Journal of Materials and Manufacturing 4(2): 9-16 (2025)

Journal of Materials and Manufacturing

Numerical modelling of velocity and impact energy on ballistic behavior of plates

İsmail Efe[a], Savas Evran[b]*

[a]*Department of Occupational Safety, Institute of Pure and Applied Sciences, Marmara University, Istanbul, Türkiye*
(ORCID: 0009-0005-9550-3149), ismaaiilefe@gmail.com
[b]*Department of Jewelry and Jewelry Design, Faculty of Applied Sciences, Marmara University, Istanbul, Türkiye*
(ORCID: 0000-0002-7512-5997), sevran@marmara.edu.tr

Abstract

In this paper, which includes the numerical and statistical methods, the effect of the initial velocity of the ball and material properties of the plates on the ballistic behavior such as exit velocity and impact energy was analyzed. Calculations for explicit dynamics were implemented via ANSYS commercial software. In calculations, the fixed boundary conditions for all edges of the plates were employed. The sequences of analyses were considered via L9 orthogonal sequence with two evaluator parameters in Taguchi method. Ball velocity and material type with non-linear (NL) properties were chosen as evaluator parameters. Stainless Steel NL, Copper Alloy NL, and Aluminum Alloy NL were chosen to be material types, whereas initial velocities of the ball were selected to be 450 m/s, 475 m/s and 500 m/s. Effect of evaluator parameters and their optimum levels on exit velocity and impact energy was determined by employing analysis of signal to noise (S/N) ratio. The effective evaluator parameters and their presentence contribution ratios were decided by employing analysis of variance (ANOVA). Results of this paper displays that the most effective materials on the exit velocity of the ball were observed when using Aluminum Alloy NL, Copper Alloy NL, and Stainless Steel NL, respectively. The most powerful evaluator parameter on impact energy and the exit velocity of the ball was decided to be material type.

Keywords: ANOVA, Explicit dynamics, Material, Taguchi method

1. Introduction

In ballistic investigation, the material properties can be significant on the impact energy and initial velocity of the bullet. Selection of materials suitable for usage situations may be necessary to achieve the ideal impact energy. There are numerous studies involving ballistic examination and composite materials [1-3]. The metal materials [4, 5] in numerous of these studies were determined. Additionally, the layered plates [6-9] have been used. Besides that, the velocity in the ballistic investigation may be very significant case and thus several studies regarding to the impact of the velocity have been analyzed [10-12]. The ballistic performance investigation for various materials such as aluminum alloys [13, 14], titanium [15], copper [16], cold rolled sheet [17] to designation a few. Yunfei *et al.* [18] evaluated of initial and residual velocity based on the experimental methods and they used different metal plates such as monolithic and multi-layered steel. Kushwaha *et al.* [19] examined the ballistic behavior of the composite materials and they applied the finite element software ANSYS and different materials made from Graphene and Kevlar. Also, they found to obtain the best ballistic performance using Graphene fiber compared to Kevlar fiber material. Arslan and Güneş [20] studied the ballistic behavior of plates made from ceramic and metal materials and they employed finite element method to perform the numerical examines. Jena *et al.* [21] analyzed the ballistic behavior of various materials such as Al-7017 and

* Corresponding author
E-mail addresses: sevran@marmara.edu.tr
DOI: 10.5281/zenodo.18062148
Received: 4 August 2025, Revised: 31 August 2025, Accepted: 27 September 2025
ISSN: 2822-6054

high strength armor steel, Also, they found the highest performance for armor steel in accordance with ballistic behavior. Muskeri *et al.* [22] studied the ballistic influence of various materials made from complex alloy. Durmuş *et al.* [17] reported the experimental ballistic performance of plates made from metals and they employed the cold rolled sheet metals in the study. According to the literature relating ballistic behavior, there are numerous studies but studies containing ANSYS and Taguchi method are quite limited. In this paper, ballistic behavior of plates which have nonlinear properties was evaluated via ANSYS explicit dynamics approach, Taguchi method, and ANOVA.

Nomenclature

m	mass
V	velocity
V_i	initial velocity of the ball
V_e	exit velocity of the ball
ϱ	density
x	coordinate in x position
y	coordinate in y position
z	coordinate in z position
b	the external effect
$\dot{e}$	energy
n	test number in the explicit dynamics analysis
y_i	calculated numerical data for i^{th}
$\overline{T_v}$	the overall data of the exit velocity
$\overline{T_E}$	the overall data of the impact energy
$\overline{M_1}$	the overall results of material types for the first level
$\overline{M_3}$	the overall results of material types for the third level
$\bar{V_1}$	the overall results of the initial velocity for the first level
$\bar{V_3}$	the overall results of the initial velocity for the third level

2. Material and Method

In explicit dynamics analysis, square plate with 100 mm x 100 mm and ball with a diameter of 10 mm were operated. Material type for the ball was chosen to be stainless steel NL in the examination. Plates were modelled in accordance with fixed boundary conditions. Each plate was planned by applying metal materials with various mechanical properties. Material properties of metals were tabled in Table 1.

Table 1. Material Properties [23]

Materials	Density	Young's Modulus	Poisson's Ratio	Bulk Modulus	Shear Modulus
	ρ, kg/m³	E, GPa	v, (-)	K, GPa	S, GPa
Stainless Steel NL	7750	193	0.31	169.3	73.664
Copper Alloy NL	8300	110	0.34	114.58	41.045
Aluminum Alloy NL	2770	71	0.33	69.608	26.692

3. Explicit Dynamics Analysis

In ANSYS workbench commercial software was employed to conduct the explicit dynamics analysis for the plate and ball. Side division and body sizing approaches were applied in the mesh processes. Face meshing procedure was employed to plates in order to realize the sensitive mesh method. In body sizing for the meshing of the ball, element size value was operated to be 0.5 mm. Number of divisions in all edges of the square plates was assumed as 100. Plate was considered as flexible, whereas the ball was determined as rigid. End time for numerical explicit dynamic investigation was selected to be 8.10^{-5} s. Plates in ANSYS WORKBENCH software were determined in accordance with fixed boundary conditions for all edges. In numerical explicit dynamic investigation, the equations for density, momentum and energy can be solved as follows [24, 25]:

$$\frac{\varrho_0 V_0}{V} = \frac{m}{V} \tag{1}$$

$$\varrho\ddot{x} = b_x + \frac{\partial\sigma_{xx}}{\partial_x} + \frac{\partial\sigma_{xy}}{\partial_y} + \frac{\partial\sigma_{xz}}{\partial_z} \tag{2}$$

$$\varrho\ddot{y} = b_y + \frac{\partial\sigma_{yx}}{\partial_x} + \frac{\partial\sigma_{yy}}{\partial_y} + \frac{\partial\sigma_{yz}}{\partial_z} \tag{3}$$

$$\varrho\ddot{z} = b_z + \frac{\partial\sigma_{zx}}{\partial_x} + \frac{\partial\sigma_{zy}}{\partial_y} + \frac{\partial\sigma_{zz}}{\partial_z} \tag{4}$$

$$\dot{e} = \frac{1}{\varrho}(\sigma_{xx}\dot{\varepsilon}_{xx} + \sigma_{yy}\dot{\varepsilon}_{yy} + \sigma_{zz}\dot{\varepsilon}_{zz} + 2\sigma_{xy}\dot{\varepsilon}_{xy} + 2\sigma_{yz}\dot{\varepsilon}_{yz} + 2\sigma_{zx}\dot{\varepsilon}_{zx}) \tag{5}$$

Impact energy may be determined as follows [26]:

$$E_{impact} = \frac{1}{2}m(V_i^2 - V_e^2) \tag{6}$$

4. Statistical Analysis

Taguchi method and ANOVA were selected as different statistical approaches. Exit velocity and impact energy for the ball were considered in accordance with L9 orthogonal array including two evaluator parameters. The first evaluator parameter was selected to be material type of plate, whereas the second evaluator parameter was taken as the initial velocity for the ball. Evaluator parameters and their levels are charted in Table 2. In this study, the highest exit velocity and impact energy for the ball were intended. According to this aim, the ideal levels of evaluator parameters were operated. To achieve the maximum outcome, "Larger is Better" quality characteristic was implemented by Minitab statistical program and this quality characteristic can be determined as follows [27]:

$$(\mathrm{S/N})_{\mathrm{LB}}\ \text{for ball.} = -10.\log\left(\mathrm{n}^{-1}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{y}_{\mathrm{i}}^{2})^{-1}\right) \tag{7}$$

Table 2. Evaluator parameters and levels

Evaluator Parameters	Symbols	Units	Levels		
			Level 1	Level 2	Level 3
Material Type	M	-	Stainless Steel NL	Copper Alloy NL	Aluminum Alloy NL
Initial Velocity	V	m/s	450	475	500

5. Results and Discussion

In the paper, numerical analyses of exit velocity and impact energy for ball were operated by applying ball and plate with fixed boundary conditions. Exit velocity and impact energy of the ball were determined by ANSYS commercial software and theoretical approach. Outcomes achieved were converted to S/N ratios and S/N ratios were charted in Table 3. Visual consequences for explicit dynamics data based on ANSYS commercial software were exhibited in Figure 1.

Table 3. Results for exit velocity and impact energy of balls

Analysis	Evaluator Parameters		Results			
	Material Type	V_i, (m/s)	V_e, (m/s)	S/N ratio, (dB)	E, (J)	S/N ratio (dB)
1	Stainless Steel NL	450	342.97	50.7051	174.424	44.8321
2	Stainless Steel NL	475	383.76	51.6812	161.028	44.1380
3	Stainless Steel NL	500	419.65	52.4577	151.863	43.6290
4	Copper Alloy NL	450	389.58	51.8119	104.252	40.3617
5	Copper Alloy NL	475	417.72	52.4177	105.090	40.4312
6	Copper Alloy NL	500	444.66	52.9606	107.438	40.6232
7	Aluminum Alloy NL	450	421.60	52.4980	50.872	34.1296
8	Aluminum Alloy NL	475	447.40	53.0139	52.321	34.3734
9	Aluminum Alloy NL	500	473.13	50.7051	53.738	34.6056
	Overall Means		415.61	-	106.781	-

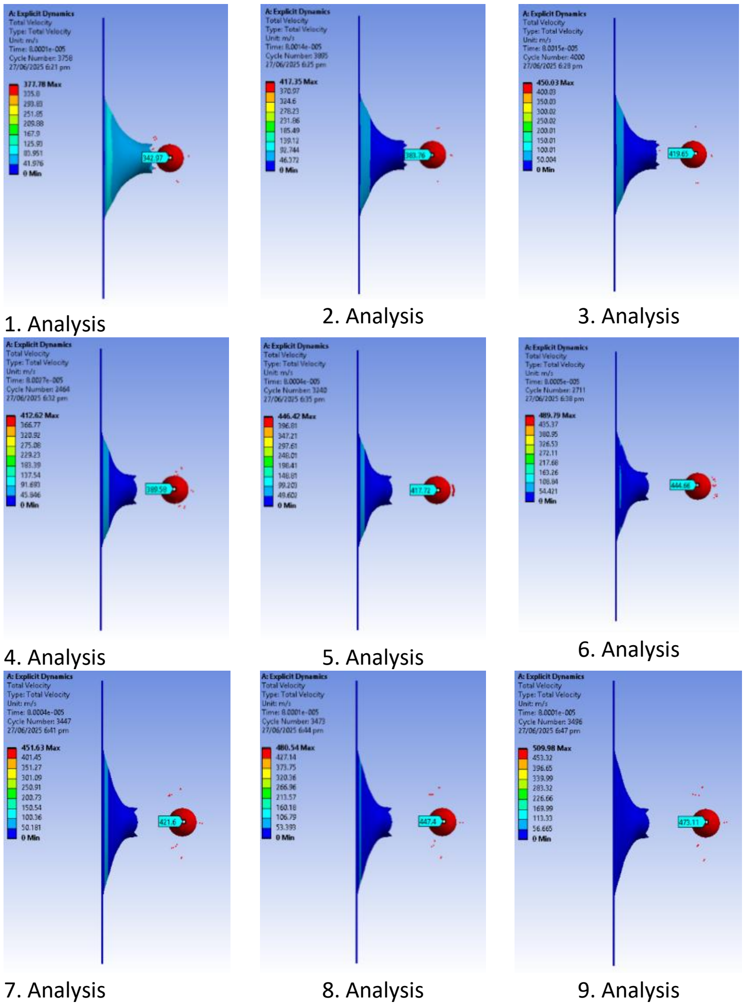


Fig. 1. Contours for explicit dynamics

As clarified in Figure 1, the highest exit velocity was observed on the ball, whereas the lowest velocity data were monitored at the plate edges. As publicized in Table 3, the highest exit velocity of the ball was achieved by operating aluminum alloy NL and initial velocity of 500 m/s, whereas the peak impact energy of the ball was considered by employing stainless steel NL and initial velocity of 450 m/s. To conclude the major impact and contribution ratio of evaluator parameters on the exit velocity and impact energy for the ball, ANOVA was achieved under 95% confidence level. ANOVA outcomes for exit velocity and impact energy of the ball were explained in Table 4.

Table 4. ANOVA results for exit velocity and impact energy of the ball

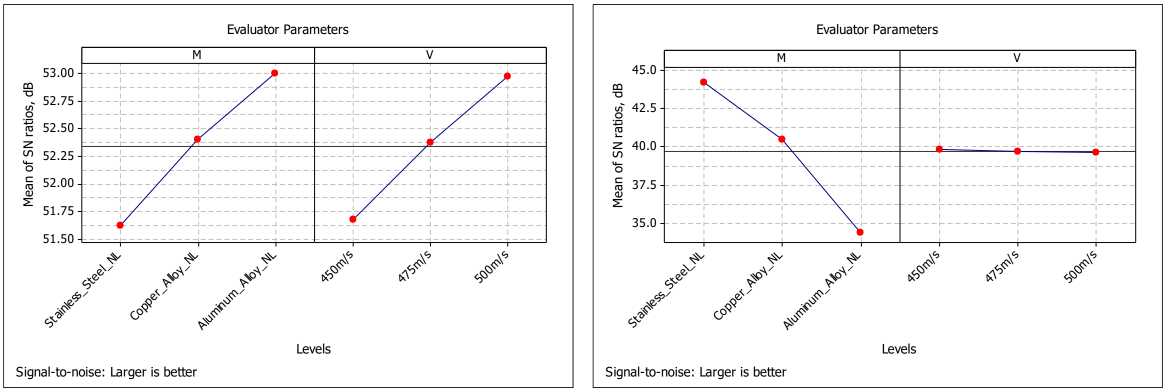
Source		Exit velocity					Impact energy				
	DF	Seq SS	Adj MS	F	P	% Effect	Seq SS	Adj MS	F	P	% Effect
M	2	6399.5	3199.8	68.3	0.001	52.51	18198.6	9099.3	165.59	0	98.55
V	2	5601.3	2800.7	59.78	0.001	45.96	47.2	23.6	0.43	0.678	0.26
Error	4	187.4	46.9			1.54	219.8	55			1.19
Total	8	12188.3				100	18465.6				100
R-Sq = %98.46, R-Sq(adj) = %96.92							R-Sq = %98.81, R-Sq(adj) = %97.62				

ANOVA outcomes in Table 4 display that evaluator parameters such as material type and initial velocity have important influences for the exit velocity of the ball due to 95% confidence level. Furthermore, the major influences for exit velocity of ball were achieved as the material type with 52.51% effect and initial velocity with 45.96% effect, respectively. Additionally, the most dominant parameters in the impact energy for ball were determined as material type with 98.55% influence and initial velocity with 0.26% influence, respectively. Material type on the exit velocity and impact energy was achieved to be meaningful parameter since P value was less than 0.05, whereas the initial velocity for the ball on the impact energy was considered to be meaningless parameter since P data was bigger than 0.05. However, initial velocity was assumed to be significant parameter on the exit velocity due to 95% confidence level. The overall results of exit velocity and impact energy of the ball at all levels of evaluator parameters were solved in accordance with "Larger is Better" quality methodology. Results achieved for the exit velocity and impact energy were established in Table 5.

Table 5. Response table for exit velocity and impact energy

Level	Exit Velocity				Impact Energy			
	S/N ration in dB		Means in m/s		S/N ration in dB		Means in J	
	M	V	M	V	M	V	M	V
1	51.61	51.67	382.10	384.70	44.20	39.77	162.44	109.85
2	52.40	52.37	417.30	416.30	40.47	39.65	105.59	106.15
3	53.00	52.97	447.40	445.80	34.37	39.62	52.31	104.35
Delta	1.39	1.30	65.30	61.10	9.83	0.16	110.13	5.50
Rank	1	2	1	2	1	2	1	2

From outcomes in Table 5, the optimal levels for the material type and initial velocity on exit velocity of the ball were assumed as the third levels. However, the ideal levels of both the material type and initial velocity for impact energy were achieved as the first levels. Additionally, rank outcomes display that the dominant evaluator parameters for exit velocity and impact energy were noticed to be material type and initial velocity, respectively. To investigate the impact of material type of the plate and initial velocity of the ball for exit velocity and impact energy in accordance with numerical explicit dynamics approach, the overall outcomes of exit velocity and impact energy for all levels of evaluator parameters based on S/N ratios were considered and main influence graphs were indicated in Figure 2a and Figure 2b, respectively.



a) Effect of material and velocity on exit velocity   b) Effect of material and velocity on impact energy

Fig. 2. Main effects schemes based on S/N ratios

From Figure 2a, increase from the first level to the third level for material type leads to an increase in exit velocity. Additionally, the increase based on the initial velocity from 450 m/s to 500 m/s leads to an increase for ball exit velocity. Therefore, the highest ball exit velocity was reached by employing aluminum alloy NL and an initial velocity of 500 m/s. Figure 2b demonstrations that the variation at the material type from the first level to the third level leads to a reduction in impact energy. Additionally, the increase based on the initial velocity from 450 m/s to 500 m/s causes a decrease for the impact energy. Therefore, the highest impact energy of the ball was considered by employing Stainless Steel NL and an initial velocity of 450 m/s. To estimate the optimal exit velocity and impact energy of the ball, the ideal levels of the evaluator parameters such as material type and initial velocity were selected. The estimated means of exit velocity and impact energy may be determined as [27], respectively:

$$\mu_{V_e} = \overline{M_3} + \overline{V_3} - \overline{T_v} \quad (8)$$

$$\mu_{E_i} = \overline{M_1} + \overline{V_1} - \overline{T_E} \quad (9)$$

Substituting the numerical data obtained from evaluator parameters including the optimal levels in Equation 8 and Equation 9, μ_{V_e} and μ_{E_i} were calculated as 477.59 m/s and 165.509 J, respectively.

Table 6. Comparison of ANSYS and predicted results

Designation	Response	ANSYS Data	Predicted Data	% Difference	Residual
M_3V_3	Exit Velocity	473.13	477.59	0.93	± 4.46
M_1V_1	Impact Energy	174.424	165.509	5.11	± 8.915

Table 6 indications that the % difference among the ANSYS and predicted outcomes were solved quite closely. This finding expresses that results achieved from numerical and statistical approaches are consistent with each other.

6. Conclusion

In the study, which includes the numerical and statistical approaches, exit velocity and impact energy obtained from the impact of the ball under different initial velocity were calculated by employing explicit dynamics analysis and theoretical approach, respectively. Exit velocity of the ball was found by applying ANSYS explicit dynamics analysis. Square plates were modelled with metals such as Stainless Steel NL, Copper Alloy NL, and Aluminum Alloy NL. For explicit dynamics calculations, fixed boundary conditions for all edges of the plates were used. Impact energy of the ball was considered by employing exit velocity in accordance with ANSYS outcomes and it was also solved theoretically. In examination, analysis conditions for ball exit velocity were determined by employing L9 orthogonal array in Taguchi method. Material type of plate and ball initial velocity were selected to be evaluator parameters, respectively. To compute the optimal levels and influence trends of evaluator parameters in exit velocity and impact energy for the ball, S/N ratio analysis were operated. In addition, the significance levels and percent contributions of evaluator parameters on exit velocity and impact energy were determined by employing ANOVA at the 95% confidence level. The comprehensive study may be summarized:

- The most efficient materials for achieving the highest exit velocity for the ball were considered as Aluminum Alloy NL, Copper Alloy NL, and Stainless Steel NL, respectively.
- The exit velocity increases with increasing initial velocity of the ball.
- The maximum exit velocity of the ball was achieved by employing plate made of Aluminum Alloy NL and the ball with initial velocity of 500 m/s.
- The materials with dominant effects for the impact energy were determined to be Stainless Steel NL, Copper Alloy NL, and Aluminum Alloy NL, respectively.
- The highest impact energy for the ball was obtained by employing plate made from Stainless Steel NL and initial velocity of 450 m/s.
- According to ANOVA data considered at 95% confidence level, the major evaluator parameters in the exit velocity of the ball were achieved to be material type and initial velocity. In addition, material type in the impact energy of the ball was determined to be strong evaluator parameter, whereas initial velocity was achieved as unimportant parameter.
- Contribution ratios for the materials and initial velocity in the exit velocity of the ball were found as 52.51% and 45.96%, respectively.
- The strongest evaluator parameters for impact energy were defined to be material type with 98.55% influence and initial velocity with 0.26% influence, respectively.
- Difference and residual results for ANSYS and predicted results based on exit velocity were solved to be 0.93% and ± 4.46, respectively, whereas difference and residual data for impact energy were calculated as 5.11% and ± 8.915, respectively.

Author Contribution Statement

İsmail Efe: Drafted and wrote the manuscript, performed the numerical results.

Savas Evran: Assisted in theoretical equations, supervised the numerical calculation and helped in manuscript preparation.

Acknowledgements

This study was supported by Marmara University Scientific Research Projects Coordination Unit (Project Number: FYL-2025-11862).

References

[1] Sah, A. K., Pathak, R. K., & Patel, S. (2023). Design and analysis of hybrid composite panels under ballistic impact. *Materials Today: Proceedings*, *87*, 104-109.

[2] Doddamani, S., Kulkarni, S. M., Joladarashi, S., TS, M. K., & Gurjar, A. K. (2023). Analysis of light weight natural fiber composites against ballistic impact: A review. *International Journal of Lightweight Materials and Manufacture*, *6*(3), 450-468.

[3] Xu, S., Li, Y., Zhou, S., Jiang, X., Xie, W., & Zhang, W. (2023). Ballistic performance and damage analysis of CFRP laminates under uniaxial pretension and precompression. *International Journal of Impact Engineering*, *178*, 104620.

[4] Goncalves, D. P., De Melo, F. C. L., Klein, A. N., & Al-Qureshi, H. A. (2004). Analysis and investigation of ballistic impact on ceramic/metal composite armour. *International Journal of Machine Tools and Manufacture*, *44*(2-3), 307-316.

[5] Benloulo, I. C., & Sanchez-Galvez, V. (1998). A new analytical model to simulate impact onto ceramic/composite armors. *International journal of impact engineering*, *21*(6), 461-471.
[6] Flores-Johnson, E. A., Saleh, M., & Edwards, L. (2011). Ballistic performance of multi-layered metallic plates impacted by a 7.62-mm APM2 projectile. *International Journal of Impact Engineering*, *38*(12), 1022-1032.
[7] Dey, S., Børvik, T., Teng, X., Wierzbicki, T., & Hopperstad, O. S. (2007). On the ballistic resistance of double-layered steel plates: An experimental and numerical investigation. *International journal of solids and structures*, *44*(20), 6701-6723.
[8] Woodward, R. L., & Cimpoeru, S. J. (1998). A study of the perforation of aluminium laminate targets. *International Journal of Impact Engineering*, *21*(3), 117-131.
[9] Radin, J., & Goldsmith, W. (1988). Normal projectile penetration and perforation of layered targets. *International Journal of Impact Engineering*, *7*(2), 229-259.
[10] Signetti, S., & Heine, A. (2022). Transition regime between high-velocity and hypervelocity impact in metals–A review of the relevant phenomena for material modeling in ballistic impact studies. *International Journal of Impact Engineering*, *167*, 104213.
[11] Liu, J., Long, Y., Ji, C., Liu, Q., Zhong, M., & Ge, S. (2018). Ballistic performance study on the composite structures of multi-layered targets subjected to high velocity impact by copper EFP. *Composite Structures*, *184*, 484-496.
[12] Di Sciuva, M., Frola, C., & Salvano, S. (2003). Low and high velocity impact on Inconel 718 casting plates: ballistic limit and numerical correlation. *International journal of impact engineering*, *28*(8), 849-876.
[13] Demir, T., Übeyli, M., & Yıldırım, R. O. (2008). Investigation on the ballistic impact behavior of various alloys against 7.62 mm armor piercing projectile. *Materials & Design*, *29*(10), 2009-2016.
[14] Woodward, R. L. (1979). Penetration behaviour of a high-strength aluminium alloy. *Metals Technology*, *6*(1), 106-110.
[15] Zheng, C., Wang, F., Cheng, X., Liu, J., Fu, K., Liu, T., ... & Jin, D. (2015). Failure mechanisms in ballistic performance of Ti–6Al–4V targets having equiaxed and lamellar microstructures. *International Journal of Impact Engineering*, *85*, 161-169.
[16] Murr, L. E., Garcia, E. P., Rivas, J. M., Huang, W., Grace, F. I., & Rupert, N. L. (1997). Ballistic penetration in thick copper plates: Microstructural characterization. *Scripta materialia*, *37*(9), 1329-1336.
[17] Durmuş, A., Güden, M., Gülçimen, B., Ülkü, S., & Musa, E. (2011). Experimental investigations on the ballistic impact performances of cold rolled sheet metals. *Materials & Design*, *32*(3), 1356-1366.
[18] Yunfei, D., Wei, Z., Yonggang, Y., & Gang, W. (2014). The ballistic performance of metal plates subjected to impact by projectiles of different strength. *Materials & Design*, *58*, 305-315.
[19] Kushwaha, A., Kushwaha, P., & Nagayach, N. (2018). Impact analysis of bullet on different ballistic resistant material using Ansys. *Int J Recent Technol Sci Manage*, *12*(1), 33-42.
[20] Arslan K, & Güneş R. International Journal of Engineering Research and Development. 2017;9:12-20. doi: 10.29137/umagd.371100
[21] Jena, P. K., Mishra, B., Kumar, K. S., & Bhat, T. B. (2010). An experimental study on the ballistic impact behavior of some metallic armour materials against 7.62 mm deformable projectile. *Materials & Design*, *31*(7), 3308-3316.
[22] Muskeri, S., Jannotti, P. A., Schuster, B. E., Lloyd, J. T., & Mukherjee, S. (2022). Ballistic impact response of complex concentrated alloys. International Journal of Impact Engineering, 161, 104091.
[23] ANSYS. Engineering Data Sources, Canonsburg, PA: ANSYS Inc. 2021.
[24] Uzun, İ., Sözeri, S., Salihoğulları, S., Durak, D., & Pehlivanlı, Z. O. (2022). Numerical Analysis of Ballistic Behavior for Aluminum Al 7075-T6. *International Journal of Engineering Research and Development*, *14*(3), 286-302.
[25] ANSYS. Ansys Explicit Dynamics Analysis Guide, Inc. Release R2. Canonsburg, PA. 2021.
[26] Subaşı, M., Doğru, M. H., Yeter, E., & Yılmaz, N. F. (2020). Investigation of the bullet impact energy performance according to variable tip geometry. *The International Journal of Materials and Engineering Technology*, *3*(1), 10-15.
[27] Ross PJ. Taguchi Techniques for Quality Engineering: McGraw-Hill International Editions, 2nd Edition, New York, USA; 1996.