Numerical investigation on anti-penetration behavior of ceramic/metal target under ballistic impact

H Mei¹, Y C Wang¹, X Liu¹, D F Cao², L S Liu²,⁴

¹Department of Engineering Structure and Mechanics, Wuhan University of Technology, Wuhan 430070, P. R. China
²State Key Laboratory of Materials Synthesis and Processing, Wuhan University of Technology, Wuhan 430070, P. R. China

E-mail: Liulish@whut.edu.cn

Abstract. In the paper, we used the LS-DYNA FE code to simulate the bullet penetration against the target plate with different ceramic-steel ratio of thickness. The main stages of the bullet penetration and damage contours of the target were studied by analyzing the residual velocity-time curves. We also studied energy absorption of the ceramic/metal target. Considering curves of residual velocity-time, we reckon the process of penetration contains four stages. Ceramic performed good resistance before the formation of damage cone of ceramic. But after the damage cone formed, the anti-penetration behavior kept declining. When the bullet started to penetrate the layer of metal, the anti-penetration behavior of target rose slightly. Compared with thickness ratio of 0.4 and 0.6, ceramic with 0.2 absorbed more energy and works longer. Of several different thicknesses, layers of ceramic and steel were studied. Steel per cm absorbed more energy than ceramic per cm.

1. Introduction

The extremely complex problem of a projectile impacting a ceramic backed by a metal plate has already been studied in the past decades. Penetration of composite armors by a high-speed projectile has been a subject of considerable research interest. Wilkins [1] and Florence [2] were among the early investigators of the subject of penetration mechanics of composite armors. Florence [2] developed an analytical model for the two-component armor. The model assumes a ceramic hard facing and a ductile backing plate impacted by a rigid projectile. It predicts the protection ballistic limit velocity which is a measurement of the resistance of protective armor to projectile penetration. Woodward [3] later proposed a one-dimensional model for the penetration of a projectile into ceramic armor using a lumped mass approach, which takes into account the erosion of both projectile and target in a simple way. Reijer [4] gave a more complicated model which allows projectile erosion, mushrooming, and different deformation modes for the backing plates. Ben-Dor et al. [5] proposed a slightly modified Florence’s model by introducing a coefficient in order to increase the accuracy of the
predictions.

Armor design based on the developed impact analysis models has received increasing attention during the past three decades. As Florence’s model demonstrated satisfactory agreement with experimental data [6-8], it has been widely used as a guide for the optimum design of two-component armors. Based on that model, Hetherington [9] developed an equation to obtain the optimum thickness ratio of the front and backing plates, which provides the best protection for a given aerial density. Wang and Lu [10] proposed a design criterion for calculating the optimum thickness ratio in a way that provides for optimum performance of two-component ceramic armor under a given total armor thickness. Ben-Dor et al. [5] presented an optimum design solution for the two-component armor in terms of dimensionless variables, whereby all the characteristics of the projectile and the armor are expressed as a function of two.

In this study, we used the LS-DYNA FE code to simulate the bullet penetration against the target plate with different ceramic-steel ratio of thickness. The main stages of the bullet penetration and damage contours of the target were studied by analyzing the residual velocity-time curves. We also studied energy absorption of the ceramic/metal target. In this paper, the ceramic AlN, the metal target Al and the bullet steel are selected for this investigation.

2. Numerical model

The finite element model and material parameters in this numerical analysis are described in this section.

2.1. Finite element model

In the LS-DYNA FE code, the 2D, axi-symmetric, Lagrangian, dynamic-explicit and non-linear analysis has been utilized. The sketch for the projectile, ceramic and metal layers are shown in Figure 1. A 2D axi-symmetric quadratic shell element with four nodes with y axes of symmetric has been used. The projectile and ceramic brick elements size is 0.5mm×0.5mm and the every layer of metal material is 0.5mm×0.2mm element size. The FE model considers realistic boundary conditions of the system during perforation. A zero values are imposed to the displacement in the z-direction and rotations in x and y direction for all the elements, also the edges of ceramic and metal layers is fixed. The initial impact velocity of projectile is considered as initial condition.

![Figure 1. A numerical model](image)

2.2. Material parameters

The brittle failure model proposed by the Johnson-Holmquist is well suited to the numerical constitutive modeling of brittle failure in ceramic material. The ceramic material is subjected to loading conditions that include high pressures, high strain rates and large deformations.
Table 1. JH2 parameters of ceramic (AlN)

| Density (kg/m³) | Elastic Constants | Damage Constants | Equation of State |
|-----------------|-------------------|------------------|-------------------|
| ρ (GPa)         | K (GPa)           | D1               | K1 (GPa)          |
|                 |                   | D2               | K2 (GPa)          |
|                 |                   | D3               | K3 (GPa)          |
| 3226            | 127               | 201              | 201               |
|                 | 0.02              | 1.85             | 260               |
|                 | 0                 | 0.0              | β                 |

Table 2. JC parameters of steel

| HEL (GPa) | σHEL (GPa) | PHEL (GPa) | T | T* | A | B | C | N | M | σ*fmax |
|-----------|------------|------------|---|----|---|---|---|---|---|--------|
| 9.0       | 6.0        | 5.0        | 0.32 | 0.064 | 0.85 | 0.31 | 0.013 | 0.29 | 0.21 | N/A    |

The constitutive model is based upon a GRMNEISEN equation, which evaluates the current state of pressure as a function of the volumetric change. The intact and fractured ceramic material strengths are evaluated as nonlinear functions of normalized pressure (P*), tensile strength (T*) and the normalized total incremental strain rate. The AlN material parameters are listed in table 1.

The Johnson-Cook material behaviour equation, which considers the effects of work hardening, strain rate and temperature in mechanical behaviour of projectile, has been used for metal targets (table 2). To characterize the plastic material behaviour at high pressures, typical for highly dynamic processes, the relation among the hydrostatic pressure, the local density (or specific volume), and local specific energy has been used. This relation is known as equation of state (EOS). The most commonly used reference curve to establish the Mie-Gruneisen EOS for solid materials is the shock Hugoniot and is defined in the LS-DYNA code (table 3).

Table 3. EOS_GRMNEISEN parameters of steel

| C | S1 | S2 | S3 | GAMAO | A | EO | VO |
|---|----|----|----|-------|---|----|----|
| 0.4569 | 1.49 | 0 | 0 | 2.17 | 0.46 | 0 | 1.0 |

The *MAT_PLASTIC_KINEMATIC, which is suited to model isotropic and kinematic hardening plasticity with the option including rate effects, is used for projectile (listed in table 4).

Table 4. Material properties of bullets

| Density (g/cm³) | Elastic modulus E (GPa) | Poisson ratio v | Yield stress σy (GPa) | Tangent modulus σt (GPa) | Beta β |
|-----------------|-------------------------|-----------------|------------------------|--------------------------|-------|
| 7.65            | 200                     | 0.29            | 1.6                    | 80                       | 1.0   |

3. Result and discussion

3.1. Bullet penetration and damage contour
To study the main stages in bullet penetration, we consider several different kinds of models and find a suitable model which contains integer stages of penetration and considered finally. Figure 2 shows residual velocity-time curve in the process of penetration when the steel layer sets as 0.4cm and the ceramic layer 1.6cm. The curve shows that the process of bullet penetrating contains four stages. Stage one corresponds to line OA in Figure 3, and maintains 1. Stage one is similar with ditching in theory of penetration; Stage two (line AB) is the start of form of cone, in which damage cone is constructed and the target deformation resist penetration. Stage three (line BC) is the process of bullet penetrating cone and target. Stage four (line CD) is the process of bullet penetrating over ceramic layer and move on to deformed metal layer up to the end. Stage one is transient and ignored for raising anti-penetration behavior of ceramic and steel, while stage two is significant in armor design.
The main stages can also be explored in damage contours of target. In figure 3, we choose the same model as figure 2 to explore the main stages by simulate the damage contour of target. Figure 3(a) corresponds to line OA in figure 2 and Figure 3(b) line AB. Figure 3(c) corresponds to the start of line BC, while figure 3(d) the end of line BC. Figure 3(e) corresponds to CD. When damage cone forms well (Figure 5(c)), the bullet is far from the conjunction place of ceramic layer and steel layer. But since the acceleration is declining, ceramic works at the stage of OA and AB in figure 2. The stage of ditching is limited in time. Hence the increment of ceramic will not work at contact time between ceramic and bullet. It will work to raise thickness of ceramic in improving the anti-penetration behaviour. But the increment of ceramic is will be a part of damage cone.
3.2. Energy absorption of target with different thickness ratios
Energy absorption of target is studied in the constraint of total layers with a 2cm thickness. The layer of ceramic and metal varies. In figure 4, curves of energy absorption-time in ceramic slab thickness ratios set 0.2, 0.4 and 0.6 separately when the speed of bullets set as 1000 m/s. Thickness ratio is a ratio between the thickness of a ceramic layer and a metal layer. Three curves in figure 4 are almost the same in variation. At first, the energy is linearly increasing with time until it reaches stable. Model with ratio of 0.2 has highest absorption energy at last and has longest effective time in all of them.

Figure 4. Curves of energy absorption-time when thickness ratios set 0.2, 0.4 and 0.6 separately.

Figure 5. Relation of a layer of ceramic and steel in different thickness ratio.

Figure 5 shows the compare among models with various thickness ratios in total energy absorption with a linear fit. It shows that with the increase of thickness ratio, the total energy absorption of AlN goes low, while that of steel target increases. According to the slope of fitted curves, the layer of ceramic in total energy absorption is 0.25kJ/cm, while the lay of metal in that is 1kJ/cm. In few words, when the whole thickness is fixed, steel per cm performs better in anti-penetration behavior than ceramic per cm.

4. Summary
In the article, penetrations of bullet and damage features are studied using simulation software LSDYNA. We also investigate anti-penetration of composite armor when thickness is constant and ratios of thickness vary. Conclusions are as follow:

Considering curves of residual velocity-time, we reckon the process of penetration contains four stages. Ceramic performs good resistance before the formation of damage cone of ceramic. But after the damage cone has formed, the anti-penetration behavior keeps declining. When the bullet starts to penetrate the layer of metal, the anti-penetration behavior of target rises slightly.
Compared with thickness ratio of 0.4 and 0.6, ceramic with 0.2 absorbs more energy and works longer.

With several different thicknesses, layers of ceramic and steel have been studied. Steel per cm absorbs more energy than ceramic per cm.

Acknowledgements
The work was supported by Fundamental Research Funds for the Central Universities.

Reference
[1] Wilkins ML 1978 Mechanics of penetration and perforation Int J EngSci 16 793–807
[2] Florence AL 1969 Interaction of projectiles and composite armour Part II Standford Research Institute Menlo Park California AMMRC-CR-69-15 August
[3] Woodward RL 1989 A basis for modelling ceramic composite armour defeat Material research laboratory DSTO Ascot Vale Victoria, Australia MRL-RR-3-89
[4] Den Reijer PC 1991 Impact on ceramic faced armour Ph.D. thesis Delft Univ Tech Delft The Netherlands
[5] Ben-Dor G, Dubinsky A, Elperin T and Frage N 2000 Optimisation of two-component ceramic armor for a given impact velocity Theor Appl Fract Mech 33 185–190
[6] Prior AM 1988 July The ballistic impact of small calibre ammunition on ceramic composite armour Ph.D. thesis RMCS Shrivenham
[7] Gagne MP 1989 The penetration mechanics of small arms projectiles in ceramic-faced vehicle armours 16 MVT Course RMCS Shrivenham UK
[8] Rajagopalan BP 1989 The experimental validation of an analytical model for use in composite armour design 17 MVT Course RMCS Shrivenham UK
[9] Hetherington JG 1992 The optimization of two-component composite armors Int J Impact Eng 12 409–414
[10] Wang B and Lu G 1996 On the optimization of two-component plates against ballistic impact J Mater Process Tech 57 141–145