRITE, TAURUS, FAILNAME, K transformed into LS-DYNA keyword file. For FE model minimizing, a two-plane symmetry (quarter symmetry) and a butterfly meshing technique were assumed to be used (Fig. 8).

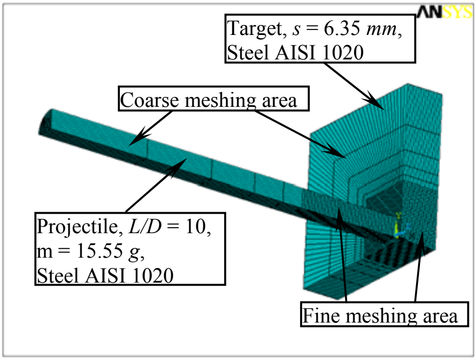


Fig. 8 Quarter symmetry FE computational model

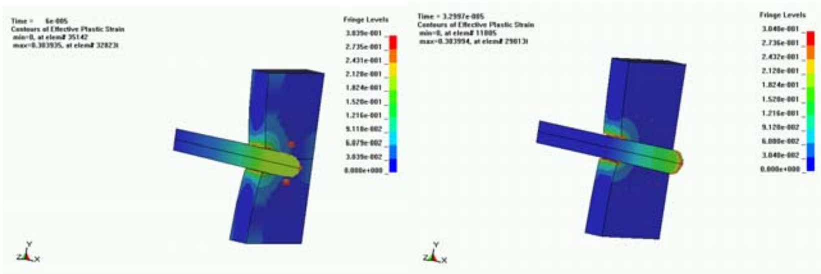
After a few trials a fine meshing zone was determined as the main criterion was failure of the material and had to be placed in the fine meshing zone. FE model size is 40442 elements and 45119 nodes. This type of the meshing involves the construction of a relatively small FE model for this kind of the simulation. The contact between the projectile and the target was described by LS-DYNA contact interaction between two parts, using a "master-slave" methodology. The projectile was set as a master, while the target as a slave. The friction in the contact, expressed as a dependent on the relative velocity of the surfaces in contact, is described in the following way:

$$f = f_D + (f_S - f_D)e^{-DC|V_{rel}|} \quad (8)$$

here: f_D – the dynamic coefficient of friction; f_S – the static coefficient of friction; DC – exponential decay coefficient; V_{rel} – relative velocity.

As mentioned above, the friction is set as negligible and the coefficient of friction is f=0.

After many trials, in the analysis and comparison of the kinematic and isotropic hardening models, Cowper-Symonds relation's constants of the material for described computational model were assumed to be C=495.5 s^{-1}, p=3, when the failure criterion is a failure strain which is calculated as "real" strain and equals to 0.304. The terminal ballistics process was simulated with two initial velocities: 738 *m/s* and 1290 *m/s*. The results are presented in figure 9.



a) b)

a) Effective plastic strain contour. Projectiles initial velocity 738 *m/s*, residual velocity 544,8 *m/s*;
b) Effective plastic strain contour. Projectiles initial velocity 1290 *m/s*, residual velocity 1219,8 *m/s*

Fig. 9 Effective plastic strain contour. Vertical plane x0y symmetry for visualization were used

During the simulation it was difficult to control the mesh and the shape of the model in the application task. In the latest stages the influence of the model mesh and friction will be checked. When FE model size was increased, Cowper-Symonds relation constants were influenced by it. This required a re-estimation of Cowper-Symonds relation constants set. In this case when the mesh's size was approximately 0.19 mm, Cowper-Symonds constants were C=495.5 s^{-1}, p=3. The comparative analysis of the performance of different meshes is carried out in the next section of this chapter.

In preliminary computations the friction between interacting parts was assumed as negligible. Later, the influence of the mesh refinement and the friction were checked. The influence of the friction was analyzed by using four different values in the relation (Eq. 8): three static values f_S=0, 0.2, 0.5 and one set of dynamic coefficient values f_S=0.2, f_D=0.02, D=0.0135. As a result, the influence of the friction was obtained and was negligible. The reason for this is a very simple regular geometric shape of the model and a rather short duration of the load.

Computational analysis of the ballistic limit

The influence of the mesh size on Cowper-Symonds relation constants was investigated. The criterion for the comparison of different models was the difference between the obtained initial and residual velocity values. The friction between contact surfaces was estimated by equation 8 with constants, the values of which were: f_S=0.2, f_D=0.02, DC=0.0135. Table 5 shows the results of the analysis of the two finite element models and Lambert residual velocity prediction model by using which the estimations of the residual velocity values were made. The ballistic limit (V_{bl}) and residual velocity against initial velocity curves are presented in figure 10.

Table 5

Ballistic limit calculation results

Model	FE edge length, mm	Constants, C and p	Ballistic limit V_{bl}, m/s
FE element (first mesh)	0.30	$C = 495{,}5\ s^{-1}$, p = 3	556
FE element (second mesh)	0.19	$C = 618\ s^{-1}$, p = 3	545
Lambert residual velocity prediction	–	–	535

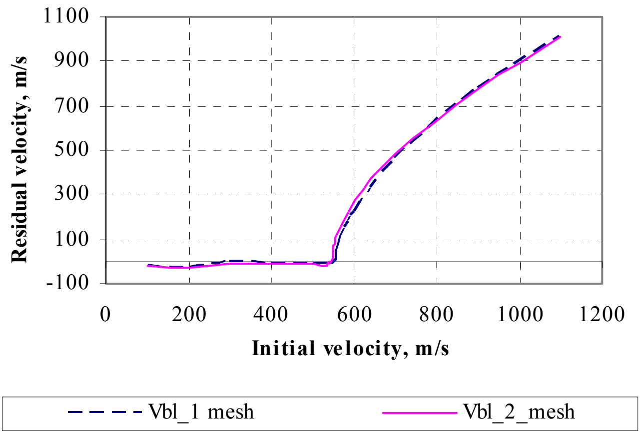


Fig. 10 Residual velocity against the initial velocity curves for two FE models

The lowest value of the ballistic limit was obtained by using Lambert's residual velocity prediction model. However, in this model the projectile was considered as a rigid body and; therefore, the ballistic limit value are intentionally diminished. The ballistic limit value, obtained by using two FE models, was very similar. When the initial velocity exceeded 700 m/s, practically no difference between the two residual velocities could be observed.

The main results

In this chapter terminal ballistics task were solved. For terminal ballistic applications, when the target is fully perforated by the projectile, it is proposed to use isotropic hardening model for steel.

In the range of high strain rates, the adequate simulation results can be obtained only adjusting the finite element mesh edge length and material constants values properly. Moreover, the values of the constants are slightly different for each individual range of the interaction velocity.

The results of the investigation of the cylindrical rod-plate terminal ballistic system demonstrated that the influence of the friction between interacting surfaces is very small and can be neglected in practical computations. The reason for this is a very simple and regular geometric shape of the investigated model and a very short duration of the load.

In the initial interaction when the velocity range is 700-1300m/s, the recommended mesh edge length is ~0.3 mm. The conclusion is valid when the target thickness and projectile diameter values are close to each other. For steel AISI 1020 the recommended values of Cowper-Symonds constants are C=495.5 s^{-1} and p=3.

The derived computational models and estimated materials dynamic constants can be used for small arms ammunition bullet development, for armour design and other engineering applications.

4 THE RESEARCH OF THE BULLET INTERACTION WITH THE TARGET

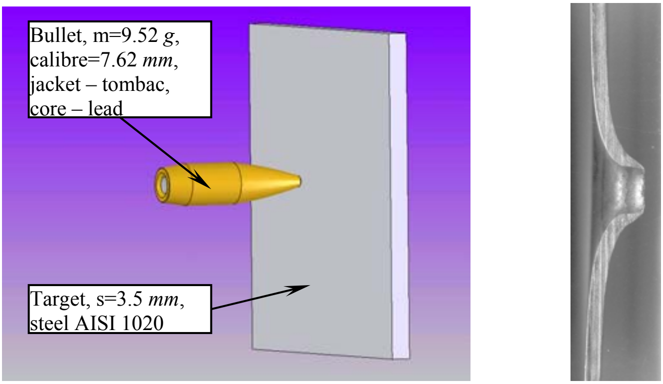
In this chapter two engineering tasks are solved:

- The interaction of a bullet and a solid target;
- The interaction of a bullet and a textile target.

The first task is common for ammunition and armament developers and producers, the second one for light weight body armor developers and producers.

Research of the bullet and the solid continuous target terminal ballistics

7.62 mm (.308 WIN FMJ) bullet's interaction with the target, made from 3.5 mm thick AISI 1020 steel plate, was chosen as a research object. The computational model and a steel plate after bullet's perforation is presented in figure 11.



a) b)

a) 7.62 mm bullet and steel target 3.5 mm thick computational model;
b) Target's vertical section through bullet's duct in the target.

Fig. 11 Bullet and solid target terminal ballistics

During the test, the target was situated at 550 m distance from the barrel muzzle. Bullet's initial velocity for terminal ballistics was found during exterior ballistic research in the second chapter. The initial bullet velocity is 437.2 *m/s* (Table 2). Model's material static mechanical properties are presented in table 6.

Table 6

Computational model's material properties (static)

Parameter	**Units**	**Model's parts**		
		Jacket	**Core**	**Target**
Material	-	Tombac	Lead	AISI 1020
Elastic modulus	10^{11} *Pa*	1,17	0,17	2
Poisson's ratio	-	0,33	0,40	0,29
Yield stress	*MPa*	100	8	276
Ultimate stress (nominal)	*MPa*	270	20	370
Tangent modulus ("true")	*MPa*	786,33	54,32	1550
Failure strain ("true")	-	0,372	0,405	0,304
Mass density	kg/m^3	8800	11270	7870

During the experiment it was observed that the bullet after the steel plate perforation is partially destroyed and the fragments of the bullet parts could be found. In the test there were no possibilities to measure bullet's residual velocity

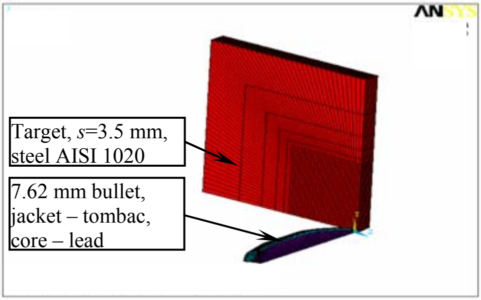
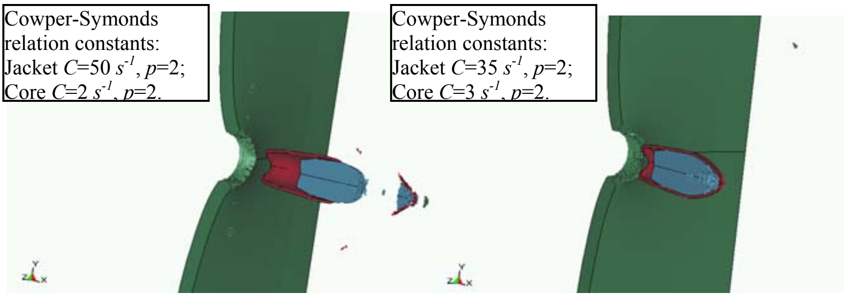


Fig. 12 Quarter symmetry FE model

and the validation was performed using bullet's duct in the target parameters and a qualitative notice that the bullet fragments were found. 7.62 mm bullet and target FE computational model is presented in figure 12. It was assumed to use a two-plane symmetry. The mesh size was chosen according to the first mesh size in the third chapter. The contact between the parts was described by a master-slave methodology. Three contacts pairs were set: core-jacket (the coefficient of the static friction is f_S=0.5); jacket-target (the coefficient of the friction is f_S=0.5, f_D=0.04, DC=0.02 (Eq. 8); core-target (the coefficient of the static friction is f_S=0.7). A good correlation with Cowper-Symonds relation constants sets was obtained: for jacket C=50 s^{-1}, p=2, for core C=2 s^{-1}, p=2 residual velocity 156 *m/s* and for jacket C=35 s^{-1}, p=2, for core C=3 s^{-1}, p=2 residual velocity 220.9 *m/s*. The deformed model in both cases is presented in figure 13.

From simulation results it can be seen that even when one material (target) static and dynamic mechanical properties are known, terminal ballistics process can be simulated and the results can be used for the prediction of bullet's residual velocity.



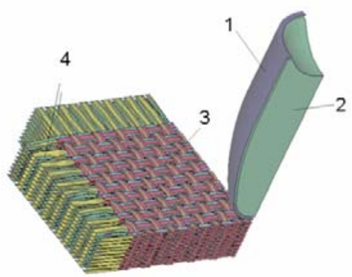
a) b)

a) Deformed computational model after target's perforation, seen jacket's and core's fragments. Residual velocity 156 *m/s*;
b) Deformed computational model after target's perforation, partial affected core and jacket. Residual velocity 220.9 *m/s*;

Fig. 13 Deformed terminal ballistics model after target's perforation

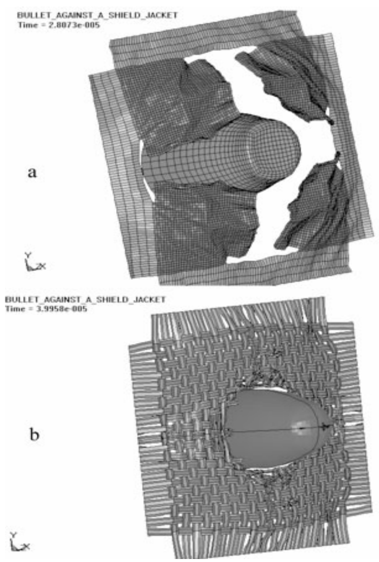
Research of the bullet and textile target terminal ballistics

Developing the body armors, a good understanding of the bullet and textile fabric interaction is required. Moreover, self cost optimization requires decreasing physical prototyping which has to be as smaller as possible. For this analysis FE computational model, symmetric to two planes, was built (Fig. 14). The model was built on the basis of a model, experimentally researched in Lithuanian Textile Institute (LTI). 9 mm PARA bullet's and body armor's textile package's terminal ballistics was analyzed. Bullet's initial velocity is 300 *m/s*. The textile target acts completely differently in comparison with the solid continuous targets. Solid targets failure process in the high-speed impact dynamics looks like a fracture with a sharp crack tip. In a woven structure the failure propagation is slower (Fig. 15). To reach this, a single textile (TWARON) layer, "numerically" woven, was made using a mezzo-mechanical model. Yarn was described as a shell element and the contact interaction between weaves was set. The static coefficient of the friction was used with value f=0.5. The failure was set only for textile material.



1 – Brass jacket, 2 – Lead core, 3 – Multi-layer textile package, 4 – Package fixture.

Fig. 14 Quarter symmetry computational model



a) macro-mechanical model (cloth layer is continuous membrane);
b) mezzo-mechanical model (individual yarns and weave are presented).

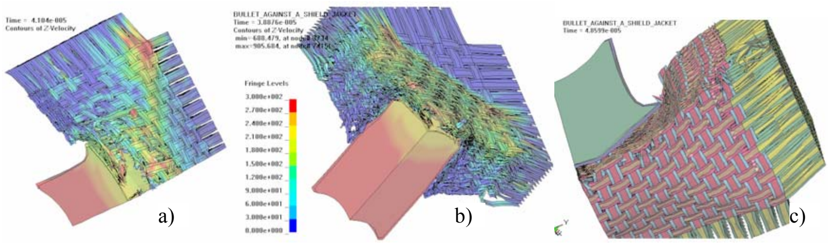
Fig. 15 Response of a single Twaron layer against 9 mm PARA bullet

The model was built using Twaron yarn fabrics CT 709. The density of the material was 1440 kg/m^2 and elastic modulus was 90 *GPa*. Lead properties are presented in table 6. Brass elastic modulus was 117 *GPa* and yield stress was 120 *MPa*. For strain rate imitation yield stress was increased, comparing the test and computational results qualitatively.

The bending stress of the yarn was assumed to be negligible. In order to eliminate bending stiffness, a single integration point (LS-DYNA, Hughes-Liu shell with single integration point) was used.

Applying structural damping of the system, a macro-mechanical model, which will be able to localize the failure of elements in the vicinity of the interaction zone, can be achieved. The situation influences the case of the model. A macro model can be used when it is enough to know if it was short through or not. But usually for the validation of dynamic properties of the material, the model closest to the real one, is advisable to be used. For this approach a mezzo-mechanical model is better. When this is done, an equivalent macro-mechanical model can be built, which could be used for global analysis of the system.

9 mm PARA and Twaron multi-layer package's terminal ballistics model was simulated with different number of Twaron layers, using different friction coefficient values. The results are presented in figure 16. The behavior of the interaction was analyzed and the results indicate that the interaction depends on the number of fabric (9 mm PARA bullet made of brass shell and lead core, moving at a speed of 300 *m/s* is shot (fired) into10-15 layer Twaron fabrics package), the friction coefficient between the bullet and the fabrics and between fabrics layers (the bullet's holdup effect increases when the friction coefficient between bullet and layers decreases and increase between fabric layers), and the touch stiffness between the piece of package and the bullet. For the simplicity Twaron's Cowper-Symonds relation constants were assumed to be C=100000-500000 s^{-1} and p=1.



a) Bullet moving with initial velocity 300 *m/s* against 10 layer Twaron sandwich sloth packet: velocities in the Oz direction. Static friction coefficient between sloth layers and between layers and the bullet equals 0.5;
b) Bullet moving with initial velocity 300 *m/s* against 15 layer Twaron sandwich sloth packet: velocities in the Oz direction. No friction between layers and between layer and the bullet;
c) Bullet moving with initial velocity 300 *m/s* against 15 layer Twaron sandwich sloth packet: velocities in the Oz direction. Static friction coefficient between sloth layers 0.5 and between layers and the bullet equals 0.0.

Fig. 16 9 mm PARA bullet and textile packages interactions.

The main results

In this chapter practical terminal ballistics tasks were solved.

Obtained steel's AISI 1020 dynamic properties involve 7.62 mm bullet's residual velocity after steel target perforation, calculation for engineering purpose.

Computational models for the solid and for the textile woven structure are quite different. For solid structure the main object is the determination of dynamic properties of the material and the textile woven structure requires the additional estimation of the yarn interaction between them and textile layers.

The textile fabric computational FE model was developed. Yarns were simulated and were woven into the fabric by applying shell elements and using contact interaction between yarns.

During the analysis it was obtained that the friction between fabrics layers has a big influence on the body armor vest resistance. The increase of the friction invokes the increase of the ballistic resistance of the armor vest.

CONCLUSIONS

By using computer-aided modeling and experimental methods, ballistic processes of a bullet were investigated. The original approaches for interior and terminal ballistics solution were presented and the results, suitable for engineering applications, were obtained.

1. A traditionally used equation of the motion of the bullet was supplemented with the extraction force from the case. The computational model of the bullet motion in a rifled barrel was simplified to an axi-symmetric form by introducing the concept of the equivalent smooth barrel.

2. By means of the numerical integration of the equation of the motion of the bullet and by employing the experimentally estimated powder gas pressure-time relationship, the main exterior ballistics relationships, describing the displacement of the bullet in the barrel were indicated. By taking into account the extraction force of the bullet from the case, more accurate estimations of interior ballistics relation in the first stage of the bullet's motion in the barrel were obtained. On the basis of this model, the bullet's velocity at the muzzle was calculated with the accuracy of 0.05%.

3. It was demonstrated that the calculation accuracy decreases when the initial interaction velocity increases. The main reason for this is the increase of the role of the dynamic properties of the material, the values of which have to be determined for certain ranges of interaction velocities as well as for certain ranges of the computational mesh refinement.

4. By experimental and computational investigations of projectile-target interaction ballistics, the dynamic properties of steel AISI 1020 were indicated. The obtained values are valid when target thickness and projectile diameter values are close to each other. The recommended values of Cowper-Symonds constants of the elasto-plastic material model are C=495.5 s^{-1} and p=3. For 7.62 mm bullet terminal ballistics investigation the recommended mesh edge length is ~0.3 mm.

5. The model enabled to predict the residual velocity of the projectile for initial velocity ranging from 700-1300 m/s with the accuracy of 0.3-0.5 %. Better accuracy values are obtained at lower initial velocities.

6. The textile target computational model was developed. Yarns were simulated by using shell elements, and the fabric was presented as a woven yarn structure. The developed model enables to obtain a better adequacy of simulation results to the reality in comparison with simpler uniform membrane computational model.

7. It was demonstrated that the friction between fabrics layers of the textile body armor plays a significant role for providing its ballistic strength. The increase of the friction coefficient facilitates the increase of the ballistic strength of a multilayer textile package of the armor vest.

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In the periodical Lithuanian scientific publications:

1. V. Vasauskas, A. Vilkauskas, V. Čapas. Evaluation of Nonferrous Alloys in High Speed Contact Operating // Mechanika. ISSN 1392-1207. Kaunas: Technologija, 2002, No. 4(36) p. 11-17.

2. A. Abraitienė, L. Valasavičiūtė, R. Barauskas, A. Vilkauskas. Finite Element Analysis of Ballistic Properties of a Multilayer Textile Package in LSDYNA // Medžiagotyra. ISSN 1392-1320. Kaunas: Technologija, 2002, No. 4, p. 500-505.

Presentations, published as scientific conference material:

1. R. Barauskas, A. Vilkauskas. Finite Element Analysis of Ballistic Properties of a Multilayer Textile Package in LSDYNA // Proceedings of the Nordic LS-DYNA Users‘ Conference, Gotteborg, 2002, Proceedings on CDROM, p. 6.

2. R. Barauskas, A. Vilkauskas. Terminal Ballistics Simulation of Rod-Plate Interaction // Proceedings of International Conference, Transport Means, Kaunas, 2004, p. 23-26.

Information about the author

Andrius Vilkauskas was born in 1975, in Alytus. In 1993 he entered Kaunas University of Technology, the faculty of Mechanics. In 1997 obtained Bachelor of Sciences qualification degree in Mechanical Engineering. In 1999 obtained a qualification degree of Master of Sciences. From 1999 to 2003 he studies in Kaunas University of Technology as a doctoral student in Mechanical Engineering sciences.

MAŽKO KALIBRO KULKŲ BALISTINIŲ PROCESŲ MODELIAVIMAS IR TYRIMAS

REZIUMĖ

Darbo struktūra. Darbą sudaro įvadas, keturi skyriai, išvados, naudotos literatūros sąrašas, priedai. Disertacijos apimtis – 141 puslapis, joje yra 75 paveikslai ir 35 lentelės.

Pirmame skyriuje supažindinama su pagrindiniais balistikos objektais bei uždaviniais, išsamiau nagrinėjamos kulkos ir taikinio balistinės sąveikos problemos ir šiuo metu naudojami jų sprendimo metodai. Atkreipiamas dėmesys į tai, kad šioje srityje vyrauja empiriniai tyrimo metodai, o skaitiniai metodai dar tik pradedami plačiau taikyti. Trumpai apžvelgiami modeliai, apibūdinantys medžiagų elgseną esant dideliam deformacijos greičiui.

Antrame skyriuje sprendžiamas 7,62 mm kulkos vidinės ir išorinės balistikos uždavinys naudojant analitinius ir eksperimentinius metodus. Pritaikius pasipriešinimo kulkos judėjimui vamzdyje jėgos modelį, kuriame graižtvinis vamzdis pakeičiamas ekvivalentiniu lygiu vamzdžiu, apskaičiuota kulkos pasipriešinimo vamzdyje jėga. Vėliau, skaitiškai integruojant kulkos judėjimo vamzdyje lygtį, kulkos judėjimo lygtis papildoma dar viena dedamąją – kulkos ištraukimo iš tūtelės jėga. Išsprendus šią lygtį, nustatytos pagrindinės vidinės balistikos charakteristikos. Integruotu eksperimentiniu-analitiniu išorinės balistikos tyrimu, nustatyta 7,62 mm kulkos greičio priklausomybė nuo kulkos padėties.

Trečiame skyriuje, naudojant paprastos geometrinės formos sąveikaujančius kūnus – cilindrinį strypą ir plokštę, ir tarpusavyje derinant skaitinio modeliavimo bei eksperimentinį tyrimo metodus, pagal sviedinio (strypo) liekamąjį greitį nustatytos sviedinio ir taikinio medžiagų dinaminės charakteristikos. Nustatytoms medžiagos konstantoms parinktas racionalus baigtinių elementų skaidymo tinklelis, leidžiantis gauti tikslius rezultatus lyginant skaičiuojamuosius ir eksperimentinius rezultatus.

Ketvirtame skyriuje spręsti du inžineriniai kulkos ir taikinio balistinės sąveikos uždaviniai. Pirmame uždavinyje, įvertinus trečiame skyriuje nustatytas taikinio medžiagos dinamines charakteristikas, prognozuotas liekamasis kulkos greitis pramušus taikinį.

IŠVADOS

Modeliuojant baigtinių elementų metodu ir eksperimentiškai ištirti balistiniai mažo kalibro kulkų procesai, pasiūlyti originalūs kulkos vidinės balistikos, taip pat kulkos ir taikinio balistinės sąveikos uždavinių sprendimo būdai, gauti nauji praktinę svarbą turintys rezultatai.

1. Iki šiol tradiciškai naudota kulkos judėjimo lygtis papildyta nauju nariu, aprašančiu kulkos ištraukimo iš tūtelės jėgą. Sudarant matematinį kulkos judėjimo modelį, realaus vamzdžio kanalo skerspjūvio plotas panaudotas kaip parametras graižtviniam vamzdžiui pakeisti ekvivalentiniu lygiu vamzdžiu.

2. Skaitiškai integruojant kulkos judėjimo lygtį, papildytą kulkos ištraukimo iš tūtelės nariu, ir taikant eksperimentiškai nustatytą parako dujų slėgio priklausomybę nuo laiko, nustatytos pagrindinės kulkos vidinės balistikos charakteristikos. Įvertinus kulkos ištraukimo iš tūtelės jėgą tiksliau aprašytas kulkos judėjimas pradinėje fazėje (kelių milimetrų kelyje). Nustatyta, kad kulkos judėjimo greičio ties vamzdžio žiotimis eksperimentiniai ir skaičiavimo rezultatai skiriasi ne daugiau kaip 0,05 %.

3. Nustatyta, kad balistinės sąveikos uždaviniuose sprendinio tikslumas mažėja didėjant pradiniam sąveikos greičiui. Tokiu atveju didžiausią įtaką turi medžiagos dinaminių charakteristikų reikšmės, kurios nustatomos individualiai parinktam tam tikram tinklelio smulkumo (t.y. vidutinio elemento linijinio matmens) intervalui.

4. Tiriant sviedinio ir taikinio balistinę sąveiką skaitinio modeliavimo ir eksperimentinio tyrimo metodais pagal liekamąjį sviedinio (strypo) greitį, nustatytos dinaminės plieno AISI 1020 charakteristikos. Kai sviedinio skersmuo artimas taikinio storiui, medžiagos plastiškumo ribos priklausomybę nuo deformacijų greičio pakoreguojančios Cowper-Symonds funkcijos konstantos yra C=495,5 s^{-1} ir p=3. 7,62 mm kalibro kulkų sąveikos su taikiniu skaitiniams tyrimams rekomenduotas tinklelis, kurio elemento kraštinės ilgis yra ~0,3 mm.

5. Naudojant sukurtą balistinės sąveikos modelį, pakankamu inžinerinėms reikmėms tikslumu apskaičiuotas liekamasis sviedinio greitis pramušus taikinį plačiame sviedinio (strypo, kulkos) pradinių greičių intervale. Palyginant tarpusavyje eksperimentinius ir skaitinius rezultatus, nustatyta, kad 700–1300 m/s pradinės sąveikos greičio intervale liekamasis greitis

apskaičiuojamas 0,3–0,5 % tikslumu. Didesnis tikslumas gaunamas esant mažesniems sąveikos greičiams.

6. Sukurtas iš laisvų tekstilinių audinių sudaryto taikinio skaičiuojamasis baigtinių elementų modelis. Audinio gijos ir sluoksniai modeliuojami tarpusavio kontaktine sąveika susietais kevaliniais baigtiniais elementais. Šis modelis yra tikroviškesnis, nei iki šiol tradiciškai taikytas ištisinis membraninis (kevalinis) audinio modelis.

7. Nustatyta, kad kulkos ir tekstilinio audinio paketo balistiniam atsparumui didelę įtaką turi trintis tarp audinio sluoksnių. Didėjant trinties koeficientui, paketo balistinis atsparumas didėja.

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