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Ballistic Limit Evaluation for Impact of Pistol Projectile 9 mm Luger on Aircraft Skin Metal Plate

J. Hub[1*], J. Komenda[2] and M. Novák[3]

[1]Department of Aerospace and Rocket Technologies, University of Defence, Brno, Czech Republic
[2]Department of Weapons and Ammunition, University of Defence, Brno, Czech Republic
[3]Prototypa-ZM, Brno, Czech Republic

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Abstract:

The article describes the method of determination of limit velocity for the aluminium alloy sheet metal from the airplane fuselage skin hit by a pistol projectile of calibre 9 mm with utilisation of 2D FEM model of interaction between the projectile and the sheet metal. The simulations are based on accomplished firing experiments and results are compared. The results of simulation can be utilised for prediction of level of damage of aircraft fuselage in case of firing on board of the plane.

Keywords:

Aluminium alloy 2024-T3, pistol ammunition, 9mm Luger bullet, penetration, ballistic limit, FEM

1. Introduction

The article summarizes the results of firing experiments and Finite Element Method (FEM) simulations based on the determination of ballistic limits of duralumin sheet metal used as the outer skin layer of the aircraft. The firing experiments on sheet metals were carried out using standard and modified pistol cartridges of the calibre of 9 mm Luger with full metal jacket bullet which can be a risk factor inside the aircraft (e.g. police action on board of the airliner using a firearm).

The main aim of the experiments and subsequent simulations is to determine the limit velocity of the bullet at which the sheet metal does not puncture. The limit velocity is an important characteristic of ballistic resistance of the sheet metal. Because the experimental determination of the limit velocity is very expensive, the

[*] *Corresponding author: Department of Aerospace and Rocket Technologies, University of Defence, Kounicova 65, CZ-662 10 Brno, Czech Republic, phone: +420 973 445 189, fax: +420 973 445 147, E-mail: juraj.hub@unob.cz*

velocity is determined using theoretical-experimental method based on computer simulation utilisation supported by the results of the shooting.

2. Experimental Shooting

The firing experiment was carried out on the experimental shooting range of the company Prototypa-ZM Brno [1]. The square sheet metal samples of a dimension of 250 mm × 250 mm of the thickness of 1.2 mm and high-strength 2024-T3 duralumin material were used for experiments. This material has been designed especially for aircraft structures. The sheet metal sample was fixed in stand using four corner screws and a square-round cover plate. The movement of the bullets before they penetrate the plate and after penetration was recorded by high-speed digital camera Redlake HG 100K.

The plates were shot by monoogival pistol bullets, of a calibre of 9 mm Luger, of weight 7.5 g (standard ammunition Sellier & Bellot). With respect to the given purpose of fire shooting a standard factory ammunition was used as well as modified standard ammunition with very low initial bullet velocity around 100 m/s to achieve the shooting conditions as close as possible to the ballistic limit condition.

Modifications of ammunition consisted of a reduction of cartridge propellant charge to the lowest acceptable level in order to achieve the lowest initial bullet velocity, which corresponds to approximately one third of a standard initial velocity. Drop in initial bullet velocity is reflected in a drop in the rotation angular velocity of the bullet, however the rise in the bullet instability after leaving the ballistic weapon was not observed. Very low initial velocity due to extra reduced powder charge caused the repeated capture of bullets in the barrel.

The scheme of the shooting experiment is shown in Fig. 1.

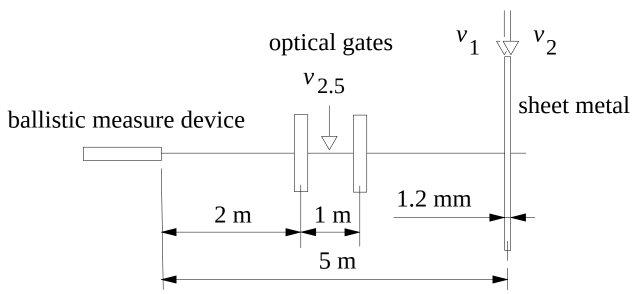


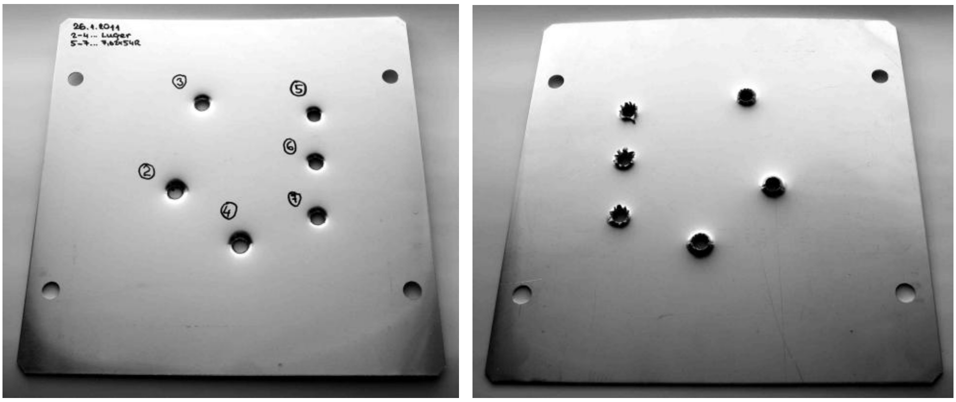
Fig. 1 Scheme of ballistic experiment

Description of symbols in Fig. 1:
$v_{2.5}$ – bullet velocity in a distance 2.5 m from muzzle of ballistic measure device measured using optical gates,
v_1 – impact velocity of the bullet before the penetration of the duralumin sheet metal captured by high-speed camera, the impact velocity v_1 is considered equal to measured velocity $v_{2.5}$,
v_2 – output velocity of the bullet penetrating the duralumin sheet metal measured using high-speed camera.
Velocities measured are shown in Tab. 1.

Tab. 1 Experimental parameters

Cartridge	No. of shots	$v_{2.5}$	v_1	v_2
		[m/s]	[m/s]	[m/s]
Standard 9 mm Luger	3	396	395	383
Standard 9 mm Luger	4	387	386	367
Average values		391	390	375
Modified 9 mm Luger	25		159	117
Modified 9 mm Luger	30		101	40

The following Fig. 2 shows perforated duralumin samples with No. of shot 3 and 4 as an example.



a) b)

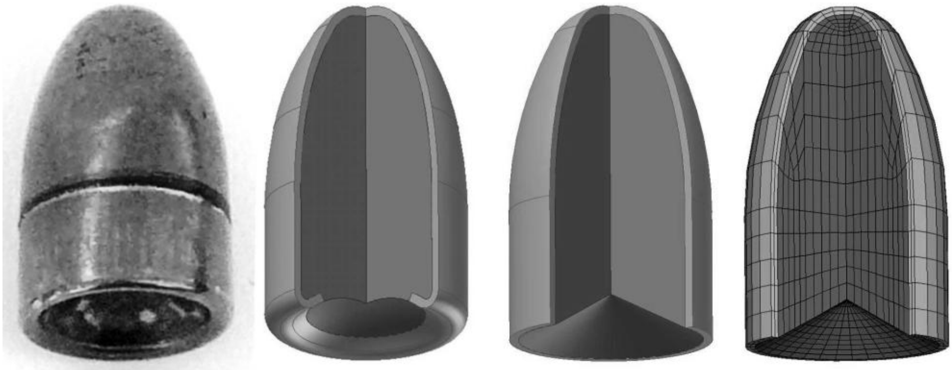
Fig. 2 Sheet metal sample penetrated by a 9mm Luger bullet with full metal jacket of standard velocity, see shot No. 3 and 4 from impact side (a) and output side (b).

3. Numerical Model

3.1. Geometry of Bullet and Sheet Metal Plate

A geometrical model of the bullet was created first using CAD system Inventor 2010 upon real geometry of the bullet, see Fig. 3b. Then a simplified model of the bullet was created which corresponds to the actual weight of a standard bullet, see Fig. 3c. And finally, the simulation model is shown in Fig. 3d with the character of mesh. Also the simulation model follows the requirement to meet the actual weight of the origin bullet of a value 7.5 g. The simulation methodology is based on [1-4].

The simulation model of the bullet and the target was created using explicit Finite Element Method system Autodyn v.13.0 with 2D symmetry so only a half of all parts were modelled. The bullet and the sheet metal parts use mesh-based Lagrangian method. The diameter of the simulation perforating sheet metal is 200 mm and it has a thickness of 1.2 mm.



a) b) c) d)

Fig. 3 9mm Luger FMJ/RN bullet – the standard bullet (a), model upon standard geometry (b), simplified model (c) and simulation model (d)

3.2. Boundary Conditions

The boundary conditions for the penetration action are initial velocity of the bullet and the gripping of the sheet metal. The velocity of the bullet is presented in Tab. 2.

Tab. 2 Bullet velocities

Bullet	No. of shots	$v_{2.5}$ [m/s]	v_1 [m/s]	v_2 [m/s]	v_{2sim} [m/s]
9 mm Luger	3	396	395	383	–
9 mm Luger	4	387	386	367	–
Average values	3, 4	391	390	375	381

The simulation model uses an average impact velocity v_1 and simulation output velocity after penetration v_{2sim} is compared with the average experimental output velocity v_2. The experimental velocities v_1 were determined using the velocities measured by optical gates $v_{2.5}$ including the reduction of the velocity caused by air drag. Neither rotation of the bullet nor air drag is considered. The gripping of the sheet metal represents restraint of outer circular perimeter in terms of zero axial velocity for boundary nodes of the sheet metal model.

3.3. Material Models

All material models for the bullet and the plate were retrieved from the Autodyn material library and in some cases, they were modified.

A sheet metal plate of the target made of aluminium alloy ASTM 2024-T3 uses the Gruneisen form of the hydrodynamic shock equation of state [5] with the following constants: $\Gamma = 2.0$, $\rho = 2780$ kg/m^3, $C_0 = 5328$ m/s and $S_1 = 1.338$.

The constitutive model expressing the relation between the shear stress and strain uses Johnson-Cook model [6]. The five material constants of the model are as follows: $A = 368.5$ MPa, $B = 683.9$ MPa, $n = 0.73$, $C = 0.0083$ and $m = 1.7$. The actual values of the constitutive constants used for the material 2024-T3 are based upon [7, 8].

The failure model uses Johnson-Cook failure model [9]. The values for the fracture Johnson-Cook material model of 2024-T3 alloy according to [7, 8] are following: D_1 = 0.112, D_2 = 0.123, D_3 = 1.5, D_4 = 0.007, D_5 = 0.

The 9mm Luger bullet consists of lead core and gilding metal jacket.

The gilding metal jacket also uses a shock equation of state with the following values: ρ = 8950 kg/m^3, Γ = 2.0, C_0 = 3958 m/s and S_1 = 1.497. The constitutive model of modified Copper retrieved from Autodyn library uses the Piecewise Johnson-Cook constitutive model. The parameters used in gilding metal jacket simulation are: G = 68800 MPa, Y_0 = 120 MPa, ε_{P1} = 0.3, Y_1 = 450 MPa, Y_2 = 450 MPa, m = 1.

The lead core is represented also by retrieved model Lead from Autodyn library using shock equation of state and Steinberg-Guinan constitutive model [10] with the following parameters: Y_0 = 8 MPa, G = 8600 MPa, β = 10000, n = 0.52, G'_P = 1, G'_T = –9.976 MPa, Y'_P = 93000.

3.4. Results of Simulations

The simulation is focused on achieving the best correlation of for two experimental and simulation shooting parameters:

- impact velocity of the bullet before penetration of the target and the residual velocity of the bullet after penetration the target,
- character of bullet and target deformations.

Fig. 4 shows the simulation model of the 9mm Luger bullet and the sheet metal at the very beginning of the simulation penetration process (a) and after the penetration of the sheet metal for the full impact velocity 391 m/s (b). The deformation of the bullet is very small on the bullet tip, the sheet metal is partly bending and partly shearing and debris occur. The whole sheet metal is bended as well and springing.

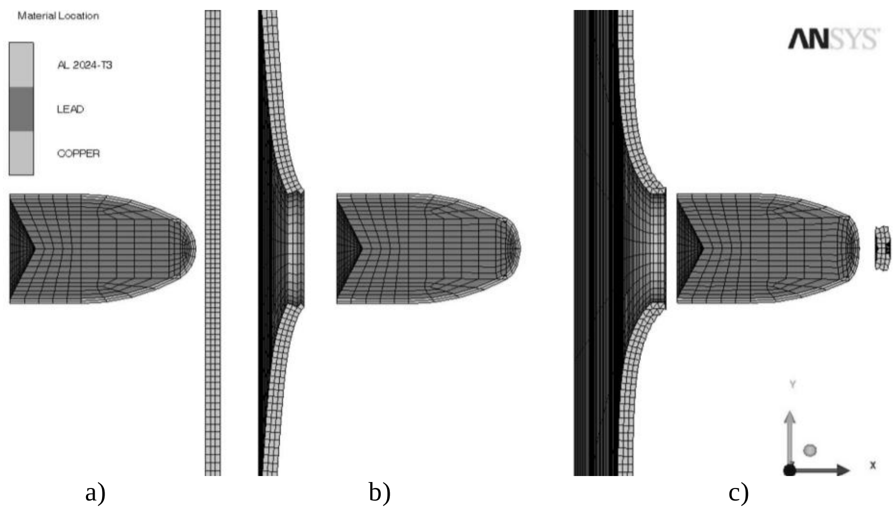


Fig. 4 Simulation model before impact (a) and after penetration of sheet metal for v_1 = 391 m/s (b) and for v_1 = 101 m/s (c)

Fig. 4c shows the simulation of the penetration of the bullet travelling with impact velocity of 101 m/s. It is possible to see larger deformation of the sheet metal when comparing to full velocity in case (b). In the process of low velocity the influence of friction arises. The bullet is deformed more on the tip than in the case (b). The debris occurs in front of the bullet.

The deformation of the output side of the sheet metal after penetration of the sheet metal is shown in Fig. 5. The simulation results (b) are created using rotation of the 2D results so it is not possible to cover the original shape of torn debris around the hollow as it occurs with experimental samples (a). Such accordance requires performing 3D simulations. Anyway the character of deformed hollow is similar.

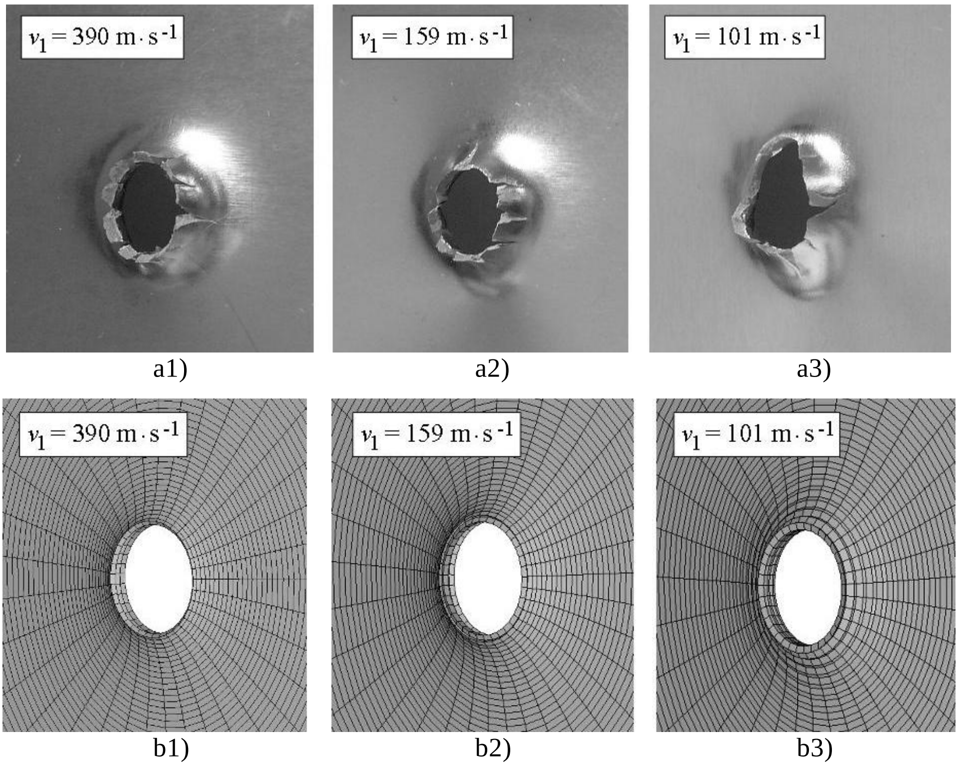


Fig. 5 Comparing the experimental (a) and simulation (b) output side of the sheet metal

When comparing the experimental cases (a1) and (a2), the bending character of deformation of hole edges a little bit more engaged is in case (a1). The shape of the penetrated sheet metal in experimental case (a3) indicates the firing conditions very close to those of ballistic limit due to the tearing character of the penetrated shape.

4. Ballistic Limit of the Bullet and the Sheet Metal Plate

In order to estimate ballistic limit of the sheet metal, experiments were conducted in order to achieve the bullet velocity as low as possible using modification of the cartridge propellant. The experimental results are shown in Tab. 4, as well as the output velocity of the bullet after penetration of the sheet metal. To achieve the exact limit velocity when the bullet does not penetrate the sheet metal is experimentally a very hard task due to instability of the bullet in low velocities. Therefore the FEM simulation approach is proposed which is based on [11] to find the limit velocity using the simulation model developed in the previous section. The simulation conditions were aimed to meet the lowest experimental velocity value due to the sensitivity of the FEM model to simulation conditions especially at low velocities.

The deformation of the bullet and the target is similar to that in previous case using standard ammunition and full bullet velocity. The values of impact and output bullet velocities are shown in Tab. 4. Velocity values with the number of shot come from experiment and they are written in bold letters.

Tab. 4 Parameters for ballistic limit estimation of the 9mm Luger bullet

No. of shots	v_1 [m/s]	v_2 [m/s]	v_{2sim} [m/s]	E_1 [J]	E_2 [J]	E_{2sim} [J]	ΔE_{2sim} [J]	$\Delta\overline{E}_{2sim}$ [%]
3, 4	**390**	**375**	**381**	**465**	**429**	**444**	**21**	**5**
	275		261	231		209	22	10
25	**159**	**117**	**132**	**77**	**42**	**53**	**24**	**31**
	140		109	60		36	23	39
	120		81	44		20	24	54
30	**101**	**40**	**41**	**31**	**5**	**5**	**26**	**84**
	98		27	29		2	27	92
	96		17	28		1	27	97
	95		0	28		0	28	100

Tab. 4 contains also derived values in terms of kinetic energy of the bullet at the moment of impact E_1, the energy after perforation of the target on experiment E_2 and the energy estimated using FEM E_{2sim}, the difference between impact and residual simulation energies, which means the energy consumption during the perforation of the target ΔE_{2sim} and the same parameter in per cent units $\Delta\overline{E}_{2sim}$ is determined using following equation

$$\Delta\overline{E}_{2sim} = \frac{E_1 - E_{2sim}}{E_1} \cdot 100$$

The difference between impact and residual simulation energies shows growing tendency from the value of 21 J at the highest velocity to the value of 28 J at the lowest ballistic limit velocity. Average value of the mentioned energy difference is 25 J.

The course of residual velocity after penetration of the bullet with respect to the impact velocity is shown on the graph in Fig. 6a. The circle marks represent the three experimental values. The simulation course is partly linear. The linear tendency of the residual velocity rapidly changes when approaching the limit velocity and this tendency follows theoretical expectations upon [12]. We assume the increased influence of the friction and bullet jacket deformation during the process of very slow bullet velocity. The FEM ballistic limit has the value of **95 m/s** when the bullet gets stuck in the penetrated sheet metal and debris occur. The limit velocity when no debris occurs has the value of **80 m/s**, so in this case no penetration occurs at all.

From the point of view of airframe damage probably no loss of the pressure in the passenger cabin caused by bullet impact happens in any of the cases. This is true for the first case with presumption of hermetizing the hole by the bullet kept stuck in the sheet metal. In the second case with no penetration the integrity of the fuselage skin in not broken by any means.

Fig. 6b shows the course of the energy consumption during the perforation of the target $\Delta\overline{E}_{2sim}$ in percent units with respect to the impact velocity v_1. The derived power equation helps to estimate the energy consumption during the perforation process and the limit velocity of the sheet metal plate 2024-T3 of the thickness 1.2 mm penetrated by the 9mm Luger bullet.

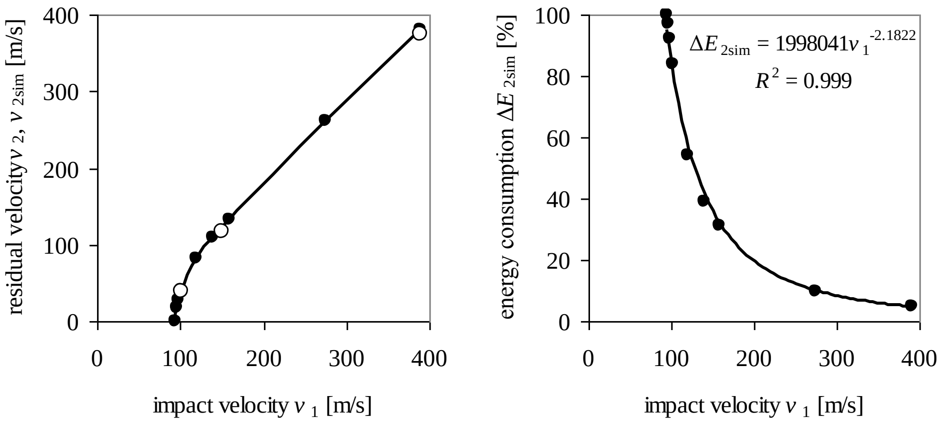


Fig. 6 Course of limit velocity (a) and course of energy consumption (b)

5. Conclusion

Presented results may be a useful basis for further work on evaluation of piercing and combined potential of pistol cartridges, both from the experimental point of view and from a theoretical analysis based on simulation models.

A numerical model has been developed supported by firing experiments that simulates the penetration of aluminium alloy sheet metal 2024-T3 of the thickness 1.2 mm used in airplane structures by 9mm Luger bullet.

The FEM simulation results show:

- Ansys Autodyn is possible to be used for modelling the bullet penetration process including the boundary conditions and implemented material models that can be modified to meet the real behaviour of the simulated parts,
- a good correlation between the experimental and simulation results in terms of comparison the residual velocities after penetration of the bullet through the target,
- a crucial influence of geometry, friction and material characteristics for simulation results,
- AL 2024-T3 duralumin sheet metal of the thickness 1.2 mm expresses just a limited ballistic resistance facing the impact of the 9mm Luger projectile fired from close distance due to the limit velocity of the value 95 m/s.

References

[1] HUB, J. et al. Determination of ballistic limit of pistol ammunition and aircraft fuselage skin metal plate. In *Proceedings of International Conference in Military Technology ICMT'11.* Brno: University of Defence, 2011, p. 1663-1682. ISBN 978-80-7231-785-5.

[2] HAZELL, P. Numerical simulations and experimental observations of the 5.65-mm L2A2 bullet perforating steel targets of two hardness values. *Journal of Battlefield Technology*, 2009, vol. 6, no. 1, p. 1-4. ISSN 14405113.

[3] HUB, J. Contribution to the FEM simulation of 7.62-59 bullet penetration of the aluminium alloy sheet metal. In: *Proceedings of 9th Symposium on Weapon Systems*. Brno: University of Defence, 2009, p. 50-53. ISBN 978-80-7231-654-0.

[4] HUB, J. Contribution to the ballistic resistance of the helicopter fuselage penetrated by 7.62-59 projectile using FEM. In: *Proceedings of the 9th International Scientific Conference New Trends in Aviation Development*. Košice: Technical University, 2010, p. 62-69. ISBN 978-80-553-0475-5.

[5] STEINBERG, D.J. *Equation of state and strength properties of selected materials*. Lawrence Livermore National Laboratory, 1996.

[6] JOHNSON, G.R. and COOK, W.H. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. In: *Proceedings of 7th International Symposium on Ballistics*. The Hague, 1983, p. 541-547.

[7] *Failure modelling of titanium 6Al-4V and aluminium 2024-T3 with the Johnson-Cook material model* [Final report DOT/FAA/AR-03/57]. Washington: U. S. Department of Transportation, 2003. 24 p.

[8] DOUBRAVA, R. Simulation of rigid projectile impact on the real aircraft structure. *Czech Aerospace Proceedings*, 2009, no. 2, p. 18-20. ISSN 1211-877X.

[9] JOHNSON, G.R. and COOK, W.H. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures. *Engineering Fracture Mechanics*. 1985, vol. 21, no. 1, p. 31-48.

[10] STEINBERG, D.J., COCHRAN, S.G. and GUINAN, M.W. A constitutive model for metals applicable at high strain rate. *Journal of Applied Physics*, 1980, vol. 51, no. 3, p. 1498-1505.

[11] HUB, J. and JEDLIČKA, L. Some aspects of machine gun penetration of the aluminium sheet-metal plate using Ansys Autodyn. In: *Proceedings of 18th Ansys Conference*. Brno: SVS FEM s.r.o., 2010, p. 45-61. ISBN 978-80-254-8388-6.

[12] CARLUCCI, D.E. and JACOBSON, S.S. *Ballistics – theory and design of guns and ammunition*. New York: CRC Press, 2008. ISBN 978-1-4200-6618-0.

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