NUMERICAL STUDY OF THE PROJECTILE TRAJECTORY DISTURBING DURING THE OBLIQUE IMPACTS

Andrzej Morka, Tadeusz Niezgoda

Military University of Technology
Department of Mechanics and Applied Computer Science
Gen. S. Kaliskiego 2 Street, 00-908 Warsaw, Poland
tel.: +48 22 6837610, fax: +48 22 6839355
e-mail: amorka@wat.edu.pl

Abstract

The numerical investigations have been performed to determine the effect of the projectile trajectory disturbing during oblique impacts. An impact of the 14.5x118mm B32 armour piercing projectile on the Al2O3 different shape elements backed by 7017 aluminum alloy plate was analyzed. The oblique impact was realized by different shapes of the frontal ceramic elements, including hemispheres and pyramids, with respect to standard flat tiles. The influence of the impact point location was also under considerations.

The Computer simulations were performed with the Element Free Galerkin Method (EFG) implemented in LS-DYNA code. Full 3D models of the projectile and targets were developed with strain rate and temperature dependent material constitutive relations. The Johson-Cook model was applied to describe the metallic parts, while the ceramic was modelled by Johnson-Holmquist constitutive relations. The models of the projectile, ceramic and aluminium alloy targets were validated with utilization of the experimental data found in literature.

The obtained results confirmed that the projectile trajectory undergoes essential deviation because of the projectile angular velocity. The conditions for maximizing the value of this angular velocity were studied and it is possible to reach several radians per millisecond. The conclusions presented in this paper can be applied to develop modern impact protection panels where the appropriate balance between the mass and protection level must be accomplished.

Keywords: *computational mechanics, impact problem, armour perforation, ballistic resistance, oblique impact*

1. Introduction

Modern ballistic protection systems, especially for light-weight armoured vehicles, are based on the multilayer armour concept. The main task to resist the projectile is given the ceramic layer backed by aluminum, titanium alloys or polymer composite material, typically. The surface density of the panel is a crucial parameter at given effectiveness then its minimizing is especially important. There is no alternative to ceramics in case of the Armour Piercing (AP) projectiles containing hard cores made off steel or tungsten alloys. The study of the projectile trajectory disturbing in oblique impacts can be important for improvement of the ballistic resistance and simultaneously reduction of the panel surface density.

In this work the oblique impact was realized by different shapes of the frontal ceramic elements, including hemispheres and pyramids, with respect to standard flat tiles. Generally armour plates have flat frontal surface, but more and more often possibility of convex or concave frontal surface panels usage is mentioned. This makes possible to determine how convex or concave frontal surface influences the result of numerical analysis. The quantitative assessment was based on the calculated value of the projectile angular velocity versus time – $\omega(t)$ of the no destroyed part of projectile. The numerical simulations were performed with the Element Free Galerkin Method (EFG) implemented in LS-DYNA code [2, 5]. Three dimensional numerical models for each frontal surface idea were developed. An explicit time integration algorithm was used as a method for the problem equations solution.

Currently the most expected ballistic resistance is related to the 14.5x118 mm B32 projectile. It ensures IV level of the ballistic protection according to the STANAG 4569 norm. Therefore this paper focuses on this kind of threat. That type of projectile consists of the soft metal jacket, incendiary material and the hard steel core. The last one part is the crucial element in penetration effectiveness. It carries overwhelming part of the projectile kinetic energy, more than 17 kJ with the impact velocity equals 910 m/s. The geometric characteristics of the hard steel core are presented in Fig. 1.

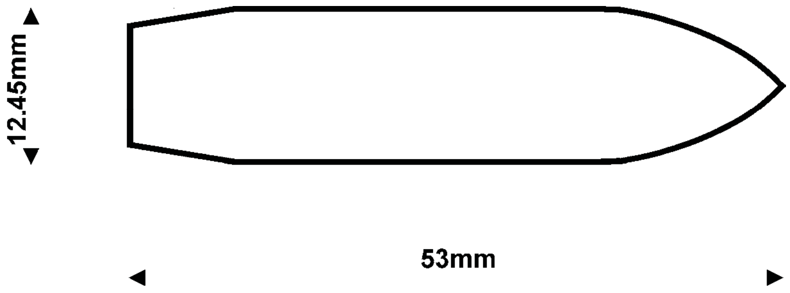


Fig. 1. A scheme of the 14.5x114 mm B32 projectile's hard steel core

2. Description of the numerical model

For the purpose of the study of the frontal surface shape influence on the armour perforation several models of targets were built: flat, convex, and concave type, Fig. 2. All of them were made of ceramic Al_2O_3 and formed on the hexagonal base plate. Two kinds of convexities and concavities were considered. First, they were formed by regular pyramids with hexagonal base. The length of the base edge equals 8 mm. The pyramids height also equals 8 mm. They are regularly spaced, starting from the centre of the target. Additionally, 8mm thick ceramic hexagonal base plates with the edge length 50 mm were located behind the pyramids layer. That plate and pyramids formed a fully integrated single body. The second type of the rough surface was prepared very similar way, but the convexities/concavities were formed by hemispheres with diameter 16 mm regularly spaced, starting from the centre of the target. It was assumed reference case with flat frontal surface 16mm thick ceramic hexagonal tile. The 10 mm thick 7017 aluminium alloy hexagonal plate was applied as a backing plate for all analyzed cases. Fig. 2 represents a crossed view of the studied configurations aimed at the projectile trajectory analysis: *B3* – convex pyramidal target surface, *C3* – concave pyramidal, *D3* – convex hemispherical, *E3* – concave hemispherical. All of them were built with application of the four node tetrahedron solid element topology. The typical node to node distance was equal about 1mm in all cases of targets and projectiles. The total number of nodes per single case exceeded 200k including 3.5k of the nodes belonging to the steel core.

The excessive deformations often met in the perforation/penetration issues caused the choice a meshless method as the method for the problem solution. The Element Free Galerkin (EFG) method implemented in the LS-DYNA solver was selected. EFG only uses a set of nodal points describing a geometry of the body, no mesh in the classic sense is needed to define the problem [1, 5]. Nodes can be generated regularly or they can be locally concentrated. The connectivity between the nodes and the approximation functions are entirely constructed by the method [3]. It uses Moving Least Squares Approximation (MLSA) technique for the construction of the shape functions. The Galerkin weak form is applied to develop the discretized system of problem equations. Either a regular background mesh or a background cell structure is used for solving partial differential equations, in order to calculate the integrals in the weak form.

The proper dynamic behaviour of metal alloys (hard steel, 7017 aluminium alloy) was realized by application of the Johnson-Cook (JC) constitutive model [4, 6] with the Gruneisen form of the Equation of State (EOS). The values of appropriate parameters are included in Tab. 1. The ceramic

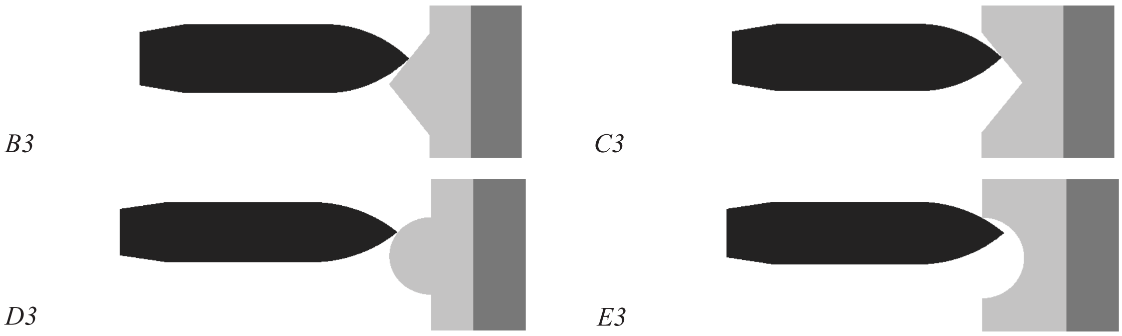


Fig. 2. A crossed view of the studied configurations aimed at the projectile trajectory analysis: B3 – convex pyramidal target surface, C3 – concave pyramidal, D3 – convex hemispherical, E3 – concave hemispherical

Tab. 1. Johnson-Cook model and Gruneisen EOS constants [4, 6]

parameter	units	hard steel	7017 Al alloy
JC			
ρ	kg/m³	7790	2470
A	GPa	1.235	0.435
B	GPa	3.34	0.343
C		0.0114	0.01
m		0.94	1.0
n		0.89	0.41
T_m	K	1800	878
T_r	K	293	293
c_p	J/kgK	460	893
EOS			
c	m/s	4570	5240
S_1		1.49	1.4
S_2		0.0	0.0
S_3		0.0	0.0
γ_0		1.93	1.97
a		0.5	0.48

Tab. 2. Johnson-Holmquist model constants [3, 5]

parameter	units	high purity Al_2O_3
JH-2		
ρ	kg/m³	3840
A		0.88
B		0.45
C		0.007
m		0.6
n		0.64
T	GPa	0.462
HEL	GPa	7.81
D_1		0.0125
D_2		0.7
EOS		
k_1	GPa	210
k_2	GPa	0.0
k_3	GPa	0.0

material was described by Johnson-Holmquist ceramic model (JH-2) [3, 5]. The material constants for high purity Al_2O_3 are presented in Tab. 2.

The initial condition was reduced to the given projectile velocity, 910 m/s. The boundary condition was assumed as the full fixing on the lateral edges of the backing hexagonal plate. The penalty type of contact was applied to characterize the model parts interaction, projectile/target and target/target. The eroding criteria thresholds, needed to reduce the calculation time, were defined at the validation stage. They are selected this way to minimize the result perturbations and keeping the acceptable agreement with the experimental data.

The developed numerical models were validated by exploitation of the literature data. The detail description can be found in [7]. Mentioned validation process was based on the comparison of the Depth of Penetration (DoP) in target material between numerical results and ballistic tests.

3. Analysis of the results

The computer simulations were performed for the selected cases. High performance computing system based on the cluster architecture was used. It let to assign 4 to 8 CPUs per single job limiting the total computing time to reasonable level. The case with the flat frontal surface is treated as the reference case and indicated by *A1*. Fig. 3 shows the residual shape of the projectile and its orientation for reference case for normal impact on the flat ceramic surface at selected moment of time. It is visible, that the projectile trajectory is not disturbed. The projectile continuous motion without rotation, but its front part underwent significant erosion.

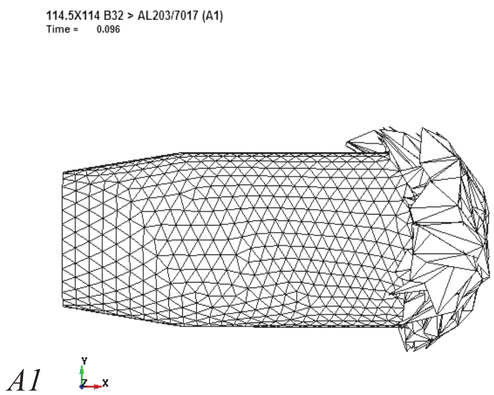
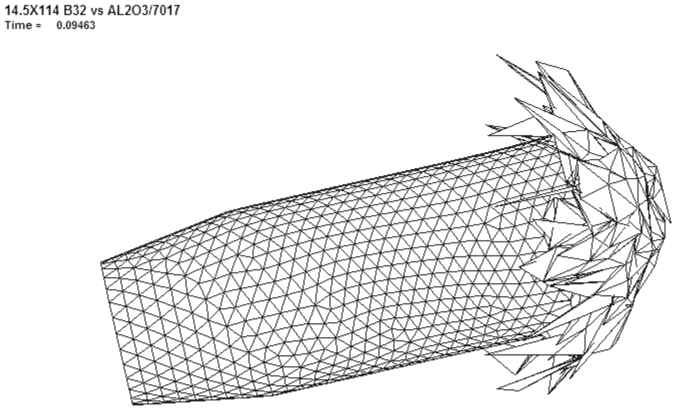


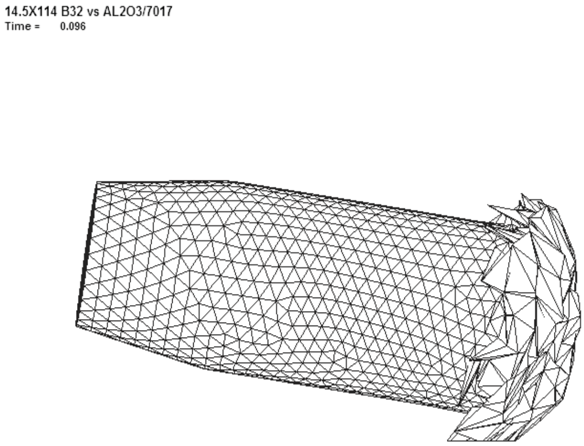
Fig. 3. The residual shape of the projectile and its orientation for reference case for normal impact on the flat ceramic surface at selected moment of time

During the calculations the time history of the projectile angular velocity was stored with given time interval. Only the integral part of the projectile was considered. The accumulated data were used to conduct an assessment of the projectile trajectory deviation. The results presented in Fig. 4 depict the residual shape of the projectile and its orientation for studied cases of oblique impacts at selected moment of time. It is observed the trajectory disturbing in all cases and erosion of the front part of projectiles. Because of rotation projectile effectiveness decreases dramatically if the impact happens with side face. Successive layers of the armour panel may be located exactly there when the projectile has been rotated by 90 degrees.

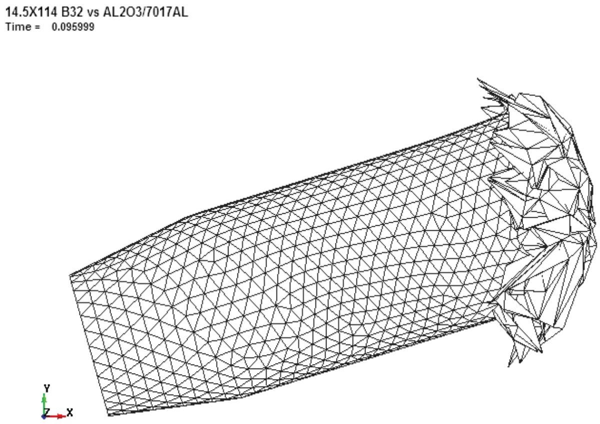
The time histories of the angular projectile velocity for all analysed cases were depicted in Fig. 5. The comparison with the standard flat surface is also showed by the black dashed line marked as *A1*. The highest value of the angular velocity is identified for the case *D3* with convex hemispherical target shape. It reached the 4 rad/ms. Considering the residual velocity of the projectile 718 m/s, it needs the distance about 28 cm to perform the 90 degrees rotation. That distance exceeds acceptable values available in realistic applications. However the further study aimed at maximizing the angular velocity and reduction of the residual projectile velocity can be conducted.



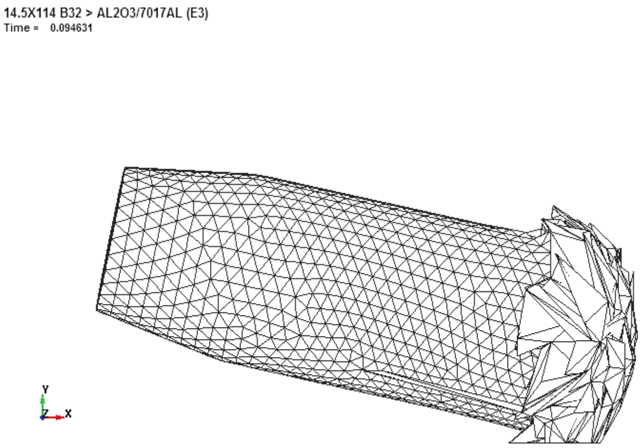
B3



C3



D3



E3

Fig. 4. The residual shape of the projectile and its orientation for studied cases at selected moment of time

5. Conclusions

The studies performed in this paper identified very interesting and promising dependencies with regard to role of the frontal surface shapes in the perforation problems.

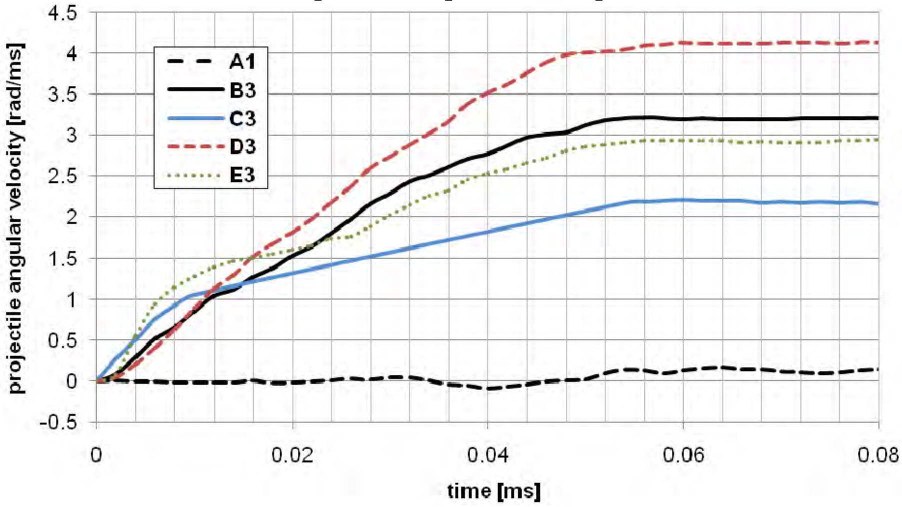


Fig. 5. Time history of the projectile's angular velocity for studied cases

The effect of the projectile trajectory disturbing due to oblique impacts was identified and measured by the angular velocity of the residual projectile part during perforation process. It is observed for all considered cases except the flat surface configuration. This angular velocity can reach even 4 rad/ms in case of convex hemispherical target shape.

The conclusions presented in this paper can be applied to develop modern impact protection panels where the appropriate balance between the mass and protection level must be accomplished.

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