UDC 539.4

Simulation of the Lightweight Ceramic/Aluminum Alloy Composite Armor for Optimizing Component Thickness Ratios

Z.-L. Chang,[a] W.-L. Zhao,[b] G.-P. Zou,[a,1] and H.-Q. Sun[a]

[a] College of Aerospace and Civil Engineering, Harbin Engineering University, Harbin, China

[b] College of Science, Heilongjiang University of Science and Technology, Harbin, China

[1] zouguangping901@163.com

The lightweight ceramic/aluminum alloy composite armor design is examined and optimized to get better protective performance. The armor penetrability is simulated via the smooth particle hydromechanics approach using the ANSYS/AUTODYN software. The accuracy of the program was verified by comparing with known data. Three composite armor types with the total thickness of 30, 40, and 50 mm, and five different ceramic/metal thickness ratios were analyzed in simulation of the residual bullet speed and the final distance. Simulation results are compared with the theoretical model. The best bullet protective performance of the three armor types was obtained with the ceramic/aluminum alloy thickness ratio of 4:1.

Keywords: ceramic composite armor, smooth particle hydromechanics method, penetration.

Introduction. With the development of modern missiles and other weapons, protective armors get thicker and heavier. Heavy armor substantially affects the mobility of various military vehicles, ships, airplanes, etc. It is believed that ceramic with high hardness can inactivate the projectile body and reduce its penetration ability. However, the brittleness and low tensile strength of ceramic materials make them unable to absorb a large amount of energy during fragmentation [1]. Therefore, in practice, ceramic is usually used as a panel in combination with a metal back plate to form a ceramic/metal composite armor for enhancing its dynamic penetration resistance. Among the various factors affecting the penetration resistance of ceramic/metal composite armor, the ratio of ceramic to metal thickness is an extremely important issue.

For these reasons, we numerically simulated the breakout process to find the optimal ratio of ceramic/metal composite armor of different thicknesses by the smooth particle hydromechanics (SPH) method in ANSYS/AUTODYN. Compared with the traditional finite element method, the SPH method [2, 3] is a mesh-free particle method based on Lagrange's description. It does not pull in background mesh and complex erosion algorithm, and can simulate high-speed intrusion and other large deformation problems. In this paper, SPH particle method is used to study the optimal ratio of ceramic/aluminum alloy composite armor with three different total thicknesses. The residual speed and the final length of a bullet were studied at five different thickness ratios and compared with known experimental results. The accuracy of SPH method was verified. It provides a theoretical basis for numerical calculation and design of the ceramic composite armor. The optimal ratio value is consistent with the theoretical solution. The study supplies an important knowledge for practical applications.

1. **Experimental Materials and Principles**.

1.1. ***Experimental Materials and Methods***. According to the experimental plan described in [4], the thickness (in mm) of the ceramic/aluminum composite armor was configured as follows: F20/B10, F20/B15, F25/B10, and F25/B15, where F represents the ceramic front panel and B represents the aluminum alloy backboard. The diameter of the ceramic composite armor specimen was 150 mm. The short bullet has a diameter of 12 mm, a length of 35.2 mm, a speed of 1240 m/s and tungsten metal material. The SPH method in ANSYS/AUTODYN was used for simulation.

1.2. ***Experiment Principle***.

1.2.1. *Optimization Model of the Ceramic Composite Armor with the Given Thickness*. The classic model of a projectile penetrating into the ceramic composite armor is the Florence–Ahrens model [5], as is shown in Fig. 1. In the Florence–Ahrens model, the bullet is simplified to a short, flat round rod that hits the ceramic panel. Then the bullet moves forward together with the ceramic cone formed by the impact and continues to penetrate the rest of the composite armor. The metal plate absorbs the residual energy of the bullet through deformation. To derive the expression of the ballistic limit speed, the following aspects need to be simplified:

(1) The diameter of the front surface of the ceramic cone equals to the diameter of the bullet head, and the angle of the ceramic cone formed is 63°.

(2) The deformation history of the metal backplane can be modeled as an indentation of the ceramic cone in a backplane. The initial state of the formed ceramic cone is controlled by the initial state of the bullet and the conservation of the momentum of the bullet and the bulge.

(3) The metal back plate reaches its limit tensile strain and destroy.

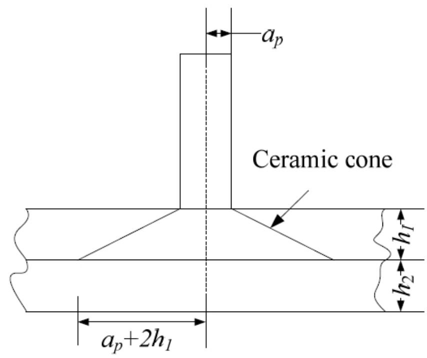

Fig. 1. The Florence–Ahrens intrusion model.

The ballistic limit speed of the Florence–Ahrens model [5] is

$$V_p = \sqrt{\varepsilon_2 \sigma_2 h_2 / [0.91 m_p f(a)]}, \tag{1}$$

$$a = a_p + 2h_1, \qquad f(a) = m_p / \{[m_p + (h_1 d_1 + h_2 d_2)]\pi a^2\},$$

where ε_2 is the fracture strain of the back plate, σ_2 is the tensile strength of the back plate, a_p is the radius of the bullet, m_p is the mass of the bullet, h_1 and h_2 are the thicknesses of the ceramic panel and the back plate, respectively, and d_1 and d_2 are the densities of the ceramic panel and the back plate, respectively.

It can be seen from the above formula that the anti-ballistic performance of the entire ceramic composite armor is related to the mass of the bullet, the density and the thickness of the ceramic panel and back plate. When the material density is higher, and the plate thickness is thicker, the armor ballistic performance is better. Also, the armor ballistic performance is better if the fracture strain of the back plate is higher and the tensile strength is larger.

Wang and Lu [6] developed the optimal design method of the ceramic composite armor under given thickness constraints within the framework of the Florence–Ahrens theory model for the ceramic composite armor penetration. Based on the Florence–Ahrens model, Wang and Lu considered the total thickness of the composite armor T as follows [6]:

$$h_2 = T - h_1 = a - a_p/2. \tag{2}$$

Substituting Eq. (2) into (1), there is

$$\frac{0.91 V_p^2 m_p}{\varepsilon_2 \sigma_2} = \frac{1}{f(a)}\left(T - \frac{a - a_p}{2}\right). \tag{3}$$

Derivation of Eq. (3) with the variable a yields:

$$\frac{f(a)}{\dot{f}(a)} = -2T + a - a_p. \tag{4}$$

The following dependence can be obtained from Eq. (3):

$$\dot{f}(a) = -\frac{f(a)[2m_p + 4Td_2\pi a^2 + \frac{d_1 - d_2}{2}\pi(5a - 4a_p)a^2]}{m_p a + Td_2\pi a^3 + \frac{d_1 - d_2}{2}\pi(a - a_p)a^3}. \tag{5}$$

From Eqs. (4) and (5) we obtain

$$3(d_1 - d_2)\pi a^4 + 5\pi[(d_1 - d_2)a_p + (2d_2 - d_1)T]a^3 -$$

$$-2\pi[4T^2 d_2 + 4(d_1 - d_2)T]a_p + (d_1 - d_2)a_p^2]a^2 + 3m_p a - 2m_p(2T + a_p) = 0. \tag{6}$$

For given composite armor parameters, the value of a can be determined. Thus, the thickness ratio of the front and back plate is

$$\frac{h_1}{h_2} = \frac{\frac{a - a_p}{2}}{T - \frac{a - a_p}{2}} = \frac{a - a_p}{2T - (a - a_p)}. \tag{7}$$

When the value of a is determined, the thickness ratio can be calculated.

For small-caliber bullets, Eq. (7) can be simplified, removing m_p and a. They are small and make a little effect on the overall value. Therefore, Eq. (7) becomes

$$3(d_1 - d_2)a^2 + 5(d_2 - d_1)Ta - 8T^2 d_2 = 0. \tag{8}$$

The solution is

$$\frac{a}{T} = \frac{-5(2d_2 - d_1) + \sqrt{25(2d_2 - d_1)^2 + 96d_2(d_1 - d_2)}}{6(d_1 - d_2)}. \tag{9}$$

The thickness ratio is

$$\frac{h_1}{h_2}=\frac{a/T}{2-a/T}=\frac{-5(2d_2-d_1)+\sqrt{25(2d_2-d_1)^2+96d_2(d_1-d_2)}}{7d_1-2d_2-\sqrt{25(2d_2-d_1)^2+96d_2(d_1-d_2)}}. \tag{10}$$

It can be seen that the optimal solution of the problem under this constraint is only related to the density of the material, the total thickness, and the bullet speed not affect it. From Eq. (10) it can be found the best thickness ratio of alumina ceramic/aluminum alloy of 4.2.

1.2.2. *Numerical Simulation of Breakout Process in Ceramic/Aluminum Composite Armor*. A bullet is made of tungsten metal, its equation of state is described by the shock equation [7]. The bullet strength is modeled by the Steinberg et al. [8] material strength model. Alumina ceramic material model uses Johnson–Holmquist strength and damage model to describe the damage of ceramic material process [9]. A description of the dynamic mechanical behavior of metal materials mostly uses Johnson–Cook strength model [10].

The ceramic/aluminum alloy thicknesses (in mm) were: F20/B10, F20/B15, F25/B10, and F25/B15, where F is the ceramic panel and B is the aluminum alloy backplane. The penetration process is shown in Fig. 2. The residual bullet speed and its final length are compared with the experimental results in [4]. The results are presented in Table 1.

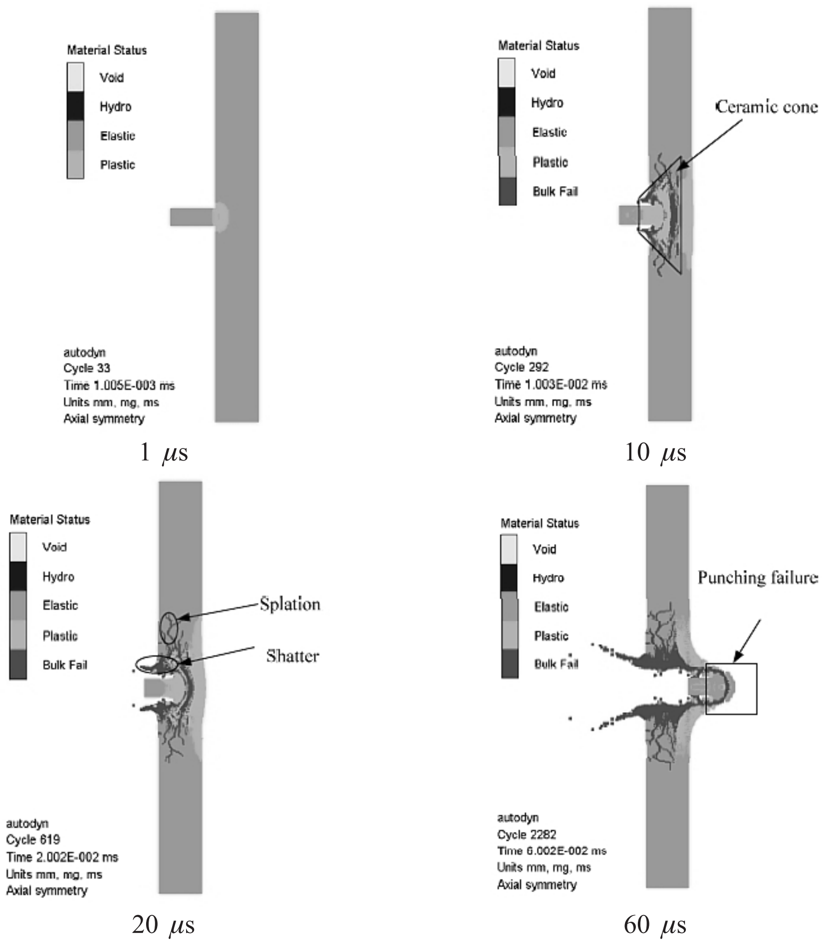

Fig. 2. The penetration process in the alumina oxide ceramic/aluminum alloy composite armor.

Table 1

Comparison between the Numerical Simulation and Experimental Result

Thickness (ceramic/ aluminum alloy, mm)	Experimental residual bullet speed in [4] (m/s)	Numerical calculation of the residual bullet speed (m/s) in [4]	Residual bullet speed (m/s) calculated numerically in this paper	Experimental final bullet length (mm)	Final bullet length (mm) calculated numerically in [4]	Final bullet length (mm) calculated numerically in this paper
F20/B10	930	1035	970	22	23	25
F20/B15	930–960	970	930	24–27	20	25
F25/B10	960	960	910	25	22	24
F25/B15	939	880	870	24	18	23

Different time stages of the composite armor penetrated by the bullet are shown in Fig. 2. At the initial stage of the collision, the bullet interacts with the ceramic. Due to a high ceramic hardness, the head of the bullet erodes and shatters, the energy of the bullet dissipates. Under the bullet impact a cone of about 63° forms in a ceramic layer. Since the stress wave is faster than the bullet, the wave reflected from the back plate causes radial damages of the far end of the bullet, accompanied by spallation. Bullet and the formed ceramic cone moves forward, and the blunted bullet intrudes into ceramics. Finally, under the effect of tensile and shear stresses, the ceramic breaks down. During this process, due to the formation of the ceramic cone, the interaction with the aluminum alloy back plate increases, so the energy absorbed by the back plate through the deformation increases as well. The aluminum alloy back plate supports ceramic and mitigates its destruction, and also absorbs impact energy due to toughness.

Comparing the residual bullet speed and its final length calculated by ANSYS/ AUTODYN with the experimental and numerical results in [4], the numerical simulation results are in good agreement with the experimental ones, indicating the applicability and high precision of the SPH particle method.

2. **Results and Analysis**. Consider the total armor thickness of 30 mm as an example. The diameter of the ceramic composite armor is 150 mm. A short tungsten bullet has a diameter of 12 mm, a length of 35.2 mm and its speed is 1240 m/s. A monitoring point to obtain the residual speed is set at the tail of the bullet. The state of the ceramic composite armor with different thickness ratios after the breakout is shown in Fig. 3.

It can be seen from Fig. 3, at different thickness ratios, the bullet forward distance and loss are not the same. The damage degree of the ceramic panel under the bullet impact is also different. The metal back plate is also damaged in different ways; the deformation area of the thick plate is obviously smaller than the deformation area of the thin plate. And in the process of disruption, the thinner plate not only forms a protrusion which moves forward with the bullet but also has tensile failure fracture nearby. The final bullet length and the residual speed in composite armors with different ceramic/aluminum thickness ratio are listed in Table 2.

It can be seen from Table 2 that the ceramic composite armor with 1:1 thickness ratio is more efficient than 2:1 and 3:1 ratio composite armors, while less efficient than 4:1 ratio armor. From 2:1 to 4:1, with the increase of the proportion of ceramic thickness, the residual speed of the bullets also reduces, and the armor anti-ballistic efficiency improves. With the increase in the thickness of the ceramic panel, the loss of bullets also increases, but the loss of a bullet in the armor with 5:1 ratio is smaller than in the armor with 4:1 ratio. This is because the thickness of the aluminum alloy backplane is too small, the support to

T a b l e 2

The Bullet Final Length and Residual Speed in 30 mm Composite Armor with Different Thickness Ratio

Ceramic/aluminum thickness ratio	Final bullet length (mm)	Residual bullet speed (m/s)
1:1	26.6	960
2:1	26.1	970
3:1	25.9	963
4:1	25.2	950
5:1	25.3	975
No aluminum back plate	25.3	990

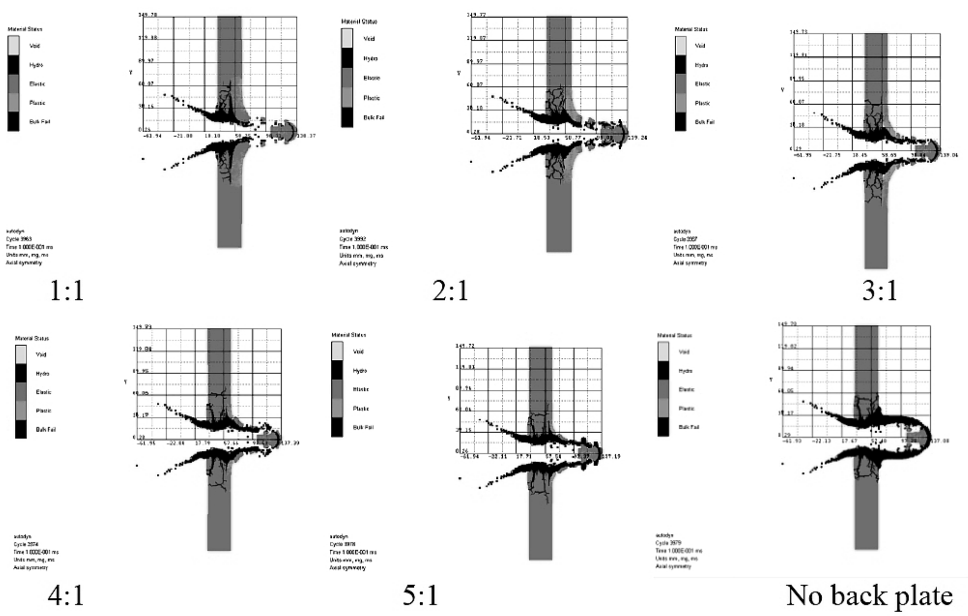

Fig. 3. The breakout of 30 mm composite armor with different ratio of ceramic/aluminum thicknesses.

the ceramic panel is less efficient, thus the erosion of the bullet is reduced. And the ceramic without aluminum alloy backing has the lowest ballistic performance.

Figure 4 shows the residual bullet speed as a function of the thickness ratio at three different total thicknesses of the composite armor. It can be seen from the curves that under the protection of ceramic composite armor with different total thickness, the minimum bullet residual speed is near the thickness ratio of 4:1. For the armor with the total thickness of 30 mm, 40 mm, and 50 mm, the minimum residual velocities after bullet breakout are 950, 807, and 653 m/s, respectively. The obtained by numerical simulation optimal anti-ballistic performance of the ceramic/aluminum composite armor is in good agreement with the calculated optimal thickness ratio of 4.2:1 in the theoretical model by Wang and Lu. It can be seen from Fig. 4, that with the decrease in the aluminum alloy back plate thickness after the optimal configuration ratio of 4:1, the overall ballistic performance of the composite armor obviously decreases regardless the total thickness.

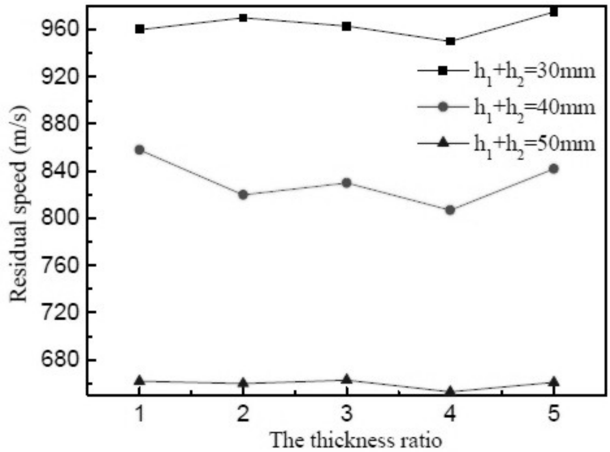

Fig. 4. The bullet residual speed with different total thickness and different thickness ratio.

Conclusions. In this paper, we used the SPH particle method and ANSYS/AUTODYN software to study the failure process of ceramic/aluminum alloy composite armors with different thickness configurations at high-speed projectile impact. The results obtained made it possible to draw the following conclusions.

1. The numerical simulation results of the residual bullet speed and its final length calculated by AUTODYN are in good agreement with the experimental and numerical results obtained earlier in [4]. This indicates the applicability and high precision of the SPH particle method for design of ceramic/aluminum alloy composite armors.

2. Using the SPH program of ANSYS/AUTODYN finite element simulation software, the numerical simulation of ceramic composite armors with different total thickness and five different ceramic/aluminum alloy thickness ratios was performed. The simulation and experimental results were compared and analyzed. Ceramic/aluminum composite armors of 3 different thicknesses possess the best anti-ballistic efficiency at the thickness ratio of 4:1. This is consistent with the theoretical model introduced by Wang and Lu 4.2:1, which provides an important reference for the engineering design.

Acknowledgments. This work was supported by the National Natural Science Foundation of China (Nos. 11602068 and 11602066) and Fundamental Research Funds for the Central Universities (Nos. HEUCFM170203, HEUCFP201744, and HEUCFP201762).

1. H.-L. Hou, X. Zhu, Z.-J. Liu, et al., “Experimental study on performance of ceramic composite warship armor under impact of high speed fragment,” *Ordnance Mater. Sci. Eng.*, No. 3, 5–10 (2007).
2. L. B. Lucy, “A numerical approach to the testing of the fission hypothesis,” *Astron. J.*, **82**, 1013–1024 (1977).
3. R. A. Gingold and J. J. Monaghan, “Smoothed particle hydrodynamics – Theory and application to non-spherical stars,” *Mon. Not. R. Astron. Soc.*, **181**, 375–389 (1977).
4. V. Sánchez Gálvez and L. Sánchez Paradela, “Analysis of failure of add-on armor for vehicle protection against ballistic impact,” *Eng. Fail. Anal.*, **16**, No. 6, 1837–1845 (2009).
5. A. L. Florence and T. J. Ahrens, *Interaction of Projectiles and Composite Armor*, Final Report, Stanford Research Institute, Menlo Park, CA (1967).
6. B. Wang and G. Lu, “On the optimisation of two-component plates against ballistic impact,” *J. Mater. Process. Tech.*, **57**, Nos. 1–2, 141–145 (1996).

7. D. Grady, "Impact failure and fragmentation properties of tungsten carbide," *Int. J. Impact Eng.*, **23**, No. 1, 307–317 (1999).

8. D. J. Steinberg, S. G. Cochran, and M. W. Guinan, "A constitutive model for metals applicable at high-strain rate," *J. Appl. Phys.*, **51**, No. 3, 1498–1504 (1980).

9. T. J. Holmquist, D. W. Templeton, and K. D. Bishnoi, "Constitutive modeling of aluminum nitride for large strain, high-strain rate, and high-pressure applications," *Int. J. Impact Eng.*, **25**, No. 3, 211–231 (2001).

10. G. R. Johnson and W. H. Cook, "Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures," *Eng. Fract. Mech.*, **21**, No. 1, 31–48 (1985).

Received 15. 03. 2018