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Experimental Research and Numerical Analysis of Penetration of the Twaron T750 Aramid Fabric with the 9 mm Parabellum Projectile*

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Abstract. The paper presents results of experimental research and numerical analysis of the penetration process of the Twaron T750 aramid fabric with the 9 mm Parabellum projectile (brass jacket, lead core). Numerical simulations of the 9 mm Parabellum projectile impact into 10 and 16 layers of the Twaron T750 fabric with the use of the Ansys Autodyn v13 program for dynamic analyses were conducted on the basis of 3-dimensional solid numerical models. As a boundary condition in the experiment and in the numerical simulations it was assumed that all the four edges of the fabric were fixed. In the numerical simulations the sample of 50×50 mm dimensions and the impact velocities V_i = 448 m/s for 16 layers of the Twaron T750 fabric and V_i = 454 m/s for 10 layers of Twaron T750 fabric were adopted. In the paper the results of the numerical simulations for three material configurations with the same friction coefficients and for different values of yarn-yarn friction in case of one material configuration are presented. Residual velocity of the penetrator for the highest friction coefficient $\mu_s = 1$ decreased of 13.1% in comparison to simulation with no friction ($\mu_s = 0$).
Keywords: mechanics, numerical simulations, aramid woven fabric, Autodyn

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1. INTRODUCTION

Resistance to perforation of ballistic fabrics depends on their capabilities to absorb energy locally, in the zone of impact, and to spread it out from this area. The process of the fabrics penetration is influenced by:

1. fibre / yarn properties (density, modulus of elasticity, critical strain);
2. fabric properties (weave, areal density);
3. projectile properties (shape, mass, materials);
4. friction between fibers, yarns, fabric layers and friction between fabric and projectile;
5. interactions between the yarn families:
   - crimp interchange – the change of yarn undulation (changes in amplitude and wavelength);
   - trellising (the relative yarn rotation) – the change in angle (in fabric plane) between the warp and the weft;
   - locking – the resistance to fabric deformation which occurs when the inter-woven yarns jam against each other;
   - yarn slip, yarn pull out – the displacement of one yarn family (of warp or weft) in relation to the other;
6. boundary conditions (fabric gripping and orientation in the grip);
7. impact angle and velocity.

Complexity of the behaviour of the woven fabrics and a great number of factors which influence the penetration process make it difficult to predict and analyze their reaction during the impact of the projectile and to design novel protective fabrics. Analytical models, empirical studies and experimental works nowadays are supported by numerical modelling [1-10]. It allows the shortening of research time, a decrease in costs and to obtain new parameters.

This article presents results of experiments and the numerical analysis of penetration the process of the Twaron T750 aramid fabric with the 9 mm Parabellum projectile, which consists of a brass jacket and a lead core.

2. TESTS

In the Military Institute of Armament Technology (Zielonka, Poland) the tests of the 9 mm Parabellum projectile impact into the Twaron T750 aramid fabric of 500×500 mm size were carried out.

The test stand, the sample gripping, the fragment of investigated aramid fabric and the projectile are shown in Figure 1.

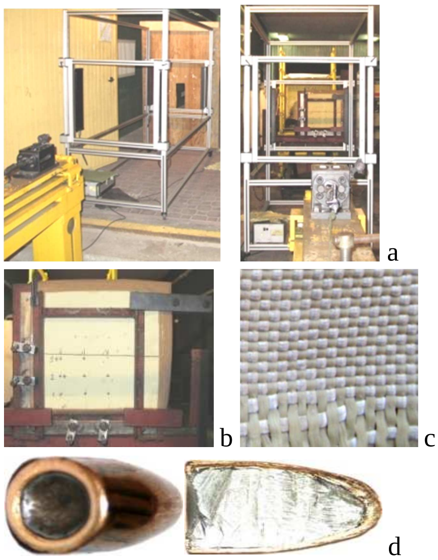

Fig. 1. Stand for ballistic tests of the sample: a – metal platform with ballistic barrel and gates with photocells for determination of the projectile velocity, b – sample in frame, c – investigated aramid fabric, d – 9 mm Parabellum projectile and its cross section

The investigated layers of fabric were inserted between two parts of the ballistic frame (with a target area for shooting/work space of 320 × 320 mm), stretched and fixed by the mutual clamping of both parts of the ballistic frame (by means of attaching them with clamping elements consisting of screws, clamping jaws and additional clamps). The ballistic barrel, from which the 9 mm Parabellum projectiles were fired, was connected with the 292BI type handle, screwed on a metal platform and fixed firmly to the ground. On the basis of computer analysis of the signals from the gates with the “start” and “stop” photocells, and the ballistic characteristics of the projectile, the velocity of the projectile impact into the sample was determined. After each ballistic test the creased and delaminated layers of the fabric were flattened and stretched before the next shot (it allowed us to achieve similar conditions for all the experiments).

The aim of the experiments was to investigate the behaviour of samples with different numbers of the Twaron T750 layers for the impact velocity of 450 m/s.

In order to obtain the demanded impact velocity of the 9 mm Parabellum projectile the mass of gunpowder in a case was increased. The impact velocities from 429 to 454 m/s were achieved during the tests.

When the sample was shot, the numbers of perforated and damaged layers of the investigated fabric were counted.

The 9 mm Parabellum projectile deformations: minimum and maximum diameter of the mushroom, the length of the projectile, the depth of the hole of the deformed projectile (*DHDP*) and maximum cracking were measured.

Figure 2 shows the shape and dimensions projectiles that were not deformed, Figure 3 illustrates the places of measurements of the deformed projectile and Figure 4 presents the way of measuring the area of the mushroom projection using the Autodesk Inventor 2012 program.

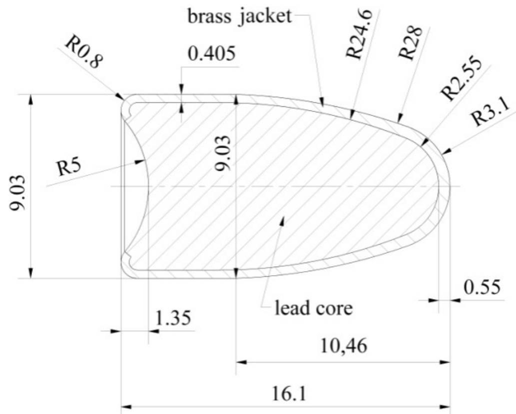

Fig. 2. Dimensions of the 9 mm Parabellum projectile

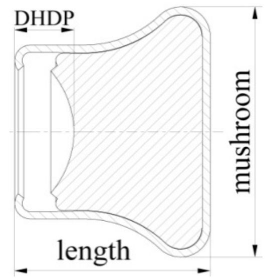

Fig. 3. Places of measurements of the deformed projectile

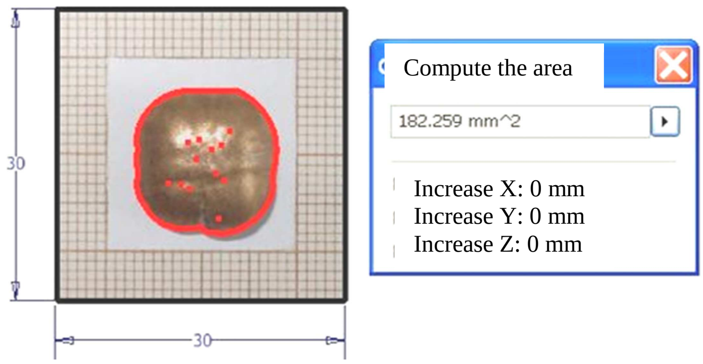

Fig. 4. Measurement of area of the mushroom projection in the Autodesk Inventor 2012 program

In case of the 9 mm Parabellum projectile stopping (impacted into 16 layers of the Twaron T750 fabric) the projectile mushroom had a square-like shape and a cracking of the jacket occurred. In the case of the fabric perforation (impacted into 10 layers of the Twaron T750 fabric) the projectile deformations were smaller (in comparison to shots no. 2 and no. 10: the projectile length was bigger by 44%, the minimum and maximum diameter of the mushroom was smaller by 6 and 16% respectively, the area of the mushroom projection was smaller by 21% and the mushroom had an oval shape.

In Figures 5 and 6 the projectiles deformations are shown.

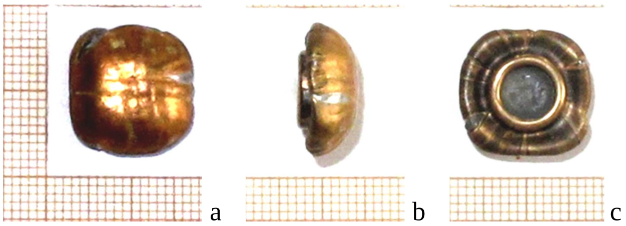

Fig. 5. Projectile 2 after ballistic test:
a – front,
b – side,
c – back

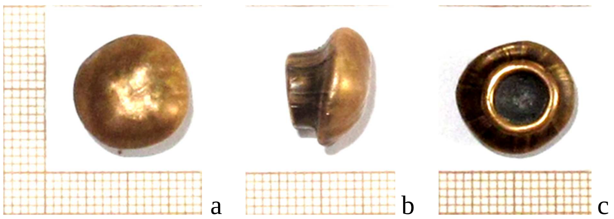

Fig. 6. Projectile 10 after ballistic test:
a – front,
b – side,
c – back

The results of the ballistic tests are included in Table 1.

Table 1. Results of the ballistic tests

No. of shot	No. of layers	Projectile impact velocity, V_i, m/s	Result P/Z[1]	No. of layers		Projectile deformations					
				Perforated	Damaged	Length, *L*, mm	Mushroom diameter, mm		Mushroom area[2], A, m^2	*DHDP*[3] mm	Maximum cracking length, L_c, mm
							D_{Max}	D_{Min}			
1	16	429	Z	5	7	8.2	15.8	14.2	182	2.5	4.8
2	16	448	Z	6	7	6.9	16.8	14.6	192	2	5.8
3	16	437	Z	8	10	7.8	17.0	13.6	201	2.7	13.6
9	10	453	P	10	10	the projectile not found					
10	10	454	P	10	10	9.9	14.2	13.7	151	2.8	-[4]
11	10	451	P	10	10	the projectile not found					

[1] P – sample perforation (all fabric layers), Z – projectile stopping; [2] area of frontal projection (perpendicular to the projectile axis) of the projectile mushroom;
[3] *DHDP* – depth of hole of the deformed projectile; [4] no cracking on the projectile jacket

3. NUMERICAL SIMULATIONS

With the use of the Ansys Autodyn v13 program for dynamic analyses, 3-dimensional numerical simulations of the 9 mm Parabellum projectile impact into samples of 10 and 16 layers of the Twaron T750 fabric were carried out.

Parameters of the Twaron T750 fabric, the yarn and the fibre from which the yarn is composed are given in Table 2.

Table 2. Parameters of the Twaron T750 fabric and the CAD model

Level	Real fabric				CAD model
	Parameter		Value	Reference	
Fibre 1000	diameter		12 μm	[12]	–
	area of cross-section		1.13×10^{-4} mm^2	counted	–
	density		1.44 g/cm^3	[12]	–
	strength		2.4÷3.6 GPa	[12]	–
Yarn	linear density	warp	3360 dtex	[12]	3360 dtex
		weft	3360 dtex		3360 dtex
	number of fibres		2000	[12]	–
	area of cross-section		0.226 mm^2	counted	0.284 mm^2
	density		< 1.44 g/cm^3		1.183 g/cm^3
	thickness		0.296 mm	[13]	0.296 mm
	width		1.426 mm	[13]	1.426 mm
	strength		1.91 GPa	[13]	4 GPa
Fabric	weave		plain	[12]	plain
	areal density		460 g/m^2	[12]	457 g/m^2
	thickness		0.592 mm	[13]	0.592 mm
	yarn span		1.472 mm	[13]	1.472 mm

To reduce the computing time, dimensions of the samples of 50×50 mm were adopted. With symmetry conditions on two orthogonal planes, the numerical model was further diminished to a quarter of the whole assumed system, of 25×25 mm dimensions. After being built with the use of the Inventor Professional 2012 program, the CAD model of the woven fabric and the 9 mm Parabellum projectile was imported into the Ansys Mechanical v12.01 program. The mesh, initial and boundary conditions as well as the relations among each elements of the model were defined there. Further works for numerical model building, among other assignment of materials, were carried out in the Ansys Autodyn v13 program, which is dedicated to dynamic analyses.

To achieve approximately the same areal density as in the real fabric, based on the aramid fibre (yarn: 3360 dtex, areal density 460 g/m^2) under the defined shape and dimensions of the yarn cross-section (area of yarn cross-section: 0.284 mm^2) and used fabric weave dimensions, the density of the yarn equal to 1.183 g/cm^3 was adopted. Finally the areal density of the fabric equal to 457 g/m^2 and the linear density of the yarn, equal to 3360 dtex, were obtained.

The impact velocities (448 m/s for 16 layers and 454 m/s for 10 layers) and the boundary conditions on the side surfaces of the fabric were adapted analogically to the tests. The shape and dimensions, shown in Figure 2, were used in the numerical model of the 9 mm Parabellum projectile.

The parameters for equation of state, the strength model and the failure model for the projectile core (lead) and jacket (brass) were adopted on the basis of the earlier tests and numerical models [11]. The projectile core and jacket in the numerical model were discretized by means of hexagonal solid elements of 0.5 mm size and tetragonal, four-nodal solid elements of 0.25 mm size respectively.

By means of the orthotropic linear elastic model the yarns of the Twaron T750 aramid fabric are presented. This model uses an incremental stress-strain relation to calculate the stress at cycle *n* as follows:

$$[\sigma]^n = [\sigma]^{n-1} + [S]\left[\dot{\varepsilon}\right]\Delta t \,, \tag{1}$$

where: [S] – stiffness matrix, $\left[\dot{\varepsilon}\right]$ – strain rate vector, Δt – time step.

Stiffness matrix for orthotropic material is described by following formula:

$$S = \begin{bmatrix} \frac{1-\nu_{23}\nu_{32}}{E_2E_3\Delta} & \frac{\nu_{21}-\nu_{31}\nu_{23}}{E_2E_3\Delta} & \frac{\nu_{31}-\nu_{21}\nu_{32}}{E_2E_3\Delta} & 0 & 0 & 0 \\ \frac{\nu_{21}-\nu_{31}\nu_{23}}{E_2E_3\Delta} & \frac{1-\nu_{13}\nu_{31}}{E_1E_3\Delta} & \frac{\nu_{32}-\nu_{12}\nu_{31}}{E_1E_3\Delta} & 0 & 0 & 0 \\ \frac{\nu_{31}-\nu_{21}\nu_{32}}{E_2E_3\Delta} & \frac{\nu_{32}-\nu_{12}\nu_{31}}{E_1E_3\Delta} & \frac{1-\nu_{12}\nu_{21}}{E_1E_2\Delta} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2G_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & 2G_{23} & 0 \\ 0 & 0 & 0 & 0 & 0 & 2G_{31} \end{bmatrix} \tag{2}$$

for $\Delta = \dfrac{1-\nu_{12}\nu_{21}-\nu_{23}\nu_{32}-\nu_{31}\nu_{13}-2\nu_{21}\nu_{32}\nu_{13}}{E_1E_2E_3}$,

where: E_i – Young moduli in the principal directions, ν_{ij} – Poisson's ratios, defined as the transverse strain in the *j*-direction when the material is stressed in the *i*-direction, G_{12}, G_{23}, G_{31} – shear moduli in planes (1, 2), (2, 3), (3, 1) respectively.

Regarding the symmetry of stiffness, the matrix elastic constants satisfy conditions [5]:

$$\frac{\nu_{12}}{E_{11}} = \frac{\nu_{21}}{E_{22}}, \qquad \frac{\nu_{13}}{E_{11}} = \frac{\nu_{31}}{E_{33}}, \qquad \frac{\nu_{23}}{E_{22}} = \frac{\nu_{32}}{E_{33}} \tag{3}$$

Furthermore, Poisson's ratios, Young moduli and shear moduli must satisfy the following conditions:

$$E_1, E_2, E_3, G_{12}, G_{23}, G_{31} > 0, \tag{4}$$

$$1 - \nu_{12}\nu_{21} - \nu_{23}\nu_{32} - \nu_{31}\nu_{13} - 2\nu_{21}\nu_{32}\nu_{13} > 0, \tag{5}$$

$$\nu_{21} < \sqrt{\frac{E_1}{E_2}}, \qquad \nu_{32} < \sqrt{\frac{E_3}{E_2}}, \qquad \nu_{13} < \sqrt{\frac{E_1}{E_3}}. \tag{6}$$

It is assumed as a criterion of the yarn destruction, that failure is initiated when the material reaches the critical value of stress (defined as σ_1 = 4 GPa) alongside the main direction (length) of the given yarn (weft or warp).

The Twaron T750 fabric and the CAD model made with the use of the Inventor Professional 2012 program are presented in Figure 7. The yarns in the numerical model were represented by means of hexagonal solid elements with dimensions along yarn width and length equal to 1/4 of yarn width.

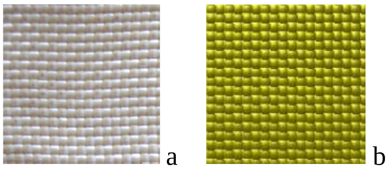

Fig. 7. The Twaron T750 aramid fabric: a – real fabric, b – CAD model made with the use of the Inventor Professional 2012 program

Assumed yarns dimensions and the Twaron T750 fabric discretization are shown in Figure 8.

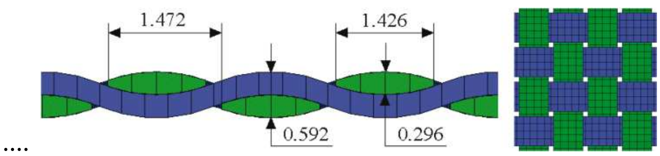

Fig. 8. Adopted yarn dimensions and the Twaron T750 fabric discretization

Friction between contacting surfaces was defined by the following relation:

$$\mu = \mu_k + (\mu_s - \mu_k) \cdot e^{-\alpha|\upsilon_{rel}|} \tag{7}$$

where: μ_s – static coefficient of friction, μ_k – dynamic coefficient of friction, υ_{rel} – relative sliding velocity between two surfaces, α – decay constant.

There were used the friction coefficients [9]:

- for yarn-yarn contact: $\mu_k = 0.19$; $\mu_s = 0.23$; $\alpha = 10^8$;
- for projectile-fabric contact: $\mu_k = \mu_s = 0.18$.

For three material configurations V, VI and VII (Table 3) from the several dozen of the investigated variants of parameters (from literature and modified) it was possible to finish the numerical simulation.

Table 3. Parameters of yarn of the Twaron T750 aramid fabric

Material configuration name	V	VI	VII
Longitudinal Young modulus, E_{11}, GPa	122	72.2	92
Transverse Young modulus, E_{22}, GPa	0.12	22.2	2.2
Transverse Young modulus, E_{33}, GPa	0.12	22.2	2.2
Poisson's ratio, ν_{12}	0	0	0
Poisson's ratio, ν_{23}	0	0.6	0
Poisson's ratio, ν_{31}	0	0	0
Shear modulus, G_{12}, GPa	0.12	31	0.92
Shear modulus, G_{23}, GPa	0.12	0.16	0.92
Shear modulus, G_{31}, GPa	0.12	31	0.92
Critical stress, σ_1, GPa	4	4	4

In other cases overly large deformations of the numerical model elementary cells made it impossible to continue the calculations. The results of the simulations for the material configurations V, VI and VII are presented in Table 4 and in Figures 9-15.

Table 4. Numerical results of the 9 mm Parabellum projectile impact into the Twaron T750 fabric layers – projectile and fabric deformations

Material configuration name	Number of layers	Projectile impact velocity, V_i, m/s	Result: P/Z	Projectile residual velocity, V_r, m/s	Projectile deformations				
					Length, L, mm	Mushroom diameter, mm		*DHDP*, mm	Jacket cracking Yes / No
						D_{Max}	D_{Min}		
V	16	448	P	300	10.9	14.3	13.3	3.3	Yes
	10	454	P	364	12.5	12.2	11.8	3.1	Yes
VI	16	448	P	340	11.4	13.5	13	4	No
	10	454	P	399	13	10.6	10.5	2.4	No
VII	16	448	P	320	11	13.7	13.5	3.9	Yes
	10	454	P	378	13	10.6	10.5	2.4	No

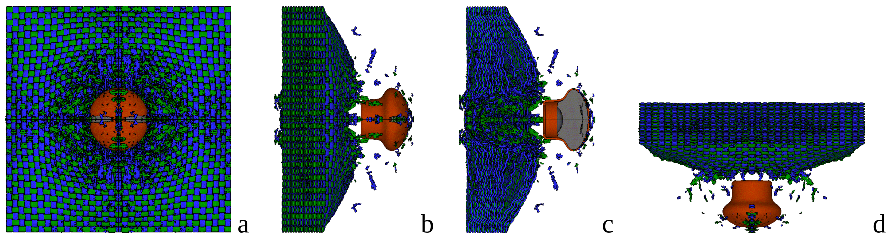

Fig. 9. Views of the 9 mm Parabellum projectile and 16 layers of the Twaron T750 fabric after impact (material configuration V): a – front, b – side, c – cross-section, d – top (t = 0.076 ms)

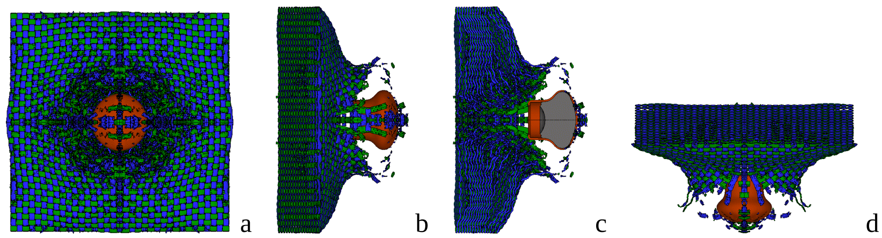

Fig. 10. Views of the 9 mm Parabellum projectile and 16 layers of the Twaron T750 fabric after impact (material configuration VI): a – front, b – side, c – cross-section, d – top (t = 0.076 ms)

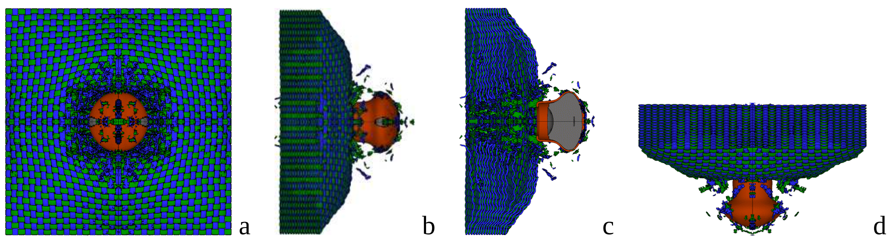

Fig. 11. Views of the 9 mm Parabellum projectile and 16 layers of the Twaron T750 fabric after impact (material configuration VII): a – front, b – side, c – cross-section, d – top (t = 0.076 ms)

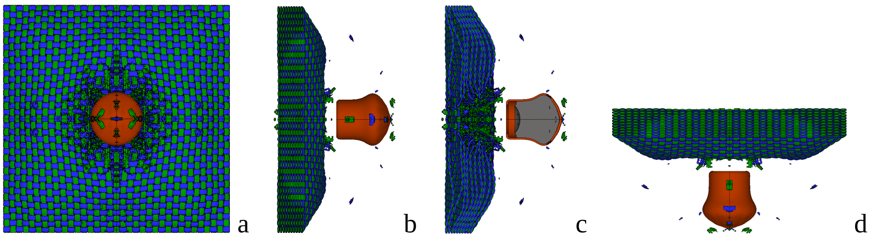

Fig. 12. Views of the 9 mm Parabellum projectile and 10 layers of the Twaron T750 fabric after impact (material configuration V): a – front, b – side, c – cross-section, d – top (*t* = 0.076 ms)

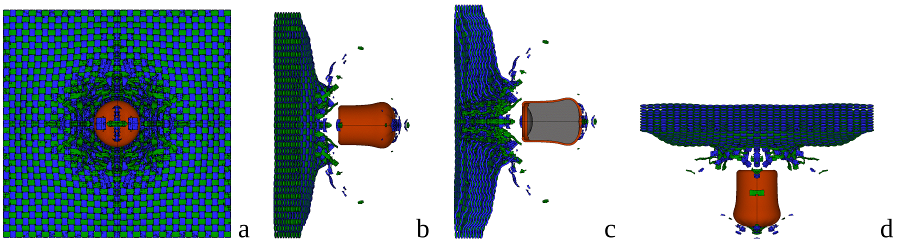

Fig. 13. Views of the 9 mm Parabellum projectile and 10 layers of the Twaron T750 fabric after impact (material configuration VI): a – front, b – side, c – cross-section, d – top (t = 0.076 ms)

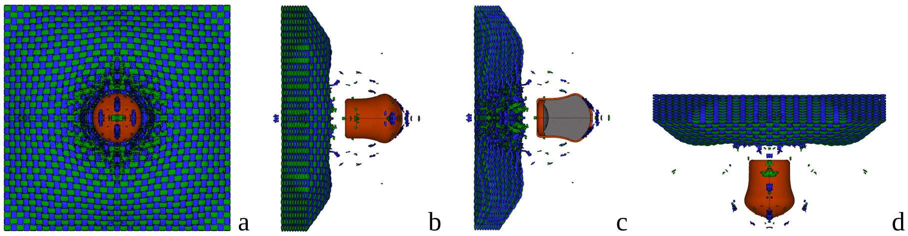

Fig. 14. Views of the 9 mm Parabellum projectile and 10 layers of the Twaron T750 fabric after impact (material configuration VII): a – front, b – side, c – cross-section, d – top (*t* = 0.076 ms)

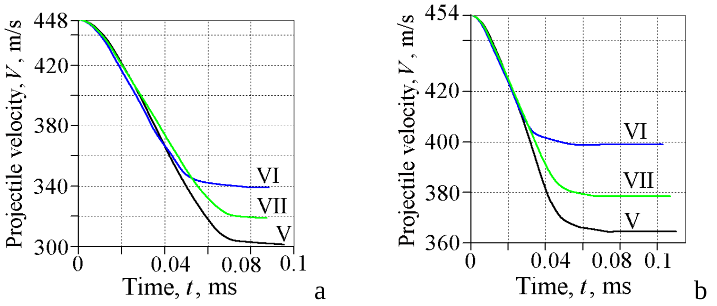

Fig. 15. Results of numerical simulations of the 9 mm Parabellum projectile impact into the Twaron T750 fabric, carried out for different material parameters: a – 16 layers, b – 10 layers

In numerical simulations carried out the satisfying agreement with the experiment was not achieved (Table 5). Further works over a numerical model are necessary (increasing mesh density, increasing sample model dimensions to 100 × 100 mm and validation of the fabric model on the basis of the tests with a steel puncher [13]). Differences in the dimensions of the projectile deformation between the simulation and the experiment in the case of the 9 mm Parabellum projectile impacted into 10 layers of the Twaron T750 fabric may be caused by the fact that in the tests after the fabric perforation the projectile impacted the aramid fabric layers inserted in the target trap. In the case of further tests it seems purposeful to stop projectiles in the gelatine or in another medium which would not deform them, and to use the high-speed camera for the determination of the projectile residual velocity.

Table 5. Differences between results of experiment and numerical simulation

Material configuration name	Number of layers	Difference in result: Yes / No	Differences in projectile deformations				
			Length, *L*, %	Mushroom diameter, %		*DHDP*, %	In jacket cracking Yes / No
				D_{Max}	D_{Min}		
V	16	Yes	58	15	9	63	No
	10	No	26	14	14	12	Yes
VI	16	Yes	65	20	11	98	Yes
	10	No	31	25	23	13	Yes
VII	16	Yes	59	19	8	93	No
	10	No	31	25	23	13	Yes

4. INFLUENCE OF THE YARN FRICTION ON THE BALLISTIC PERFORMANCE OF THE FABRIC

The works in relation to the yarn friction coefficients and the ballistic response of a woven fabric are reviewed in papers [8, 9]. The tribological properties of the woven fabrics made from Kevlar for different linear densities of the Kevlar yarns and different surface treatment of the yarns were investigated by Rebuillat [8]. The paper refers to the works of Dischler, who developed ~2 µm thick coating, which increases the yarn-yarn frictional coefficients when applied to the aramid fibres, and of Chitrangad, who developed a fluorinated finish for aramids which increased the fibre-fibre friction. Works on the effect of water on ballistic performance of the Armos fabric made by Bazhenow, in which the author found that the decrease of the yarn-yarn friction and the yarn-projectile friction, as a result of lubricant properties of water, deteriorates ballistic properties of the aramid fabrics are also mentioned in paper [8]. The test procedure for the determination of the yarn friction coefficients, obtained values (μ_k = 0.19; μ_s = 0.23; α = 10^8) and reference to results of other authors (Briscoe and Motamendi – Kevlar 49 Yarns – μ_s= 0.22; Zeng – range of optimum friction coefficient: $0.1 \leq \mu_s \leq 0.6$) are described in paper [9].

On the basis of the above mentioned literature for the material configuration VII the numerical simulations of the 9 mm Parabellum projectile impacted into 10 layers of the Twaron T750 fabric were performed for different values of the yarn-yarn friction (Fig. 16÷18).

No extremum was found in relation to the projectile's residual velocity and the yarn-yarn friction coefficients. The projectile's residual velocity decreases together with the increase of the friction coefficients.

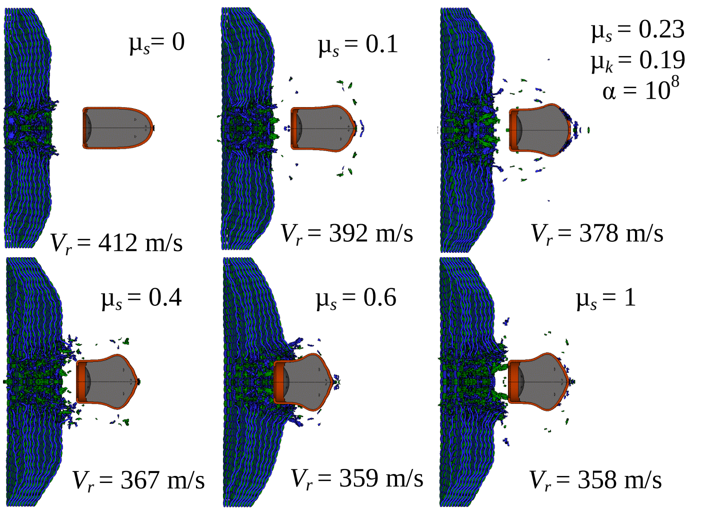

Fig. 16. Results of numerical simulations of the 9 mm Parabellum projectile impact into 10 layers of the Twaron T750 fabric, carried out for different yarn friction coefficients

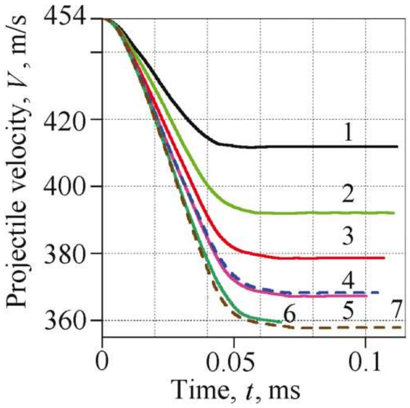

Fig. 17. Velocity of the projectile in function of time for different values of the yarn-yarn friction (the 9 mm Parabellum projectile impact into 10 layers of the Twaron T750 fabric) for the material configuration VII:
1 – $\mu = 0$,
2 – $\mu_s = 0.1$,
3 – $\mu_s = 0.23$, $\mu_k = 0.19$, $\alpha = 10^8$,
4 – $\mu_s = 0.3$,
5 – $\mu_s = 0.4$,
6 – $\mu_s = 0.6$,
7 – $\mu_s = 1$

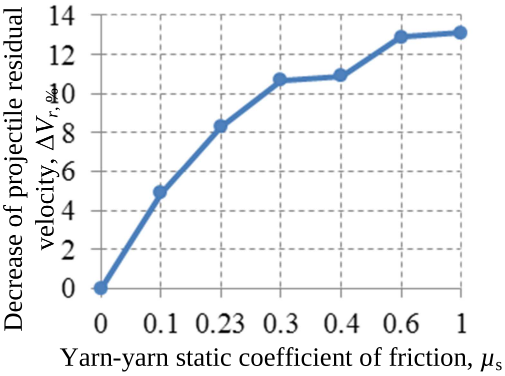

Fig. 18. Decrease of projectile residual velocity ΔV_r in relation to simulation with no friction in function of yarn-yarn static coefficient of friction μ_s

In the case of no friction between the yarns, the projectile residual velocity was equal to $V_r = 412$ m/s. When the static coefficient of friction was adopted as $\mu_s = 0.1$, the projectile residual velocity diminished by 4.9% (20 m/s). For the friction coefficients from paper [9] (experimental results: $\mu_s = 0.23$, $\mu_k = 0.19$, $\alpha = 10^8$) the projectile residual velocity decreased by 8.3% (34 m/s) in relation to the simulation with no friction.

Further increase in the yarn-yarn static coefficient of friction to $\mu_s = 0.3$, $\mu_s = 0.4$, $\mu_s = 0.6$, $\mu_s = 1$ (without respect to dynamic coefficient of friction μ_k) caused a decrease of the projectile residual velocity of 10.7%, 10.9%, 12.9% and 13.1% respectively, in relation to the simulation with no friction. The increase in the yarn-yarn static coefficient of friction above $\mu_s = 0.6$ had no significant influence on the ballistic performance of the fabric. In the numerical simulations the increase of the yarn-yarn static coefficient of friction from $\mu_s = 0.6$ to $\mu_s = 1$ caused a residual velocity decrease of 0.3% (1 m/s).

5. CONCLUSIONS

On the basis of the tests and the numerical simulations the following conclusions can be drawn:

1. In the numerical simulations overly small fragments of the fabric and oversized elementary cells (elements) were used. The rear displacement of the fabric reached the boundary of the model and caused fabric stretching, inconsistently with the experiment. This phenomenon with numerical erosion of the deformed elements caused a premature failure of the fabric.
2. Modelling of the 9 mm Parabellum projectile impacted into the Twaron T750 fabric should be preceded by fabric validation on the basis of the impact of the penetrator which would not be deformed (steel ball impact or punch test [13]).
3. The fabric absorbed more energy with the increase of friction between yarns. In the numerical simulations of the 9 mm Parabellum projectile impacted into 10 layers of the Twaron T750 fabric the residual velocity of the penetrator for the highest friction coefficient $\mu_s = 1$ decreased by 13.1% in comparison to the simulation with no friction ($\mu_s = 0$).
4. The increase of the yarn-yarn static coefficient of friction above $\mu_s = 0.6$ had no significant influence on the ballistic performance of the fabric. In the numerical simulations of the 9 mm Parabellum projectile impacted into 10 layers of the Twaron T750 fabric the increasing of yarn-yarn static coefficient of friction from $\mu_s = 0.6$ to $\mu_s = 1$ caused residual velocity decrease of 0.3% (1 m/s).
5. Ballistic performances of the fabric (100×100 mm) placed on the ballistic gelatine will be investigated in further works.

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