Numerical and Experimental Analysis of the Influence of Projectile Impact Angle on Armour Plate Protection Capability

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ABSTRACT

This research manuscript describes the process of degradation of an Armox 600 armour plate during the impact of a 5.56×45 mm SS109 projectile. The creation process of the numerical FEM model of the projectile is presented. The projectile impact angle is set between 15° and 90°, and this phenomenon is investigated via numerical and experimental approaches. The experiment is conducted under the same conditions as the numerical approach to validate the FEM model. The experiments are conducted using a high-speed camera. This research manuscript presents the influence of the projectile impact angle on the degradation of the armour plate and its protection capability for different angles. The results demonstrate the dependence of the transferred energy on the armour plate, speed of the particles after impact, and trace dimensions on the armour plate for different impact angles.

Keywords: Mechanics; Terminal ballistics; Finite element method; Armour plate; Projectile ricochet

NOMENCLATURE

A	: Static yield stress
B	: Strain hardening coefficient
C	: Strain rate coefficient
c_0	: Bulk speed of sound inmaterial
D_1	: Material constant 1
D_2	: Material constant 2
D_3	: Material constant 3
D_4	: Material constant 4
D_5	: Material constant 5
d_p	: Depth of a trace
e	: Energy
e_H	: Internal energy per unit mass
E_{k0}	: Initial kinetics energy – before an impact of a projectile
E_{kr}	: Residual kinetics energy – after an impact of a projectile
E_T	: Energy transferred into the armour plate
h	: Height of a trace
G	: Shear modulus
K	: Bulk modulus
m	: Thermal softening exponent
n	: Strain hardening exponent
p	: Pressure
p_0	: Initial pressure
p_H	: Hugoniot pressure
s	: Material parameter
s_1	: Shock EOS linear parameter S1
s_2	: Shock EOS quadratic parameter S2
t	: Time

T	: Temperature
T^*	: Homologous temperature (dimensionless value of temperature)
T_p	: Room temperature
T_t	: Melting temperature
u_p	: Particle velocity
u_s	: Shock velocity
V	: Volume
V_0	: Initial volume
w	: Width of a trace
Y	: Yield stress
Γ	: Gruneisen coefficient
Γ_0	: Initial Gruneisen coefficient
$\Delta\varepsilon$	: Increment of the effective plastic strain
ε	: Equivalent plastic strain
$\dot{\varepsilon}^*$	: Dimensionless plastic strain rate
ε_0	: Reference rate of plastic deformation
ε_f	: Equivalent plastic strain at failure
ρ	: Density due to shock compression
ρ_0	: Initial density
σ	: Yield stress
σ^*	: Pressure/stress measureless dependence
$\overline{\sigma}$	: Equivalent of the von Misses' stress

1. INTRODUCTION

There are many published studies[1-19] concerning FEM numerical models of a projectile impact on a target. Fang and Zhang[1] describeda finite element analysis approach by which to investigate the impacts of projectiles on rock-rubble overlays, focusing on the accidentally of the structure. Another study by Kędzierski[2], *et al.* concerns the capabilities of five different numerical approaches, namely, FEM, FEM-

remeshing, ALE-smoothing, ALE-Euler, and SPH, and focuses on 9 mm Parabellum deformable projectiles. Other studies by Bresciani[3], et al. present an approach for the Lagrangian finite element modelling of the fragmentation of a tungsten heavy-alloy blunt-shaped projectile penetrating a ceramic alumina tile. A paper written by Myagkov[4], et al. contains experimental and numerical research on the impact of polyethylene and aluminium projectile sonstring and mesh bumpers at high velocities. Żochowski[5], et al. describes numerical and experimental approaches of human bone failure mechanisms during projectile impacts. The authors of numerous studies[6-8] use FEM to determine the protective abilities of personal armour, armour for vehicles (e.g., Kurtaran[9], et al.), and general use armour[10-13]. Fras[14] described an investigation that thoroughly examined the influence of the initial pitch and yaw angles on the after-perforation of a 7.62 mm×51 AP P80 projectile's performance.

There are a few available works[15-21] on similar topics, and these works include considerations of the influences of the impact angles of different types of projectiles on terminal ballistics parameters. A study conducted by Weiss[15], et al. focuses on the ricochets caused by a 25 mm APDS-T projectile. Three different hardness armour steel plates were impacted at varying angles of incidence. The main conclusion was that the ricochet angle decreased with an increase in target hardness. Goldsmith[16], et al. describes investigations of targets subjected to non-standard collisions that involve different impact angles. Ansari[17], et al. conducted experimental and FEM analyses of the perforation of unidirectional glass fibre-reinforced cross-ply laminates, considering different projectile nose shapes, incidence velocities, incidence angles, and laminate thicknesses. The influences of the projectile shape and impact angle on the ballistic limit, failure mechanism, and ricochet angle were studied by Iqbala[18], et al. Luo[19], et al. examined the effect of high-rate dynamic comminution on the penetration of projectiles with different velocities and impact angles into concrete. Lamontagne[20], et al. tested the effects of projectile density, impact angle and energy on the damage caused by hypervelocity impacts (2.71–7.14 km/s) on carbon fibre/PEEK composites. The aforementioned literature[16-20] mainly concerns the analysis of penetrators that are not in use; they are only experimental models. The present work focuses on a 5.56×45 mm SS109 military bullet in use. It is a full metal jacket bullet with a steel core placed in the front and a lead core located in the rear. In cases of ricochets, such double-core projectiles can act differently from standard (single-core) bullets, as described by Muster[21], et al.

This study focuses on numerical and experimental research on the impact of projectiles on an armour plate. The numerical approach provides more detailed information on this phenomenon, thereby enabling the determination of the velocity and energy in all axes of the projectile or its debris after impact. The analysis of this phenomenon using only a high-speed camera was limited, as it was not possible to accurately determine the projectile parameters, particularly the projectile particles. However, experimental tests allow for the validation of a numerical model based mainly on traces after impact on an armour plate.

The following analysis determines the influence of the impact angle on the armour protection capability and effects of this impact. This information is important during the development process of newly designed vehicles or personal armours.

2. NUMERICAL MODEL
2.1 Mathematical Description of Numerical Model

An (equation of state) linear material model was used for the steel core of the projectile and armour plate. This model defines a linear equation of state using the bulk modulus, which is characterised by the following Eqn.[22].

$$K = -V \frac{dp}{dV} \tag{1}$$

Shock equations of state (EOS) linear material models were adopted for the Tombac jacket and lead core of the projectile. This model describes the dependence of shock velocity and particle velocity using the following Eqn.[22-25].

$$u_S = c_0 + s_1 u_p + s_2 u_p^2 \tag{2}$$

The Mie-Gruneisen form of the state equation based on Hugoniot shock was used. This is described by the following formula[22-25],

$$p = p_H + \Gamma \rho (e - e_H) \tag{3}$$

where, it is assumed to follow the following formula[22-25].

$$\Gamma \rho = \Gamma_0 \rho_0 = const. \tag{4}$$

The Hugoniot pressure and internal energy per unit mass can be calculated the following equation[22-25].

$$p_H = \frac{p_0 c_0^2 \left(1 - \frac{V}{V_0}\right)}{\left[1 - s\left(1 - \frac{V}{V_0}\right)\right]^2} \tag{5}$$

$$e_H = \frac{1}{2} p_H (V_0 - V) \tag{6}$$

Table 1 includes the material data adopted for the EOS linear model and shock EOS linear model.

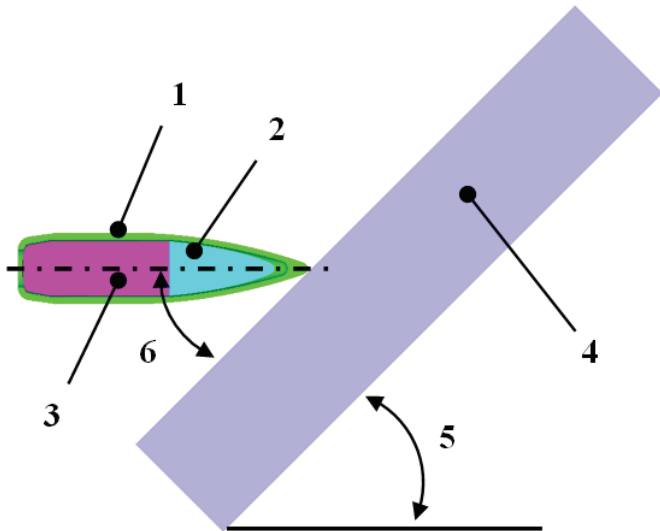**Table 1. Material parameters for the equations of state[25]**

Material	EOS linear model			
	K (GPa)			
Steel (core)	172.5			
Armox 600 armour steel	172.5			
	Shock EOS linear model			
	Γ	c_0 (m/s)	S_1	S_2
Tombac	2.04	3726	1.434	0
Lead	2	2092	1.452	0

The Johnson-Cook strength model was used in the study. This model contains the stresses, strains, strain rates, and temperature distribution in the material and was adopted for the Tombac jacket, steel core, and steel armour plate. This is described by the following Eqn.[6,22-23,25-26].

$$\sigma = \left[A + B\varepsilon^n\right] \times \left[1 + C \ln \dot{\varepsilon}^*\right] \times \left[1 - T^{*m}\right] \tag{7}$$

Table 2. Material data used in the numerical models[6,25-27]

Material	Johnson–cook strength model					Johnson–cook failure model				
	A (GPa)	B (GPa)	C	n	m	D_1	D_2	D_3	D_4	D_5
Steel (core)	0.792	0.51	0.014	0.26	1.03	0.05	3.44	-2.12	0.002	0.61
Tombac	0.112	0.505	0.009	0.42	1.68	0.54	4.89	3.03	0.014	1.12
Armox 600 armour steel	1.58	0.958	0.00877	0.175	0.712	-0.4	1.5	-0.5	0	0

Von Mises Strength Model	
Y(MPa)	G(GPa)
Lead 30	11.13

Figure 1. Numerical model. 1, 2, 3—parts of the 5.56×45 mm SS109 projectile;1—tombac jacket; 2—steel core; 3—lead core; 4—Armox 600 armour plate;5—elevation angle of the plate; 6—impact angle of projectile.

The dimensionless plastic strain rate and homologous temperature, which are dimensionless temperature values, can be calculated using the following Eqn.[6,22-23, 25].

$$\dot{\varepsilon}^* = \frac{\varepsilon}{\varepsilon_0} \tag{8}$$

$$T^* = \frac{T - T_p}{T_t - T_p} \tag{9}$$

The Johnson-Cook failure model was adopted for the Tombac jacket, steel core, and steel armour plate. This model determines deformation at failure using the following Eqn.[6,22-23,25].

$$\varepsilon^f = \left[D_1 + D_2 e^{D_3 \sigma^*}\right] \times \left[1 + D_4 \ln\left(\dot{\varepsilon}^*\right)\right] \times \left[1 + D_5 T^*\right] \tag{10}$$

The pressure/stress measureless dependence can be calculated the following Eqn.[6,22-23, 25]

Figure 2. Laboratory stand used during the tests. 1—Photron fastcam SA-Z 2100K high-speed camera; 2—mounting stand for plates; 3—Armox 600 armour plate; 4—ballistic mount and ballistic barrel; 5—projectile.

Table 3. Comparison of the high-speed camera frames and FEM simulation
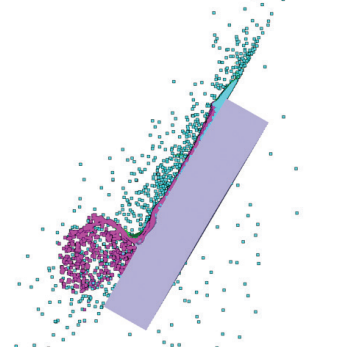
t (µs)	$t_0 = 0$	$t_1 = 20$	$t_2 = 40$
High-speed camera frames 45°			
Simulation 45°			
Simulation 15°			
Simulation 30°			
Simulation 60°			
Simulation 90°			

$$\sigma^* = \frac{p}{\overline{\sigma}} \qquad (11)$$

When the parameter D is equal to 1, a failure occurs[6,22-23, 25].

$$D = \sum \frac{\Delta\varepsilon}{\varepsilon^f} \qquad (12)$$

The von Mises strength model was used for the projectile lead cores. The model assumes that the yield stress and shear modulus have constant values[23, 25].

Table 2 lists the material data used in the Johnson–Cook strength, Johnson–Cook failure, and von Mises strength models.

2.2 Development of Numerical Model

The FEM numerical model (Fig. 1) was developed using ANSYS Autodyn software. The projectile impact velocity was set at 987 m/s, which is the value that was measured in the experiment. The Armox 600 armour plate was fixed on four

(a) (b) (c)

Figure 3. Comparison of the traces from the FEM simulation and experiment for a projectile impact angle of 45°.

side surfaces with a thickness of 10 mm, as in the experiment. The elevation angle of the armour plate was set equal to the impact angle of the projectile on the plate.
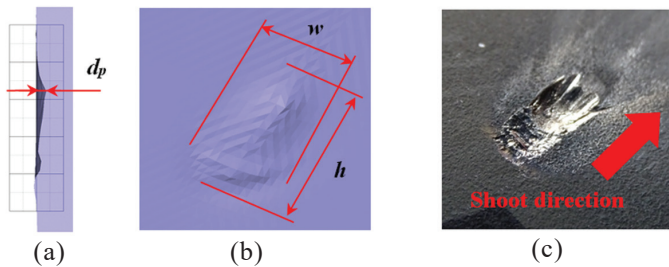
3. EXPERIMENTAL TESTS

The laboratory stand used for the experimental tests (Fig. 2) consisted of a Photron Fastcam SA-Z 2100 K high-speed camera, mounting stand with a 500 mm ×500 mm ×10 mm Armox 600 armour plate, and ballistic mount with a 5.56×45 mm ballistic barrel. The recording speed of the high-speed camera was 50,400 frames per second (fps), the ammunition used in the experiment was 5.56×45 mm HC (SS109) Ruag, the projectile weight was 4.0 g[28], the projectile impact velocity was 987 m/s, and the projectile impact energy was 1948 J (the last two values measured during the experiment).

4. RESULTS AND VALIDATION OF THE NUMERICAL MODEL

The high-speed camera frames and FEM simulation presented in Table 3 compare the course of the phenomenon for the times of 0 μs, 20 μs and 40 μs. Table3 shows a comparison of the numerical simulation results for different impact angles of the projectile (elevation angle of the armour plate):15°, 30°, 45°, 60°, and 90°. The time of 0 μs corresponds to the beginning of the impact.

The most important factor for the validation of the numerical model is the comparison of the traces on the amour plate from the numerical investigation and experiment. Figure 3 and Table 4 show the qualitative and quantitative

Table 4. Comparison of the trace parameters obtained experimentally and via a numerical approach

Parameters of the trace	h (mm)	w (mm)	d_p (mm)
Numerical investigation, 45°	7.4	5.4	0.44
Experimental test, 45°	9.7	4.8	0.35
Difference compared with the experiment	-2.3	+0.6	+0.09
Relative difference, %	-23.7	+12.5	+25.7
Numerical investigation, 15°	0	0	0
Numerical investigation, 30°	5.6	6.3	0.25
Numerical investigation, 60°	7.55	5.6	1.18
Numerical investigation, 90°	12.09	12.22	1.61

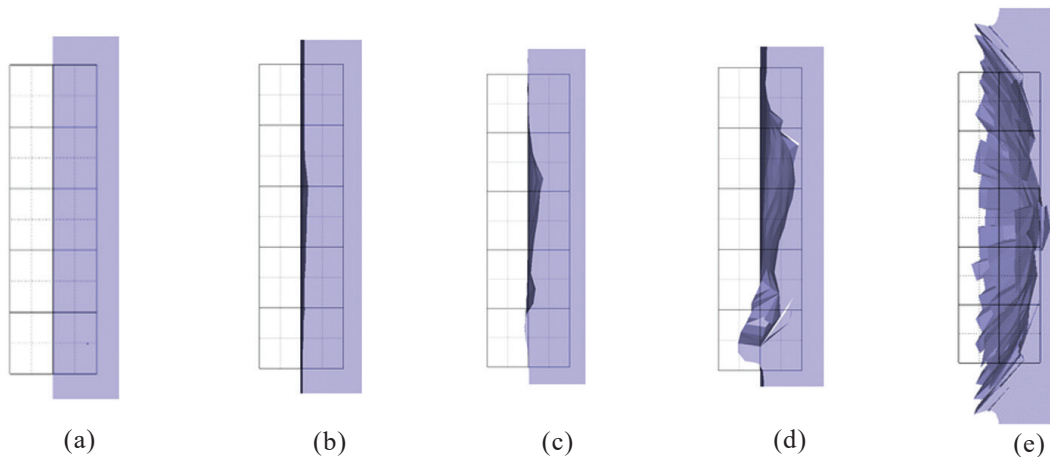

(a) (b) (c) (d) (e)

Figure 4. Comparison of the traces from the FEM simulations forvarious projectile impact angles.
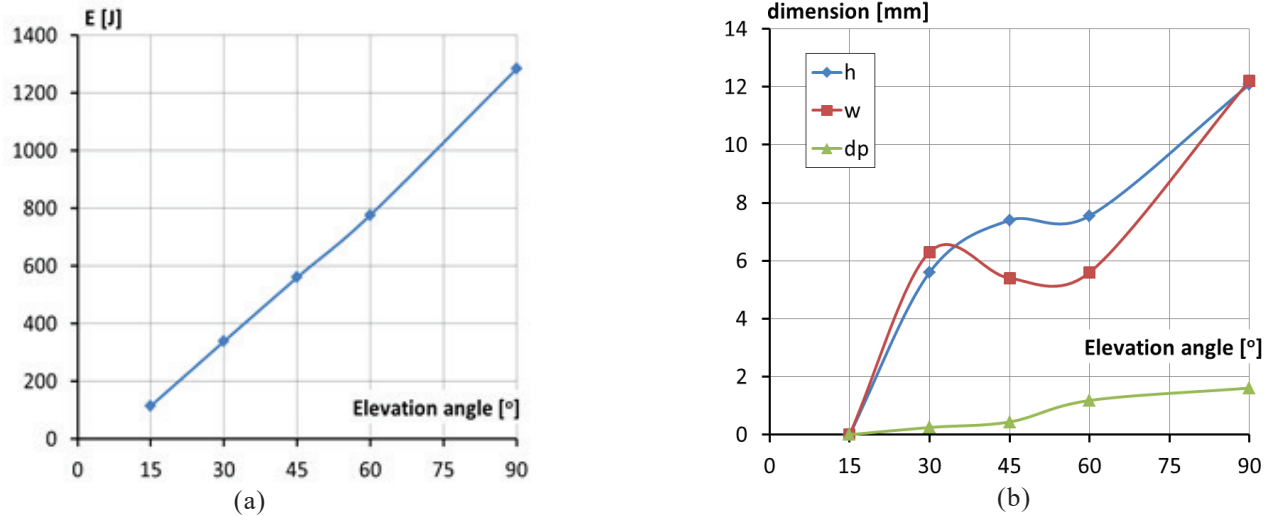
Figure 5. (a) Energy transferred into the armour plate versus projectile impact angle. (b) Trace dimensions (height, width, and penetration depth) versus projectile impact angle.

Figure 6. Influence of the projectile impact angle on the average velocity of projectile debris. (a) Average velocity of projectile debris versus time. (b) Average velocity of projectile debris(t = 0.08 ms) versus projectile impact angle.

Figure 7. Influence of the projectile impact angle on the gauge velocity along different axes.

similarities between the traces obtained using both the experiment and FEM investigation for a 45° projectile impact angle.

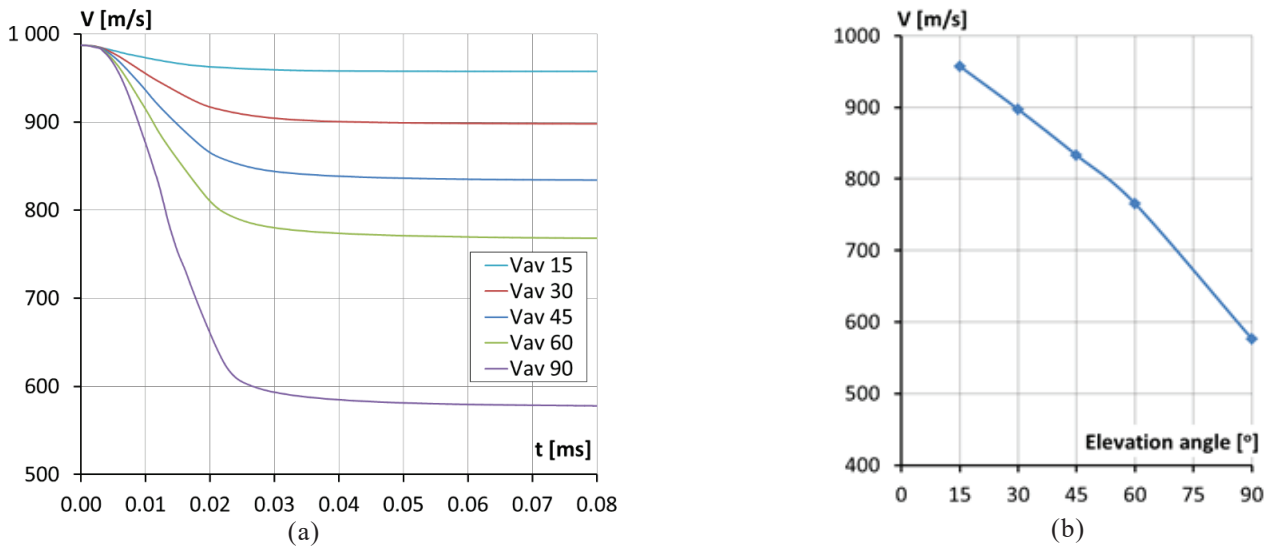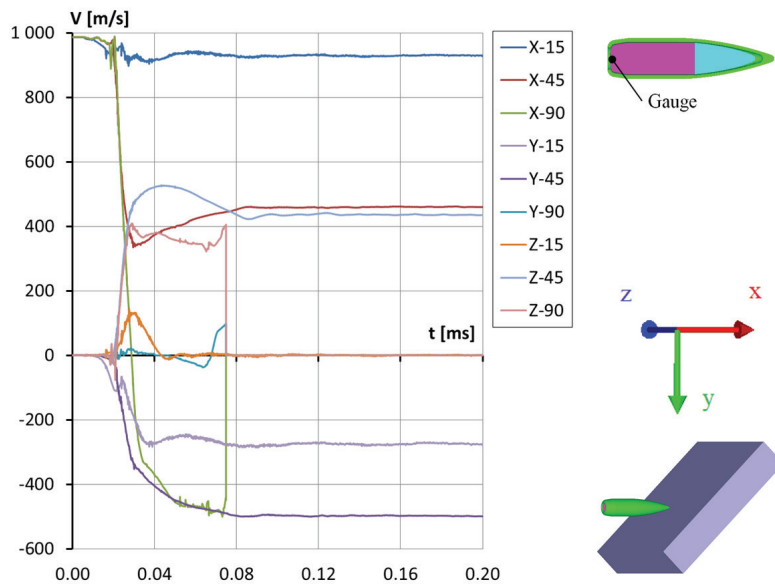Figure 4 shows the traces on the armour plate after the impact of the projectile at different impact angles. Table 4 lists the trace dimensions for these angles. The largest difference is noticeable for the traces for impact angles of 15° and 90° because there is an 11 times difference in the energy transferred to the armour plate (Fig. 5a). The energy transferred to the plate corresponded to the energy loss of the projectile, which can be described as follows.

$$E_T = E_{k0} - E_{kr} \tag{13}$$

Figure 5(b) shows the dependence between the trace dimensions and projectile impact angle. Figure 6 shows the decrease in the average velocity of the projectile debris after impact with the armour plate.

Figure 7 shows the velocities of the gauge located in the rear part of the projectile along different axes.

5. DISCUSSION

A comparison of the traces obtained from the numerical investigation and experimental tests (Fig. 3, Table 4) revealed qualitative and quantitative similarities, thereby proving the accuracy of the numerical model. The developed numerical model accurately describes the real phenomenon of a projectile impacting an armour plate. This analysis allowed us to closely investigate the phenomenon of armour plate degradation during projectile impact. It was possible to determine the average speed of the projectile particles and their speeds in different directions (OX, OY, and OZ axes). This study also determined the projectile temperature during impact and estimated the fire hazard from a ricocheting projectile, as described by Badurowicz[29], et al. Additionally, this type of analysis can be used for research on new armour systems or to improve existing ones, such as those composed of new materials or composite structures.

6. CONCLUSIONS

After carrying out the above investigations, the following conclusions can be drawn.
- The highest deformation of the armour plate occurred for a 90° projectile impact angle (Table 4, Fig. 4). This occurs because the amount of energy transferred to the armour plate increases with an increase in the projectile impact angle (in the range of 0–90°)
- The dependence of the energy transferred to the armour plate and the decrease in the average velocity of the projectile debris as a function of the projectile impact angle were almost linear (Fig. 5(a), Fig. 6(b))
- The transfer of energy into the armour plate is strictly related to the dimensions of the traces after impact. As the energy increased, the dimensions of the traces increased (Fig. 5(b))
- The largest decrease in the average velocity of the projectile debris occurs for a projectile impact angle of 90° (Fig. 6)
- The greatest decrease in velocity along the OX axis occurs for a projectile impact angle of 90°, and the greatest increase in velocity along the OY and OZ axes occurs for a projectile impact angle of 45° (Fig. 7)
- The protection capability of an armour plate increases when the projectile impact angle decreases (in the range of 0–90°).

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Contributions in current study is conceptualisation, methodology, software, validation, formal analysis, investigation, resources, data curation, writing, original draft preparation and visualisation.

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Contributions to the current study is conceptualisation, methodology, software, validation, formal analysis, investigation, resources, data curation, writing - original draft preparation, and visualisation.