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Analytical and Numerical Consideration of Projectile Density Effect on Its Penetration Ability in Alumina Armor

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Abstract: In this paper, penetration of high velocity impact of 4340 steel and tungsten carbide projectiles with specific shapes in to ceramic armor that includes 10 mm alumina (95%) is considered analytically and simulated with Ls-Dyna software. Bernoulli equation used to consider the penetration velocity in ceramics, shows that the penetration is better and easier by increasing projectile density. The simulations showed the same results as well. Using the numerical solution, ballistic limit velocity (BLV) of ceramic armor is calculated and the results showed that the increase in projectile density decreased BLV and so the tungsten carbide projectile which is heavier than steel, penetrates alumina target easier and better and with lower velocity (about 100 m/s) with respect to steel projectile in which BLV is about 170 m/s. Also, comparison between the analytical and the numerical method reveals that the compatibility of these solutions are better at higher range of velocity.

Keywords: Ballistic Limit Velocity, Density, Alumina, Ls Dyna

1. Introduction

Terminal ballistic is the first step in weapon design which considers perforation and penetration ability of projectiles in different targets. One of the most important types of the targets is ceramic armors. For example in anti bullet vests, ceramics are used to absorb the kinetic energy of projectiles and blunt its tip to prevent the penetration in Kevlar fibers that are backing materials in anti bullet vests [1].

Since the Second World War there has been a demand to develop lightweight armor systems to stop rifle bullets. The material which met this demand during that period was steel. However, with the development of fiberglass composites in early 1960s a material lighter than steel was invented [2]. This material was developed by combining a hard surface consisting of aluminum oxide ceramic and backed with a fiberglass reinforced composite. The hard ceramic surface shatters the bullet and fragmented bullet and ceramic pieces are contained in the fiberglass backing. The material is relatively cheap and easy to manufacture. The total areal density of this composite material was in excess of 60 kg/m^2 [2]. With the technology advancement in the area of ceramics, a new lower-weight ceramic was developed based on boron carbide. The boron carbide ceramics are about 20% lower in density but with a hardness surpassing the aluminum oxide. However, two problems associated with the boron carbide slowed down adoption by the military.These problems are (a) steep cost compared to aluminum oxide ceramic and (b) difficulty in maintaining consistent quality of boron carbide ceramics [2]. A change in composition and manufacturing methods resulted in a hot-pressed boron carbide ceramic. This change has also increased the reliability and reduced the cost of the ceramics. Ceramic materials are known to be stiff, brittle, very hard, and stronger in compression than in tension. Such properties are desirable to blunt and break bullets that have a steel or tungsten penetrator inside the bullet's casing [2]. However, ceramics are heavy compared with lightweight high-performance ballistic materials. Lightweight ballistic materials are not stiff or brittle and are strong in tension but poor in compression. The combination of ceramic

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facing with lightweight composite armor material backing makes the best of both materials to defeat armor-piecing bullets at the lowest weight [2]. Aluminium oxide (specific gravity 3.43 g/cm^3) was the first hard-faced ceramic to be exploited for large volume protection against armor-piercing rifle bullets (Fig. 1). Other higher performance ceramics are silicon carbide (specific gravity 3.20 g/cm^3) ceramics and boron carbide (specific gravity 2.48 g/cm^3) [2].

Ceramic faced configurations are increasingly considered for armor applications where weight efficiency is the major constraint. Wilkins presented experimental data to determine the best ratio of ceramic tile to back-up substrate thickness, against armor piercing (AP) projectiles [3,4].

A number of studies have shown that ballistic performance of ceramic-faced armor scales to some extent with the hardness of ceramic. It has also been shown that the ceramic must have a hardness that is significantly greater than that of the projectiles. For steel-based projectiles, which are common in light armor-piercing ammunition, alumina-faced armor has sufficient hardness to achieve adequate performance [5]. However tungsten-carbide-cored ammunition has a hardness level equal to or greater than some alumina compositions. Therefore, where such hard-cored projectiles are a threat there is a need to choose the correct ceramic material [5].

Alumina is one of most common ceramic materials that are used in body armors Alumina panels are fitted in pockets of vest to conserve important organs of the human body. The aim of this study is analytical and numerical consideration of projectile density effect on its penetration ability in standard alumina armor.

In this section, the alumina armor and the projectile shapes and also the dimensions are defined. Fig. 2 shows the dimensions of projectile and target. The projectile is rod which its diameter is 5.8 mm and its length is 21 mm. also, the target is 100 ×100×10 mm alumina panel.

NIJ Standard–0101.03 establishes six formal armor classification types, depends on their application. Alumina tiles with this standard dimensions are used in type IV vests [1]. Type IV body armor provides the highest level of protection currently available. Because this armor is intended to resist "armor piercing" bullets, it often uses ceramic materials with composite backing [1]. Also, this projectile is the standard core of small caliber bullets [1].

Impact velocities are varied between 100 to 500 m/s. According to Fig. 3, this range of velocity is classified as high velocity impact problem.

2. Analysis and simulations

Because of the impact of projectiles on ceramic target, the conical shape piece of ceramic panel is accelerated and therefore the ceramic fractures in this zone. Fig. 4 shows the formation of this conical fragment [6].

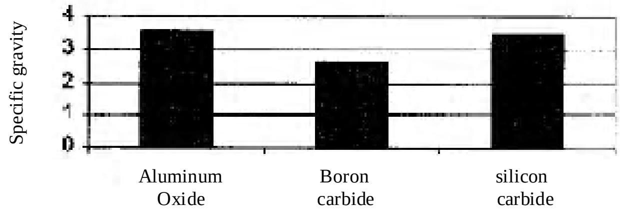

Fig. 1. Ceramics specific gravity [2].

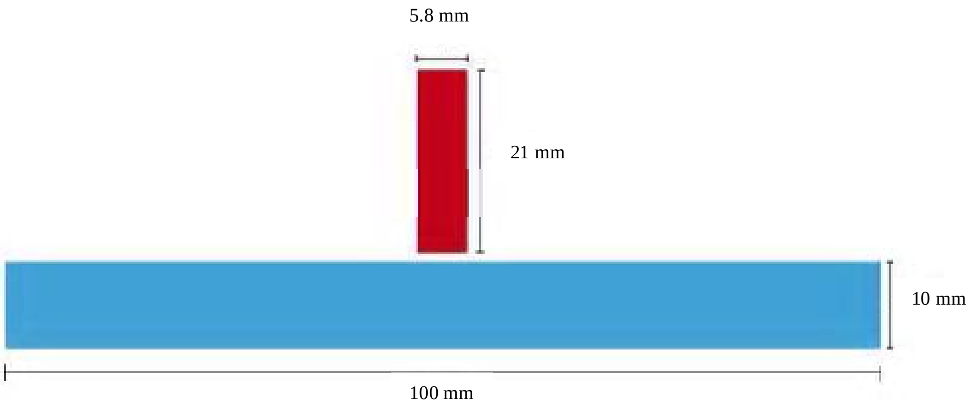

Fig. 2. Dimensions of projectile and target.

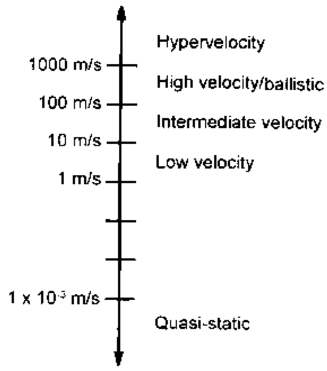

Fig. 3. Classification of impact velocity [2].

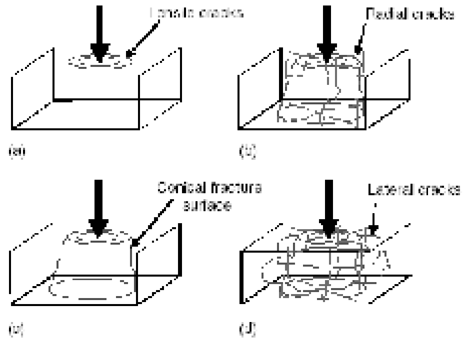

Fig. 4. Formation of conical zone in ceramic subjected to impact a) tensile cracks, b) radial cracks, c) conical fracture surface and d) lateral cracks [6].

The Bernoulli equation which used to calculate penetration velocity in semi-infinite targets is [7]:

$$\frac{1}{2} r_P (v-u)^2 + Y_P = \frac{1}{2} r_t u^2 + R_1 \qquad (1)$$

Where, V is the projectile velocity, u is the penetration velocity, ρ_p is the projectile density, Y_P is the projectile dynamic strength, ρ_t is the target density, and R_t is the ballistic resistance of the target which is assumed to be equal to its dynamic strength.

Actually, there is no semi-infinite target in nature. So, when the thickness of target is bigger than the projectile diameter, it is assumed that the target is semi-infinite and hence Eq. (1) is used.

Tate and Alekseevskii [7] solved this equation with good approximation as shown below:

$$u = \frac{v - m(v^2 + A)^{1/2}}{1 - m^2} \qquad (2)$$

where:

$$m = \left(\frac{r_r}{r_P}\right)^{1/2} \qquad A = \frac{2(R-Y)(1-m^2)}{r_r} \qquad (3)$$

So, the penetration velocity is calculated by Eq. (2). For this problem, the mechanical properties of the projectiles and the alumina armor are as follows:

$r_{steel} = 7.8\, g / cm^3$

$r_{WC} = 14\, g / cm^3$

$r_{Alu\min a} = 3.7\, g / cm^3$

$v = 800 m / s = 0.08\, cm / m\,\mathrm{sec}$

$Y_{Alu\min a} = 2GPa$

$Y_{Steel} = 2GPa$

$Y_{WC} = 2GPa$

Also, in the simulation, the 2D problems were modeled with Hypermesh software and solved with Ls dyna software. The impact velocity range is high, so the rate of strains are high and therefore JOHNSON–COOK (*mat-johnson-cook) material model used for projectiles [8]. Table 1 shows some of the constant value of Johnson-cook material model for 4340 steel [9].

Also, JOHNSON–HOLMQUIST (*mat-johnson-holmquist) used to evaluate the alumina armor (and other ceramics) behavior [11].

The GRUNEISEN equation of state (*EOS-GRUNEISEN) is used to show the flow behavior of the projectiles. The elements are quadratic (4 nodes). The models and elements are shown in Figs. 5 and 6.

Also, some constrains should be defined in the outer edge of the target to prevents its moving during impact of the projectile. This could be done by Ls-dyna software. Lagrangian solution method used to solve this problem in Ls-Dyna software.

The simulations are used to obtain the ballistic limit velocity of the projectiles. When the impact velocity is known, the numerical analysis gives the residual velocity (exit velocity of projectile from backside of the target).

3. Results and discussion

For tungsten carbide and steel projectiles with specific initial velocity, the penetration velocity in alumina is calculated by Eq. (2). In this problem, strength of the projectiles and the target are assumed to be equal (A=0 in Eq. (3)). Therefore, Eq. (2) converts to the simple form as follow:

$$u = \frac{v}{1+m} \tag{4}$$

Fig. 7 shows the variation of penetration velocity by impact for 4340 steel impacted the alumina armor.

Also, Fig. 8 shows the variation of penetration velocity by impact for tungsten carbide impacted the alumina panel.

The results revealed that increasing the projectile density at constant strength increased the penetration velocity in alumina armor. So, it could be conclude from these results that the penetration ability of dense materials like tungsten carbide in to alumina armour (or other ceramics) is more than that of other materials, like steel, which have a lower density.

To obtain the ballistic limit velocity, the numerical method is used. Ls Dyna has the ability to calculate the residual velocity for different initial velocities. In Figs. 9 and 10, the results of the simulations are shown**.**

From Figs. 9 and 10, it is revealed that the ballistic limit of 4340 steel is about 170 m/sec, but the ballistic limit is about 100 m/sec for the tungsten carbide projectile. Therefore, increasing the density decreases the ballistic limit velocity and so improves the penetration ability in the alumina panel.

Fig. 11 shows the simulation of penetration of 4340 steel in alumina panel.

Table 1. Johnson-cook material model constant values for 4340 steel [9]

A (MPa)	B (MPa)	n	c	m
950.0	725.0	0.375	0.015	0.625

Table 2. Johnson-cook material model constant values for tungsten carbide [10]

A (MPa)	B (MPa)	n	c	m
1506	177	0.12	0.016	1.0

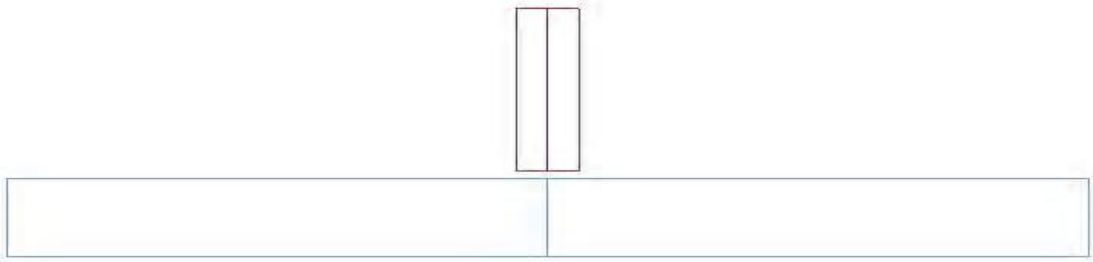

Fig. 5. Modeling of the problem in hypermesh software.

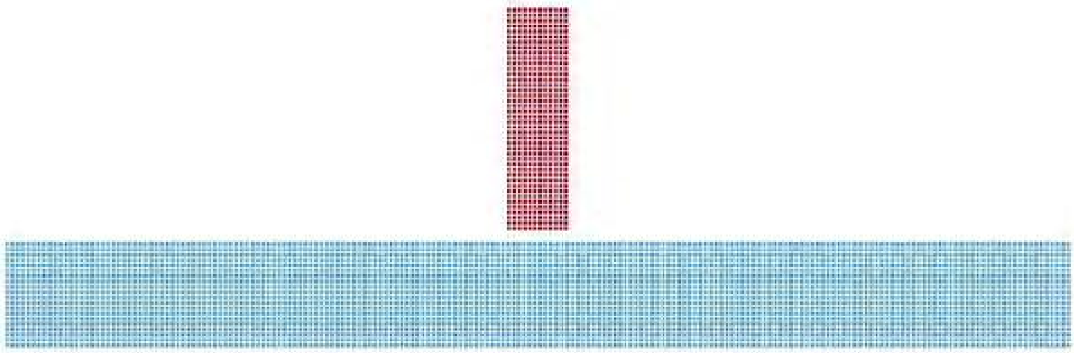

Fig. 6. Meshing the model in hypermesh software with quadratic elements.

Table 3. Johnson-holmquist material model constant values for alumina [11]

Density (Kg/m^3)	**3700**
Shear Modulus (GPa)	**90.16**
Strength Constants	
A	0.93
B	0.31
C	0.0
M	0.6
N	0.6
Ref Strain Rate (EPSI)	1.0
Tensile Strength (GPa)	0.2
Normalized Fracture Strength	NA
HEL (GPa)	2.79
HEL Pressure (GPa)	1.46
HEL Vol. Strain	0.01117
HEL Strength (GPa)	2.0
Damage Constants	
D1	0.005
D2	1.0
Equation of State	
K1 (GPa) (Bulk Modulus)	130.95
K2 (GPa)	0
K3 (GPa)	0
Beta	1.0

Fig. 11 also shows that the von mises stress near the impact region of steel in alumina (and also for impact of tungsten carbide to alumina) is greater than that of the other; regions; and so it renders to forming conoid plug that was explained earlier.

Simulations revealed that deformations of the projectiles are neglected in comparison with the armor deformations. So, by assuming that the projectiles are rigid and its mass loss is neglected, according to Ref. [7] it is obtained that:

$$u = v_r \tag{5}$$

Where u is the penetration velocity and V_r is the residual velocity of the projectile from backside of the target. Figs. 9 and 10 show that the complete penetration is occurred, when the impact velocities are higher than those of the ballistic limits. Therefore, Eq. (5) is valid just for higher velocities.

Figs. 12 and 13 demonstrate the comparison of theorical and numerical variations of residual velocities by initial impact velocities. From Figs. 12 and 13, it can be concluded that by increasing the impact velocity, compatibility between the theorical and numerical solution is better and so it could be said that the Bernoulli equation accuracy is better at higher velocities

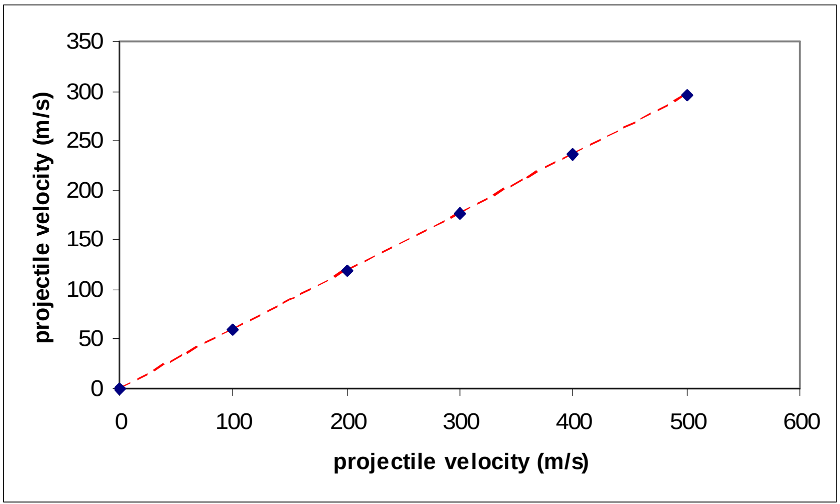

Fig. 7. Variation of penetration velocity by impact for 4340 steel impacted the alumina armor.

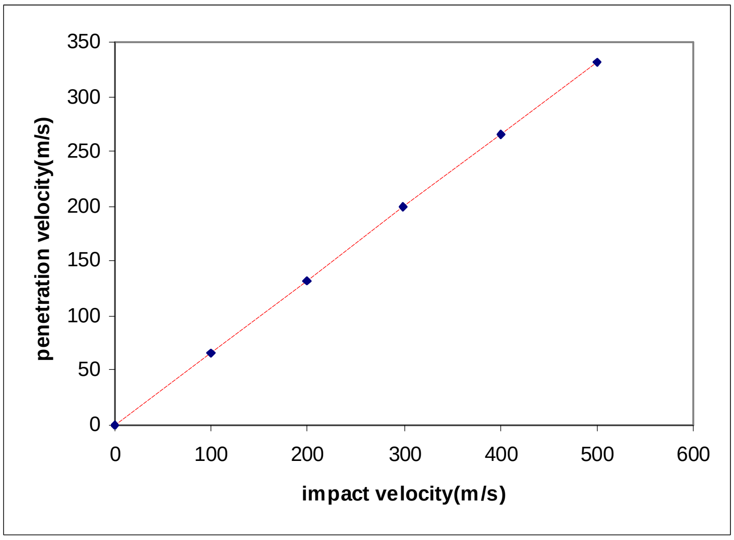

Fig. 8. Variation of penetration velocity by impact for tungsten carbide impacted the alumina armor.

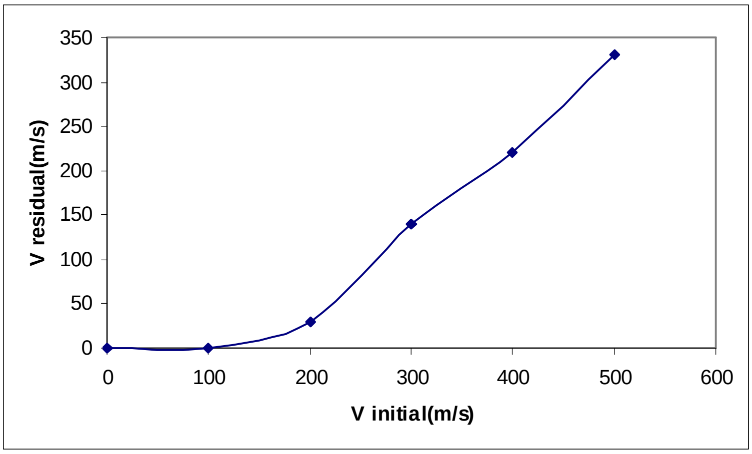

Fig. 9. Simulation results for impact of 4340 steel in alumina armor.

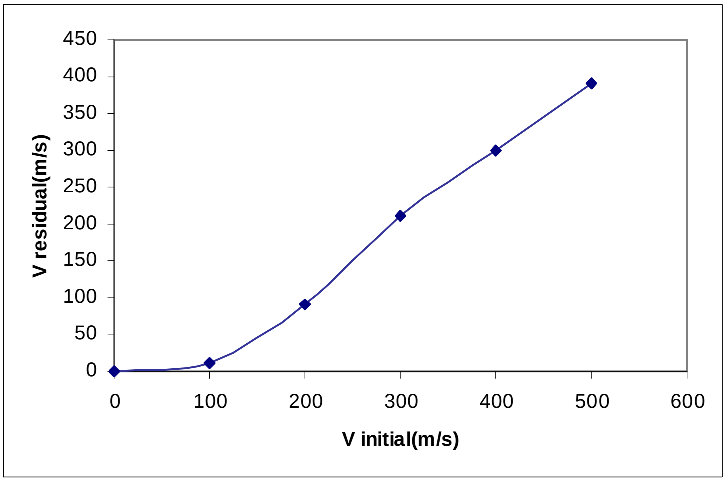

Fig. 10. Simulation results for impact of tungsten carbide in alumina.

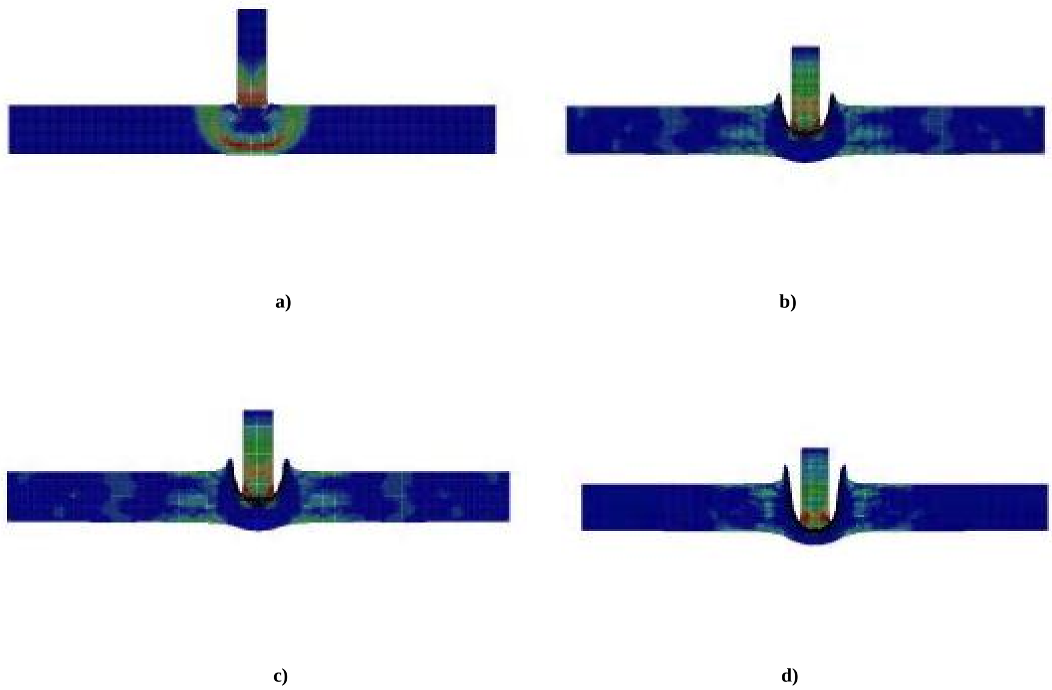

Fig. 11. Penetration of 4340 steel in alumina at a) 2 µsec, b) 10 µsec, c) 15 µsec and d) 25 µsec.

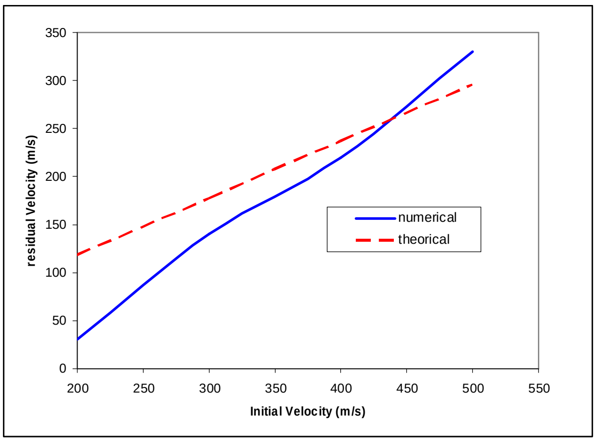

Fig. 12. Theorical and numerical variations of residual velocities by initial impact velocities for 4340 steel projectile.

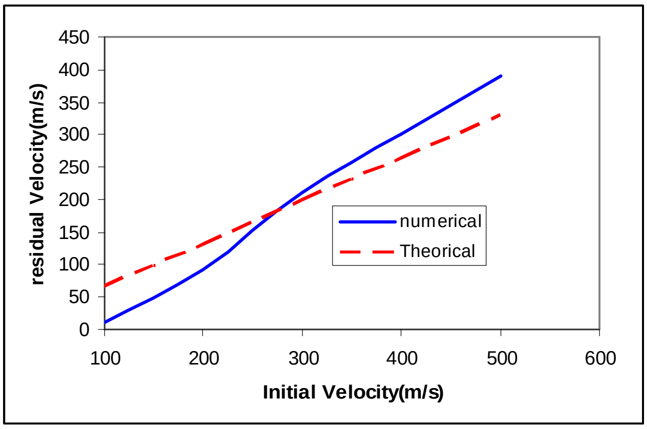

Fig. 13. Theorical and numerical variations of residual velocities by initial impact velocities for tungsten carbide projectile.

4. Conclusions

Based on the results obtained in this research, the following conclusions are drawn:

1. Growth of density of the projectile with constant shape and strength increases the penetration ability of the projectile into the alumina target.
2. Deformation of the projectiles is low; so mass losses of the projectiles could be ignored.
3. Ballistic limit velocity is 100 m/s for tungsten carbide and 170 m/s for 4340 steel projectile, therefore the penetration ability of tungsten carbide is higher than 4340 steel projectiles.

4. Comparison between analytical and numerical method reveals that the compatibility of these solutions are better at higher range of velocities.

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