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VALIDATION OF THE NUMERICAL MODEL OF THE 9 MM PARABELLUM PROJECTILE

Abstract: In order to verify the correctness of the numerical model the experimental tests of the 9 mm Parabellum projectile impact onto the Armox 500 armour steel plate were carried out. The behaviour of the projectile for the impact velocities 100 m/s, 126.5 m/s, 134.3 m/s, 136.4 m/s and 143.8 m/s was examined. After firing tests the deformation of the mushroom, the length of the projectile and the depth of the hole of the deformed projectile (DHDP) were measured. The model curve for determination of the projectile deformation work E_{dp} in function of its shortening ΔL was elaborated. The 3D numerical simulations of the 9 mm Parabellum projectile impact onto the Armox 500 steel plate for the velocities obtained during the experimental tests with the use of the Ansys - Autodyn v12.1.0 program were performed. The difference between the dimensions of the projectile deformation achieved during the 3D numerical simulations and the experimental tests amounted to X_M = 0.1÷4.6%, X_L = 1÷7.9%, X_{DHDP} = 6.7÷47.3%, for the mushroom, length of the projectile and the depth of hole of the deformed projectile (DHDP) respectively. The 2D numerical simulations considering the friction coefficients between the coat and core of the projectile (X_M = 0.1÷6.1%, X_L = 0.1÷4.6%, X_{DHDP} = 0.6÷24.1%) were performed.

WALIDACJA MODELU NUMERYCZNEGO POCISKU 9 MM PARABELLUM

Streszczenie: W celu weryfikacji poprawności modelu numerycznego przeprowadzono badania eksperymentalne uderzenia pocisku 9 mm Parabellum w płytę ze stali pancernej Armox 500. Zostało zbadane zachowanie pocisku dla prędkości uderzenia: 100 m/s, 126.5 m/s, 134,3 m/s, 136,4 m/s, 143,8 m/s. Po przeprowadzeniu badań ostrzałem wykonano pomiary odkształcenia pocisków: grzybka, długości pocisku, głębokości dołka zdeformowanego pocisku (DHDP). Opracowano krzywą wzorcową służącą do określania pracy deformacji pocisku E_{dp} w funkcji jego skrócenia ΔL. Przeprowadzono symulacje numeryczne 3D uderzenia pocisku 9 mm Parabellum w płytę Armox 500 dla prędkości uzyskanych podczas badań eksperymentalnych z użyciem programu Ansys - Autodyn v12.1.0. Różnica pomiędzy wymiarami odkształcenia pocisku uzyskanymi podczas symulacji 3D i badań eksperymentalnych wyniosła X_M = 0,1÷4,6%, X_L = 1÷7,9%, X_{DHDP} = 6,7÷47,3% odpowiednio dla grzybka, długości pocisku i DHDP. Wykonano symulacje 2D z uwzględnieniem współczynników tarcia pomiędzy płaszczem i rdzeniem pocisku (X_M = 0,1÷6,1%, X_L = 0,1÷4,6%, X_{DHDP} = 0,6÷24,1%).

1. Introduction

Simulation of the phenomenon of the impact onto the armour requires building of the numerical models of the projectile and the armour, defining the contact between them and conditions: the initial and boundary. The aim of the numerical model is to reflect the real armour (the existing or designed one). The model is to enable foreseeing behaviour of the armour in the defined conditions or to describe, how its parameters should be changed to achieve the required properties (possibilities of application). The construction of the numerical model needs some assuming and simplifications, whereas the model is error-laden by the selected numerical method, resulting from imperfection of the environment in which the model is constructed. In order to verify its correctness, the reference to the experimental tests is necessary. These tests can be divided into the material dynamic parameters tests and the impact tests, in which the correctness of the numerical model is verified on the base of dimensions of the object deformation, its residual velocity (registered e.g. by means of the photocells system and a sufficient program) and the observation of the impact process (with the use of a high-speed camera).

This work describes the numerical model of the 9 mm Parabellum projectile which consists of a brass coat and a lead core.

2. Experimental tests

The deformation and destruction phenomena in the projectile, as well as in the armour, can occur during the impact. For the numerical modelling, the simplest is the case (with a limited number of variables), when the armour does not deform, whereas the projectile deforms but is not destructed. So built type simplifies further construction of the model, taking into consideration the destruction process.

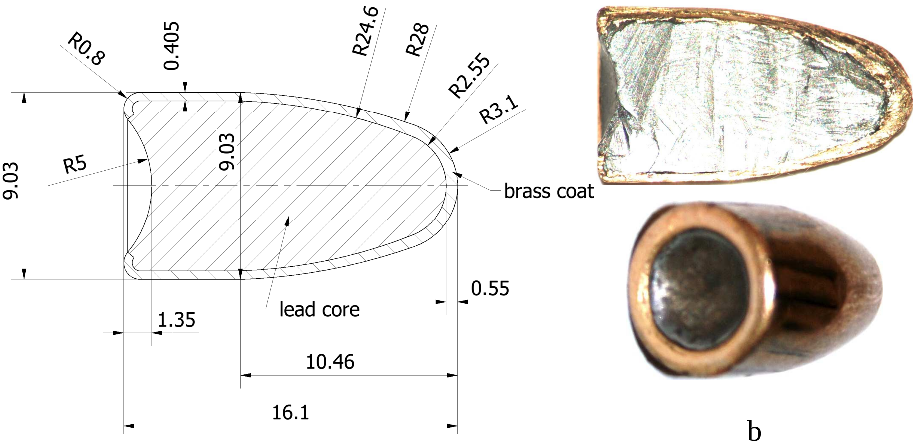
In the Military Institute of Armament Technology (Wojskowy Instytut Techniczny Uzbrojenia) the experimental tests of the 9 mm Parabellum (Fig. 1) projectile impact onto the Armox 500 armour steel plate of the size 500x500x10 mm were carried out. The surface of the Armox 500 plate was ground out before the firing tests, for to simplify the way of description of the physical and numerical contact between the plate and projectile. The plate was inserted between two parts of the frame, the latter fixed then stiffly on the immoveable stand (basis). The ballistic barrel, from which the 9 mm Parabellum projectiles were fired, was connected with the 292BI type handle, screwed on the metal platform and fixed stiffly on the ground. For to determine the velocities of the projectile impact onto the armour the gates with the photocells and the computer program were used.

The behaviour of the projectile for different velocities of impact onto the Armox 500 plate was examined. In order to achieve velocities lower than the normal outlet velocity of the 9 mm Parabellum projectile (350 m/s), for which this projectile would destruct entirely (would become flatenned and fragmented into very fine elements), the mass of the gunpowder in a case was diminished.

The following impact velocities V_u of the 9 mm Parabellum projectile onto the Armox 500 plate, amounted to: 100 m/s, 126.5 m/s, 134.3 m/s, 136.4 m/s and 143.8 m/s were achieved during the tests. For the values amounted to 100÷134.3 m/s the projectile mushroomed without cracking of the coat. In case of the values amounted to 136.4 m/s and 143.8 m/s the mushrooming of the projectile and cracking of the coat occurred. After the tests, the deformation of each of the used 9 mm Parabellum projectiles, i.e. the diameter of the mushroom, the length of the projectile and the depth of the hole of the deformed projectile DHDP was measured.

Figure 2 shows the places of measurements of the deformed projectile and Table 1 includes the results for the non-deformed (0) and deformed (1÷5) projectiles.

For the purpose of better evaluation of the projectiles deformation and for observation of the connection between the coat and core, the projectiles were flooded with resin, then after its hardening all was cut parallelly to the axis, so that the halves of the projectiles could be obtained (Table 2).



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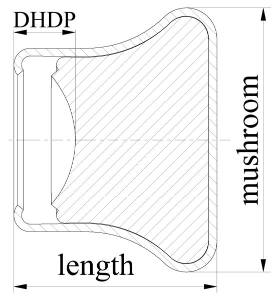


Fig. 1. The 9 mm Parabellum projectile:
a - dimensions,
b - a real projectile and its cross-section

Fig. 2. Places of measurements of the deformed projectile

Table 1. Results of the impact test of the 9 mm Parabellum projectiles ontothe Armox 500 plate

No.	Velocity of the projectile impact, V_u, m/s	Dimensions of the projectile, mm			Cracking of the coat, Yes/No
		diameter / mushroom	length	DHDP[1]	
0	-	9.03	16.10	1.35	No
1	100.0	11.20	11.45	2.70	No
2	126.5	12.95	9.90	3.00	No
3	134.3	13.50	9.55	3.10	No
4	136.4	13.85	9.45	3.30	Yes
5	143.8	14.95	9.35	3.55	Yes

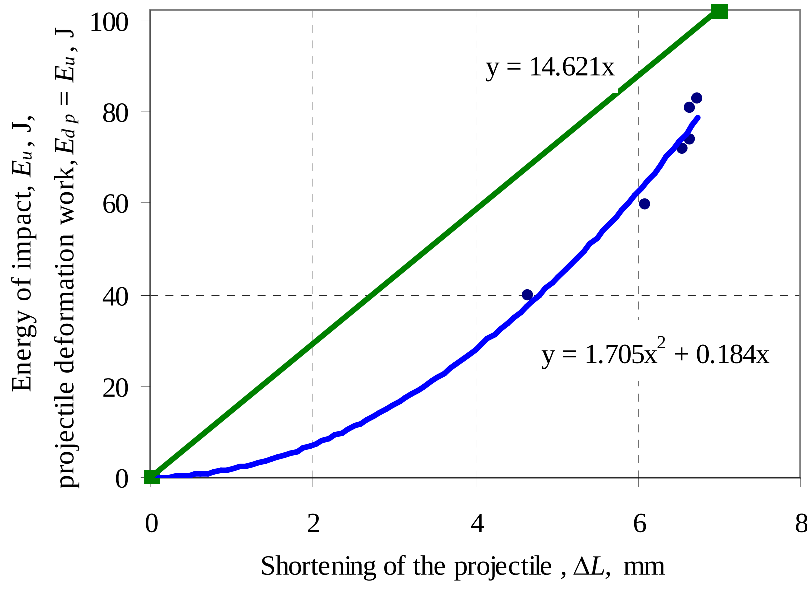
[1]DHDP - the depth of the hole of the deformed projectile

Table 2. Cross-sections and view of the front of the projectiles subjected to the firing tests

V_u, m/s	100	126.5	134.3	136.4	143.8
Cross- section of the projectile					
Front of the projectile					

For comparison of the results of the carried out tests with the analogical experimental ones, found in the literature [1], the model curve for determination of the projectile deformation work E_{dp} in function of its shortening ΔL was elaborated. This curve is for the case of the impact onto the non-deformable target, when all the kinetic energy E_u of the projectile is changed into the work connected with its deformation ($E_u = E_{dp}$). The curve allows indirectly for determination of the absorbed kinetic energy, by means of description of the projectile deformation work, in case of firing test of the other kinds of armours, which are deformable during the 9 mm Parabellum projectile impact (e.g. onto the aramid layers).

The comparison between the projectile deformation work in function of its shortening, obtained during the experimental firing tests, and the analogical curve [1] is shown in Figure 3.



Difference between the results:
$\left|\Delta E_{dp}\right| = \left|1.705\Delta L^2 - 14.437\Delta L\right|$

Fig 3. Comparison of the projectile deformation work (own experimental test – literature data)

3. Construction of the numerical model

The 2D simulations (in the axial symmetry) and the 3D simulations with the use of the Ansys - Autodyn v12.1.0 program for dynamic analyzes were performed.

The shape and dimensions, shown in Figure 1, were used in the numerical model of the 9 mm Parabellum projectile. For the calculation time shortening the size of the plate amounted to 100x100x10 mm was adopted for the 2D simulation, and amounted to 50x50x10 mm for the 3D simulation, instead of the size amounted to 500x500x10 mm of the Armox 500 plate used in the experiment. The boundary condition (*fixed support*) on the side surfaces of the plate (the surfaces of the size 100x10 mm and 50x10 mm, respectively to the simulations 2D and 3D) was also adopted. The significant decrease of the plate size does not influence the simulation process, because the plate remains non-deformable either during the experiment or in the performed simulation.

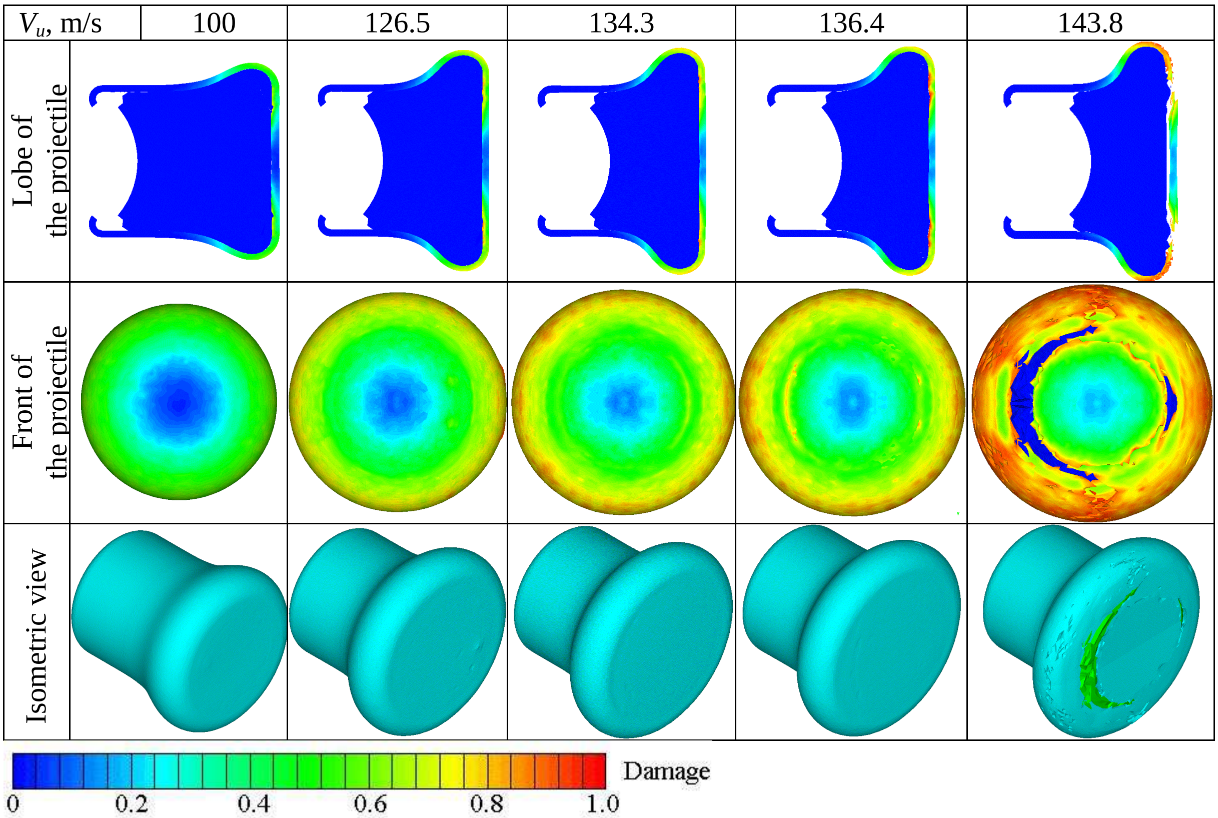
The material properties in form of the equations of state, the endurance model and the destruction model were adopted on the base of the literature data [2÷7] and the Ansys - Autodyn v12.1.0 program library database. For the coat of the 9 mm Parabellum projectile, based on the accumulation of the plastic strain the Johnson-Cook destruction model was selected and expressed by the equation:

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f}; \qquad \varepsilon^f = \left[D_1 + D_2 e^{D_3\sigma^*}\right]\cdot\left[1 + D_4 \ln\left|\dot{\varepsilon}^*\right|\right]\cdot\left[1 + D_5 T^*\right] \tag{1}$$

where: D_1, D_2, D_3, D_4, D_5 - material constants; $\sigma^* = \frac{p}{\overline{\sigma}}$ - pressure/stress measureless relation, p - pressure; $\overline{\sigma}$ - equivalent of the von Misses' stress; $\Delta\varepsilon_p$ - gain of the equivalent plastic strain, ε^f - equivalent plastic strain at cracking. When the parameter D = 1, the cracking in the material occurs.

In the first order the numerical simulation was performed for one of the measured projectile impact velocities, in which case the cracking of the coat did not occur: V_u = 100 m/s. The correction of the lead and brass endurable models allows to obtain satisfying results (the difference between dimensions of the projectile deformation achieved in the simulation and the experimental tests amounted to X_M = 4.6%, X_L = 1%, X_{DHDP} = 6.7%, respectively to the mushroom dimension, length of the projectile and the depth of the hole of the deformed projectile). Further numerical simulations were performed for the remaining measured impact velocities of the projectile, amounted to 126.5 m/s, 134.3 m/s, 136.4 m/s and 143.8 m/s. In case of the two last values the cracking of the coat in the experimental tests occurred (for the value of 143.8 m/s with the front part of the coat torn off). In order to reflect this phenomenon in the numerical simulation the parameters of the brass destruction model were modified. Results of simulation for the particular velocities of the projectile impact are included in Table 3.

Table 3. Results of the 3D simulation of the 9 mm Parabellum projectile impact onto the Armox 500 plate



4. Verification of the correctness of the numerical model

In the Ansys - Autodyn v12.1.0 program the deformations of the projectile: the diameter of the mushroom, the length of the projectile and the depth of the hole of the deformed projectile DHDP, achieved in the 3D numerical simulations, were measured. Table 4 presents the deformations and the difference between them, and the values obtained in the experimental tests. The difference in dimensions of the projectile deformation between the simulation and the experiment, depending on the projectile impact velocity, are illustrated in Figure 4.

Table 4. Parameters of the projectiles achieved in the simulation and the experiment

No.	Velocity of the projectile impact, V_u, m/s	Dimensions of the projectile deformation in the simulation, mm			Difference in dimensions of the projectile deformation between the simulation and the experiment, %		
		mushroom	length	DHDP	X_M	X_L	X_{DHDP}
1	100.0	11.71	11.34	2.88	4.6	1.0	6.7
2	126.5	13.12	10.23	3.89	1.3	3.3	29.7
3	134.3	13.49	10.08	4.32	0.1	5.5	39.4
4	136.4	13.61	10.00	4.45	1.7	5.8	34.8
5	143.8	14.31	10.09	5.23	4.3	7.9	47.3

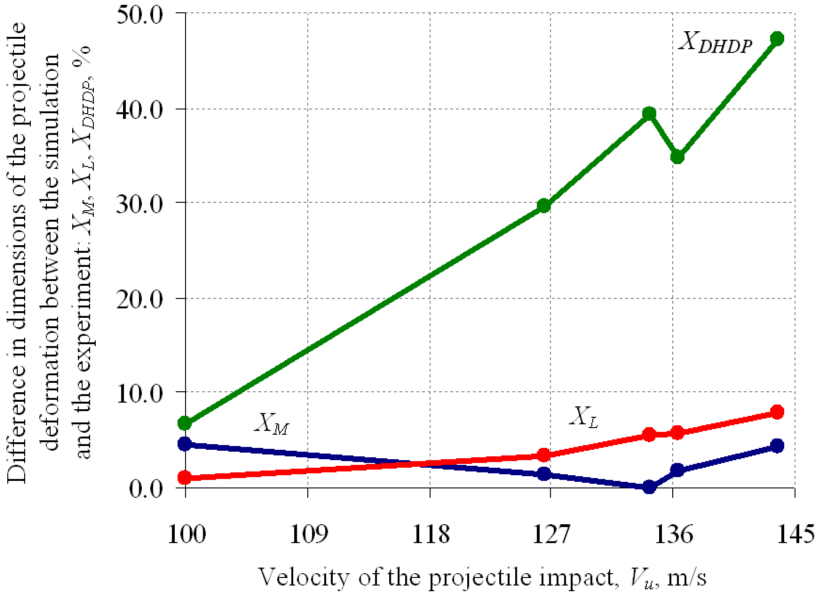
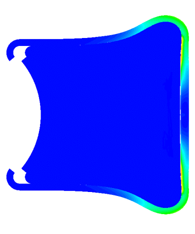
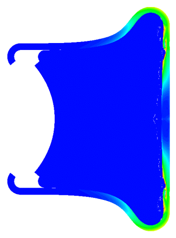
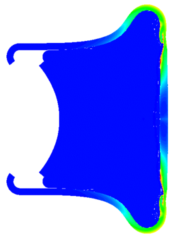
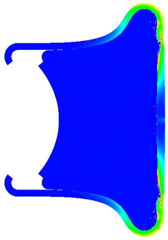
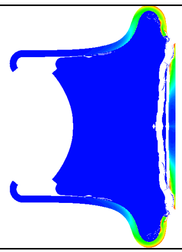


Fig 4. Difference in dimensions of the projectile deformation between the simulation and the experiment depending on the projectile impact velocity

For simplification of the numerical model in the performed 3D simulations the contact between the core and coat of the projectile was considered as frictionless. Large difference between the values of the DHDP, obtained in the experiment and simulation (up to 47.3%), indicated however the needs of selection of the friction coefficients (for limitation of the core slippage on the coat surface). For different values of these coefficients, the 2D simulations in the axial symmetry were performed and the results of that simulation, for which the biggest conformity with the experimental results were achieved, are presented in the Table 5 and 6, and in Figure 5.

Table 5. Results of the 2D simulation performed with consideration of the friction coefficients between the coat and core, for various impact velocities of the projectile

V_u, m/s	100	126.5	134.3	136.4	143.8
					

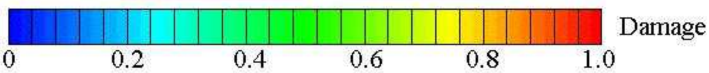


Table 6. Parameters of the projectiles obtained in the simulation and the experiment

No.	Velocity of the projectile impact, V_u, m/s	Dimensions of the projectile deformation in the simulation, mm			Difference in dimensions of the projectile deformation between the simulation and the experiment, %		
		mushroom	length	DHDP	X_M	X_L	X_{DHDP}
1	100.0	11.88	10.92	2.05	6.1	4.6	24.1
2	126.5	13.38	9.66	2.81	3.3	2.4	6.3
3	134.3	13.64	9.57	3.12	1.0	0.2	0.6
4	136.4	13.84	9.47	3.20	0.1	0.2	3.0
5	143.8	14.38	9.33	3.76	3.8	0.2	5.9

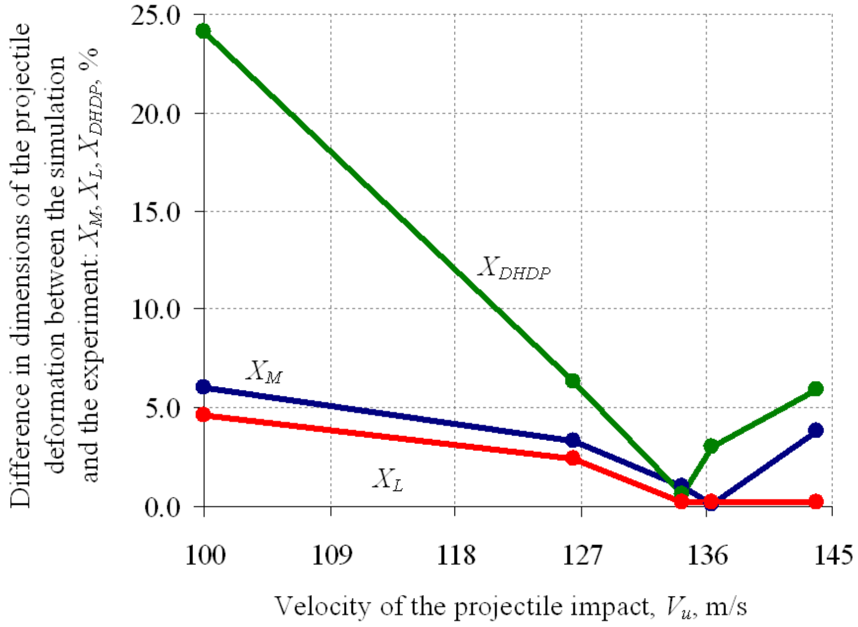


Fig 5. Difference in dimensions of the projectile deformation between the simulation and the experiment, depending on the projectile impact velocity

5. Conclusions

On the base of the carried out experimental test and the performed numerical simulations one can drawn the following conclusions:

1. The correct construction of the numerical model of the projectile requires consideration of its behaviour for various impact velocities. It is necessary to investigate the range of the velocities, taking into account the deformation of the projectile, both with and without its destruction (cracking of the coat).
2. The model curve describing the energy of the 9 mm Parabellum projectile deformation in dependence of its shortening is expressed by the equation:
   $\Delta E_{dp} = 1.705 \Delta L^2 + 0.184 \Delta L$ (ΔE_{dp} [J], ΔL [mm]).
3. The differences between the results of the experiment and numerical simulation can be caused by overriding the precise angle of the 9 mm Parabellum projectile impact onto the Armox 500 plate in the simulation. In case of further experimental tests it seems purposeful the use of the high-speed camera for determination of this angle.
4. Friction between the lead core and the brass coat of the projectile has the significant meaning in case of the impact of the 9 mm Parabellum projectile onto the armour. In the performed numerical simulations consideration of this phenomenon allowed

to achieve higher conformity of the results (measured parameters of deformation) with the experimental tests. With regard to all the tested impact velocities, the maximum difference of the depth of the deformed projectile DHDP between the simulation and experiment was decreased of 23.2%. Moreover, for the impact velocity V_u = 143.8 m/s, only in case of the simulation considering the friction between the coat and core, the entire separation of the coat front of the projectile was obtained, what conforms with the experimental tests results (Table 2). However, for the simulation without consideration of the friction, the entire separation of the coat front from the core was not achieved, what does not conform with the experimental results.

5. In the performed simulations, both for the 3D simulation without consideration of the friction between the core and coat of the projectile, as well as for the 2D simulation taking into account this phenomenon, the cracking was not possible to obtain when the projectile impact velocity amounted to 134.3÷136.4 m/s. In case of the 3D simulation, for the value of the velocity impact velocity amounted to 136.4 m/s, a dent is visible on the front mushroom surface, responding to the size and location of the cracking obtained in the experimental tests.
6. In the future, it is necessary to build the numerical model of the aramid fabric and to perform the simulation of the 9 mm Parabellum projectile impact onto it.

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