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# Modeling of Hypervelocity Impact of an Armor Piercing Projectile on the Ceramic/Metallic Composite Plate

Chainarong Srikunwong

Department of Mechanical and Aerospace Engineering
Faculty of Engineering
King Mongkut's University of Technology North Bangkok,
Bangkok 10800, Thailand
Corresponding author: csw@kmutnb.ac.th

***Abstract***

In this paper, the smooth particle hydrodynamic (SPH) computation in Autodyn was applied to simulate the hypervelocity impact on the composite layered plate. Research feature was focused on the study of penetration mechanism of the armor piercing projectile, namely 7.62 mm-AP ammunition, in the ceramic/metallic specimen. This projectile was launched at velocity of 870 m/s. Numerous models were constructed aiming for parametric study associating with the influence of backup plate thickness and material selection on the performance of armor protection.

Alumina ceramic material was placed as strike-face plate. Two different metallic materials including aluminum and steel were inserted as backup plate in order to absorb the residual kinetic energy of the projectile core. Penetration mechanism of the core into the backup plate was studied.

It was revealed from the computational results that the frontal plate material plays a great role on erosion mechanism of the projectile jacket and core. Ultra-high compressive strength ceramic material helps defeating projectile during the prior stage of impact process. Penetration mechanism of steel core into the backup metallic plate was comprehensively studied and it was shown that protection performance of armor can be improved in terms of plate indentation and energy absorption with the usage of higher strength material and thicker backup plate.

Finally, the validation between the computational and the experimental results was made in order to verify the reliability of model.

***Keywords***: Armor piercing projectile, Composite armor, Numerical analysis

## 1. Introduction

Currently, a demand of personnel body armor for the protection and security of police and military officers against political conflict and terrorist's activity in the three southernmost provinces of Thailand is increased greatly during the last decade. Protection level of this personnel armor is classified to NIJ level III which indicates that wearer can be protected from the ammunitions including SS109 ballistic lunched from the M16-A2 rifle, and 7.62 mm ballistic lunched from the Kalashnikov-AK47 rifle. Their muzzle velocity can attain 850-870 m/s for 7.62 mm and 990 m/s for SS109 ball. This very high kinetic energy generates violent energy dissipation not only to the armor but also to the personal trauma. Successful commercial armor materials in terms of projectile deterioration and residual energy absorption are widely known and documented in literature [1] and can be underlined as high compressive strength ceramic, namely alumina and silicon carbide, as a conventional material for the strike-face panel and backup material, namely aluminum or 4340 steel.

However, particular Russian ball design of an armor piercing (AP) projectile dated back to the Vietnam War period, namely the 7.62-mm AP projectile, is frequently employed by the terrorist attacking the officer wearing the level III armor vest. Internal physic of such perforation process for this type of projectile is complicated even its simple design.

Many researchers contributed their effort to this science of ballistics. Gonçalves *et al.* [2] studied the impact of AP projectile against ceramic/metal armor using a simple one-dimensional model. The ceramic/metal configuration is widely used as a basic combination for the armored vehicle. They concluded that the thickness of ceramic plate plays an important role on energy reduction of the impact projectile.

Lee *et al.* [3] focused their study on the numerical simulation along with the experiment for alumina ceramic/aluminum armor against 7.62 mm-AP projectile. Smooth particle hydrodynamic (SPH) scheme was employed in their model. A comparison between experimental and numerical result was made. They concluded that the simulation method is powerful tool and cost-effective approach than experiments for optimal design of a reliable composite armor.

Recently, Kilic *et al.* [4] made an intensive effort on experiment as well as modeling of high strength steel armor against the 7.62 mm-AP ammunition. SPH computation technique was employed to simulate the damage and perforation mechanism of the projectile into armor plate.

In this paper, research feature is focused on the modeling of impact, penetration and damage process for a test serie of ceramic/metal specimens against the 7.62 mm-AP projectile lunched at 870 m/s.

## 2. Methodology of Finite Element Analysis

### 2.1 Model construction and mesh topology

A study on mesh sensitivity is conducted in [5].

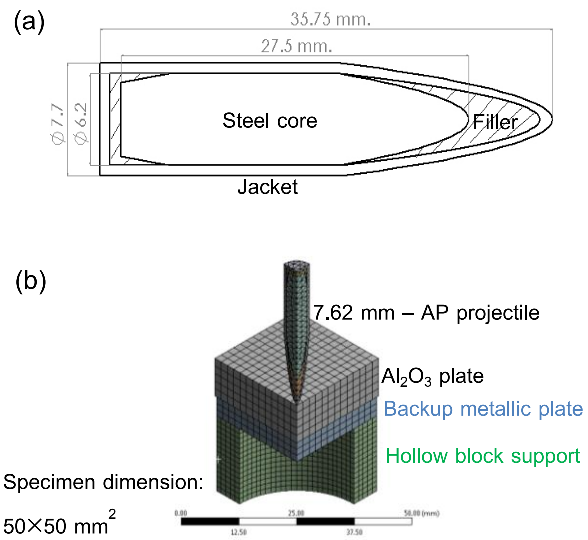


Fig.1 Model construction *(a)* the dimension of 7.62 mm-AP (0.3 Caliber AP) projectile including internal steel core *(b)* a quarter model including projectile and specimen

It is revealed that mesh size of 1.5 mm and 2 mm for projectile and plate structure yields reliable result in terms of good agreement with experiment and acceptable computation cost. The projectile dimension and mesh construction are shown in Fig. 1a and 1b, respectively. In order to simulate this phenomenon in cost-effective manner, a quarter model is constructed for both projectile and armor specimen as shown in Fig. 1b. Twelve models are constructed to study the influence of thickness of backup material on the indentation of support in accordance with [6]. The strike-face plate is made of alumina ceramic ($Al_2O_3$) for all configurations. Two materials are selected for the backup plate with thickness of 5 and 10 mm, respectively. Experiment setup and firing test program are scheduled in Table. 1.

**Table. 1** Case study of AP test schedule [6]

| Case No. / Backup mat. | Backup thickness (mm) | $Al_2O_3$ thickness (mm) |
|---|---|---|
| 1) | 5 | 8 |
| 2) 4340 Steel | 5 | 10 |
| 3) | 5 | 12 |
| 4) | 10 | 8 |
| 5) 4340 Steel | 10 | 10 |
| 6) | 10 | 12 |
| 7) | 5 | 8 |
| 8) Al 7075 T6 | 5 | 10 |
| 9) | 5 | 12 |
| 10) | 10 | 8 |
| 11) Al 7075 T6 | 10 | 10 |
| 12) | 10 | 12 |

***Note:*** *For case 7-9, experimental result shows that the backup plates are perforated and the indentation cannot be determined*

Boundary condition is the upper ceramic and the backup plates bonded at the interface. A hollow block support is inserted underneath and attached to the specimen as shown in Fig. 1b.

**2.2 Mathematic formulation**

Smooth particle hydrodynamic (SPH) computational scheme in Ansys-Autodyn code is applied studying internal physic of the impact process in this paper. Detail of Lagrange and SPH computational cycles is given in [5]. Material strength and failure models can be briefly presented as follows:

**2.2.1 Steinberg-Guinan model**: (S-G model)

Basically, the S-G model is used for characterizing the behavior of metals at high strain rate or work hardening of the lead which is the filler material inside the bullet jacket. The yield stress and the shear modulus are the following:

$$Y = Y_0\left\{1+\left(\frac{Y_P'}{Y_0}\right)\frac{P}{\eta^{\frac{1}{3}}}+\left(\frac{G_T'}{G_0}\right)(T-300)\right\}(1+\beta\varepsilon)^n \quad (1)$$

$$G = G_0\left\{1+\left(\frac{G_P'}{G_0}\right)\frac{P}{\eta^{\frac{1}{3}}}+\left(\frac{G_T'}{G_0}\right)(T-300)\right\} \quad (2)$$

where

$Y_0$ is the initial yield stress

$Y$ is the yield stress

$G_0$ is the initial shear modulus

$G$ is the shear modulus

$P$ is the pressure

$T$ is the absolute temperature

$n$ is the hardening exponent

$\beta$ is the hardening constant

$\varepsilon$ is the effective plastic strain

$\eta$ is the compression ratio

**2.2.2 Johnson-Cook model**: (J-C model)

The J-C model is employed to characterize metallic material behavior at low strain rate. This model includes the thermal softening produced by impact process on strength of material. In this paper, J-C model is applied to describe the strength of the backup plate and also the bullet steel core and copper alloy jacket. The yield stress model is given as follows:

$$Y=\left[A+B\bar{\varepsilon}_p^n\right]\left[1+C\ln\left(\frac{\dot{\bar{\varepsilon}}_p}{\dot{\varepsilon}_0}\right)\right]\left[1-\left(\frac{T-T_r}{T_m-T_r}\right)^m\right] \quad (3)$$

Where

$A$ is the initial yield stress

$B$ is the strain hardening coefficient

$n$ is the strain hardening exponent

$\dot{\bar{\varepsilon}}_p$ is the effective plastic strain rate

$\dot{\varepsilon}_0$ is the reference strain rate ($\dot{\varepsilon}_0$ =1.0 $s^{-1}$)

$C$ is the strain rate coefficient

$m$ is the temperature softening exponent

$T$, $T_r$, $T_m$ are the instantaneous local temperature, room temperature and fusion temperature of metals, respectively

$\dot{\varepsilon}^* = \dot{\bar{\varepsilon}}_p / \dot{\varepsilon}_0$ is the dimensional plastic strain rate

$T^* = \dfrac{T-T_r}{T_m-T_r}$ is the homologous temperature

**2.2.2 Johnson-Holmquist model**:(J-H model)

The J-H is suitable for describing the strength associating with fracture behavior of brittle material at a given strain rate. It is of important for this type of modeling to capture the fracture physic of material brittleness during the impact process. The J-H model can be classified into the following conditions:

Intact surface or no damage occurs (D=0)

$$\sigma_i^* = A\left(P^*+T^*\right)^N\left(1-C\ln\left|\varepsilon^*\right|\right) \quad (4)$$

Damage but not fracture (0<D<1)

$$\sigma_D^* = \sigma_i^* - D\left(\sigma_i^* - \sigma_f^*\right) \quad (5)$$

Fracture of material (D = 1)

$$\sigma_f^* = MIN\left[B\left(P^*\right)^m\left(1-C\ln\left|\varepsilon^*\right|\right)\sigma_f^{Max}\right] \quad (6)$$

Where

$\sigma_i^*$ is the stress description with no damage

$\sigma_D^*$ is the stress at initial damage

$\sigma_f^*$ is the stress at fracture

$\sigma_f^{Max}$ is the maximum stress at fracture

$A$ is the intact strength constant

$B$ is the fracture strength constant

$C$ is the strain rate constant

$P^*$ is the normalized pressure

$T^*$ is the hydrodynamic tensile limit

## 3. Results and Discussion

The chronology of the impact process of 7.62-AP projectile can be found in Fig. 2 and 3. The influence of backup plate material on the penetration mechanism is studied. At the earlier stage of impact, smaller zone of ceramic fracture can be observed in Fig. 2 at 0.005 ms. Cracks in ceramic start propagating though thickness as well as on surface as radial cracks. However for latter stages, crack is likely to propagate more clearly through the ceramic thickness than occurring on the ceramic surface. Conical fracture can be seen at 0.02 ms. One among many key benefits of using high compressive strength ceramic as strike plate is not only for eroding the projectile, but also enlarging the contact area between impact bodies by the projectile mushrooming.

For the last stages, the radial crack growth dominates the fracture in specimen. It can be observed that the rupture dimension in ceramic is enlarged along radial direction of the tile and steel core perforates through complete ruptured ceramic specimen. It is revealed from Fig. 2 and 3 that the plate is subjected to bending moment resulting from the impact force. When core stops, the backup plate is deformed permanently.

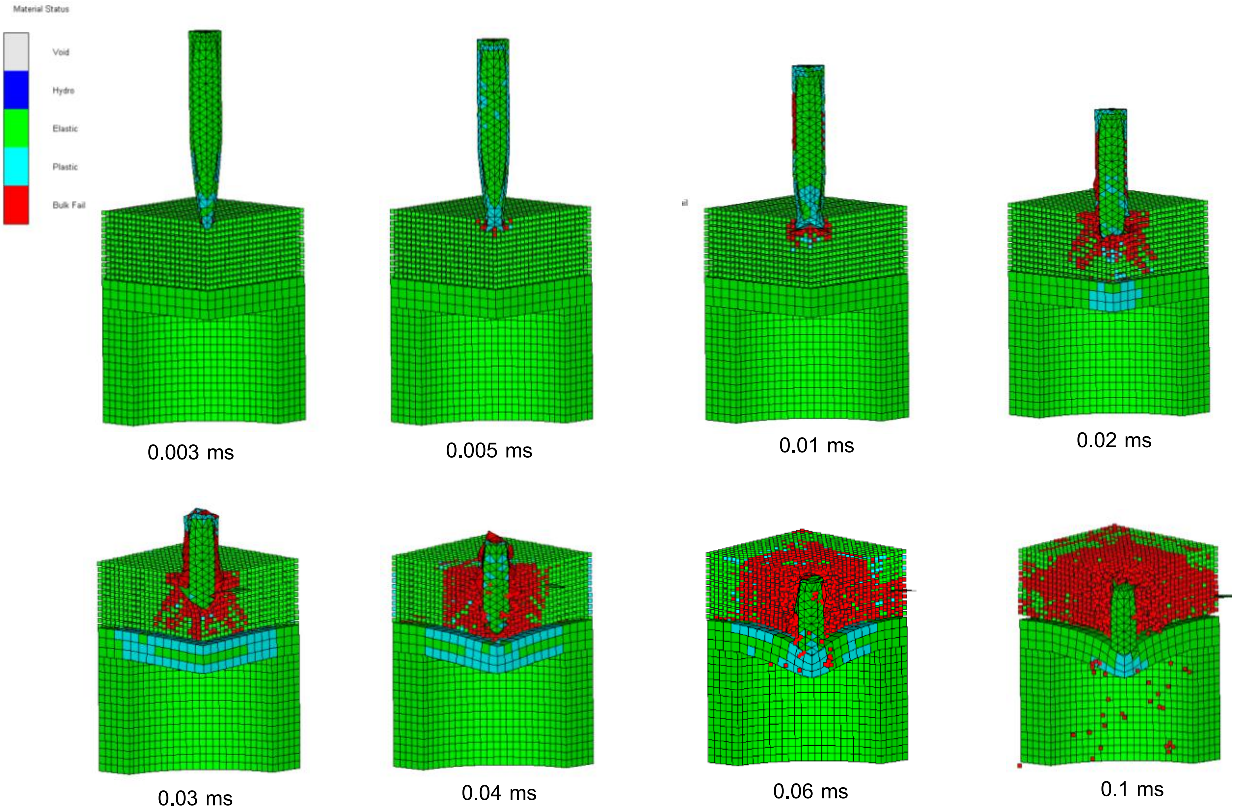


Fig. 2 Chronology of the impact process for the case 3 as indicated in Table. 1

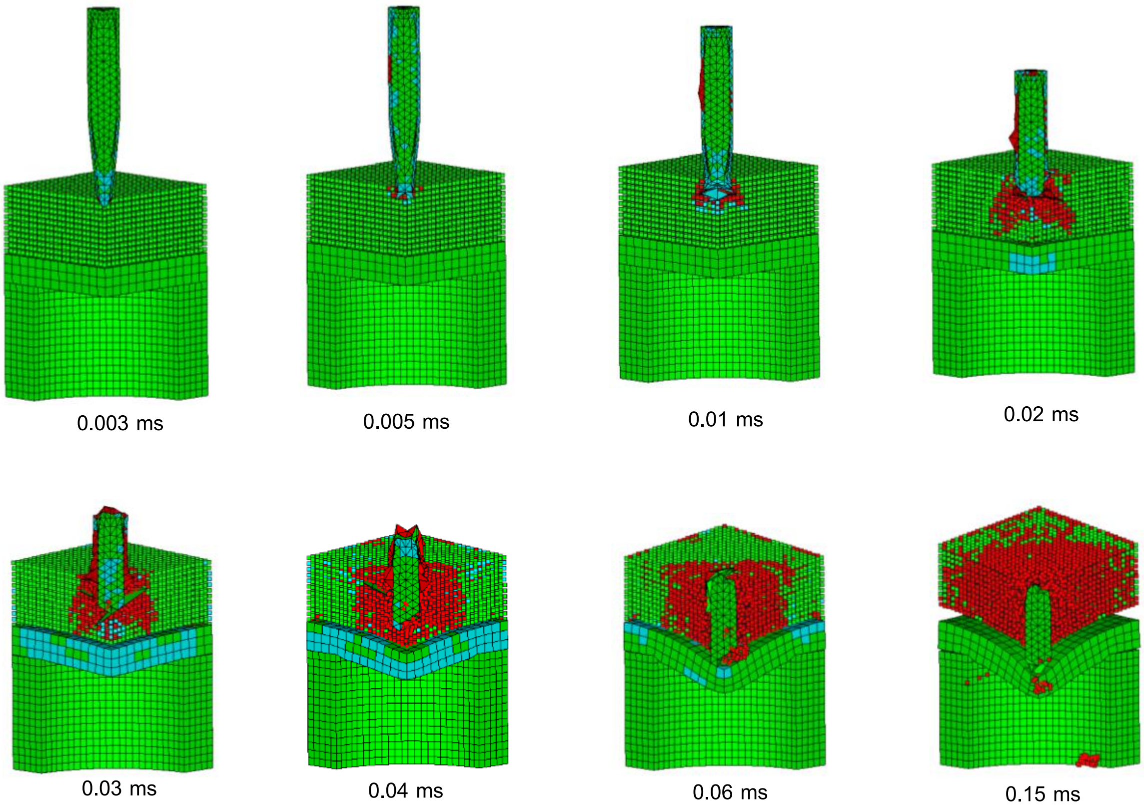


Fig. 3 Chronology of the impact process for the case 9 as indicated in Table. 1

At the final stage of process, ceramic debonding from deformed plate can be observed at o.1 and 0.15 ms, respectively.

With thicker backup plate or heavier configuration used, the plastic deformation of backup plate is reduced, however a design restriction for personnel armor is to avoid bulky and heavy armor configuration. Since the main goal in the design of an engineered armor system is to achieve the effective lightweight structure and maximum personal protection and safety.

**3.1 Energy evolution during impact process**

Velocity and energy evolution in armor system can be monitored as shown in Fig. 4. Velocity of projectile diminishes drastically and very shortly in few milliseconds as it strikes the plate. Kinetic energy of projectile shows similar trend to the velocity as it decreases with time. Total amount of kinetic energy, i.e. in an order of a thousand joules, depends on both mass and velocity of projectile component as described by the fact that higher energy level for steel core/jacket and lower energy level for the filler as shown in Fig. 4b.

Contrary to the energy evolution of projectile, the energy of the target augments as shown in Fig. 4c. It is clearly understood that most of this destructive impact energy due to projectile motion is absorbed by the frontal ceramic layer and then transferred to rupture the tile. After the global damage of alumina ceramic, the internal energy remains constant throughout the process.

A portion of residual energy is successively absorbed by the backup plate. This amount of energy is for the plastic deformation in terms of indentation and work hardening in backup material.

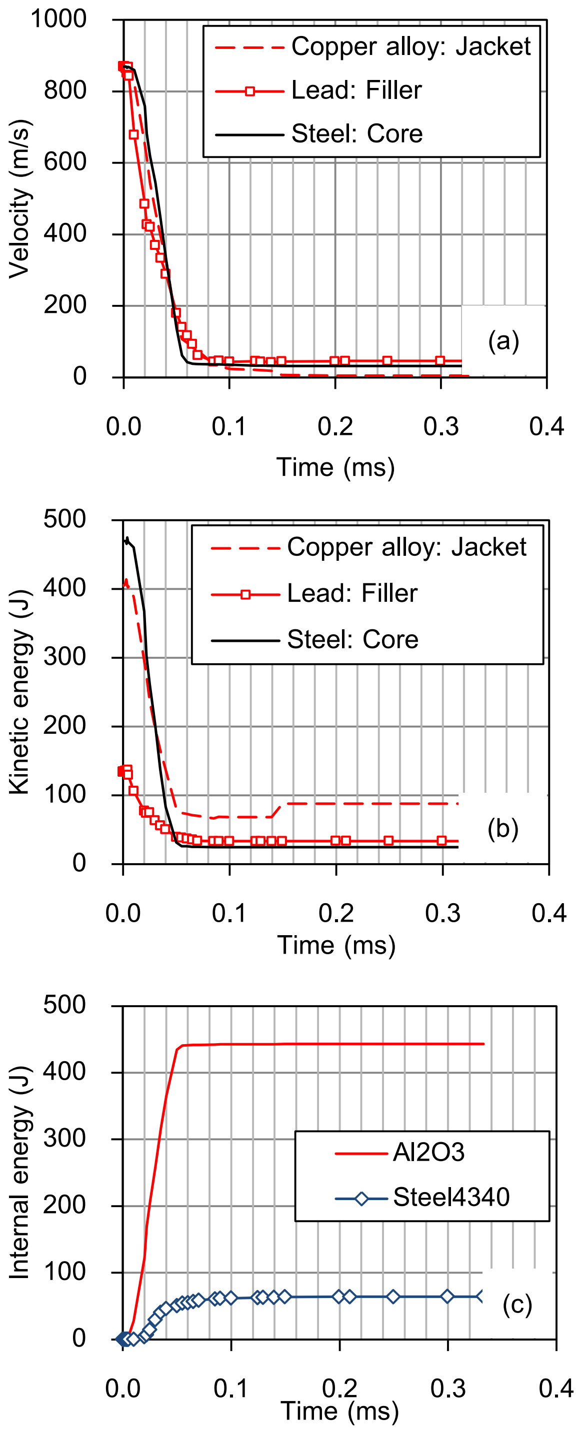


Fig. 4 Process data as a function of time
*(a)* Velocity of projectile component *(b)* Kinetic energy of projectile *(c)* Internal energy evolution of the target materials

### 3.2 Validation for plate indentation

As mentioned in the previous section, the residual energy of the projectile after ceramic rupture is used to deform the plate plastically. The plate is subjected to dynamic loading which is a combination of bending moment and thermal softening process. The plate indentation is more pronounced in the case of thinner backup material.

Indentation of backup plate is shown in Fig. 5. Constriction in specimen is found at the center of impact site where the plate thickness is reduced plastically and significantly.

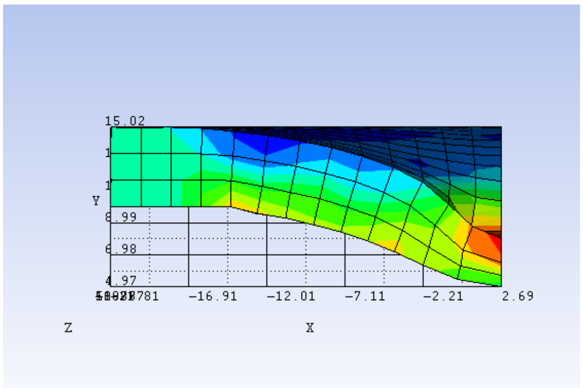


Fig. 5 Section of backup plate showing the indentation after ballistic impact process

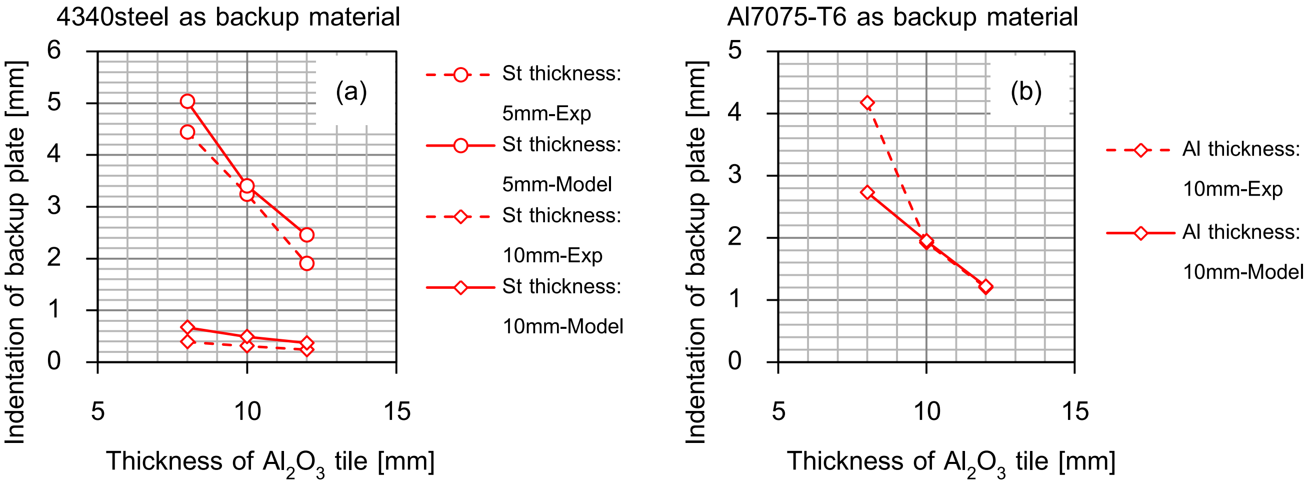


Fig. 6 Validation between numerical and experimental results *(a)* 4340steel is the backup material *(b)* Al7075-T6 is the backup material

Validation between numerical and experimental results is shown in Fig. 6. Experiment result given from [6] is compared to numerical result of this investigation. It is revealed that a good agreement of the validation can be obtained. The first important remark can be made for the thicker the backup plate the lower the indentation. It means that thicker material can absorb higher amount of residual energy and consequently produces less plastic deformation. The second remark is that the strength of backup material can be considered as a dominant parameter to reduce the indentation. Higher mechanical strength property of backup plate yields lower indentation. Little discrepancy between experimental and computational results can be observed in both Fig. 6a and 6b.

It is noted that ceramic tile thickness plays a great role on reducing the indentation if maintaining the same thickness of backup material as shown in Fig. 6.

## 4. Conclusions

Conclusions can be drawn from the result of this study as follows:

1) Numerical modeling is an effective tool to analyze the complicated impact physic of such ceramic/metallic armor plate against 7.62 mm armor piercing ballistic. A very good agreement between the experiment and modeling results can be achieved. Only little discrepancy was found in the case of thinner backup plate.

2) It was disclosed from both experimental and numerical results that the usage of thicker backup plate resulted in lowering indentation and thus improving the degree of protection to user. However, weight of the armor system and user's mobility are the dominant factor in designing or choosing an armor configuration.

3) If both plate thicknesses are maintained the same, the indentation on steel is lower than that found on aluminum. Since mechanical strength of steel is greater than that of aluminum. Consequently, steel requires more strain energy than aluminum does in order to produce the same level of indentation.

4) Increasing the thickness of ceramic tile, the protection performance of armor is improved significantly.

## 5. Acknowledgement

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## 6. References

[1] Medvedovski, E (2010). Ballistic performance of armour ceramics: Influence of design structure. Part 2, *Ceramics International*, vol. 36, pp. 2117-2127.

[2] Conçalves, D.P., de Melo, F.C.L., Klien, A.N., Al-Qureshi, H.A. (2004). Analysis and investigation of ballistic impact on ceramic/metal composite armour, *International Journal of Machine tools and Manufacturer*, vol. 44, pp. 307-316.

[3] Lee, M., Yoo, Y.H. (2001). Analysis of ceramic/metal armour system, *International Journal of Impact Engineering*, vol. 25, pp. 819-829.

[4] Kilic, N., Ekici, B. (2013). Ballistic resistance of high hardness armor steel against 7.62 mm armor piercing ammunition, *Materials and Design*, vol. 44, pp. 35-48.

[5] Takian, W., Srikunwong, C. (2011). Numerical Simulation of Ceramic/Metallic Armor Plate Subjected to Ballistic Impact, paper presented in the 25th conference of the Mechanical Engineering Network of Thailand, 19-21 Oct. 2011, Krabi, Thailand. (in Thai)

[6] Sherman, D. (2000). Impact failure mechanisms in alumina tiles on finite thickness support and the effect of confinement, *International Journal of Impact Engineering*, vol. 24, pp. 313-328.