Experimental Researches on Specifics of Terminal and External Ballistics of Damaging Elements of Cylindrical Shape with Diameter of 5.0 Mm

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This article purpose is to investigate specifics of damage formation mechanism in a viscoelastic medium that arose as a result of high-speed impact-contact interaction with ready-made cylindrical striking elements. For achieving the goal, general scientific and special methods were used. The main attention was paid to the study of striking elements with a diameter of 5.0 mm, since they are equipped with a significant number of fragmentation munitions (in particular, anti-personnel mines, ammunition for dropping from drones, as well as improvised explosive devices). Experimental researches were carried out in conditions of a ballistic route using optoelectronic measuring complexes, a biological tissue simulator (ballistic plasticine) and special cartridges. Introduction of ready-made striking elements into free flight was carried out using a neuroballistic hand-held throwing device, as well as rifled firearms of 5.6 mm and 5.45 mm caliber. It made possible to conduct full-scale experiments in a fairly wide range of contact velocities from 70 m/s to 1082 m/s during research on striking properties and in the range from 547 m/s to 1096 m/s during research on aeroballistic characteristics. As experimental shells, ready-made striking elements of cylindrical shape with a diameter of 5.0 mm and an elongation of 0.96-1.1, that are equipped with OZM-72 fragmentation barrage mines, were used. During research, it was determined that after hitting the specified ready-made striking elements in the thickness of the biological tissue simulator behave stably and form conical cavities. They cause the greatest damage in the area of the first quarter (third) of the damage channel. This is due to the almost complete transfer of their kinetic energy by the striking elements to the layers of environment adjacent to the central damage channel in this area. Dimensions of *the damage zone in this area of the channel are maximum. Based on obtained results, specifics of influence of the contact velocity and the position of striking element at the moment of impact on the parameters of the damage channel were determined. Empirical dependences of resistance coefficient of viscoelastic medium, the volume and length of the damage channel on the contact velocity were determined. The results of performed researches make possible to predict the severity of shrapnel wounds inflicted on a person and to solve a number of situational tasks related to the investigation of criminal crimes and terrorist acts, while which commission of fragmentation munitions or improvised explosive devices were used. Separate stage is the research on aeroballistic characteristics of kinetic projectile samples that makes possible to determine their striking properties depending on distance to the explosion center.*

Keywords: *ballistic plasticine; ammunition; coefficient of medium resistance; contact velocity; fragmentation-barrier mine OZM-72; fragmentation damage; cartridge; improvised explosive device; terminal ballistics; striking element of cylindrical shape.*

Research Problem Formulation

Terminal ballistics of natural fragmentation fragments and ready-made striking elements is a rather complex field of research in military and forensic medicine. Formation rapidity of shrapnel wounds, simultaneous formation of multiple wounds and the rather high contact velocities of kinetic projectiles (fragments and ready-made striking elements) do not allow us to accurately determine influence of specific factors on formation of the shrapnel wound channel and severity of the damage caused to biological tissues. It is impossible to clearly determine the zones of damage (contusion (primary necrosis) and commotion (secondary necrosis)) in the thickness of biological tissues of the human body, since it is quite difficult to determine the nature of propagation of pressure waves in a viscoelastic medium during the high-velocity interaction of a fragment of arbitrary shape or a striking element of a typical (cube, cylinder, sphere) shape, the hits of which are characterized not only by a high contact velocity, but by variability of their position at the moment of hit (lateral projection at a certain angle or end surface) and rotation around their longitudinal or polar axes (the “rollover” effect), etc. This makes impossible to predict consequences of fragments hitting human body and determine severity of the damage caused by. A separate issue is determining parameters of the flight trajectory of the studied kinetic projectiles and their striking properties depending on the distance to the explosion center, since this is also associated with the rather significant values of their initial velocities and the uncertainty of their behavior in free flight.

The only way to obtain reliable data on terminal and external ballistics of kinetic projectiles is to conduct full-scale tests and experimental researches. However, this procedure faces difficulties. First of all, this is the range of contact velocities of kinetic projectiles that can be obtained exclusively as a result of detonating charges of explosives of different masses. In addition, during detonation of charges, a multitude of fragments of natural fragmentation are formed or a significant number of ready-made striking elements are introduced into free flight that negatively affects objectivity of obtained data, since a certain number of kinetic projectiles can simultaneously hit the biological tissue simulator, which aftereffects are superimposed on each other, which makes practically impossible to identify specifics of fragmentary wound formation by a separate sample of a specific kinetic projectile. Use of devices in the form of protective shields for the separation of the fragment field does not completely solve the issue. This is due to the fact that probability of the studied kinetic projectile hitting a limited space in a specific direction after the explosion is quite small and obtaining certain results requires conducting a certain number of experiments with significant consumption of explosives and means of detonation. Use of technical devices for forced direction of the flow of fragments in the appropriate direction with their subsequent separation using protective devices does not solve this problem, since it cannot hit the biological tissue simulator directly, but as a result of ricocheting from the walls of directing device. In addition, probability of hitting the simulator simultaneously with several kinetic projectiles or their sequential hitting with overlapping consequences is not excluded.

Moreover, there are issues with determining the contact velocity of the kinetic projectiles under research. During explosion, it is quite difficult to secure the recording devices and determine the velocity of individual kinetic projectile in a fragmentation field. In general, these factors negatively affect research effectiveness and reliability degree of obtained data.

The outlined problematic issues can be solved using the methods of experimental (forensic) ballistics. Experimental researches should be carried out in a ballistic track equipped with measuring complexes (optoelectronic or Doppler radar chronograph such as *LabRadar*), using special cartridges and samples of firearms of the appropriate caliber, or using specialized ballistic installations or devices for throwing kinetic shells. As a simulator of biological tissues, it is advisable to use ballistic plasticine, since it forms a final cavity after hitting that makes possible to determine the zone of propagation of pressure waves, as well as the size and other parameters of the caused damage.

This approach helps to achieve an appropriate range of contact velocities, register the velocity value at the moment of impact, visualize nature of the damage caused, determine characteristics of this damage and exclude influence of the multiple effects of other kinetic projectiles on damage formation in the simulator of biological tissues by a separate damaging element. In addition, in this way it is possible to obtain reliable data on the stability of the damaging elements in flight and determine their aeroballistic characteristics.

Article Purpose

For investigating specifics of damage formation mechanism in a viscoelastic medium caused by high-speed impact-contact interaction with ready-made striking elements of a certain shape and size. Determine variability influence of initial contact conditions on parameters of the final cavity formed in thickness of the biological tissue simulator. Based on the results of experimental researches, determine dependence of the medium resistance coefficient, channel length, and volume of damage inflicted on the contact velocity of the projectile and its position at the moment of impact. Concurrently these researches, conduct research on the aeroballistic characteristics of ready-made cylindrical striking elements that is necessary to determine the values of their kinetic energy dissipation along the trajectory.

Research Methods

General scientific (analysis, synthesis, etc.) and special methods (aerometric one, field experiments, etc.) were applied. Optoelectronic measuring complexes, ballistic plasticine (a simulator of biological tissues of the human body) and several types of weapons were used for research.

Analysis of Essential Researches and Publications

The main research provisions in the field of terminal ballistics of fragments and ready-made striking elements are set out in a number of fundamental scientific and scientific-practical research papers by such authors as *V. Tsymbaliuk* with co-authors [1], *R. M. Coupland* with co-authors [2], *N. Rozen & I. Dudkiewicz* [3], *T. O. Terefe* with co-authors [4], et al. Their research papers not only provide general methods for studying injuries caused by fragments and bullets, but describe in detail the methods of conducting experiments, present analytical models for determining the parameters of gunshot trauma and shrapnel injuries; outline empirical dependencies for determining the depth of wound channels, size of temporarily pulsating cavities, severity of damage to biological tissues, as well as the results of computer modeling of physical processes accompanying the impact of kinetic projectiles in biological tissues and their imitators. Most of these research papers are devoted to the researches on spherical striking elements, standardized fragment simulators with flat and chisel-shaped head parts, but practically no attention is paid to the researches on ready-made striking elements and fragments of natural fragmentation of real samples of ammunition and improvised explosive devices, although research results of such samples of kinetic projectiles are of greater practical importance both for military medicine and for forensic science. In this regard, we focused on the research on striking elements of a specific sample of ammunition, namely the OZM-72 barrage fragmentation mine.

Main Content Presentation

Cylindrical destructive elements are one of the most common ready-made destructive elements that are equipped with

1 Tsymbaliuk V., Lurin I., Gumeniuk K., Herasymenko O., Furkalo S., Oklei D., Negoduyko V., Gorobeiko M., Dinets A. Modeling of wound ballistics in biological tissues simulators. *Medicni perspektivi*. 2023. Vol. 28. No. 1. C. 37—48. DOI: 10.26641/2307-0404.2023.1.275866 (date accessed: 18.09.2025).

2 Coupland R. M., Rothschild M. A., Thali M. J. Wound ballistics: basics and applications / B. P. Kneubuehl (Ed.). Berlin, 2014. 496 p. DOI: 10.1007/978-3-642-20356-5 (date accessed: 18.09.2025).

3 Rozen N., Dudkiewicz I. Wound ballistics and tissue damage / Armed Conflict Injuries to the Extremities. Berlin, 2011. Pp. 21—33. DOI: 10.1007/978-3-642-16155-1_2 (date accessed: 18.09.2025).

4 Terefe T. O., Chawla A., Datla N. V. Damage mechanisms from low-velocity penetrating shrapnel in ballistic gelatin. *Defence Technology*. 18 July 2025. DOI: 10.1016/j.dt.2025.07.008 (date accessed: 18.09.2025).

fragmentation and high-explosive ammunition, warheads of various types of weapons and improvised explosive devices. First of all, they are more technologically advanced in manufacture, and due to their high initial velocity, they have rather high damaging properties. This is due to the fact that, when they hit the target, they often transfer all their kinetic energy to biological tissues of the human body and cause significant damage.

The smallest finished striking element of cylindrical shape with a diameter of 5.0 mm. These elements are equipped with fragmentation-barrier mine OZM-72. The number of damaging elements in one mine is almost 2,400 pcs. The general view of the mine and its damaging elements is indicated in Figures 1 and 2.

Fig. 1. General view
of the OZM-72 fragmentation-barrier mine
(photo from the Internet)

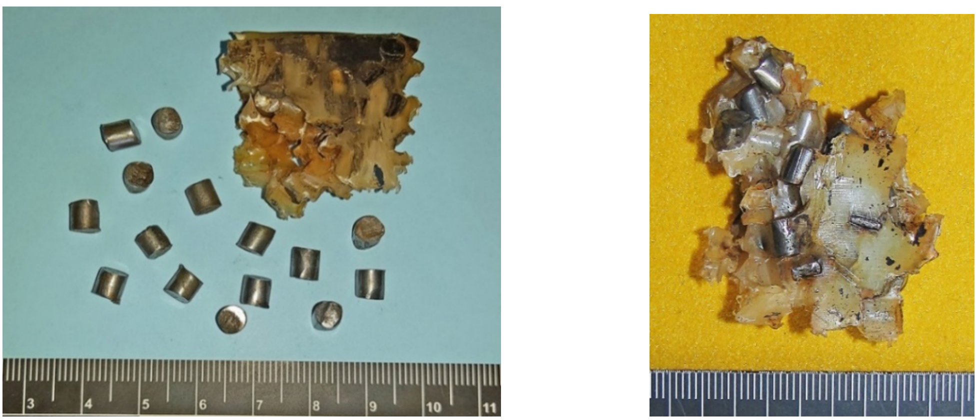

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Fig. 2. General view of the finished damaging elements
of cylindrical shape of the OZM-72 (a) mine
and fragment of polymer shirt in which they are poured (b)

The main characteristics of damaging elements:

- shape: cylinder;
- dimensions: diameter — 5.0–5.1 mm, length — 4.8–5.5 mm;
- average mass of finished element: 0.77 g (0.65-0.80 g);
- average volume value: 0.105 cm^3.

There are no reliable data on the value of the initial velocity of finished destructive elements of the OZM-72 mine in open information sources, but their initial velocity can be determined on the basis of data on the design specifics of ammunition and mass of its main structural elements involved in formation of fragmentation field.

Characteristics of OZM-72 mine:

- Explosive material (hereinafter referred to as EM) — TNT;

- detonation velocity at ρ = 1600 kg/m[3], melted 6700 m/s;
- explosive charge mass — 0.66 kg;
- average mass of finished damaging element is 0.77 g;
- number of damaging elements — 2,400 pcs.;
- average value of total mass of fragments is 1.848 kg;
- total mass of the mine is 5.0 kg;
- mass of the guide barrel of the mine with a rope is 0.675 kg;
- mass of the mine without a guide sleeve — 4.325 kg;
- lethal radius: 25–30 m;
- flight range of individual damaging elements — up to 50 m;
- mass of expelling charge (smoky powder) — 7 g;
- mass of the intermediate charge (Tetril) — 23 g.

Given that ready-to-use striking elements are located directly in the mine, that after the detonator and propellant charge are activated, flies upward from the guide cup, total mass of such a warhead will be 4.325 kg in the calculations.

According to the methods [5] initial velocity of the damaging elements can be calculated by the formula:

$$V_0 = \frac{D}{2}\sqrt{\frac{\alpha}{2-\alpha}}, \qquad (1)$$

where:

V_0 is initial velocity of the damaging element, m/s;

Detonation velocity, m/s:

α — housing filling factor:

$$\alpha = \frac{m_{вр}}{m_k}, \qquad (2)$$

where:

$m_{вр}$ — explosive mass, kg;

m_k is the mass of the munition body involved in the formation of fragments:

$$m_k = M - m_{пас}, \qquad (3)$$

where:

M is the total mass of the ammunition (warhead), kg;

$m_{пас}$ — passive mass of the ammunition body, kg.

If we assume that practically the entire mine body (warhead) is involved in the formation of fragments, then with exception of the explosive mass in accordance with (3) the value of m_k = 4.325 – 0.66 = 3.665 kg. In this case, in accordance with (2), the filling factor of the body will be α = 0.180.

Calculated value of initial velocity of the damaging elements according to the formula (1) will be V_0 = 1053 m/s. This value of initial velocity of dispersal of the finished damaging elements is approximate, it is quite difficult to determine initial velocity of dispersal of the finished damaging elements experimentally, especially the velocity of a separate damaging element.

During experimental firing, the contact velocity of the striking element before hitting the target was recorded using the ИБХ-731.4 optoelectronic measuring complex (*cf.: Fig. 3a*). Biological tissues were imitated by *Weible* ballistic plasticine (*cf.: Fig. 3b*).

5 Прохоров-Лукін Г. В., Пащенко В. І., Биков В. І. та ін. Методика комплексного дослідження вибухових пристроїв, вибухових речовин і слідів вибуху. № ДР 0103U002003. Київ, 2011. 216 с. URL: https://arm.navs.edu.ua/arm/arm_bmb_exp/idb/metod_wte.html (date accessed: 18.09.2025) ; Полениця П., Науменко І., Ліцман А., Нестеров Д. Методика оцінювання ефективності дії осколково-фугасного снаряда по наземних цілях. Київ, 2024. 46 с. Реєстр. код ВП 7-07(01).010.1.12.

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Fig. 3 General view of measuring equipment (a) and ballistic plasticine block (b)

Individual striking elements were introduced into free flight in three stages. At the first stage, a neurobalistic handheld throwing device was used. It made possible to investigate the nature of the damage at contact velocities from 70 m/s to 110 m/s. At the second stage, firing was carried out from a small-caliber TOZ-8 rifle, which made it possible to perform a research in the range of contact velocities of 140–260 m/s. At the final stage, firing was carried out from a 5.45 mm AK-74M assault rifle using special 5.45 × 39 caliber cartridges (*cf.: Fig. 4*). This provided the results of research in the range of contact velocities of 300–1082 m/s.

a b

Fig. 4. General view of a special cartridge equipped with a ready-made destructive element of the OZM-72 (a) mine and the AK-74M (b) assault rifle

Using this approach, it was possible to achieve the contact velocities of the damaging elements, commensurate with the calculated values of initial flight velocities of the damaging elements of the OZM-72 mine.

In order to determine formation specific of blind and through injuries during research impacts on the torso and limbs of the biological object were simulated.

During research on blind damage, contact velocity effect of damaging element on the damage channel parameters and e resistance force of coefficients the medium was determined depending on the value of contact velocity and depth of penetration into the medium.

During research on through damage, the values of contact velocity of damaging element and its final velocity after overcoming obstacle, loss of kinetic energy and scale of the caused damage were determined.

The results of experimental researches on blind lesions in the thickness of ballistic plasticine are presented in Fig. 5–28 and in Table 1.

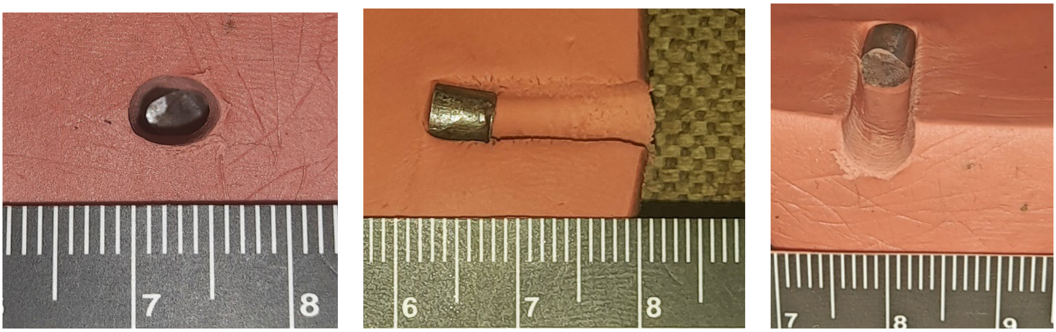

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Fig. 5. Nature of damage to ballistic plasticine
after hitting the investigated damaging element
at a contact velocity of 70.5 m/s

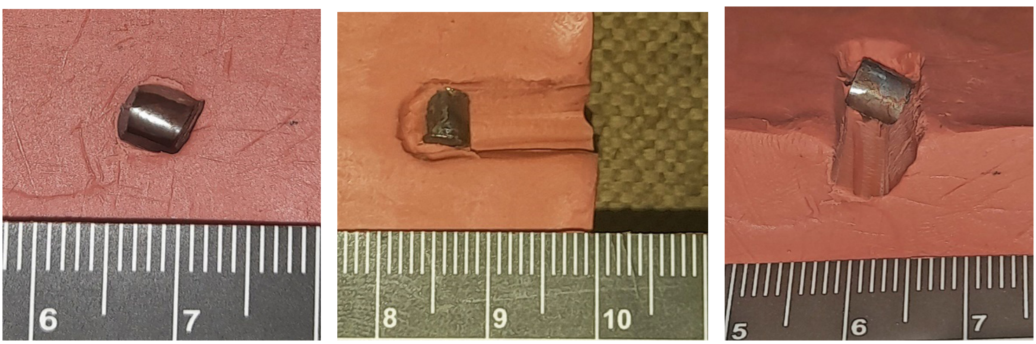

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Fig. 6. Nature of damage to ballistic plasticine
after hitting investigated damaging element
at a contact velocity of 71.2 m/s

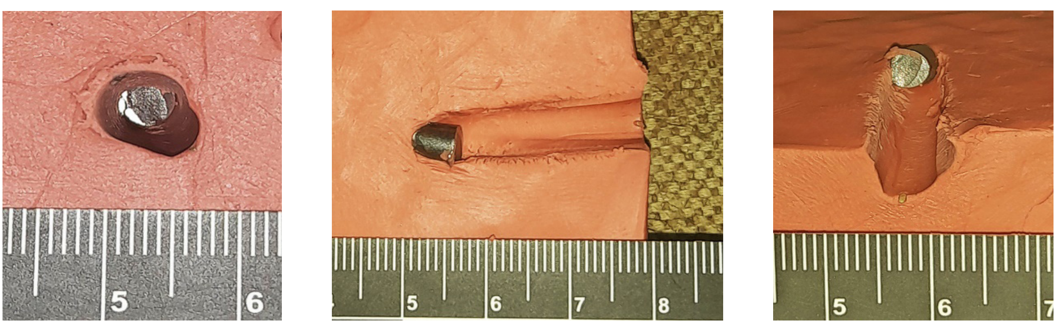

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Fig. 7. Nature of damage to ballistic plasticine
after hitting the investigated damaging element
at a contact velocity of 94.0 m/s

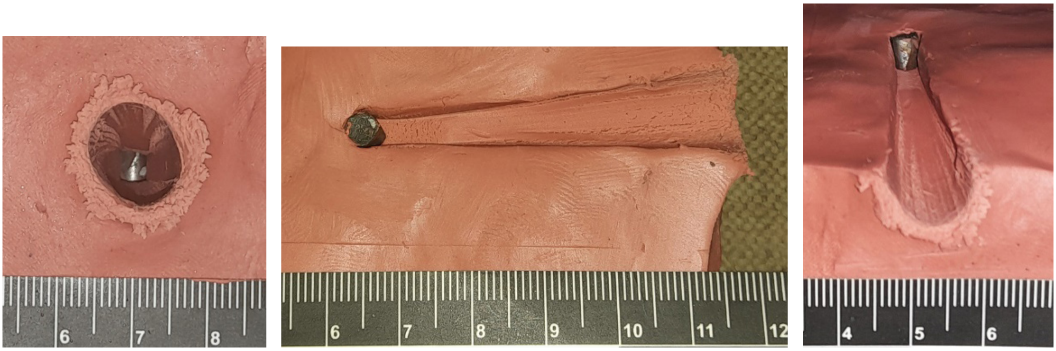

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Fig. 8. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 108.2 m/s

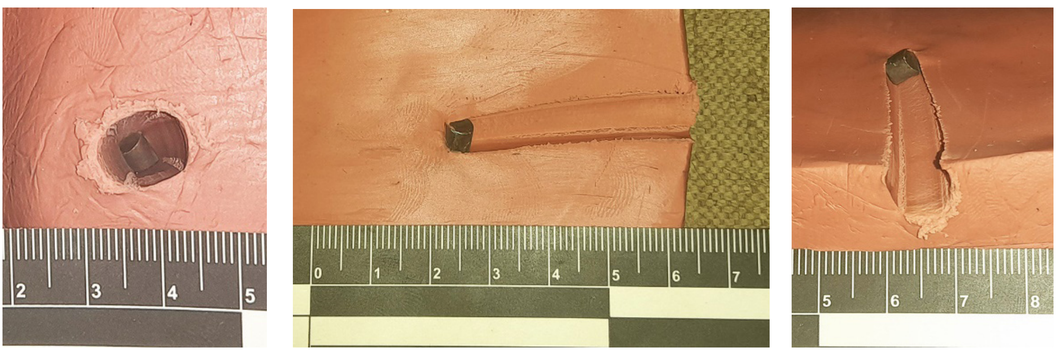

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Fig. 9. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 147.5 m/s

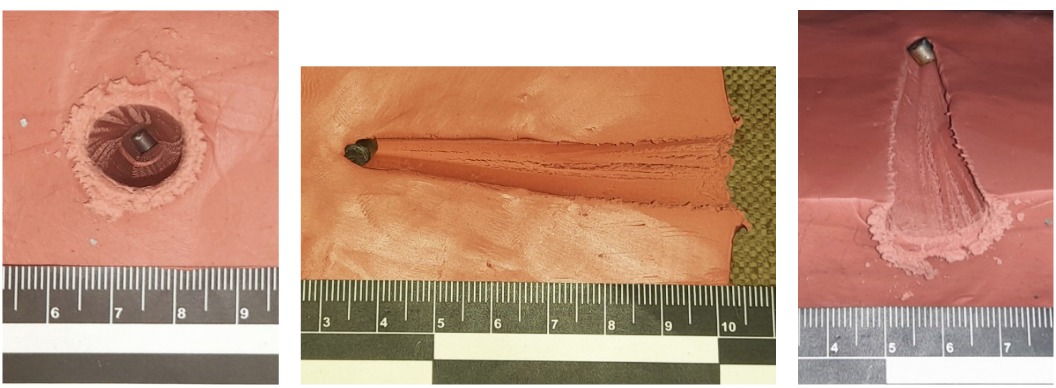

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Fig. 10. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 187.0 m/s

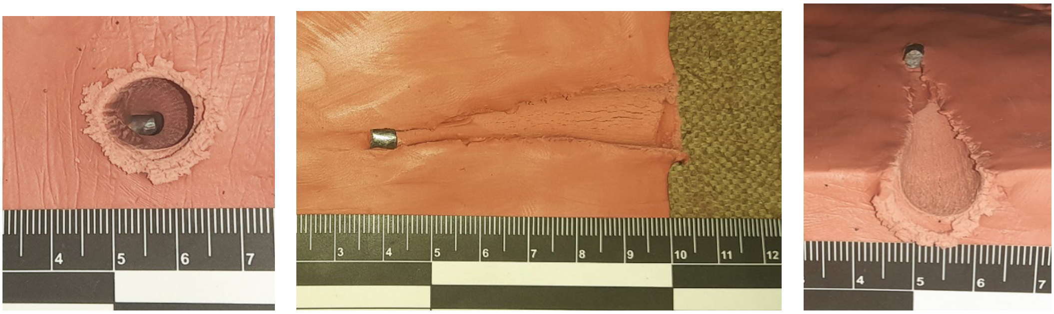

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Fig. 11. Nature of damage to ballistic plasticine after hitting the investigated damaging element at a contact velocity of 202.2 m/s

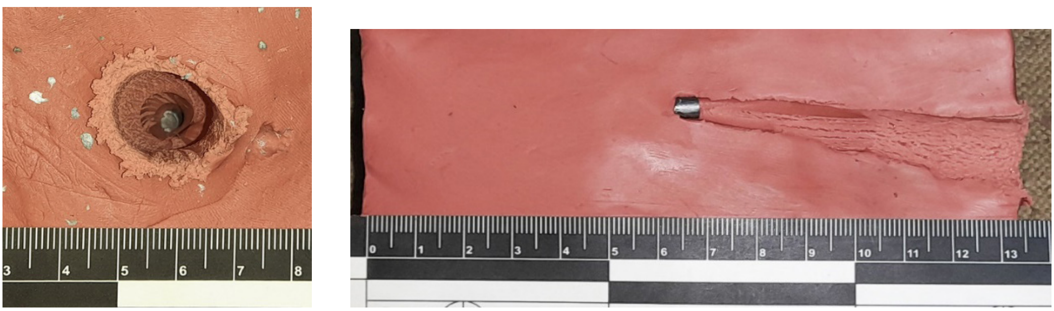

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Fig. 12. Nature of damage to ballistic plasticine after hitting the investigated damaging element at a contact velocity of 251.4 m/s

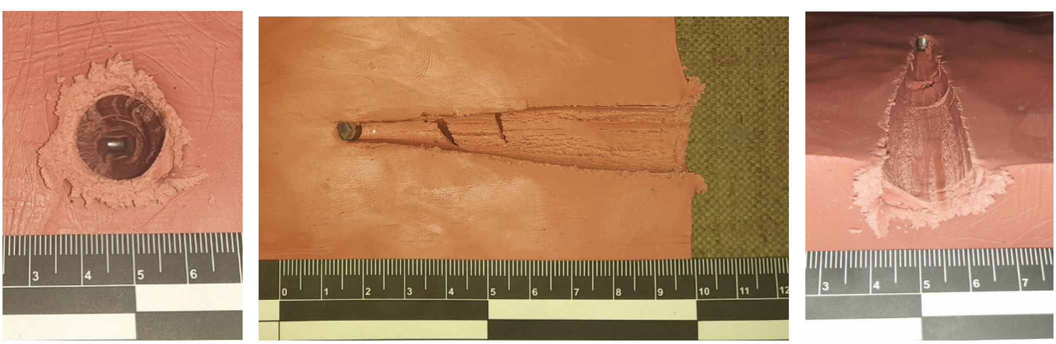

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Fig. 13. Nature of damage to ballistic plasticine after hitting the investigated damaging element at a contact velocity of 308.4 m/s

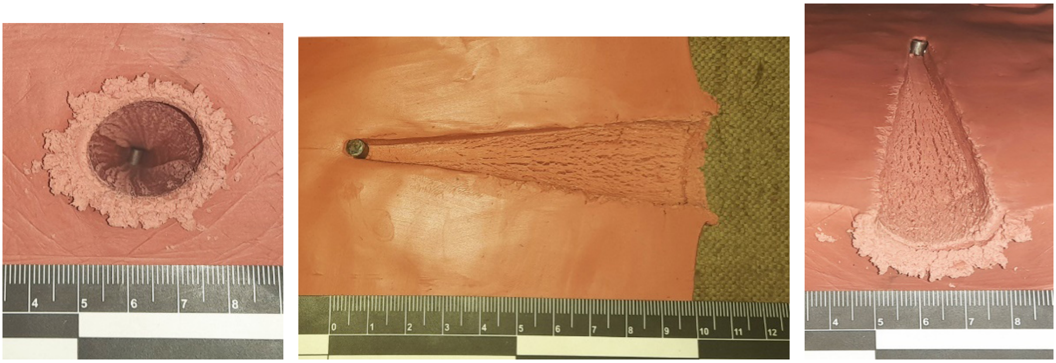

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Fig. 14. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 349.1 m/s

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Fig. 15. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 432.1 m/s

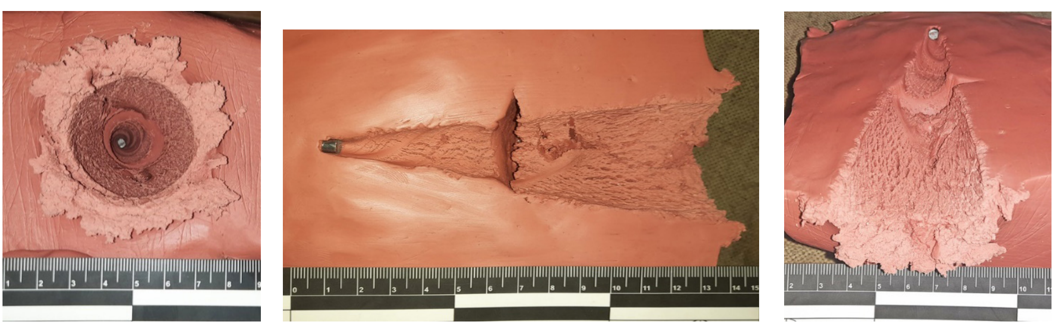

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Fig. 16. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 572.2 m/s

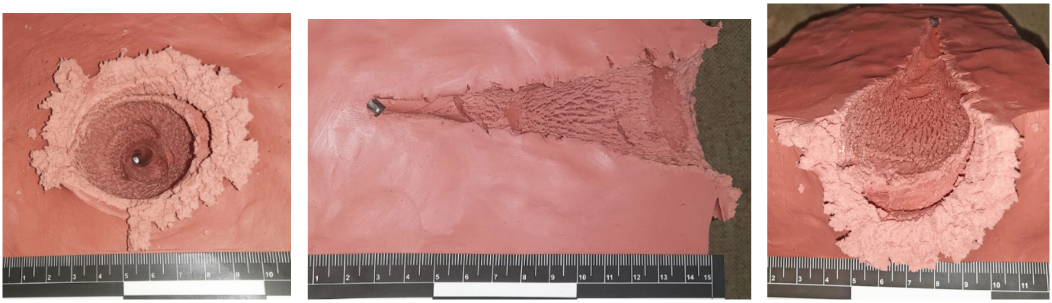

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Fig. 17. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact speed of 595.9 m/s

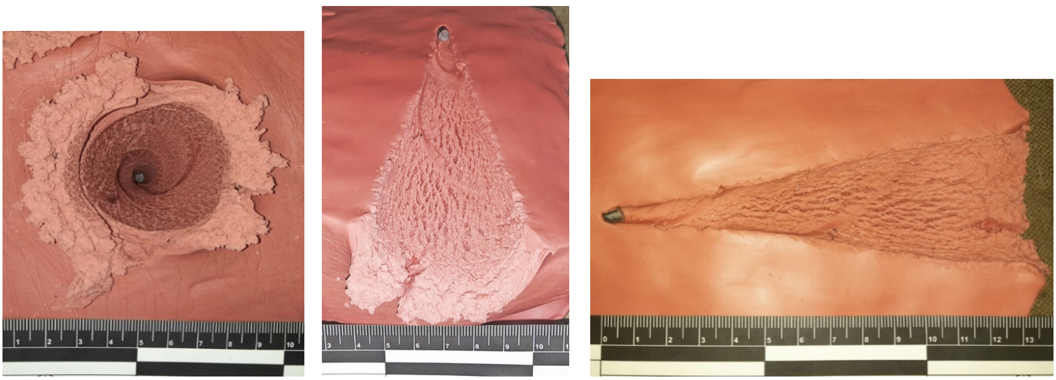

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Fig. 18. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 608.9 m/s

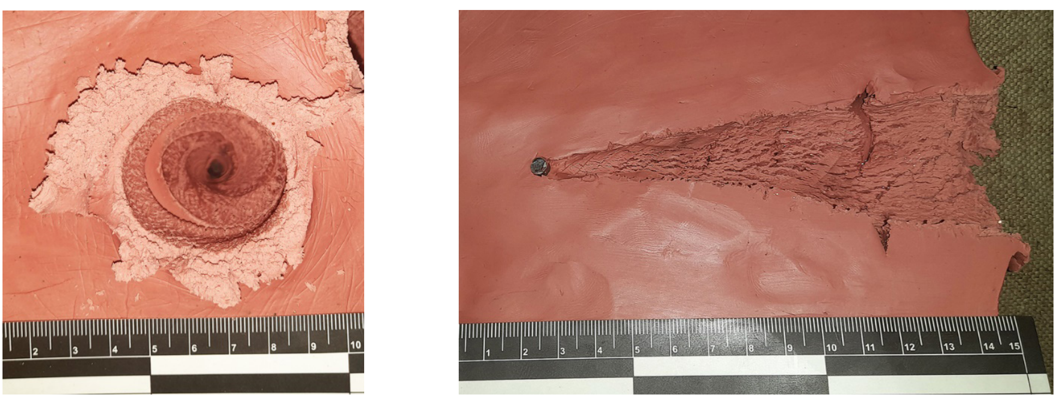

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Fig. 19. Nature of damage to ballistic plasticine after hitting the investigated damaging element at a contact velocity of 648.3 m/s

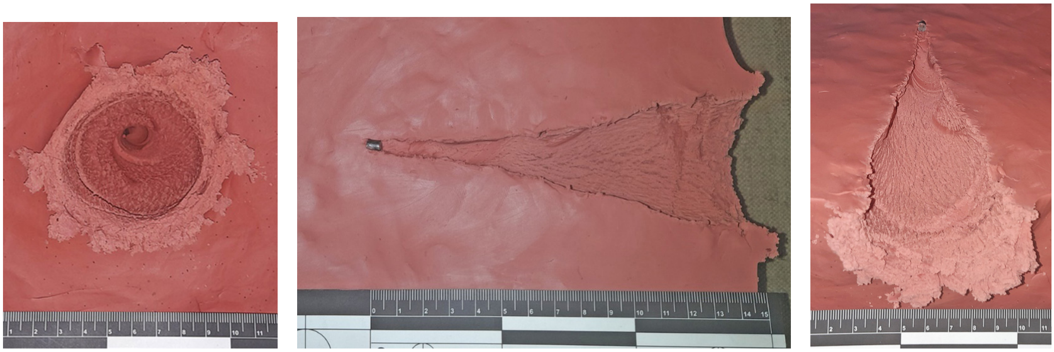

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Fig. 20. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 712.3 m/s

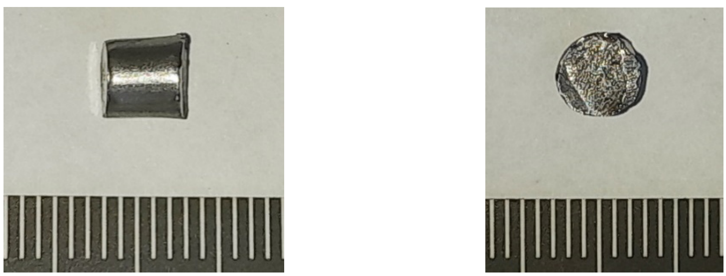

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Fig. 21. General view of the finished hitting element
after hitting the ballistic plasticine block

Since the impact of the finished striking element into the ballistic plasticine block occurred with a flat end part (*cf.: Fig. 20*), it underwent strong compression along its longitudinal axis as a result of the impact-contact interaction (*cf.: Fig. 21*). Diameter of the deformed part of the damaging element is 5.5 mm, the non-deformed part is 5.0 mm.

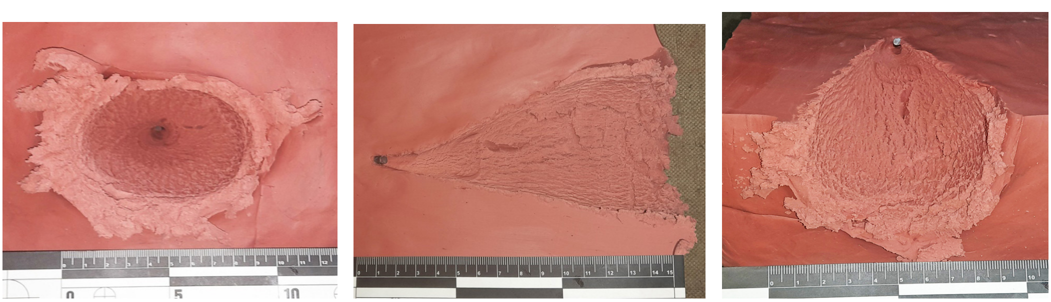

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Fig. 22. Nature of damage to ballistic plasticine
after hitting the investigated damaging element at a contact velocity of 963.2 m/s

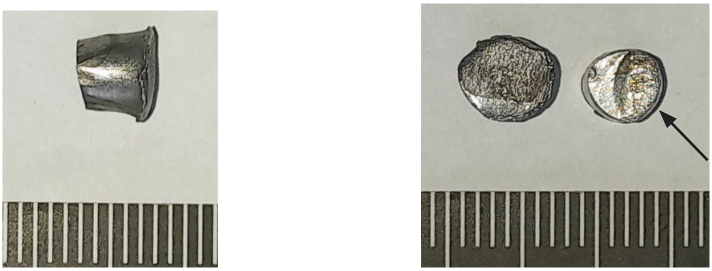

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Fig. 23. General view of the finished hitting element
after hitting the ballistic plasticine block and comparing it with the undeformed sample (marked with an arrow)

The impact of the finished striking element into the ballistic plasticine block occurred with a flat end part (*cf.: Fig. 22*), as a result of the impact-contact interaction, it underwent strong compression along its longitudinal axis (*cf.: Fig. 23*). The diameter of the deformed part of the damaging element is 6.1 mm, the non-deformed part is 5.0 mm.

a b c

Fig. 24. Nature of damage to ballistic plasticine after hitting the investigated damaging element at a contact velocity of 975.6 m/s

a b

Fig. 25. General view of the finished hitting element
after hitting the ballistic plasticine block and comparison with the undeformed sample (marked with an arrow)

Impact of the finished striking element into ballistic plasticine block occurred with a flat end part (*cf.: Fig. 24*), as a result of the impact-contact interaction, it underwent strong compression along its longitudinal axis (*cf.: Fig. 25*). The diameter of deformed part of the damaging element is 6.2 mm, the non-deformed part is 5.0 mm.

a b c

Fig. 26. Nature of damage to ballistic plasticine after hitting the investigated damaging element at a contact velocity of 1082.0 m/s

Table 1

Characteristics of blind damage caused by ready-made destructive elements of the OZM-72 mine

Mass, g	Contact velocity, m/s	Contact kinetic energy, J	Damage channel length, mm	Damage channel volume, cm³
0.77	70.5	1.91	19.3	0.52
0.75	71.2	1.90	17.1	0.68
0.76	94.0	3.36	28.1	0.92
0.78	108.2	4.57	52.7	3.71
0.78	147.5	8.48	41.2	2.21
0.81	187.0	14.16	69.8	6.91
0.78	202.2	15.95	62.9	4.72
0.74	251.4	23.38	71.0	8.71
0.78	308.4	37.09	87.2	13.40
0.78	349.1	47.53	101.1	19.40
0.75	432.1	70.02	118.2	43.31
0.75	572.2	122.78	124.0	85.21
0.75	595.9	133.16	112.0	91.30
0.75	608.9	139.03	131.0	96.51
0.75	648.3	157.61	129.0	88.30
0.76	712.3	192.80	145.0	138.0
0.75	887.3	295.24	140.0	167.0
0.77	963.2	357.19	140.0	228.0
0.80	975.6	380.72	142.0	262.0
0.79	1082.0	462.44	171.0	464.0

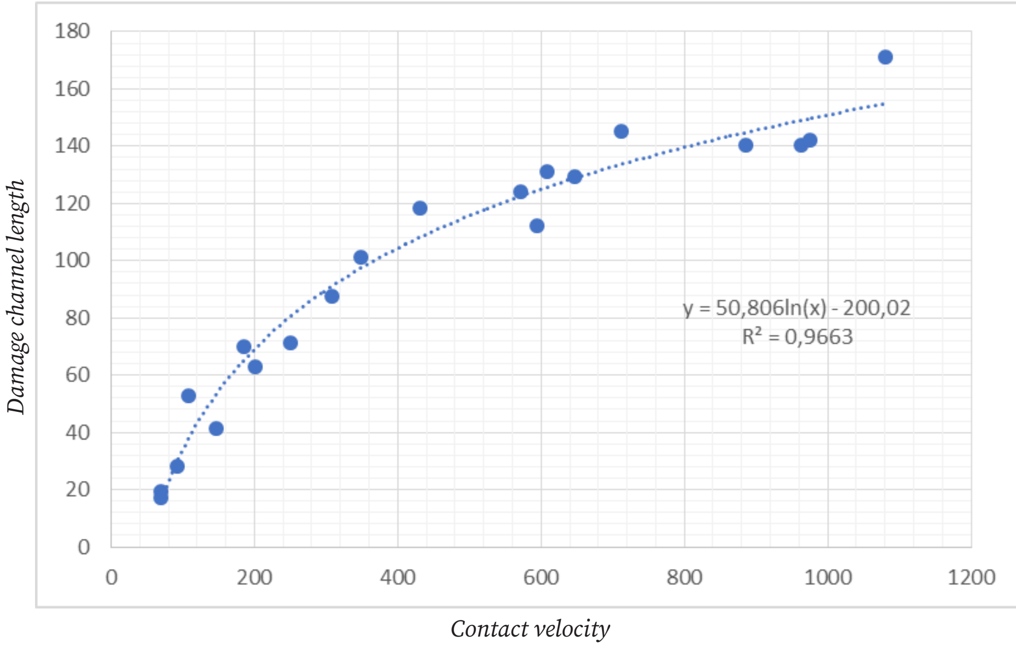

Fig. 27. Dependence of the length of damage channel in viscoelastic medium on the contact velocity of damaging element

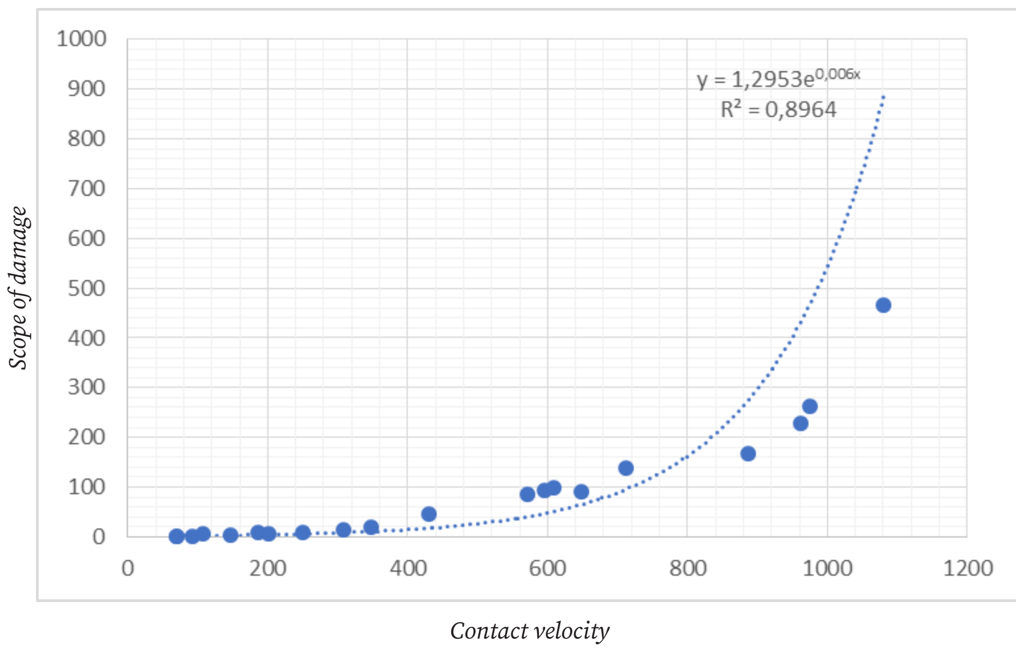

Fig. 28. Dependence of the damage volume in a viscoelastic medium on the contact velocity of the striking element

Approximation of the results of experimental researches makes possible to predict the nature of the damage and its parameters (volume of damage and depth of the wound canal).

In addition, on the basis of the empirical dependence (4), it is possible to determine the limiting velocity of the studied damaging element V_{gr}, at which it stops in visco-elastic environment [6]:

$$x = 50{,}806 \cdot \ln(V_k) - 200{,}02, \quad (4)$$

where:

x is the length of the damage channel, mm;

V_k is the velocity of the striking element at the time of impact, m/s.

Limiting velocity V_{gr} can be determined if we assume that the striking element penetrates deep into the visco-elastic medium by the value of its longitudinal size (depending on the position at the moment of impact) and stops.

The studied striking element of cylindrical shape with a diameter of 5.0 mm and an average length of 5.15 mm is characterized by hitting the target:

- end surface (x = 5.15 mm, contact area (cross-sectional area) $S_1 = 0.2\ cm^2$);
- at an the angle of 45° (x = 7.18 mm, contact area (cross-sectional area) $S_2 = 0.282\ cm^2$);
- at the angle of 90° (x = 5.0 mm, contact area (cross-sectional area) $S_3 = 0.26\ cm^2$);

Assuming that contact velocity is equal to the limiting velocity, then $\ln V_k = \ln V_{gr}$. By substituting these data into formula (4), it is possible to obtain the value of V_{gr}. The results of the studies are presented in the Table 2.

Table 2

Value of the limiting velocity V_{gr} for the studied damaging element, taking into account its position at the time of impact

Parameters	Hitting target		
	end surface, $S_1 = 0.2\ cm^2$	at an angle of 45°, $S_2 = 0.282\ cm^2$	at an angle of 90°, $S_3 = 0.26\ cm^2$
x, mm	5.15	7,18	5,0
V_{gr}, m/s	56.73	59,04	56,56

Given that the graph of the dependence of the length of the damage channel on the value of the contact velocity (*cf.: Fig. 27*) reflects the value for all positions of the striking element at the time of impact, it is possible to mediate the value of V_{gr}, which will be 57.44 m/s. Obtained calculated data on V_{gr} make possible to assert that they correlate with data of experimental researches.

Analysis of the obtained research results indicates that even at high contact velocities, the striking elements of the cylindrical shape with a degree of

6 Коломійцев О., Сапєлкін В., Ґіверц П., Герман О. Особливості визначення уражаючих властивостей малокаліберних куль після рикошету. *Теорія та практика судової експертизи і криміналістики.* 2022. Вип. 2 (27). С. 60—76. DOI: 10.32353/khrife.2.2022.05 (date accessed: 18.09.2025) ; Коломийцев А. В., Сапелкин В. В. Определение баллистических характеристик и поражающих свойств патронов самодельного снаряжения калибра 7,62×39. *Там само.* 2017. Вип. 17. С. 227—236. URL: http://nbuv.gov.ua/UJRN/Tpsek_2017_17_33 (date accessed: 18.09.2025).

elongation in the range of 1,0–1,1 (ratio of the length to the diameter of the cross-section) in the visco-elastic medium behave quite stably with the task of rectilinear channels.

Obtained research results make possible to determine indicators of the coefficient of resistance of the viscoelastic medium for hitting a cylindrical damaging element in the specified range of contact velocities (70.5–1082.0 m/s).

Resistance coefficient of the medium C_1 can be calculated by the formula (5) [7]:

$$C_1 = \frac{m}{\rho \cdot S_i \cdot x} \ln \frac{V_c}{V_{gr}}, \quad (5)$$

where:

V_s is the contact velocity of the striking element at the time of impact, m/s;

V_{gr} — maximum velocity of the damaging element, 57.44 m/s;

m is the mass of the damaging element, g;

ρ is the medium density, g/cm³ (ρ = 1.74 g/cm³);

S_i is the cross-sectional area of the damaging element at the moment of impact, cm²;

x is the length of the damage channel, cm.

The research results are presented in the Table 3. Analysis of the results of researches and calculations indicates the effect on resistance force of the mass and the position of damaging element. If the indirect values of the mass of the damaging element are applied, then using formula (4) it is possible to calculate the values of the damage channel length and using formula (5) to establish corresponding values of the resistance coefficient of the viscoelastic medium. The results of the calculations are presented in Table 4 and Fig. 29.

Table 3

Resistance value of coefficient of the visco-elastic medium C_1 depending on the contact velocity and the position of striking element at the time of impact

Mass, g	Contact velocity, m/s	Channel length, mm	Resistance coefficient of the medium, C_1		
			$S_1 = 0.2$ cm²	$S_2 = 0.282$ cm²	$S_3 = 0.26$ cm²
0.77	70,5	19,3	0,470	0,333	0,361
0,75	71,2	17,1	0,541	0,384	0,416
0,76	94,0	28,1	0,766	0,543	0,589
0,78	108,2	52,7	0,539	0,382	0,414
0,78	147,5	41,2	1,026	0,728	0,789
0,81	187,0	69,8	0,787	0,558	0,606
0,78	202,2	62,9	0,897	0,636	0,690
0,74	251,4	71,0	0,884	0,627	0,680
0,78	308,4	87,2	0,864	0,613	0,665
0,78	349,1	101,1	0,800	0,567	0,616
0,75	432,1	118,2	0,736	0,522	0,566
0,75	572,2	124,0	0,799	0,567	0,615

7 Коломійцев О., Сапєлкін В., Ґіверц П., Герман О. Зазнач. твір. DOI: 10.32353/khrife.2.2022.05 (date accessed: 18.09.2025).

Completion of Table 3

Mass, g	Contact velocity, m/s	Channel length, mm	Resistance coefficient of the medium, C_1		
			$S_1 = 0.2$ cm²	$S_2 = 0.282$ cm²	$S_3 = 0.26$ cm²
0,75	595,9	112,0	0,900	0,639	0,693
0,75	608,9	131,0	0,777	0,551	0,598
0,75	648,3	129,0	0,810	0,574	0,623
0,76	712,3	145,0	0,758	0,538	0,583
0,75	887,3	140,0	0,843	0,598	0,648
0,77	963,2	140,0	0,891	0,632	0,686
0,80	975,6	142,0	0,917	0,650	0,705
0,79	1082,0	171,0	0,779	0,553	0,600

Analysis of the graph showing dependence of coefficient resistance of the visco-elastic medium C_1 on the contact velocity at the moment of impact indicates that when the striking element of the OZM-72 mine hits a human body, it transfers a significant part of its kinetic energy to the first quarter (one-third) of the wound channel, which leads to significant damage to biological tissues in the areas adjacent to the point of impact. As the striking element penetrates deeper into biological tissues, the degree of damage in radial directions (lateral action) decreases. This differs significantly from nature of gunshot wounds caused by bullets from small arms, where, on the contrary, the greatest damage to biological tissues occurs in the middle section of the wound channel or in the terminal quarter (third) of the wound channel due to the bullet losing its gyroscopic stability as a result of its nutational oscillations.

Table 4

Calculated values of length of the damage channel and coefficient of resistance of the visco-elastic medium depending on the contact velocities at the mediated value of the mass of the damaging element 0.77 g

Contact velocity, m/s	Estimated value of damage channel, mm	Estimated value of resistance coefficient of the medium C_1
70,5	16,2	0,560
71,2	16,7	0,569
94,0	30,8	0,708
108,2	38,0	0,737
147,5	53,7	0,777
187,0	65,8	0,794
202,2	69,7	0,799
251,4	80,8	0,809
308,4	91,1	0,816
349,1	97,5	0,819
432,1	108,3	0,825
572,2	122,6	0,830
595,9	124,6	0,831

Completion of Table 4

Contact velocity, m/s	Estimated value of damage channel, mm	Estimated value of resistance coefficient of the medium C_1
608,9	125,7	0,831
648,3	128,9	0,832
712,3	133,7	0,833
887,3	144,9	0,836
963,2	149,1	0,837
975,6	149,7	0,837
1082,0	154,9	0,839

However, on the basis of performed researches, it is possible to identify the similarity of the nature and parameters of the damage caused by the studied damaging elements with the gunshot damage caused to a person as a result of hits of various types of expanding bullets [8].

Analysis of data in Table 4 and the graph (*cf.: 29 on page 102*) found that the dependence of the drag coefficient of the viscoelastic medium C_1 on the contact velocity of the striking element V_c has the formula of hyperbolic regression:

$$C_1 = a + \frac{b}{V_c}, \qquad (6)$$

where:

a, b — coefficients;

C_1 — coefficient of resistance of viscoelastic medium;

V_c is the contact velocity of the striking element at the time of impact, m/s.

Using data in Table 4, it is possible to determine the values of the coefficients of the specified regression (*cf.: Table 5*).

Table 5

Auxiliary values of values C_1 and V_c

i	x_i (V_c)	y_i (C_1)	$1/x_i$	$1/x_i^2$	y_i/x_i
1	70,5	0,560	0,0141844	0,01418440	0,0002012
2	71,2	0,569	0,01404494	0,01404494	0,00019726
3	94,0	0,708	0,0106383	0,01063830	0,00011317
4	108,2	0,737	0,00924214	0,00924214	8.5417E-05
5	147,5	0,777	0,00677966	0,00677966	4.5964E-05
6	187,0	0,794	0,00534759	0,00534759	2.8597E-05
7	202,2	0,799	0,0049456	0,00494560	2.4459E-05
8	251,4	0,809	0,00397772	0,00397772	1.5822E-05
9	308,4	0.816	0.00324254	0.00324254	1.0514E-05

8 Лурін І. А., Цема Є. В., Гуменюк К. В., Сусак Я. М., Дубенко Д. Є., Цема Є. Є. Експериментальне моделювання залишкової ранової порожнини на балістичному пластиліні з використанням стандартних та експансивних куль. *Медична наука України*. Т. 17. № 4. С. 10—17. DOI: 10.32345/2664-4738.4.2021.02 (date accessed: 18.09.2025) ; Gumeniuk K., Lurin I., Tsema Ie., Susak Ya., Mykhaylenko O., Nehoduiko V. et al. Woundary ballistics of biological tissue's plastic deformation on the model of ballistic plastiline using hollow point and shape-stable bullets. *Journal of Education, Health and Sport*. 2021. Vol. 11. No. 11. Pp. 37—57. DOI: 10.12775/JEHS.2021.11.11.003 (date accessed: 18.09.2025).

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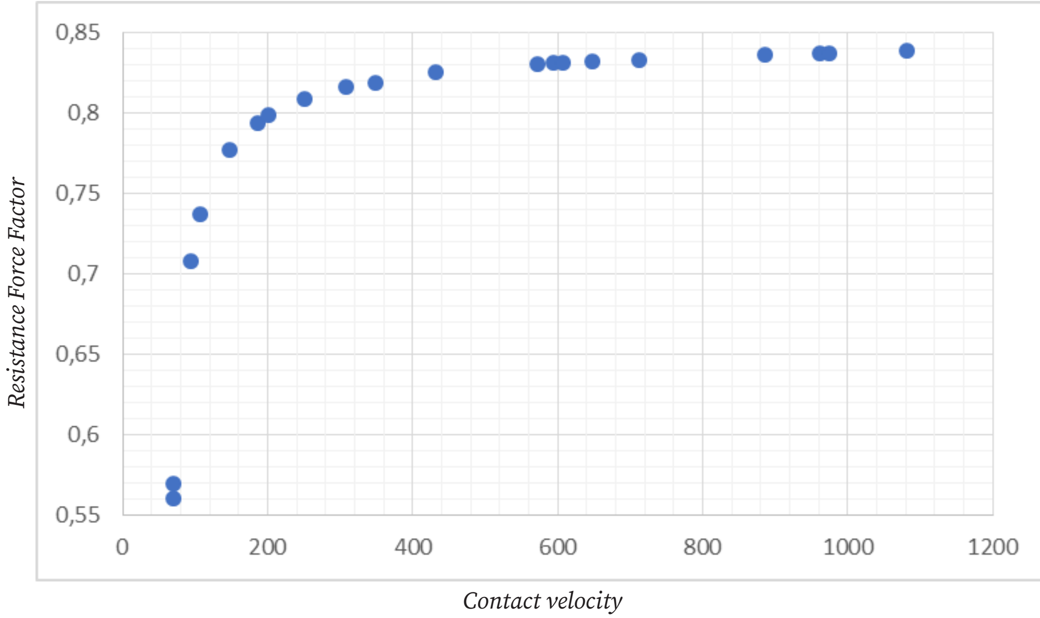


Fig. 29. Graph of dependence of the resistance coefficient of the visco-elastic medium C_1 on the contact velocity of striking element V_c

Completion of Table 5

i	x_i (V_c)	y_i (C_1)	$1/x_i$	$1/x_i^2$	y_i/x_i
10	349.1	0.819	0.00286451	0.00286451	8.2054E-06
11	432.1	0.825	0.00231428	0.00231428	5.3559E-06
12	572.2	0.830	0.00174764	0.00174764	3.0542E-06
13	595.9	0.831	0.00167813	0.00167813	2.8161E-06
14	608.9	0.831	0.00164231	0.00164231	2,6972E-06
15	648.3	0.832	0.0015425	0.00154250	2,3793E-06
16	712.3	0.833	0.0014039	0.00140390	1,9709E-06
17	887.3	0.836	0.00112701	0.00112701	1,2702E-06
18	963.2	0.837	0.00103821	0.00103821	1,0779E-06
19	975.6	0.837	0.00102501	0.00102501	1,0506E-06
20	1082.0	0.839	0.00092421	0.00092421	8,5417E-07
Σ	9267.3	15.719	0.08971061	0.08971061	0.00075314

According to the Table 5, empirical dependence of the resistance coefficient of the medium C_1 on the contact velocity V_c will be as follows:

$$C_1 = 0{,}8696 - \frac{18{,}6413}{V_c}, \qquad (7)$$

where the coefficients *a*, *b* are calculated as:

$$b = \frac{n\sum\frac{y_i}{x_i} - \sum\frac{1}{x_i}\sum y_i}{n\sum\frac{1}{x_i^2} - \left(\sum\frac{1}{x_i}\right)^2} = -18{,}6413;$$

$$a = \frac{1}{n}\sum y_i - \frac{b}{n}\sum \frac{1}{x_i} = 0{,}8696.$$

For assessing the significance of regression and correlation parameters, it is necessary to determine the mean value of the resistance force $\overline{C_1}$ coefficient, correlation index, determination index and the mean approximation error (*cf.: Table 6*).

The coefficient of resistance force is equal to:

$$\overline{C_1} = \bar{y}_i = \frac{1}{n}\sum y_i = 0{,}7859;$$

correlation index

$$R = \sqrt{1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}} = 0{,}9615;$$

determination index: $R^2 = 0.9246$;
average approximation error:

$$\bar{A} = \frac{1}{n}\sum\left|\frac{y_i - \hat{y}_i}{y_i}\right| \cdot 100\% = 2{,}4925\ \%.$$

Table 6

Auxiliary values

i	x_i (V_c)	y_i (C_1)	$\hat{y}_i$	$y_i-\bar{y}_i$	$(y_i-\bar{y}_i)^2$	ε_i	ε_i^2	A_i	$\Delta\varepsilon_i$	$(\Delta\varepsilon_i)^2$
1	70,5	0,560	0,6052	–0,2259	0,0511	–0,0452	0,002	0,0806	–	–
2	71.2	0.569	0.6078	–0,2169	0.0471	–0,0388	0.0015	0.0681	0.0064	0
3	94.0	0.708	0.6713	–0,0779	0.0061	0.0367	0.0014	0.0519	0.0755	0.0057
4	108.2	0.737	0.6973	–0,0489	0.0024	0.0397	0.0016	0.0539	0.0030	0
5	147.5	0.777	0.7432	–0,0089	0.0001	0.0338	0.0011	0.0435	–0,0059	0
6	187.0	0.794	0.7699	0.0081	0.0001	0.0241	0.0006	0.0304	–0,0097	0.001
7	202.2	0.799	0.7774	0.0131	0.0002	0.0216	0.0005	0.0271	–0,0025	0
8	251.4	0.809	0.7955	0.0231	0.0005	0.0135	0.0002	0.0168	–0,0080	0.001
9	308.4	0.816	0.8092	0.0301	0.0009	0.0069	4,7E-05	0.0084	–0,0067	0
10	349.1	0.819	0.8162	0.0331	0.0011	0.0028	7,8E-06	0.0035	–0,0040	0
11	432.1	0.825	0.8265	0.0391	0.0015	–0,0014	2,1E-06	0.0017	–0,0043	0
12	572.2	0.830	0.837	0.0441	0.0019	-0,0070	4,9E-05	0,0084	–0,0056	0
13	595.9	0.831	0.8383	0.0451	0.0020	–0,0073	5,4E-05	0.0088	–0,0003	0
14	608.9	0.831	0.839	0.0451	0.0020	–0,0080	6,4E-05	0.0096	–0,0007	0
15	648.3	0.832	0.8408	0.0461	0.0021	–0,0088	7,8E-05	0.0106	–0,0009	0
16	712.3	0.833	0.8434	0.0471	0.0022	–0,0104	0.0001	0.0125	–0,0016	0
17	887.3	0.836	0.8486	0.0501	0.0025	–0,0126	0.0002	0.0150	–0,0022	0
18	963.2	0.837	0.8502	0.0511	0.0026	–0,0132	0.0002	0.0158	–0,0007	0
19	975.6	0.837	0.8505	0.0511	0.0026	–0,0135	0.0002	0.0161	–0,0002	0
20	1082.0	0.839	0.8524	0.0531	0.0028	–0,0134	0.0002	0.0159	0.0001	0
Σ	–	–	–	–	0,1318	–	0,0099	0,4985	–	0,0061

F — Fisher's criterion:

- critical (tabular): $F_{tabl} = F(\alpha, k_1, k_2) = F(0.05; 1; 18) = 4.4139$;
- Factual:

$$F_{fakt} = \frac{R^2}{1-R^2} \cdot \frac{k_2}{k_2} = 220{,}5979.$$

In addition: $k_1 = m = 1$; $k_2 = n - m - 1 = 18$; $\alpha = 0.05$; where m is the number of parameters with variable regression equations.

Darbin-Watson factual test:

$$d = \frac{\sum(\varepsilon_i - \varepsilon_{i-1})^2}{\sum \varepsilon_i^2} = 0{,}6102.$$

Analysis of obtained results indicates a high reliability of the approximation of experimental data. Experimental data correlate quite well with the calculated ones, which makes it possible to calculate the penetration depth of the studied damaging element with a sufficiently high degree of reliability.

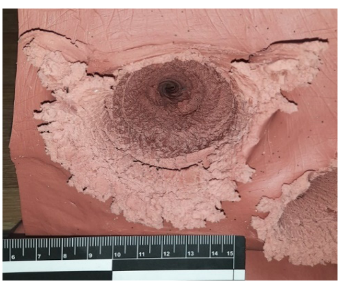
The next research stage was to determine specifics of formation of through damage in the ballistic plasticine block that made possible to establish qualitative indicators of the process of forming a fragmentation wound of human limbs.

During experimental researches, data were obtained on the contact hit rates, the velocities of the striking elements after overcoming the obstacle, as well as data on the cost of kinetic energy for breaking through the block of ballistic plasticine of a certain thickness and the value of the resistance force coefficients of the medium. The research results are presented in Tables 7, 8 and Figures 30—33.

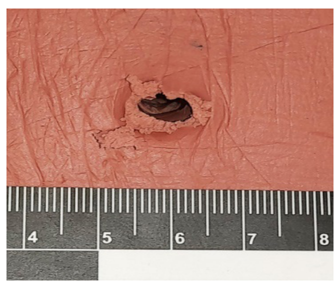
Table 7

Characteristics of through damage caused by ready-made destructive elements of OZM-72 mine

Mass, g	Contact velocity, m/s	Contact kinetic energy, J	Damage channel length, mm	Damage channel volume, cm³
0.75	770,4	222,57	145	130,9
0,77	856,0	282,10	140	224,8
0,75	1027,0	395,52	148	297,6
0,75	1066,0	426,13	90	352,4



a



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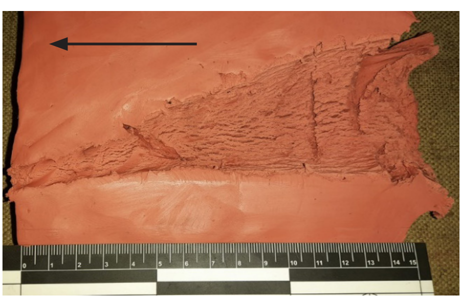
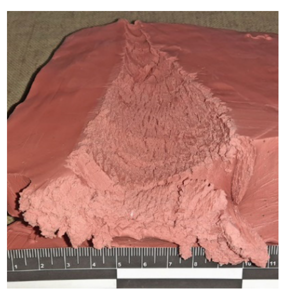


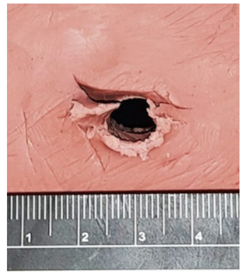
c



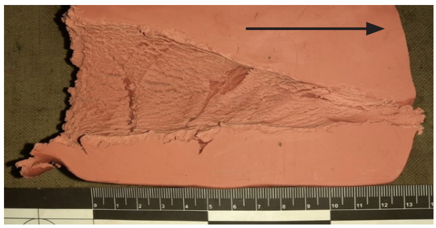
d

Fig. 30. General view of the inlet (a), outlet (b) and damage channel (c, d) caused by hitting the hitting element at a contact velocity of 770.4 m/s (movement direction of the hitting element is indicated by an arrow)

a

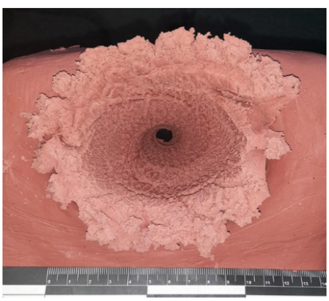


b

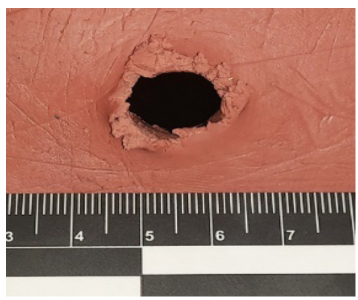


c

Fig. 31. General view of the inlet (a), outlet (b) and damage channel (c) caused by hitting the hitting element at a contact velocity of 856.0 m/s (direction of movement of the hitting element is indicated by an arrow)



a

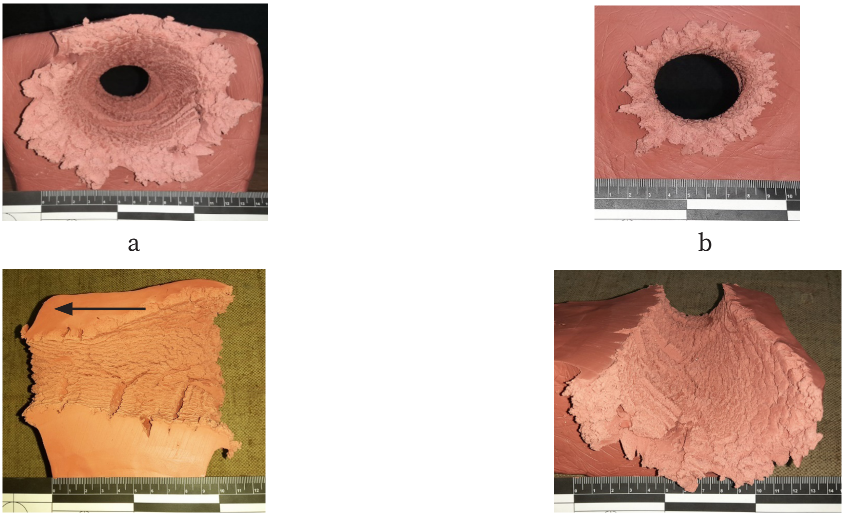


b

c

d

Fig. 32. General view of the inlet (a), outlet (b) and damage channel (c, d) caused by hitting the hitting element at a contact velocity of 1027.0 m/s (direction of movement of the hitting element is indicated by an arrow)



a b c d

Fig. 33. General view of the inlet (a), outlet (b) and damage channel (c, d) caused by hitting the hitting element at a contact velocity of 1066.0 m/s (the direction of movement of the hitting element is indicated by an arrow)

Table 8

Loss of kinetic energy of damaging elements of the OZM-72 mine at the time of penetration of the ballistic plasticine block

Mass, g	Contact velocity, m/s	Channel length, mm	Velocity after punching, m/s	Contact kinetic energy, J	Kinetic energy after penetration, J	Kinetic energy losses, J
0,75	770,4	145	24,2	222,57	0,22	222,35
0,77	856,0	140	44,8	282,10	0,77	281,33
0,75	1027,0	148	86,5	395,52	2,81	392,71
0,75	1066,0	90	190,6	426,13	13,62	412,51

Applying the formula (5) with the replacement of the limit value of the velocity V_{gr} by the value of the velocity of the damaging element after overcoming (breaking through) the obstacle (final) V_i, based on the data of Table 4, it is possible to obtain the value of the coefficient of resistance of the visco-elastic medium C_1 for the range of contact velocities 770.4-1066 m/s and depending on the position of the damaging element at the time of hitting. The results of calculations are presented in Table 9.

Table 9

Value of the resistance coefficient the medium C_1 in the range of contact velocities of the damaging elements 770.4-1066.0 m/s

Mass, g	Contact velocity, m/s	Channel length, mm	Velocity after punching, m/s	Resistance coefficient of medium C_1 for cross-sectional area		
				$S_1 = 0.2\ cm^2$	$S_2 = 0.282\ cm^2$	$S_3 = 0.26\ cm^2$
0,75	770,4	145	24.2	0.775	0.542	0.597

Completion of Table 9

Mass, g	Contact velocity, m/s	Channel length, mm	Velocity after punching, m/s	Resistance coefficient of medium C_1 for cross-sectional area		
				$S_1 = 0.2$ cm²	$S_2 = 0.282$ cm²	$S_3 = 0.26$ cm²
0.77	856.0	140	44.8	0.858	0.599	0.661
0.75	1027.0	148	86.5	0.843	0.589	0.649
0.75	1066.0	90	190.6	1.405	0.982	1.081

Analysis of data on the specific value of kinetic energy losses per unit length of the wound canal is rather ambiguous. At a contact velocity of 770.4 m/s, the loss of kinetic energy per 1 cm of the channel is 15.33 J/cm, at a speed of 856.0 m/s — 20.01 J/cm, at a velocity of 1027.0 m/s — 26.53 J/cm (at a measured thickness of the obstacle punched through 14.5 cm, 14.0 cm and 14.8 cm, respectively). Similarly, a smaller obstacle thickness (9.0 cm) leads to a significant increase in kinetic energy losses per unit length of the damage channel (45.83 J/cm), although at comparable values of contact velocities (1027 m/s and 1066 m/s), the losses at a smaller obstacle thickness are 1.73 times higher than the losses of kinetic energy at a larger obstacle thickness.

It can be due to the following: during experimental researches, it was found that at velocity's of more than 700 m/s and in case of contact of the striking element with the end surface of the ballistic plasticine block, there are significant plastic deformations of the striking element in the axial direction (*cf. Fig. 21, 23, 25*).

At the same time, even at a maximum velocity of 1082 m/s and in case of hitting the striking element by the side surface, no such deformations were detected.

Thus, a sharp increase in specific losses of kinetic energy can be explained by significant deformations of the end part of the striking element, with which it hit the obstacle. This led to an increase in the contact surface and, accordingly, a significant increase in resistance forces of the viscoelastic medium, as evidenced by the nature of the inlet and outlet holes of the damage (*cf.: Fig. 33*).

Based on results of the researches, we obtained empirical dependencies for determining the parameters of injuries caused by strikes in biological tissues of finished damaging elements of a cylindrical shape with a diameter of 5.0 mm. On their basis, it is possible to predict the volume of the final cavity of the injury that makes possible to determine maximum zones of destruction of biological tissue layers adjacent to the wound canal, as well as the length of the wound canal, which can be formed as a result of hitting the specified damaging element depending on its velocity at the time of hitting. In addition, it is possible to determine characteristics of the through damage and the velocity of the damaging element after overcoming the obstacle. Let us demonstrate this with an example.

It is necessary to determine the damaging characteristics of the finished damaging element of the OZM-72 mine, the velocity of which at the time of hit was 800 m/s.

Taking into account the average values of the mass of the damaging element 0.77 g, its diameter 5.0 mm and length 5.15 mm, these indicators will be:

- wound length of the canal is 13.96 cm;
- damage volume — 157.4 cm³;
- value of kinetic energy at the time of hitting — 246.4 J;

- specific kinetic energy — 12.32 J/mm^2 (end surface: S_1 = 0.2 cm^2); 8.74 J/mm^2 (at the angle of 45°: S_2 = 0.282 cm^2); 9.48 J/mm^2 (at the angle of 90°: S_3 = 0.26 cm^2);
- value of the resistance coefficient of visco-elastic medium C_1 is 0.846.

In case of hitting the finished damaging element in human limb at a comparable length of the wound canal of 10 cm, the velocity of the damaging element after penetration can be calculated by the formula, taking into account the assumption that there are no plastic deformations of the damaging element due to its shock-contact interaction with the obstacle:

$$V_i = V_c \cdot e^{-\frac{C_1 \cdot \rho \cdot S_i}{2m} \cdot x}. \qquad (6)$$

After substituting the corresponding values of V_{10}, we obtain:

- 257.5 m/s (end surface: S_1 = 0.2 cm^2);
- 161.8 m/s (at the angle of 45°: S_2 = = 0.282 cm^2);
- 183.3 m/s (at the angle of 90°: S_3 = = 0.26 cm^2).

By comparing the values of Table 9 with the calculated values (without taking into account plastic deformations of the damaging element), significant discrepancies were determined (*cf.: Table 10*). The analysis of tabular data indicates ambiguity of the calculations performed. The discrepancies can be explained by the fact that during the impact-contact interaction, the striking element is significantly deformed which leads to a significant increase in the contact area and, accordingly, to an increase in resistance forces and a decrease in velocity after overcoming the obstacle. It is quite difficult to take this into account when performing calculations.

Table 10

Comparison of calculated values of the velocity of the damaging element after overcoming the obstacle with the results of experimental researches and corresponding calculated values of the contact area and the equivalent diameter of the damaging element

V_s, m/s	V_i, m/s	$V_{i\ rose}$, m/s	x, cm	$S_{i\ rose}$, cm^3	$d_{i\ роз.}$, cm
770,4	24,2	155,7	14,5	0,432	0,74
856,0	44,8	90,9	14,0	0,371	0,69
1027,0	86,5	121,2	14,8	0,301	0,62
1066,0	190,6	391,9	9,0	0,344	0,66

Note: *$S_{i\ роз.}$ is the equivalent cross-sectional area of the striking element; $d_{i\ роз.}$ is the equivalent diameter of the cylindrical striking element.*

Obtained array of data on the parameters of the fragmentation wound formation process makes possible to create a mathematical model of the shock-contact interaction of the studied sample of the damaging element with a visco-elastic medium that simulates the biological tissues of the human body [9].

9 Tsymbaliuk V. et al. Op. cit. DOI: 10.26641/2307-0404.2023.1.275866 (date accessed: 18.09.2025) ; Коломійцев О., Ґіверц П., Нікітюк В., Герман О. Застосування комп'ютерних технологій для розв'язання завдань термінальної балістики. *Діджиталізація судово-експертної науки в умовах воєнного стану* : мат-ли Міжнар. наук.-практ. конф. (Харків, 08.11.2024). Харків. 2024. С. 169—173. URL: https://drive.google.com/file/d/1cDRJ14KDOGIXe5Y6HdN-VBzqAS7gbR-ML/view (date accessed: 19.09.2025) ; Susu L., Cheng X., Yaoke W., Xiaoyun Zh. A new motion model of rifle bullet penetration into ballistic gelatin. *International Journal of*

Such a model can be created using computer simulation with the finite element method with an explicit time integration scheme and "element death" technology to simulate the process of material destruction (penetration of the striking element into human soft tissue simulator block; *cf.: Fig. 34*) [10].

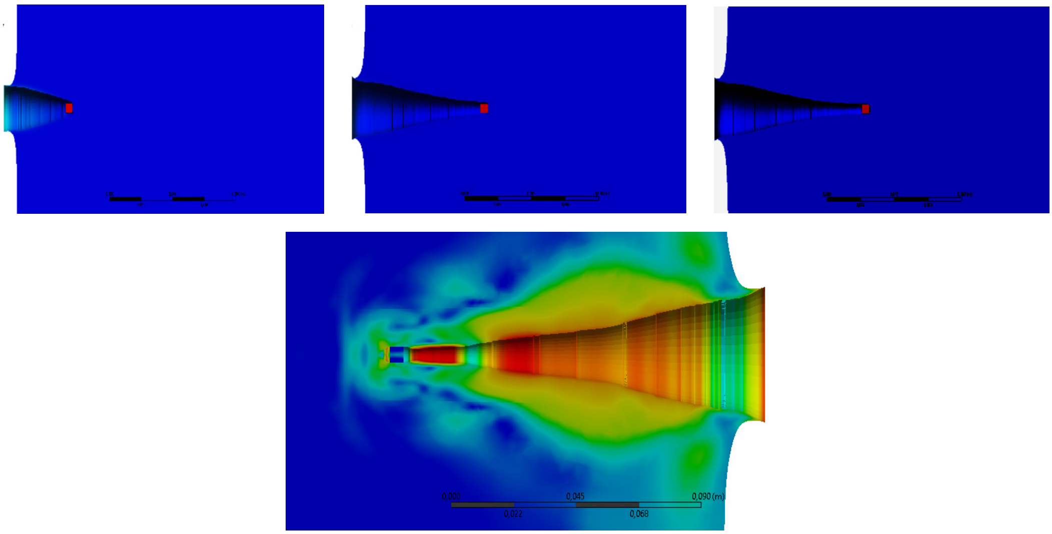


Fig. 34. Results of computer simulation of the process of damage channel formation caused by a cylindrical striking element, obtained by Prof. O. Larin during his researches [11]

Impact Engineering. 2016. Vol. 93. Pp. 1—10. DOI: 10.1016/j.ijimpeng.2016.02.003 (date accessed: 19.09.2025) ; Gilson L., Rabet L., Imad A., Kakogiannis D., Coghe F. Development of a numerical model for the ballistic penetration of Fackler gelatine by small calibre projectiles. *The European Physical Journal Special Topics*. 2016. Vol. 225 (2). Pp. 375—384. DOI: 10.1140/epjst/e2016-02640-9 (date accessed: 19.09.2025) ; Wang Y., Shi X., Chen A., Xu Ch. The experimental and numerical investigation of pistol bullet penetrating soft tissue simulant. *Forensic Science International*. 2015. Vol. 249. Pp. 271—279. DOI: 10.1016/j.forsciint.2015.02.013 (date accessed: 19.09.2025) ; Gilson L., Rabet L., Imad A., Coghe F. Experimental and numerical characterisation of rheological properties of a drop test response of a ballistic plastilina. *Ibid*. 2020. Vol. 310. Art. 110238. DOI: 10.1016/j.forsciint.2020.110238 (date accessed: 19.09.2025).

10 Larin O., Tomashevskyi R., Lurin I., Gumeniuk K., Nehoduiko V. Computational Modeling and Analysis of Wound Formation in Gunshot Injuries. *6th International Conference on Nanotechnologies and Biomedical Engineering* : Conference proceedings (Chisinau, Moldova, 20—23 Sept 2023). Chisinau, 2023. Vol. 2 : Biomedical Engineering and New Technologies for Diagnosis, Treatment, and Rehabilitation. Pp. 218—227. DOI: 10.1007/978-3-031-42782-4_24 (date accessed: 19.09.2025) ; Kolisnyk K., Sokol Y., Shchapov P., Nehoduiko V. Mathematical Modelling of the Multifactorial Influence of Striking Fragments on the Dynamics of the Rehabilitation Processes of the Wounded. *Ibid*. Pp. 160—169. DOI: 10.1007/978-3-031-42782-4_18 (date accessed: 19.09.2025) ; Моделювання вогнепальних поранень : монографія / упорядники: І. А. Лурін, В. В. Негодуйко, Р. М. Михайлусов, К. В. Гуменюк ; під заг. ред. В. І. Цимбалюка. Харків, 2022. 322 с. URI: https://repo.knmu.edu.ua/handle/123456789/32575 (date accessed: 19.09.2025).

11 Larin O., Grabovskiy A., Kolomiitsev O., Larkov S., Nehoduiko V. Numerical and Experimental Investigation of Cylindrical Shrapnel Penetration into Non-biological Soft Tissue Simulant

The results of experimental researches make possible to create a computer model of terminal ballistics of ready-made cylindrical projectiles with a diameter of 5.0 mm based on mathematical modeling methods that will be of significant practical importance for medicine and related specialized fields. Thus, it becomes possible to combine terminal and external ballistics of different types of ready-made striking elements into a single complex.

In order to determine the aeroballistic characteristics of the studied striking elements in the conditions of a ballistic range using two ИБХ-731.4 optoelectronic measuring complexes, experimental firing was carried out with a 5.45 mm AK-74M assault rifle using special cartridges[12]. During experiment, initial flight velocities of 547.2–1096.0 m/s were achieved. Based on the decrease in the flight velocity of the kinetic projectiles under study along the trajectory, the ballistic coefficient was determined. The results of researches and calculations are presented in Table 11.

Table 11

Results of experimental firing of ready-made striking elements of a cylindrical shape with a diameter of 5.0 mm

Shot number	M_i, g	V_{i0}, m/s	$V_{iк}$, m/s	L, m	C_i
1	0.79	956.6	326.1	20	175,86 *
2	0.77	615.9	455.0	15	67.67
3	0.79	534.6	389.3		70.89
4	0.76	584.3	422.9		72.25
5	0.79	681.7	515.3		62.54
6	0.76	691.9	494.1		75.25
7	0.76	658.7	480.3		70.59
8	0.79	657.6	496.2		62.94
9	0.79	547.2	408.9		65.11
10	0.77	797.0	566.9		76.14
11	0.75	939.8	690.7		68.83
12	0,75	592,7	424,9		74,39
13	0,75	851,4	602,1		77,43

(Ballistic Plasticine). *7th International Conference on Nanotechnologies and Biomedical Engineering*: Conference proceedings (Chisinau, Moldova, 7—10 Oct 2025). Chisinau, 2025. Vol. 2 : Biomedical Engineering and New Technologies for Diagnosis, Treatment, and Rehabilitation. 2025. Pp. 534—542. DOI: 10.1007/978-3-032-06497-4_53 (date accessed: 19.09.2025).

12 Коломійцев О. В. Патрони для експериментальної стрільби готовими уражаючими елементами та осколками. *Актуальні проблеми забезпечення державної безпеки* : мат-ли II Всеукр. наук.-практ. конф. (Київ, 25.10.2024). Київ, 2024. С. 136—139. URI: https://elar-kingu.kyiv.ua/handle/123456789/329 (date accessed: 19.09.2025) ; Його ж. Патрони для експериментальної стрільби високошвидкісними готовими уражаючими елементами та осколками. *Актуальні проблеми діяльності складових сектору безпеки і оборони України (до 10-ї річн. створ. Нацгвардії України)* : тези Всеукр. наук.-практ. конф. (Харків, 24.10.2024). Харків, 2024. С. 352—355. URL: http://repositsc.nuczu.edu.ua/bitstream/123456789/24214/1/Zbirnsk_tez_konfer._24.10.2024%20%281%29.pdf (date accessed: 19.09.2025).

Completion of Table 11

Shot number	M_i, g	V_{i0}, m/s	$V_{iк}$, m/s	L, m	C_i
14	0,75	759,7	553,6	15	70,73
15	0,78	1025,0	736,0		74,03
16	0,78	1096,0	816,7		65,74
17	0,78	1050,0	786,6		64,55

Note. *M_i is the mass of the individual damaging element; V_{i0} is the initial velocity of the individual damaging element (the velocity recorded by the first measuring complex); $V_{iк}$ is the velocity of the individual damaging element recorded by the second measuring complex; L is the firing distance (for 20 m the distance between the measuring complexes was 18.6 m; for 15 m — 13.6 m); C_i is the value of the ballistic coefficient for the individual damaging element; * is the movement of the destabilized damaging element.*

Table 12 presents the results of measuring the flight velocities of only test shots (with the registration of the passage of striking elements through the frames of both measuring complexes) with a series of 25 shots. Due to the significant spread of the damaging elements at a firing distance of 20 m, the passage of eight damaging elements through the frame of the second measuring complex was not recorded.

In order to control the position of the studied damaging element on the trajectory by measuring complexes, paper targets were installed. Only in one case (shot № 1, *cf.: Table 11*) it was recorded that the striking element rotated in flight (the first target had a rounded hole, and the second — a rectangular hole, which is typical for the lateral projection of the striking element). In other cases, the movement of the damaging elements was stabilized (the holes in both targets were rounded). Such features of the flight of the studied damaging elements affected the value of the ballistic coefficient C_1 (extreme value of C_i in Table 11 is marked "*").

Table 12

Trajectory parameters and ballistic characteristics of individual OZM-72 mine striking element at an initial velocity of 1053 m/s and a throwing angle of 0°

X, m	Y, m	Q	V, m/s	t, c	E, J	Eud, J/mm²
0	1.000	0.000	1053.000	0.000	426.891	21.747
10	1.000	–0,006	896.084	0.010	309.142	15.748
20	0.998	–0,015	724,988	0,023	202,359	10,309
30	0,994	–0,030	574,594	0,039	127.111	6.475
40	0.987	–0,053	451,160	0,059	78.365	3.992
50	0.975	–0,090	362,118	0,085	50,485	2,572
60	0.954	–0,144	307,224	0,116	36,339	1.851
70	0.924	–0,213	280,198	0,151	30,227	1.540
80	0.879	–0,300	244,581	0,190	23,031	1.173
90	0.818	–0,407	227,602	0,234	19,944	1.016
100	0.736	–0,532	208,332	0,281	16,708	0.851
110	0.631	–0,680	192,916	0,332	14,328	0.730
120	0.497	–0,854	176,792	0,388	12,033	0.613

Completion of Table 12

X, m	Y, m	Q	V, m/s	t, c	E, J	Eud, J/mm²
130	0.331	–1,060	162,691	0,448	10,190	0.519
140	0.125	–1,305	149,369	0,514	8,590	0.438
145,172 *	0,000 *	–1,449 *	142,989 *	0,551 *	7,872 *	0,401 *

Note: *X, m — flight range; Y, m — altitude of the flight path; Q, ° — angle of inclination of the flight path; V, m/s — flight velocity; t, s — flight time; E, J — kinetic energy; Eud, J/mm² — specific kinetic energy; * — the value of the flight path parameters at the point of incidence.*

Analysis of the obtained results of experimental firing makes possible to determine the damaging properties of the studied kinetic projectiles at different distances from the center of the explosion: in the zone of continuous damage, at distances of effective damage and maximum dispersion; as well as to determine the safe zone.

This can be demonstrated by calculating the damaging properties of the OZM-72 kinetic projectile under the following initial conditions:

- 0 is initial velocity of the damaging element — 1053 m/s;
- average mass of the finished damaging element is 0.77 g;
- position of the striking element in flight — forward movement of the end surface (angle of attack in the flow (streamlining) — 0°);
- cross-sectional area — 19.63 mm²;
- indirect value of the ballistic factor of the damaging element based on the data of Table 12 — 69.94 m²/kg;
- angle of throwing a separate striking element from the center of the explosion — 0°;
- limit value of the specific kinetic energy of the damaging element, which is sufficient to cause a penetrating wound to the human body in one of the cavities (abdominal one, thoracic one, skull) [13] — 0.5 J/mm²;
- height of the mine detonation is 1.0 m.

The results of calculations using specialized *ExtBallistic* software under normal environmental conditions are presented in Table 12. Analysis of these results shows that with the horizontal flight of the studied damaging element (throwing angle — 0°), its maximum range is almost 142 m.

In addition, at a distance of up to 130 m inclusive, a separate striking element of the OZM-72 mine under the most optimal flight conditions (end surface forward) can cause a person permeable injury.

If we take into account that for guaranteed human damage, the fragment should have a kinetic energy of at least 80 J, then under the above conditions, the effective range of action on a live target can reach 40 m.

If the throwing angle of an individual hitting element increases, in particular up to 45°, then the hitting zones change significantly, since the hitting elements quite quickly go beyond the size of the target. If we take into account the height of the growth target of the ЗСУ № 8 (1.65 m), as well as the height of the average man in Ukraine (1.753 m), then affected areas will have completely different values. Thus, at a throwing angle of 5° at a distance of almost 10 m (trajectory height — 1.874 m) from the center of the explosion, the striking element goes beyond the height of the person, which excludes any possibility of hitting the target. Consequently, it can be argued that most of the finished destructive elements of the OZM-72 mine

13 Гамов Д. Ю. Встановлення належності об’єкта до бойових припасів вогнепальної стрілецької зброї та його придатності до стрільби : методика. Київ, 2006. 29 с.

located in the upper part of the hull can be targeted only if it is quite close to the center of the explosion.

More interesting are the results of researches on destabilized damaging elements. According to Table 11, such a damaging element has the value of the ballistic coefficient C_1 = 175.86 m²/kg. The results of calculations under the above initial conditions of introducing the damaging element into free flight are presented in Table 13.

Table 13

Trajectory parameters and ballistic characteristics of the destabilized individual destructive element of the OZM-72 mine at an initial velocity of 1053 m/s and a throwing angle of 0°

X, м	Y, м	Q, °	V, м/с	t, c	E, J	Eud, J/mm²
0	1.000	0.000	1053.000	0.000	426.891	21.747
10	1.000	–0,008	638.871	0.012	157.140	8.005
20	0.996	–0,037	354.735	0.034	48.447	2.468
30	0.984	–0,107	247,111	0,070	23,510	1,198
40	0.952	–0,282	147.246	0.124	8.347	0.425
50	0.862	-0.808	100.603	0.218	3.897	0.199
60	0.656	–1,591	83.863	0.336	2.708	0.138
70	0.304	–2,450	67.708	0.458	1.765	0.090
76,107 *	0,000 *	–3,189 *	65,738 *	0,547 *	1,664 *	0,085 *

Note: ** is the value of flight path parameters of an individual striking element at the point of impact.*

According to the results of calculations, damaging properties of the destabilized test sample of the kinetic projectile are significantly lower than those of the stabilized one. Thus, the zone of guaranteed damage does not exceed 10—20 m from the center of the explosion, and the zone of tasking a person with a penetrating wound is 40 m.

The values of velocities of the affecting elements on the trajectory given in Tables 12 and 13 make it possible to predict the depth of inflicted wound canal using an empirical relationship (4). For example, at a contact velocity of 227.602 m/s, which corresponds to a distance of 90 m from the center of the explosion (*cf.: Table 12*), the depth of the wound canal could be 75.7 mm.

The results of experimental researches indicate that determining the aeroballistic characteristics of the finished striking elements, taking into account their position in flight, is a rather time-consuming process and requires a significant number of shots to obtain statistical material. However, modern mathematical methods and computer simulation of gas-dynamic processes of flowing bodies of different shapes in air in a wide range of velocities and at different values of the flow angle (angle of attack) will help to determine these parameters.

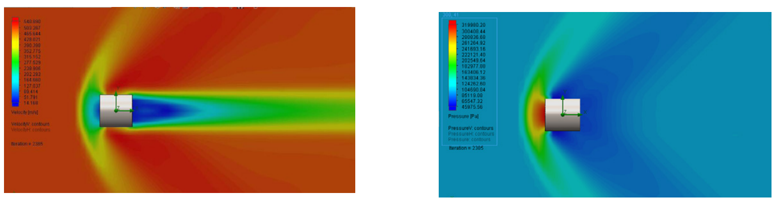
Based on the specialized *SOLID WORKS* (*Flow Simulation*) software, it is possible to obtain the results of airflow around the studied damaging elements at the velocity values set during experimental firing and at their different positions, which makes it possible to simulate real flight conditions. The values of the air resistance force, its coefficient depending on the flight velocity make possible to determine both the parameters of its trajectory and the damaging properties at different distances from the center of the explosion of the ammunition. The results of computer simulation of the flow of the striking elements are presented in Fig. 35–37 and in Table 14.

Table 14

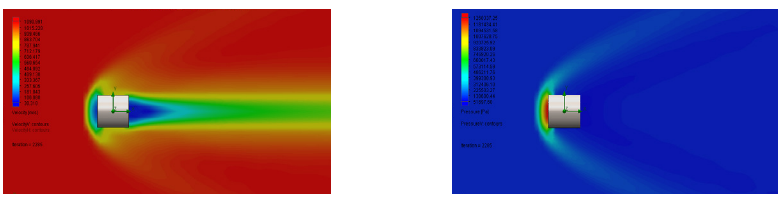
Calculation results of aerodynamic characteristics of finished damaging elements of a cylindrical shape with a diameter of 5.0 mm

Contact velocity, m/s	500			1082		
Angle of attack, °	0	45	90	0	45	90
Resistance force, N	2.887	3.747	3.588	11.811	11.655	13.132
Resistance force coefficient	0.96	1.25	1.19	0.79	0.83	0.93

Velocity distribution **Pressure distribution**



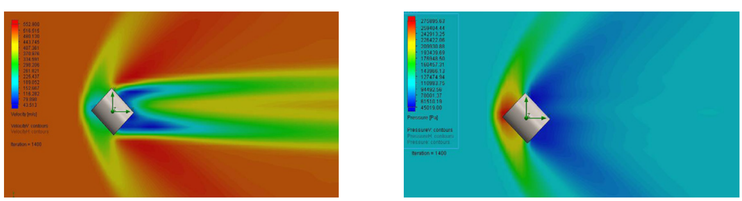
Velocity: 500 m/s



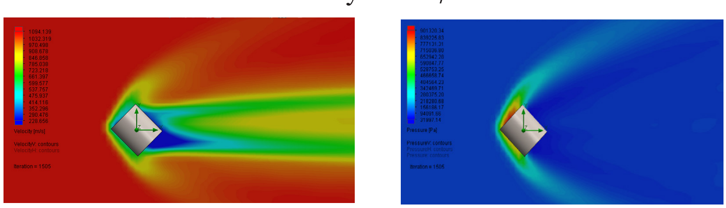
Velocity: 1082 m/s

Fig. 35. Nature of wrap around the damaging element (angle of attack — 0°)

Velocity distribution **Pressure distribution**



Velocity: 500 m/s



Velocity: 1082 m/s

Fig. 36. Nature of wrap around the damaging element (angle of attack — 45°)

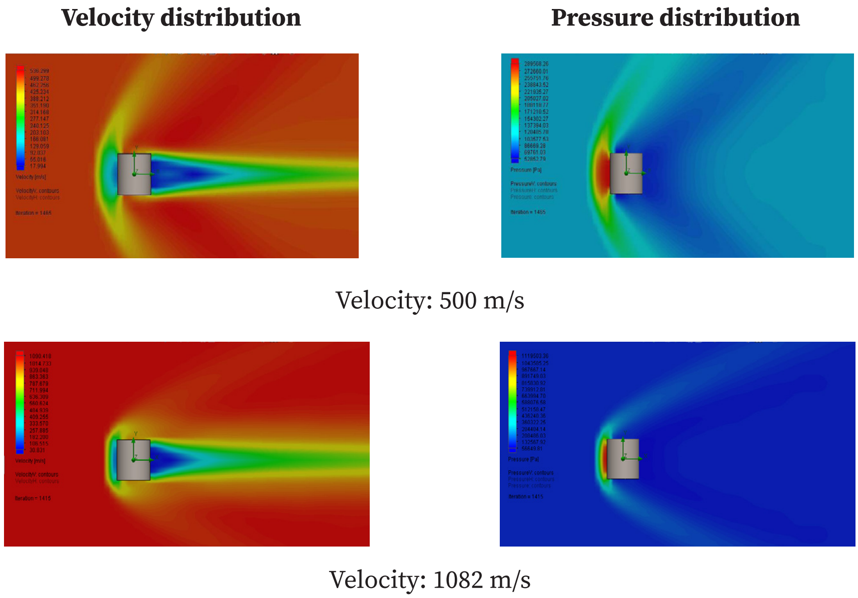


Fig. 37. Nature of wrap around the damaging element (angle of attack — 90°)

Thus, using computer simulations, it is possible to determine the motion parameters of both stabilized and destabilized finished striking elements of cylindrical shape without conducting large-scale field tests. Determining the aeroballistic characteristics of such damaging elements in full requires separate researches.

Conclusions

Introduction into free flight of individual ready-made destructive elements or fragments of free crushing in the range of velocities up to 1000 m/s and more and research on consequences of their hitting biological tissue simulators can be carried out using specialized equipment used during experimental research in the field of forensic ballistics. This opens up quite broad prospects for studying the specifics of wound (terminal) ballistics of various types of ready-made destructive elements and fragments of natural crushing of ammunition and improvised explosive devices.

Ready-made damaging elements of cylindrical shape and small degree of elongation behave stably in the viscoelastic medium. In case of impact, they form cavities of conical shape. The studied damaging elements cause the greatest damage in the area of the first quarter (third) of the damage channel. This is due to the almost complete transfer of their kinetic energy to the layers of the medium bordering on this zone with the central damage channel. Dimensions of the damage area in the designated section of the channel are maximum. With the loss of kinetic energy, the damaging elements continue to move in the stratum of obstacles and cause minimal damage to the adjacent layers of the environment.

The use of ready-made damaging elements of cylindrical shape in the target is characterized by the variability of their positions relative to the outer surface of the obstacle, which significantly affects the determination of the parameters necessary for calculating and predicting the severity and volume of the damage caused. However, this can be corrected by a significant increase in the statistical material with subsequent differentiation of the results that correspond to the specific positions of the striking element at the time of hitting the target.

In case of hitting visco-elastic medium with contact velocities of more than 700 m/s and the end surface, the finished damaging elements under research can undergo significant plastic deformations in the longitudinal direction. However, in the case of hitting the target with a lateral projection at an angle of 45°–90°, no significant plastic deformations were observed in the studied damaging elements.

The results of experiments indicate the expediency of using the methods of experimental (forensic) ballistics not only for the study of the features of wound (terminal) ballistics of ready-made destructive elements and fragments of ammunition and explosive devices, but for the researches on their external ballistics and the determination of aeroballistic characteristics. This allows you to determine the size of the affected areas with fragments (ready-made destructive elements), as well as safe distances in the event of detonation of specific ammunition or improvised explosive devices.

Use of mathematical models and computer technologies to simulate the physical processes that accompany the penetration of ready-made damaging elements into biological tissues, in combination with modern technologies for determining their aeroballistic characteristics, makes possible to create a comprehensive method for predicting the damaging properties of fragments with determining the severity of the bodily injuries caused by them in a wide range of initial conditions of shock-contact interaction.

Експериментальні дослідження особливостей термінальної та зовнішньої балістики уражаючих елементів циліндричної форми діаметром 5,0 мм

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Мета статті — дослідити особливості механізму формування у в’язко-пружному середовищі пошкоджень, які виникли в результаті високошвидкісної ударно-контактної взаємодії з готовими уражаючими елементами циліндричної форми. Для досягнення мети застосовано загальнонаукові та спеціальні методи. Основну увагу приділено дослідженню уражаючих елементів діаметром 5,0 мм, оскільки ними споряджено значну кількість осколкових бойових припасів (зокрема, протипіхотні міни, боєприпаси для скидання з дронів, а також саморобні вибухові пристрої). Експериментальні дослідження проводили в умовах балістичної траси із застосуванням оптоелектронних вимірювальних комплексів, імітатора біологічних тканин (балістичного пластиліну) і спеціальних патронів. Уведення у вільний політ готових уражаючих елементів здійснювали за допомогою нейробалістичного ручного металього пристрою, а також нарізної вогнепальної зброї калібру 5,6 мм і 5,45 мм. Це дало змогу провести натурні експерименти в доволі широкому діапазоні контактних швидкостей від 70 м/с до 1082 м/с під час дослідження уражаючих властивостей і в діапазоні від 547 м/с до 1096 м/с під час дослідження аеробалістичних характеристик. Як експериментальні снаряди *використано готові уражаючі елементи циліндричної форми діаметром 5,0 мм із подовженням 0,96—1,1, якими споряджають осколкові загороджувальні міни ОЗМ-72. Під час досліджень визначено, що після влучання зазначені готові уражаючі елементи в товщі імітатора біологічних тканин поводяться стабільно й утворюють порожнини конічної форми. Найбільшої шкоди вони завдають на ділянці першої чверті (третини) каналу пошкодження. Це обумовлено практично повною передачею уражаючими елементами своєї кінетичної енергії шарам середовища, що примикають у цій зоні до центрального каналу пошкодження. Розміри зони пошкоджень на цій ділянці каналу максимальні. На основі здобутих результатів визначено особливості впливу на параметри каналу пошкодження контактної швидкості й положення уражаючого елемента в момент улучання. Визначено емпіричні залежності коефіцієнта сили опору в'язко-пружного середовища, об'єму та довжини каналу пошкоджень від контактної швидкості. Результати проведених досліджень дають змогу прогнозувати ступінь тяжкості завданих людині осколкових поранень і розв'язати низку ситуаційних завдань, пов'язаних із розслідуванням кримінальних злочинів та терористичних актів, під час скоєння яких застосовано осколкові бойові припаси або саморобні вибухові пристрої. Окремий етап — дослідження аеробалістичних характеристик зразків кінетичних снарядів, що дає змогу визначити їх уражаючі властивості залежно від відстані до центра вибуху.*

Ключові слова: *балістичний пластилін; бойовий припас; коефіцієнт сили опору середовища; контактна швидкість; осколкова загороджувальна міна ОЗМ-72; осколкове пошкодження; патрон; саморобний вибуховий пристрій; термінальна балістика; уражаючий елемент циліндричної форми.*

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