

Numerical Investigation into the Influence of Thickness Ratio and Lateral Size of Ceramic on the Ballistic Performance of Ceramic/Metal Armor

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Abstract

Ceramic/metal bi-layer armor has received much attention due to its excellent ballistic protection performance, which is significantly contingent on configuration parameters like the ceramic/metal thickness ratio and lateral size of the ceramic. In the present manuscript, the ballistic response of 7.62-mm APM2 impacting AD995/5083-H116 armor is simulated. The ballistic limit is employed to quantitatively probe the influence of the thickness ratio, lateral size as well as coupling between two parameters on the ballistic performance. Numerical results manifest that an optimal thickness ratio exists for bi-layer armor, and several related mechanisms have been identified, such as perforative damage time, projectile/ceramic interaction time, dwell duration, fracture cone, and supporting effect of the backplate, etc. The lateral size acts on the ballistic property by strengthening or weakening the inertial self-restraint effect and changing the propagation distance of the tensile wave reflected from the lateral boundary of the ceramic. When the thickness ratio and lateral size are varied simultaneously, the ballistic limit decreases by less than 9.5 % for 1.1 ~ 3.0 thickness ratio and 91 ~ 152 mm lateral size even if it is in the most unfavorable situation. Accordingly, the armors within the above parameter ranges are capable of demonstrating a fascinating ballistic performance. The parameter value ranges given specifically are conducive to the optimal design of armor.

Keywords: Penetration, ballistic performance, ballistic limit, thickness ratio, lateral size

I. Introduction

Since 1965, the U.S. Air Force has been gradually equipping itself with alumina (Al_2O_3) armor. This armor withstood the battlefield test in the Vietnam War ¹. Hard metal (steel or tungsten) armor, although having the ability to provide adequate protection against multitudinous threats, has a comparatively high deadweight owing to its higher density, restricting the mobility of the armor and consuming a large quantity of energy. Armored vehicles should not only provide protection against different threats, they should also be lightweight to improve mobility and the specific load-carrying capacity, and to reduce fuel consumption ².

Ceramics is a boon to lightweight armor design on account of the combination of its excellent mechanical properties, like high hardness, compressive strength, abrasion capacity, and low density, which is widely used in protective structures ³. Nevertheless, a fatal drawback has emerged for ceramics, namely its low tensile strength ⁴. Therefore, how to fully exploit ceramic's excellent properties while avoiding its intrinsic brittleness has become a problem that must be addressed. Ceramic/backplate

armor seems to be a good solution. Ceramic as a strike surface gives full play to its excellent properties to blunt, erode and destroy the projectile. Ductile metal or composite as a backplate supports the ceramic tile, postponing tensile damage of the tile. Moreover, the backplate can further absorb the kinetic energy of bullet and arrest the bullet or tile fragments, to prevent damage to equipment, facilities or persons inside the armor ⁵.

Ceramic composite armor has received a lot of attention, because it not only improves ballistic performance, but also leads to a significant reduction in weight, effectively meeting the conflicting needs for improving armor protection capacity and making the armor lighter. Since Wilkins *et al.* ⁶ pioneered the study of the penetration mechanism of bi-layer ceramic/metal armor in the 1960s, abundant research has been carried out on the factors influencing the ballistic performance and anti-penetration mechanism of ceramic composite armor, such as the mechanical properties of the ceramic ⁷⁻¹⁰, including a more comprehensive review of this topic as outlined in Ref. 11, normal/oblique penetration covering experimental and numerical investigations ¹² as well as theoretical analysis ¹³, confinement effect ¹⁴, and prestress ¹⁵⁻¹⁷ and so forth. Because there are numerous parameters to control the ballistic performance,

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it is difficult to optimize them concurrently, but the ballistic performance can generally be promoted by both improving the material properties of armor and optimizing its structure¹⁸.

Enhancing material properties is still facing many technical difficulties and high cost, and has thus not been broadly adopted. Consequently, optimizing the structure appears to be the first choice. Some studies^{2,19–20} have been reported on multi-layer ceramic composite armor, where the core idea is either to prevent the ejection of tile fragments by adding a cover layer, or to place a polymer isolation layer between the ceramic and backplate to redistribute structural plastic deformation, finally achieving the purpose of more projectile energy dissipation. At present, however, the studies on the penetration mechanics of bi-layer armor against 7.62-mm small-caliber projectiles still receive the most sustained attention^{6,15,18,21}. On the premise that armor materials and incident projectile have been selected, ceramic/backplate thicknesses are of paramount importance to regulate the anti-penetration performance of armor.

As derived theoretically by Hetherington *et al.*²², there is an optimal thickness ratio 2.9 of $\text{Al}_2\text{O}_3/5083$ that can ensure the best ballistic performance of bi-layer armor. Experimental results basically consistent with theoretical predictions have been obtained from the ballistic experiments on $\text{Al}_2\text{O}_3/5083$ against 7.62-mm armor-piercing projectiles. Hereafter, a modified model proposed by Bendor *et al.*²³ takes into consideration the energy dissipation of ceramic and variable half-angle of the fracture cone to make up for the deficiency of the theoretical model in Ref. 22 to accurately determine the optimal thickness ratio of AD85/6061-T6 armor against a 7.62-mm projectile, thus obtaining the ratio of 2.4 for a given surface density, and 3.3 for a fixed total thickness of armor. Afterwards, multiple numerical simulations of different thickness ratios of AD95/5083 armors subjected to 7.56-mm steel projectile are implemented to acquire the optimal ratio of 1.6 for 50.46 g/cm² areal density of armor, also 1.3 for constant 15-mm-thick armor, respectively²⁴. More recently, a numerical investigation has been conducted²⁵ wherein AD95/2024-T3 armors with fixed 16-mm thickness against a 7.56-mm penetrator are equipped with an optimal thickness ratio of 1. However, the ballistic limits of the armors with three thickness ratios of 1, 1.67 and 3 do show unobvious differences within 10 %.

Besides the thickness parameter, the lateral size of the tile is also a key parameter to control the ballistic resistance. Depth of penetration (DOP) tests are performed in Ref. 26 on SiC/polycarbonate with different lateral sizes, and DOP first shows a significant decline and then slows down for PS-5000 SiC as the lateral size increases from 33 to 85 mm. The experimental and numerical results¹⁶ for a 7.62-mm projectile penetrating $\text{Al}_2\text{O}_3/2024\text{-T3}$ evince that when the lateral size of tile without lateral restraint

is larger than 50 mm, the ballistic property fails to display a particularly remarkable shift, however, it becomes very sensitive when the lateral size is below 50 mm. Indeed, the ballistic limit is increased by 115 m/s when sizes vary from 30 to 50 mm, which is attributed to the fact that the tensile wave reflected from the lateral boundary of tile is prone to producing the overall fracture of small-size tile. To the best of our knowledge, an up-to-date discussion on lateral dimension can be found in Ref. 27, which roughly describes the size effect, in which a larger tile facilitates energy absorption, and a smaller tile improves multi-hit capacity, but at the cost of less energy dissipation. However, no quantified data are found on the effect of lateral size.

To sum up, reported works about the effects of the optimal thickness ratio or/and lateral size on the ballistic performance remain scarce. Furthermore, in the existing literature, the underlying mechanism of optimal thickness ratio is unexplained, and the effect of thickness ratio or lateral size is also independently investigated. Nevertheless, based on coupling of the two parameters, it is probably possible to design more effective armor, but no relevant work has been reported so far.

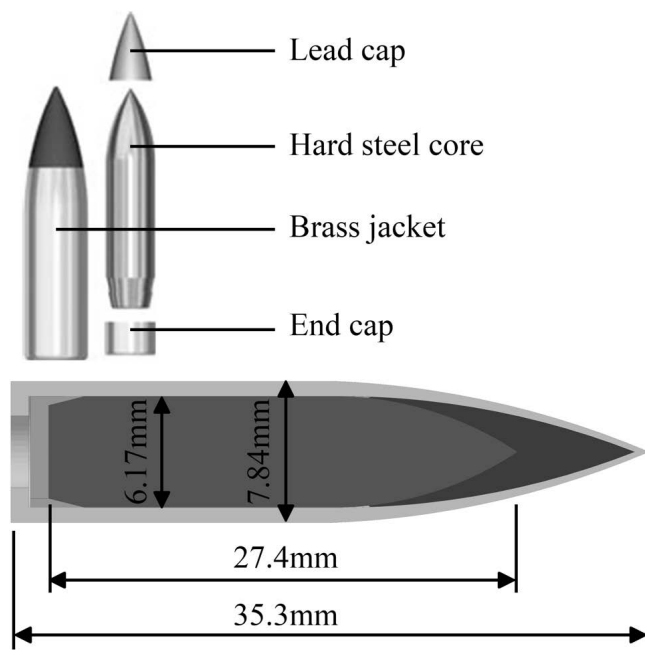
The contribution and novelty of the present manuscript mainly consists of the following points. (a) The armor design demands an in-depth understanding of the dynamic response and damage mechanism of armor subjected to high-speed impact. FEA Software is used to simulate the process of penetration into bi-layer armor, and expound the ballistic behavior and mechanism of armors with different thickness ratios or/and lateral sizes. (b) The ballistic limit is adopted to quantify the effects of dual-parameter changes of thickness ratio and lateral size on anti-penetration performance, and to elucidate in detail the mechanism underlying the existence of the optimal thickness ratio. (c) The main objective of this manuscript is to gain a more profound insight into the ballistic response behavior of bi-layer armor when the thickness ratio and lateral dimension are varied, to help optimize the design of armor.

II. Description of Material Model and Calibration of Model Parameters

Bi-layer armors composed of AD995 and 5083-H116 as the strike face and backing layer, respectively, under the high-velocity impact of an APM2 typical of 7.62-mm small-caliber armor-piercing projectile, will be numerically investigated. The main mechanical properties of AD995²⁸ and 5083-H116²⁹ are tabulated in Table 1, while a schematic of APM2²⁹ is illustrated in Fig. 1. Projectile diameter $D_p = 7.62$ mm. Total mass is about 10.7 g, in which 5.25 g is the hard steel core that plays the main role in penetration. Brass jacket 4.21 g, whose penetration capability is much smaller than the steel core, but should not be ignored. Lead cap and end cap are not modelled on account of their negligible penetration capability³⁰.

Table 1: Main mechanical properties of AD995 and 5083-H116.

Parameter	Unit	AD995 ²⁸	5083-H116 ²⁹
Density	g/cm ³	3.89	2.70
Elastic modulus	GPa	303	70
Poisson ratio	—	0.22	0.30–0.33
Yield strength	MPa	—	238
Tensile strength	MPa	—	317
Flexural strength	MPa	375	—
Compression strength	MPa	2068	—
Hardness	GPa	15	—
Fracture toughness	MPa.m ^{1/2}	4–5	—
Tensile fracture strain	—	—	0.16
Transverse wave speed	m/s	10000	—
Shear wave speed	m/s	6200	—
Cracking speed	m/s	4800±1300	—

**Fig. 1:** Schematic showing a 7.62-mm APM2 projectile ²⁹.

The materials used in this simulation encompass ceramic and metals. Appropriate or not, material models and parameters have a decisive influence on the penetration response process ⁵, involving phenomena such as projectile erosion, damage evolution of the tile, and failure morphology of the backplate, which in turn affect and determine the reliability of performance prediction and assessment. For this reason, before the formal implementation of the numerical investigation, the models and parameters of all materials to be used must be moderately calibrated.

(1) JC constitutive model

The JC model coupling the plastic flow with strain rate and local temperature rise has been repeatedly applied to model the response behavior of metals under high-speed impact ^{31–33}, and has provided a reliable numerical

prediction. For numerical simulations, the JC model (*MAT15) must be used together with the Mie-Grüneisen equation of state (EOS). JC model parameters for the core, jacket and 5083-H116 adopted by our simulations are listed in Table 2.

(2) Material model of AD995

AD995 employs the phenomenological JH2 constitutive model, and it is one of the most widely used constitutive models to reproduce the failure of ceramic during the high-speed impact ^{18,25}. The JH2 model consists of three components: strength, damage, and pressure, and it considers the impact-induced cumulative damage of ceramic material, and regards the strength relationship of intact materials and damaged materials as a function of pressure. The acquirement of JH2 model parameters is complicated, from direct ballistic experiments, material manufacturer, or fitting of available data and calibration of numerical and experiment results. The parameters for AD995 are taken from the literature ^{34–35}, as listed in Table 3.

(3) Material erosion model

The mesh-based Lagrangian algorithm will be employed in this simulation, which requires good computational efficiency and accuracy, but it will suffer from excessive mesh distortion when addressing large deformation problems. Apart from an increase in the computation time, in serious situations, the mesh distortion is likely to cause the program to terminate unexpectedly.

The erosion algorithm is available and is based on the concept that highly distorted elements have failed totally and may no longer contribute to the physics process of penetration event ³⁶. Therefore, these distorted elements will be removed from the FE model by defining erosion criteria to handle the mesh distortion. Indeed, the JC fracture criterion may also effectively remove the elements with plastic strains exceeding erosion strain, however, plastic strains of some distorted elements have not

Table 2: JC model parameters for core, jacket, and 5083-H116.

Parameter	Symbol	Unit	Core ^{32–33}	Jacket ^{32–33}	5083-H116 ^{32–33}
Shear modulus	G	GPa	80.0	43.9	26.4
Initial yield stress	A	MPa	1200	206	167
Hardening coefficient	B	MPa	50000	503	596
Hardening exponent	n	—	1.00	0.42	0.55
Thermal softening exponent	m	—	1.00	1.68	1.68
Strain rate coefficient	C	—	0.000	0.010	0.001
Reference strain rate	$\dot{\epsilon}_0$	s ⁻¹	5×10 ⁻⁴	5×10 ⁻⁴	1
Specific heat	C_p	J/kg.K	452	385	910
Melting temperature	T_m	K	1800	1189	893
Reference temperature	T_r	K	293	293	293
Damage constant	D_1	—	0.1800	2.2500	0.0261
Damage constant	D_2	—	0.0000	0.0005	0.2630
Damage constant	D_3	—	0.0000	-3.6000	-0.3490
Damage constant	D_4	—	0.0000	-0.0120	0.2470
Damage constant	D_5	—	0.0000	0.0000	16.8000
Density	ρ	kg/m ³	7850	8520	2700
Elastic wave velocity	c	m/s	4570	3940	5340
v_s - v_p curve slope	S_1	—	1.49	1.49	1.40
Grüneisen coefficient	γ	—	1.93	1.99	1.97

Table 3: JH2 model parameters of AD995.

Parameter	Symbol	Unit	AD995 ^{34–35}
Density	ρ	kg/m ³	3890
Shear modulus	G	GPa	152
Intact strength coefficient	A	—	0.93
Intact strength exponent	N	—	0.60
Fracture strength coefficient	B	—	0.31
Fracture strength exponent	M	—	0.60
Strain rate coefficient	C	—	0.00
Reference strain rate	$\dot{\epsilon}_0$	s ⁻¹	1
Normalized fracture strength	$SFMAX$	—	1
Tensile strength limit	T	GPa	0.20
Hugoniot elastic limit	HEL	GPa	19.00
Pressure at the Hugoniot elastic limit	P_{HEL}	GPa	1.46
Bulking factor	β	—	1
Pressure constant (bulk modulus)	K_1	GPa	220.24
Pressure constant	K_2	GPa	0.00
Pressure constant	K_3	GPa	0.00
Damage constant	D_1	—	0.005
Damage constant	D_2	—	1.000

yet reached the threshold, so that these elements cannot be deleted based on the JC fracture criterion. In other words, it is not possible to guarantee the complete removal of distorted elements. Hence, it will still be necessary to use the *Mat-Add-Erosion model to stabilize the numerical calculation.

Erosion strain as a non-physical parameter is extremely sensitive to mesh size. Erosion strains differ distinctly if one wants to get an accurate prediction³⁷. Therefore, enough care should be taken in choosing it. In the following simulations, effective plastic strain at failure criterion is employed to model the element erosion of materials. The erosion strains of materials obtained through repeated numerical attempts are illustrated in Table 4. It is noted that the erosion criterion is not adopted for the core, because its JC fracture criteria have been able to produce a stable numerical implementation.

Table 4: Erosion strains of materials.

Material	AD995	Jacket	5083-H116
Erosion strain	0.11	1.50	1.70

(4) Calibration of model parameters

In order to accurately predict the impact response behavior of the bullet/target interaction, the material model parameters mentioned earlier must be calibrated or verified. Only calibrated parameters can be used to carry out succedent numerical simulation to study the subject that concerns us.

(a) Parameter calibration of core, jacket and 5083-H116

The experiments performed by Børvik *et al.*²⁹ on 20-mm-thick 5083-H116 plate against 7.62-mm APM2 at velocities ranging at 480 ~ 822.4 m/s will be simulated for the validation of model parameters for the core, jacket and 5083-H116. Both the core and jacket have a mesh size of 0.3 mm, while a mesh size of 0.4 mm is used in the central impact zone (within three times projectile-diameter) of the 5083-H116 plate which needs special attention, and the mesh gradually becomes coarser as the distance from the impact site increases. In accordance with the experimental settings, the plate boundary is clamped during simulation. According to the symmetry, to simplify the modeling and save computational time, only a quarter model is modelled. It should be mentioned here that the 1/4 model is established in all subsequent modeling in this work.

The residual velocities versus initial velocities obtained from the simulations and experiments²⁹ are presented in Fig. 2, where it is more intuitive to show an excellent match between numerical and experimental results. Furthermore, after the initial velocity surpasses 525 m/s (slightly higher than the ballistic limit of 492 m/s), the residual velocity rises dramatically and later follows a linear increase, as shown in Fig. 2.

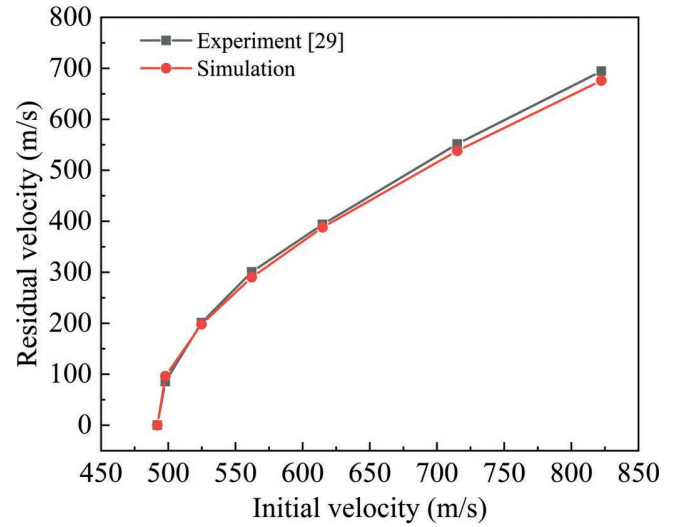


Fig. 2: Comparison between the numerical and experimental results.

(b) Parameter calibration of AD995

The simulations demonstrated in this section are based on experimental findings in Ref. 38, in which 8-mm-thick bare AD98 (comparable to the mechanical properties of AD995) with lateral size 38, 50, 60, 70 and 100 mm is subjected to the impact from 7.62 APM2 at 830 m/s. A grid size of 0.4 mm is adopted for the alumina, whilst the grid division for the core and jacket is exactly the same as that in Section II(4)(a). AD995 tile plate is set as a free boundary, as done in the experiment.

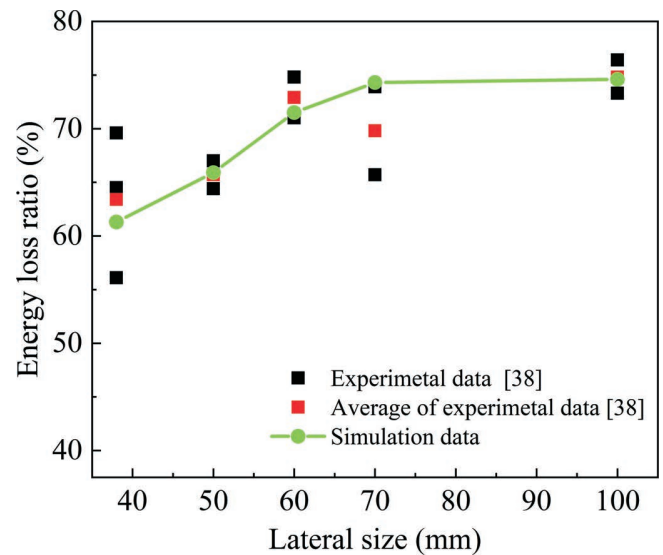


Fig. 3: Comparison of experimental and numerical results on the energy loss ratio of the core.

A good agreement between the experimental results and the numerical predictions on the energy loss of the core can be observed from Fig. 3. However, there is a slight difference between the experimental and numerical results for 70-mm lateral size. In fact, the numerical result is more accordant to the general cognition that the energy loss increases with the increased lateral size of tile, which enhances the self-restraint effect to hinder the movement of tile fragments. As indicated in Ref. 32, a small number of experiments, e.g. two or three shooting tests, are not

enough to provide reliable data support so as to get a regular understanding, which perhaps explains this disagreement.

Through the verification of the model parameters in the above two sections, there is sufficient reason to think that these validated parameters are suitable for the following numerical study.

III. Description of the Finite Element Model (FEM)

In defending against the 7.62-mm small-caliber armor-piercing projectile, the designed alumina/aluminum armor generally has an areal density of about 50 ~ 53 kg/m²,^{22, 39}. In order to arrest APM2 with a velocity of 830 m/s, the areal density of AD995/5083-H116

armor to be simulated is taken to be slightly larger, i.e. 55 kg/m². The dimensions of the square backplate with a fixed boundary condition are 160 mm × 160 mm, while the AD995 tile is unconstrained laterally. To discuss the effect of the thickness ratio ($R_c = t_c/t_b$, R_c , t_c and t_b denote the thickness ratio, tile thickness and backplate thickness, respectively), R_c is taken as 0, 0.20, 0.72, 1.30, 2.45, 3.75, 6.30 and ∞ , respectively. For the purpose of comparing the effect of lateral size (S_{cl}) of the ceramic, S_{cl} of square tile is taken as 152, 100, 70, 50 and 28 mm, respectively. Let $R_p = S_{cl}/D_p$, therein D_p for projectile diameter, and R_p represents the ratio of the lateral size to the projectile diameter. A detailed description of armor configurations is shown in Table 5.

Table 5: Detailed description of armor configurations.

Armor	Ceramic thickness t_c (mm)	Backplate thickness t_b (mm)	Ceramic lateral size S_{cl} (mm)	Ceramic/backplate thickness ratio R_c	Ratio of lateral size to projectile diameter R_p
C1-1	0	20.4	152	0	—
C1-2			100		
C1-3			70		
C1-4			50		
C1-5			28		
C2-1	3.2	15.7	152	0.20	19.9
C2-2			100		13.1
C2-3			70		9.2
C2-4			50		6.6
C2-5			28		3.7
C3-1	7.2	10	152	0.72	19.9
C3-2			100		13.1
C3-3			70		9.2
C3-4			50		6.6
C3-5			28		3.7
C4-1	9.2	7	152	1.30	19.9
C4-2			100		13.1
C4-3			70		9.2
C4-4			50		6.6
C4-5			28		3.7
C5-1	11	4.5	152	2.45	19.9
C5-2			100		13.1
C5-3			70		9.2
C5-4			50		6.6
C5-5			28		3.7
C6-1	11.9	3.2	152	3.75	19.9
C6-2			100		13.1
C6-3			70		9.2

Armor	Ceramic thickness t_c (mm)	Backplate thickness t_b (mm)	Ceramic lateral size S_{cl} (mm)	Ceramic/backplate thickness ratio R_c	Ratio of lateral size to projectile diameter R_p
C6-4			50		6.6
C6-5			28		3.7
C7-1	12.7	2	152	6.30	19.9
C7-2			100		13.1
C7-3			70		9.2
C7-4			50		6.6
C7-5			28		3.7
C8-1	14.1	0	152	∞	19.9
C8-2			100		13.1
C8-3			70		9.2
C8-4			50		6.6
C8-5			28		3.7

Note: S_{cl} in C1-(1-5) refers to the lateral size of 5083-H116 in Table 5

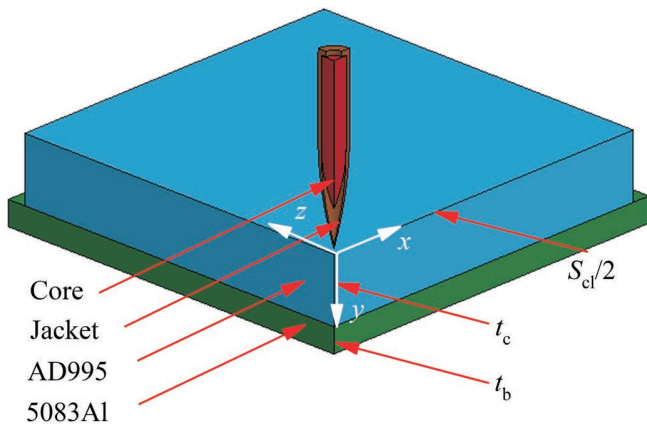


Fig. 4: 1/4 finite element model.

The adhesive layer bonding the AD995 tile and backplate is generally thinner, consequently, it may be disregarded in the modeling to simplify the calculation. The *CONTACT_TIEBREAK_SURFACE_TO_SURFACE algorithm is used to simulate the bonding effect, and tensile and shear failure stress of adhesive are taken as 120 MPa and 80 MPa, respectively⁴⁰. The projectile/armor interaction is modelled by employing *CONTACT_ERODING_SURFACE_TO_SURFACE. In the present study, we simulate the response behavior when the projectile is normally impacting the center of the armor. As stated in Section II.(4)(a), according to the symmetry, only a 1/4 model is modelled, see Fig. 4. The meshing method of each component has been described in Sections II.(4)(a) and II.(4)(b), and so will not be repeated here.

IV. Results and Discussion

The ballistic limit (V_{bl}) of armor is computed by taking average of the highest velocity of projectile giving no perforation and lowest velocity of projectile giving complete perforation to the armor with an interval of 10 m/s for the two velocities²⁵. The numerical simulations are implemented to study the ballistic performances and response

features of armors against 7.62-mm APM2 at 830 m/s³⁸, and numerical results for the ballistic limit (V_{bl}) and residual velocity (V_r) are given in Table 6.

(1) Analysis of the typical penetration process

The analysis of the ballistic response process contributes to a better understanding of the response mechanism, and this section only takes the response behavior of C4-1 armor as an example to further identify the penetration mechanism. Based on the response characteristics of the projectile and armor, the penetration process is roughly divided into four phases. Next, the main characteristic and response mechanism of each stage is analyzed.

The projectile/armor morphology and damage evolution of xoy cross-section ceramic at some typical moments are shown in Fig. 5.

Phase 1: Pre-damage effect of the jacket on the ceramic tile.

At 1.5 μ s, the jacket starts to contact the tile, producing a compression shock wave which gives rise to the pre-damage to the tile as shown in Fig. 5 and facilitates the subsequent core penetration into the tile. Due to the high plastic deformation capacity of the jacket and its much lower strength than AD995, the jacket finds no way in penetrating into AD995 tile to be spread radially across the ceramic surface, viz., well-known dwell phenomenon¹⁶.

Phase 2: Core dwell

The dynamic compressive strength (R_t) of AD995 can be simply evaluated as 7.5 GPa according to the formula $R_t = H_v/2$ used in Ref. 41, wherein parameter H_v is obtained as 15 GPa from Ref. 28. The high-rate loading produced by high-strength core penetrating AD995 tile makes the interface pressure of ceramic rise sharply from approximately 2 GPa to 5 GPa at 10 μ s, as shown in Fig. 6. At this time, the interface pressure is still lower than its dynamic compressive strength, inadequate to induce ceramic failure. The pressure is gradually increased to over 7.5 GPa in partial surface elements at 20 μ s with continuous dynamic

Table 6: Numerical results for V_{bl} and V_r

Armor	Ceramic/backplate thickness ratio R_c	Ratio of lateral size to projectile diameter R_p	Ballistic limit velocity V_{bl} (m/s)	Residual velocity of core at 830m/s V_r (m/s)
C1-1	0	19.9	490	667
C1-2		13.1	490	669
C1-3		9.2	490	667
C1-4		6.6	490	668
C1-5		3.7	490	663
C2-1	0.20	19.9	625	513
C2-2		13.1	615	531
C2-3		9.2	605	537
C2-4		6.6	595	554
C2-5		3.7	545	577
C3-1	0.72	19.9	725	382
C3-2		13.1	725	388
C3-3		9.2	695	439
C3-4		6.6	675	464
C3-5		3.7	645	522
C4-1	1.30	19.9	835	0
C4-2		13.1	825	145
C4-3		9.2	765	300
C4-4		6.6	695	426
C4-5		3.7	645	496
C5-1	2.45	19.9	825	113
C5-2		13.1	815	254
C5-3		9.2	735	441
C5-4		6.6	675	500
C5-5		3.7	625	572
C6-1	3.75	19.9	775	292
C6-2		13.1	765	334
C6-3		9.2	685	406
C6-4		6.6	615	509
C6-5		3.7	585	569
C7-1	6.3	19.9	685	364
C7-2		13.1	665	409
C7-3		9.2	645	428
C7-4		6.6	585	492
C7-5		3.7	555	569
C8-1	∞	19.9	605	462
C8-2		13.1	595	491
C8-3		9.2	575	533
C8-4		6.6	555	573
C8-5		3.7	525	617

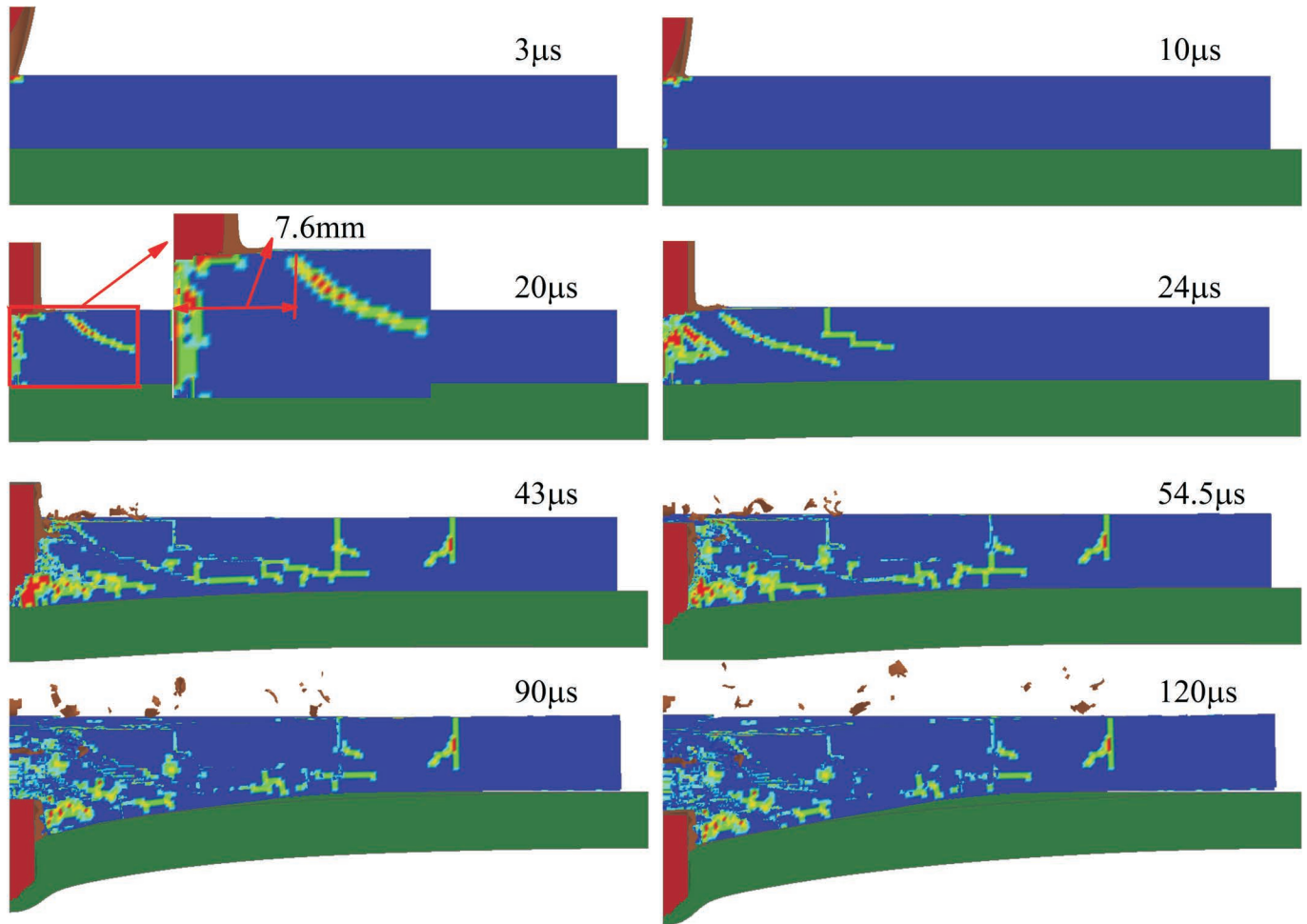


Fig. 5: Projectile/armor morphology and damage evolution of xoy cross-section ceramic at some typical moments for C4-1 armor at 830 m/s.

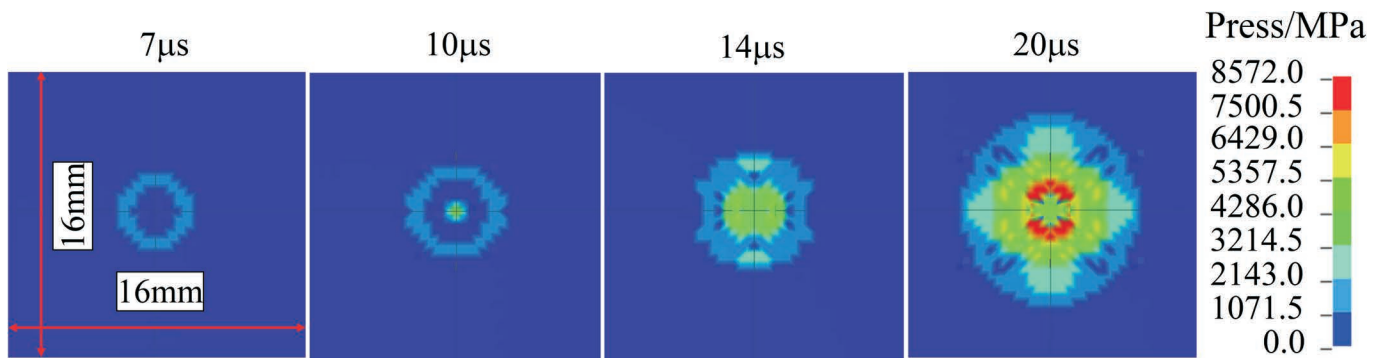


Fig. 6: Distribution of AD995 surface pressure at some typical moments for C4-1 armor at 830 m/s.

loading, besides this, the dynamic compressive strength of ceramic will be reduced by its damage accumulation as described in Ref. 28. Both of them make these surface elements start to erode, and thus the transition from dwell to penetration occurs in the core, as clearly observed from the enlarged image at 20 μ s in Fig. 5. The dwell time calculated as 10 μ s is highly consistent with the estimated value of 10~15 μ s given in Ref. 42. It can be found from Fig. 7, which plots the kinetic energy and mass loss ratio of core versus time, the kinetic energy loss contributed by the dwell stage has reached 33 % of the initial kinetic energy of the core, and it can be observed that a vital role has been played by

the dwell stage in the improvement of the armor protection performance.

Lundberg *et al.*⁴³ holds that the transition from dwell to penetration is controlled by the growth of conical crack, the reason for which lies in that the conical crack facilitates the penetration into ceramic due to the sudden loss of lateral confinement in the ceramic under the projectile. As shown in Fig. 5, at 20 μ s, the formation of the conical crack and termination of the dwell stage can be observed, and the distance between the initial impact site and the start position of the conical crack is equal to the projectile diameter of 7.6 mm as identical with the conclusion in Ref. 43. This shows that numerical results are in accor-

dance with the theoretical prediction and experimental observation in Ref. 43. However, the conical crack may not be the only reason for the transition from dwell to penetration. A through-thickness axial crack stemming from the stress wave reflection of AD995 rear-face can be observed on the projectile trajectory in Fig. 5, which is also convenient for the transition.

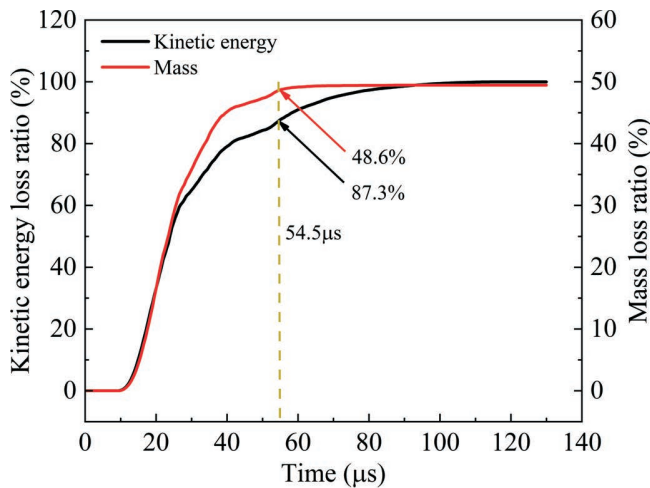


Fig. 7: Kinetic energy and mass loss ratio of core versus time for C4-1 armor at 830 m/s.

Phase 3: Core's penetration into ceramic tile.

Afterwards, the conical crack expands along a trajectory approximately 53.9° ($25 \sim 75^\circ$ test results in Ref. 44) off-axis direction and gradually approaches the tile rear-face to form the fracture cone of ceramic. Also, the formation of fracture cone may be responsible for the short and rapid increase of resistance force of

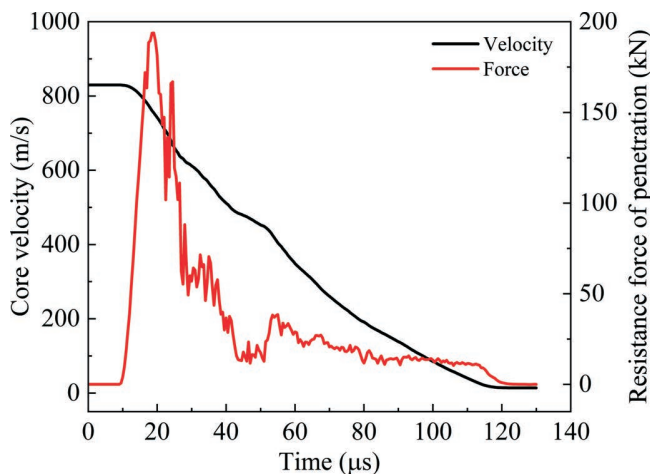


Fig. 8: Resistance force of penetration and velocity of the core versus time for C4-1 armor at 830 m/s.

penetration during $21 \sim 24 \mu\text{s}$ as observed from Fig. 8 in which the resistance force of penetration and velocity of core versus time are plotted. It helps spread the force acting on the backplate over a larger area, which prevents premature local breakage of backplate due to grievous stress concentration to reinforce the support of backplate on the ceramic. The positive effect of the fracture cone also seems to be well confirmed by Fig. 9, from which it can be observed that the stress of backplate is more dispersed, and the stress amplitude also shows a perceptible drop after the formation of the fracture cone at $24 \mu\text{s}$.

Henceforward, as the penetration continues, the ceramic materials on the penetration path of core are continuously crushed and pushed away, which will undoubtedly provide lower ballistic resistance, resulting in a significant drop in the resistance force of penetration as illustrated in Fig. 8. Additionally, the fracture cone is also destroyed, which can be observed from Fig. 5, and the ceramic materials involved in the mutual abrasion with the core will decrease in response, which will cause the force transmitted to the backplate to increase. For example, the stress amplitude in the backplate at $43 \mu\text{s}$ is 35.7 % higher than that at $24 \mu\text{s}$, as shown in Fig. 9.

Until $54.5 \mu\text{s}$, there is no ceramic material on the trajectory of core, accompanied by the end of the core's penetration into the AD995 tile. Fig. 7 indicates that the mass loss of core is as high as 48.6 % during the period of dwell and penetration into the ceramic, almost all of the mass loss of the core (49.5 %) over the entire penetration process. Meanwhile, the energy loss is also as high as 87.3 %. According to this, it can be reasonably speculated that the most important function of the ceramic is to defeat the incident high-speed projectile by eroding it.

Phase 4: Penetration into the backplate.

After $54.5 \mu\text{s}$, due to its lower strength, the backplate is rigidly penetrated by the core. At this stage, the energy loss of the core is mainly dissipated by the plastic deformation of the backplate. It can be calculated as 12.7 % from Fig. 6(a), which provides a very close match with 15 % as suggested in Ref. 42. At $120 \mu\text{s}$, the core velocity diminishes to zero, see Fig. 8. As seen from Fig. 5, the core stays in the backplate and fails to perforate it, which implies C4-1 armor is in the position to defend against 7.62-mm APM2 at 830 m/s.

All the armors except C4-1 are perforated at 830 m/s. Before being perforated, all AD995 composite armors backed by 5083-H116 backplate demonstrate a similar response process as C4-1, however, the duration of each phase differs.

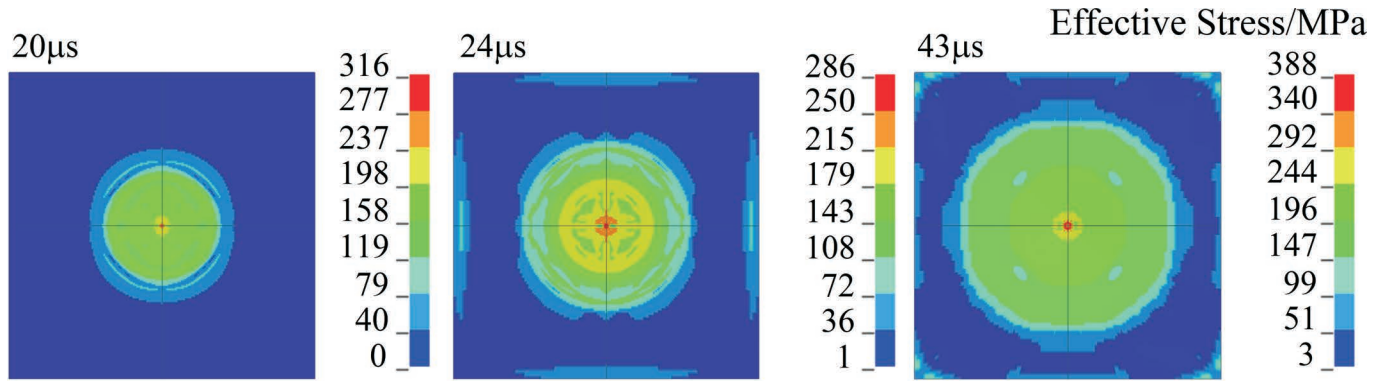


Fig. 9: Distribution of backplate stress at some typical moments for C4-1 armor at 830 m/s.

(2) Influence of the thickness ratio

As pointed out by Refs. [22–25], the thickness ratio is of vital importance to act on the ballistic response of armor. Simulations of armors with different thickness ratios as listed in Table 5 are conducted to reveal the underlying mechanism of the optimal thickness ratio.

The effect of the thickness ratio R_c on V_{bl} is shown in Fig. 10. In general, V_{bl} tends to increase and then decrease as R_c increases for different ratios of the lateral size to projectile diameter R_p . All the highest V_{bl} are obtained from armors with a thickness ratio of 1.3, which is close to the experimental result from Ref. 22 and the numerical prediction in Ref. 24. Still, for small-size ceramic armor with $R_p = 3.7$, the best ballistic performance can be achieved for 0.72 ~ 1.3 thickness ratio as can be observed in Fig. 10. The optimal thickness ratio shows a slightly decreasing trend with the decrease of the lateral size. In conclusion, there always exists a certain optimal thickness ratio for bi-layer armor to achieve the best protection.

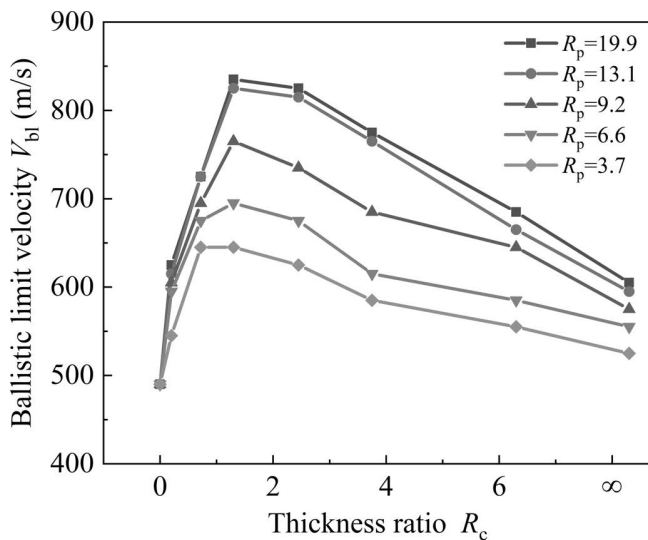


Fig. 10: Effect of the thickness ratio on ballistic limit velocity.

Anyway, as observed in Fig. 10, for ceramic composite armor with different lateral dimensions, the change trend of ballistic performance with thickness ratio is similar. Accordingly, C (1 ~ 8)-1 (i.e., $R_p = 19.9$) armors will be used as examples to interpret the intrinsic mechanism of the optimal thickness ratio.

For ceramic armors without AD995 front-layer ($R_c = 0$) and with very thin AD995 tile ($R_c = 0.2$), poor protective

properties are found from Fig. 10, as indicated in Refs. 3, 41 that ceramic tile of thickness below 5 mm supported by a finite-thickness backplate can hardly provide adequate protection against a 7.62-AP round. Limited erosion of the core due to insufficient thickness of tile is responsible for this, as seen from Fig. 11 in which $R_c = 0$ armor presents a nearly horizontal straight line with negligible mass loss. The mass loss caused by $R_c = 0.2$ armor is also only 26.4 %, but despite this, the penetration ability of the projectile has been obviously reduced, so that the ballistic limit velocity has been improved by 27.6 % in contrast with that of $R_c = 0$. The positive effect of the ceramic layer (even if very thin) on the improvement of the protective performance is distinctly identified, and the experiment conducted by Behner and Heine⁴⁵ also confirms this point. Furthermore, it is difficult for thinner ceramic to form a fracture cone, because once the core contacts the thinner tile, the impact-induced high pressure causes the tile to quickly break into pieces, which can be observed from Fig. 12, which shows the morphology of ceramic fracture cone at 27 μ s.

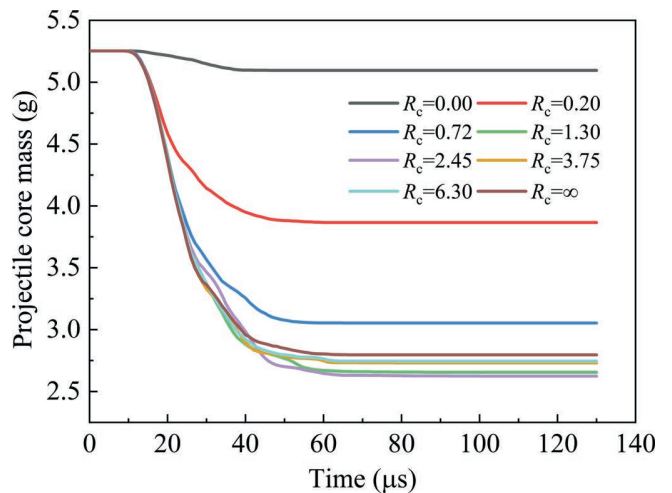


Fig. 11: The core mass time-history curves for different R_c armors with identical $R_p = 19.9$.

For C3-1 armor whose ceramic thickness is increased to 7.2 mm ($R_c = 0.72$), the time to form a perforated axial crack is delayed by 9 μ s, while the interaction time between the core and AD995 tile is increased from 15 μ s in C2-1 to 35 μ s at present, and the dwell duration is also increased by 3 μ s, as illustrated in Fig. 13. All these are beneficial to

make full use of the erosion trait of ceramic on the core and reduce the penetration ability of the core. Although it still fails to arrest the projectile, the ballistic performance of C3-1 armor is improved by 16 % in respect of C2-1, and a larger 48 % compared with C1-1.

When the tile thickness is increased to 9.2 mm, i.e. C4-1 ($R_c = 1.3$), the time for the formation of perforated crack, the interaction time between the core and tile, and the dwell duration continue to increase to a certain extent, which further promotes the consumption of ceramic tile to the core. As a result, a ballistic performance improvement of 70.4 % relative to C1-1 armor is obtained for C4-1 armor, as observed from Fig. 10.

On the premise of keeping the areal density constant, when thickness ratio is continuously increased from 1.3 to 6.3, the time of axial crack penetration, the time of the formation of perforated crack, the interaction time between the core and tile, and the dwell duration are not obviously increased. Correspondingly, the mass loss of the

core shows a slight decrease although there is insignificant change, which can be observed from Fig. 11. This also shows that the three factors shown in Fig. 13 are not all the reasons for the mass loss of the core.

With the increase of thickness ratio, the thickness of back plate will inevitably decrease so as to weaken the supporting effect of the backplate for the ceramic tile, so that the ceramic materials located in the penetration path have more movement space and can be relatively easily pushed out, thus providing less ballistic resistance and causing less core erosion. In addition, the armor of thickness ratio 1.3 has the maximum fracture cone half-angle of 53.9° , hereafter, and the cone half-angle gradually decreases with the increase of the thickness ratio, see Fig. 12. A larger cone half-angle is beneficial to disperse the force acting on the backplate, as shown in Fig. 14, it can be clearly observed that the armor for the thickness ratio 1.3 has a more uniform stress distribution on the backplate, which can effectively provide sufficient support for the ceramic tile.

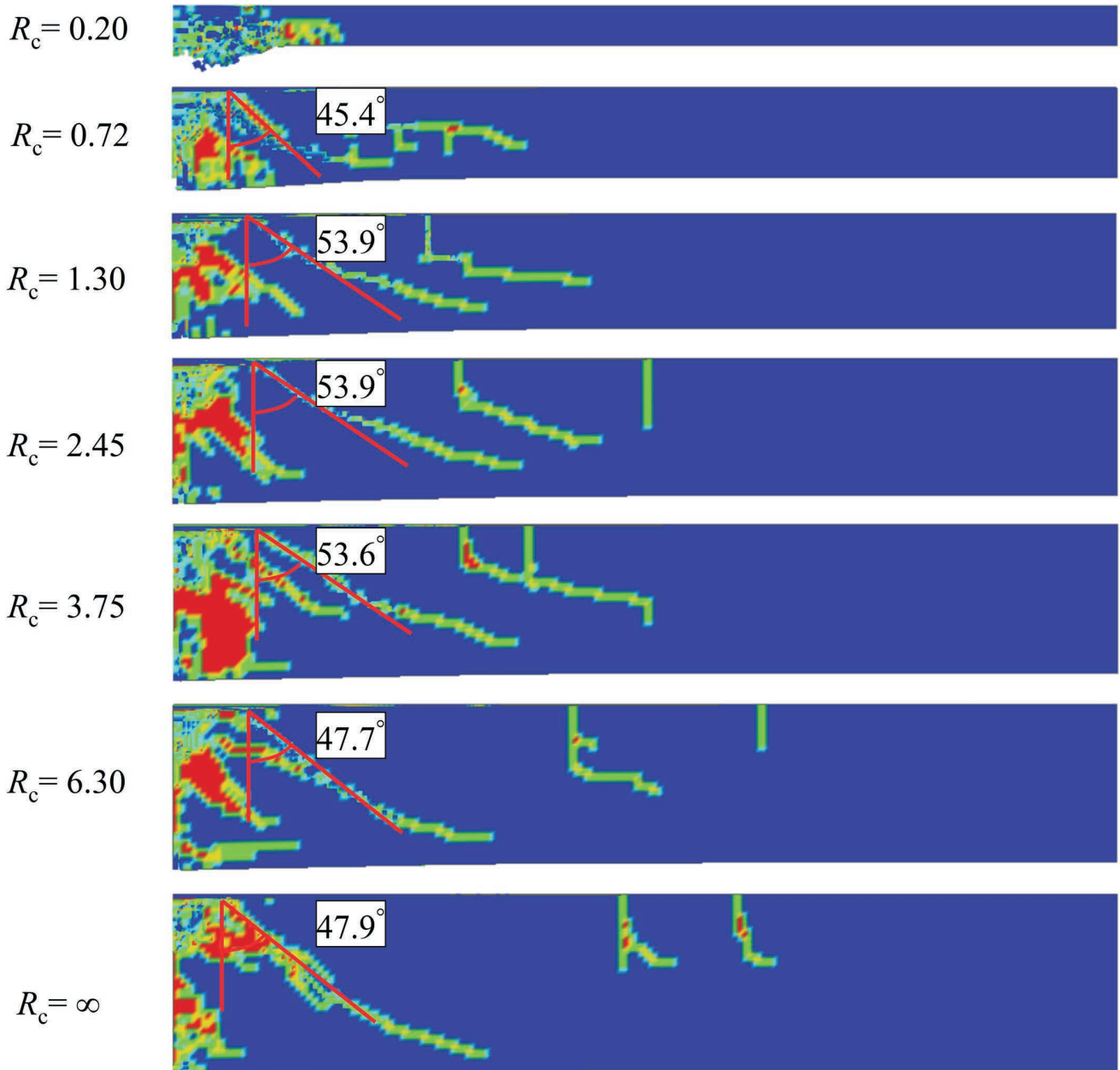


Fig. 12: Fracture cone morphology of ceramic for different R_c armors with identical $R_p = 19.9$ at 27 μ s.

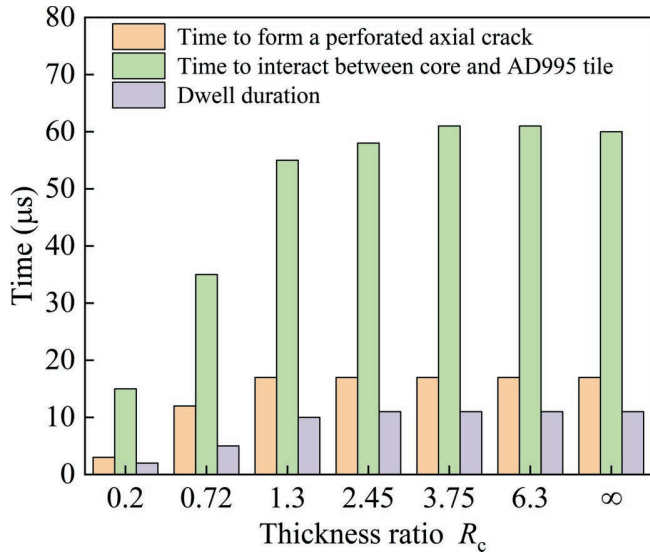


Fig. 13: Time to form a perforated axial crack in AD995 tile and for interaction between core and AD995 tile, and dwell duration for different R_c armors with identical $R_p = 19.9$.

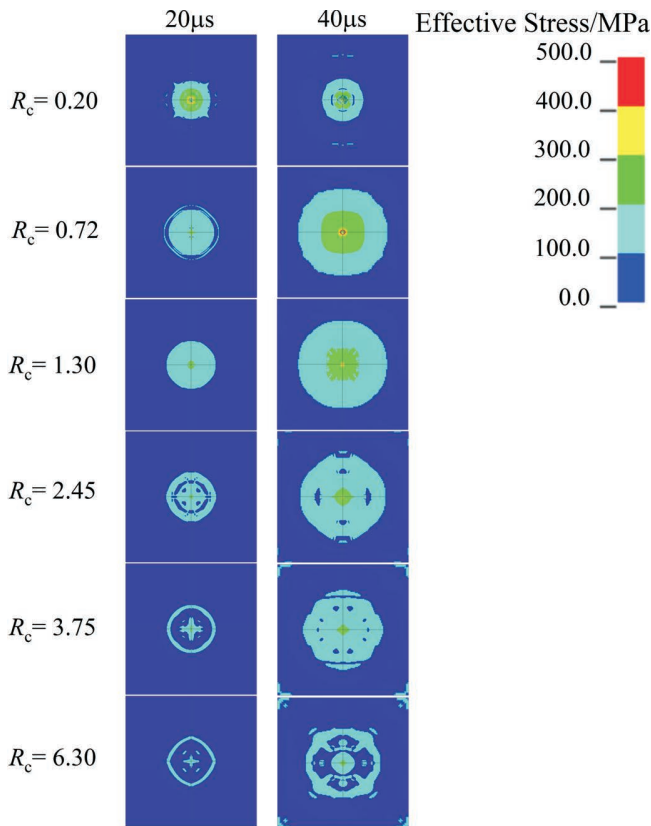


Fig. 14: Stress distribution of the backplate for different R_c armors with identical $R_p = 19.9$ at 20 μs and 40 μs .

Additionally, the reduction of backplate thickness implies that less backplate material participates in dissipating the kinetic energy of the projectile through plastic deformation. Therefore, although the mass losses of the cores for armors of the thickness ratio 1.3 ~ 6.3 present an insignificant difference, the remaining velocity of the core increases markedly. For example, the remaining velocity of armor of the thickness ratio 1.3 is 0 m/s, while that of armor of 6.3 is as high as 364 m/s, as shown in Fig. 15. By

and large, the armor with thickness ratio 1.3 achieves the best ballistic performance, and 1.3 is considered as the best thickness ratio of AD995/5083-H116 bi-layer armor.

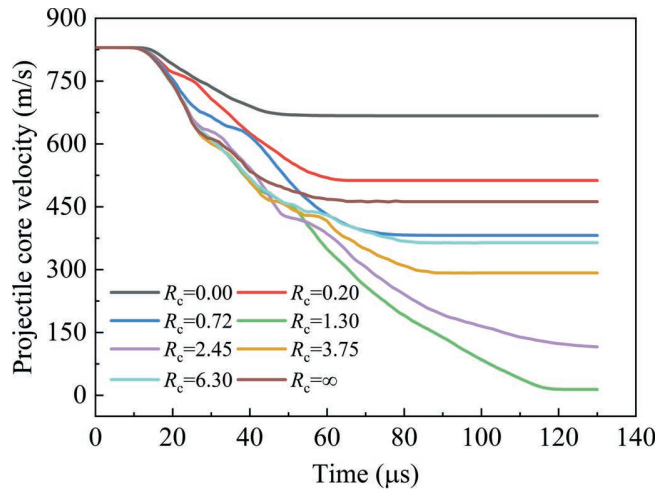


Fig. 15: The core velocity time-history curves for different R_c armors with identical $R_p = 19.9$.

It is worth mentioning that, for the dwell duration, the same conclusion has also been found in the experiments in Ref. 41 that the dwell duration depends entirely on the areal density for armor with alumina thickness over 5 mm against the penetration of the 7.62-mm AP projectile, nevertheless, irrespective of thickness ratio.

An interesting phenomenon is that in contrast to $R_c = 0.2$, V_{bl} and V_r have showed a decrease of 3.2 % and 10 % (Table 6) at $R_c = \infty$ (bare AD995 tile), respectively. It appears to be a contradictory result, because a low V_{bl} reflects the weak protection capability, while a low V_r reflects a strong protection capability. Yet, the primary purpose of armor is to protect personnel or equipment from harm, which requires that any bullet should not perforate the armor, while the residual velocity gives an indication of the perforation. Hence, in terms of ballistic performance evaluation, V_{bl} is more reliable than V_r .

(3) Influence of the lateral size

The stress wave will be reflected as a tensile wave at the ceramic tile/backplate interface or/and lateral boundary of tile, causing cracks to develop and expand in the tile. It is the lateral size of tile that regulates the damage area to a certain degree, which in turn exerts an impact on the anti-penetration performance of ceramic composite armor against single/multiple strikes. The simulation results of the effect of lateral size on the ballistic performance are illustrated in Fig. 16, from which it can be discovered that V_{bl} of the armors with different thickness ratio R_c are all monotonically increasing with uplifted R_p , and similar trend has been observed in Ref. 16 as well. As an exception, V_{bl} on bare 5083-H116 plate of $R_c = 0$ is found to have kept constant, in other words, its ballistic performance is independent of lateral size. Now that the change trend of ballistic performance of bi-layer armor with different thickness ratios is similar along with the change of lateral size, one group of many armor configurations, such as C4-

(1–5) armors with $R_c = 1.3$, may be chosen to serve as the instance of analysis.

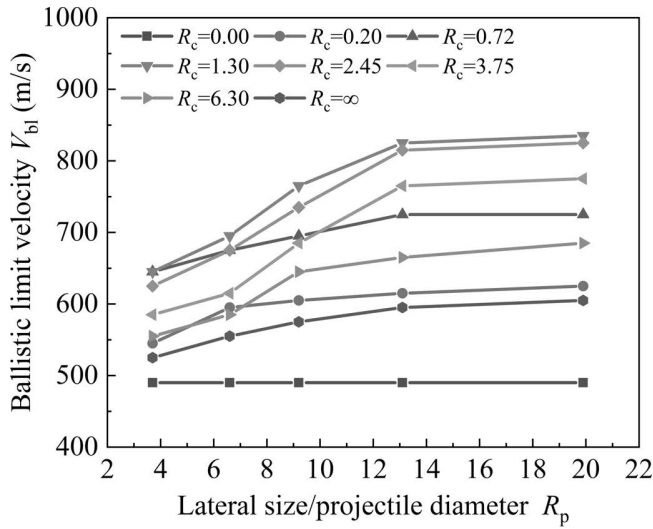


Fig. 16: Effect of the ratio of lateral size to projectile diameter on ballistic limit velocity.

In Fig. 16, the best ballistic property is demonstrated by the C4–1 armor ($R_p = 19.9$) with V_{bl} up to 835 m/s, which is attributed to the fact that AD995 tile of 152 mm lateral size has been able to provide sufficient inertial self-restraint effect²⁶. The so-called inertial self-restraint effect refers to the ability of the ceramic to maintain its original position by relying on its own inertia to resist movement, the strength of which may be characterized by both the pressure P of the ceramic and pressure pulse width τ , where τ is the time interval for the pressure to rise from 0 to peak and then decay to 0.

The projection of the Finite Element Model (FEM) of the ceramic tile is depicted in Fig. 17. E_a and E_b are selected to probe the relation of pressure and inertial self-restraint. One thing to note, to facilitate the comparison of self-

restraint effect, the ceramic elements at the same location must be selected for each armor. For C4-(1 ~ 5) armors, elements E_a are labeled as E_a -(1 ~ 5), and E_b as E_b -(1 ~ 5), respectively.

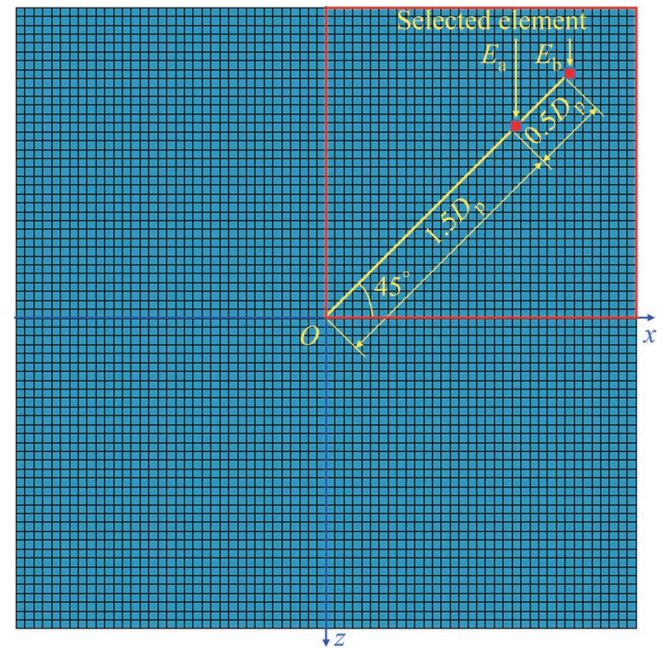


Fig. 17: Projection of the ceramic FEM in xoz plane. The downward direction perpendicular to the xoz plane is the direction of the projectile movement. The area enclosed by the red wire frame is 1/4 FEM established by simulation. The red elements E_a and E_b are located at the ceramic front-face, 1.5 and 2 times the bullet-diameter from the initial impact site, respectively.

The simulation data of duration of pressure above 200 MPa, pressure pulse width and pressure peak are provided in Table 7, while Figs. 18(a) and (b) offer the pressure versus time curves of E_a -(1 ~ 5) and E_b -(1 ~ 5) in the first 60 μ s, respectively, and the pressure tends to 0 after 60 μ s.

Table 7: Duration of pressure above 200 MPa, pressure pulse width and pressure peak.

Element	Parameter	Duration of pressure above 200 MPa t_{200} (μ s)	Pressure pulse width τ (μ s)	Pressure peak P_{max} (MPa)
E_a -1 ($R_p = 19.9$)		12	20	498
E_a -2 ($R_p = 13.1$)		11	18	441
E_a -3 ($R_p = 9.2$)		6	11	382
E_a -4 ($R_p = 6.6$)		1	7	280
E_a -5 ($R_p = 3.7$)		0	7	130
E_b -1 ($R_p = 19.9$)		11	20	352
E_b -2 ($R_p = 13.1$)		9	17	370
E_b -3 ($R_p = 9.2$)		7	12	266
E_b -4 ($R_p = 6.6$)		1	5	265
E_b -5 ($R_p = 3.7$)		0	3	102

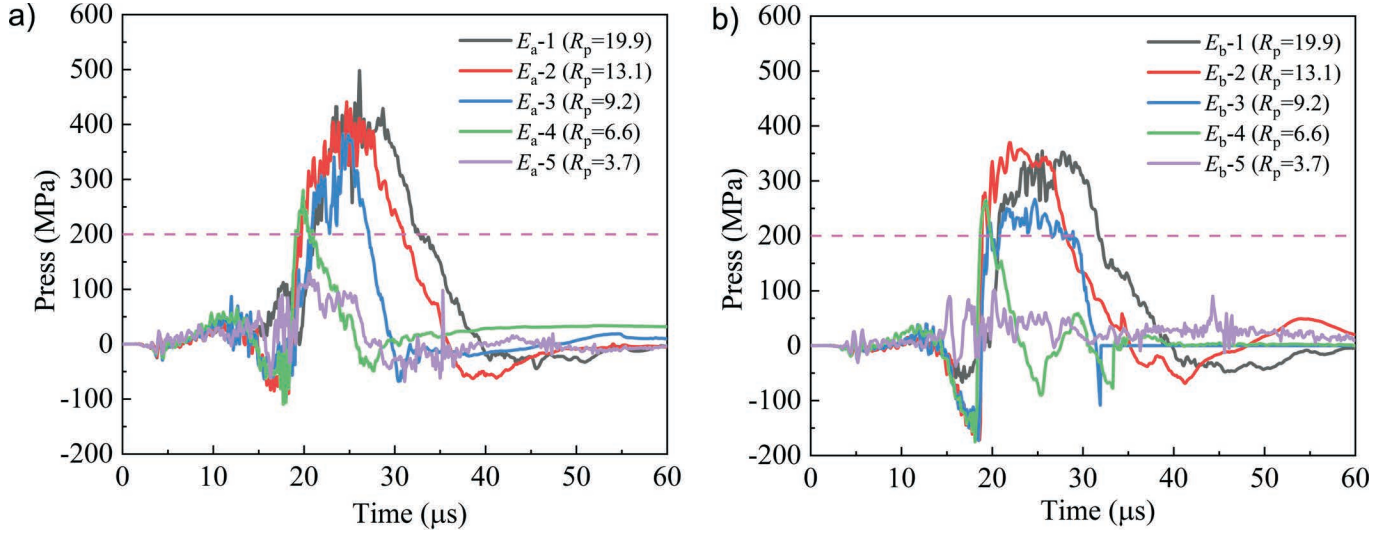


Fig. 18: (a) Pressure versus time curve of E_a -(1 ~ 5); (b) E_b -(1 ~ 5) at 830 m/s, $R_c = 1.3$.

Fig. 18 and Table 7 together manifest that $P_{\max}$, τ and t_{200} show a downward trend as R_p declines. The strength of the self-confinement effect is weighted by $P_{\max}$, τ and t_{200} together, and the larger the above three parameters are, the stronger the self-confinement effect. Since the variation laws of these parameters of E_a versus R_p are akin to E_b , the parameters for only E_a are emphasized in the subsequent analysis.

V_{bl} of C4-2 armor ($R_p = 13.1$) is reduced by a mere 1.2 % in comparison with C4-1 ($R_p = 19.9$), and the ballistic performance of C4-2 is somewhat inferior to C4-1. As presented in Fig. 18(a), t_{200} , $P_{\max}$ and τ of E_a -2 are slightly higher (10 % or so) than E_a -1, which indicates weakened self-restraint so as to undermine armor performance. However, the reduction in the ballistic performance of C4-2 armor is indistinctive, as observed from Ref. 46 that for ceramic/metal armor against a 7.62-mm AP projectile at 850 m/s, ceramic with 100 mm lateral size (i.e., $R_p = 11.2 \sim 13.1$) has presented superior anti-penetration performance, and a further increase in size is unnoticeable to improve armor performance, and our simulation results affirm this conclusion as well. In Fig. 16, the curve of performance change versus lateral size is very gentle.

However, Fig. 16 shows that ballistic performance drops obviously as the lateral size continues to decrease. C4-3 ($R_p = 9.2$), C4-4 ($R_p = 6.6$) and C4-5 ($R_p = 3.7$) armor drops by 8.4 %, 16.8 % and 22.8 % with respect to C4-1 ($R_p = 19.9$), respectively. On the one hand, the decline of ballistic performance is due to the significant reduction of the self-restraint effect. For example, for C4-4 armor, t_{200} , $P_{\max}$ and τ , which indicate the strength of self-restraint effect, decrease by 91.7 %, 65 % and 43.8 %, respectively. On the other hand, a small-sized tile facilitates the tensile wave reflected at the lateral boundary to quickly propagate back to the initial position, so that the damage of tile becomes more serious, being unfavorable for ceramic tile to resist projectile's penetration.

(4) Analysis of the coupling effect of two parameters

Sections IV(2) and IV(3) have independently discussed the influence of the thickness ratio and lateral size, respec-

tively, and in this section the influence mechanism of two-parameter coupling on ballistic performance will be studied. The numerical results V_{bl} versus R_p and R_c are plotted in Fig. 19.

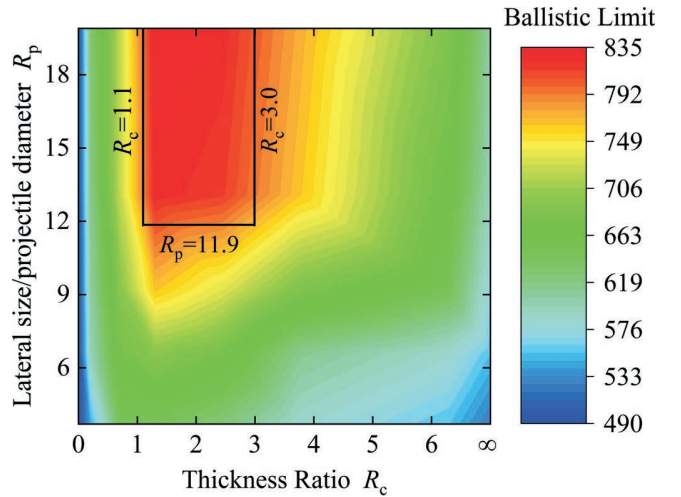


Fig. 19: Contour map of V_{bl} versus R_p and R_c .

For small-sized ceramic armors with $R_p = 3.7$ and 6.6, the ballistic performances only decrease by approximately 3 % for 0.72 ~ 2.45 thickness ratio R_c , whereas, beyond this thickness ratio range, the performance will decrease by more than 10 %, as can be observed from Fig. 10 in Section IV(2). The above conclusion implies when designing a mosaic ceramic/metal armor made of small-size tile smaller than 50 mm without lateral constraint, R_c must not exceed 2.45 and preferably be between 0.72 and 2.45. Nevertheless, with regard to ceramic armors with $R_p \geq 9.2$, the thickness ratio between 1.3 and 3.75 is favorably available, and in this case, the decline of ballistic performance basically falls within 10 %. Briefly, there is a coupling effect between thickness ratio and lateral dimension, so the influence of both should be comprehensively evaluated to assist in rational armor configuration design.

The district scope encompassed by the black wireframe in Fig. 19 is $1.1 \leq R_c \leq 3.0$, $11.9 \leq R_p \leq 19.9$ (i.e. lateral size ranging from 91 ~ 152 mm). In this region, V_{bl} is always greater than 756 m/s, being only 9.5 % lower than the maximum ballistic limit of 835 m/s among all armors. In other words, armors designed accordingly can certainly demonstrate excellent ballistic performance.

V. Conclusions

A deep understanding of the dynamic response and failure mechanism of the target subjected to a high-speed impact is the premise for optimal design of armor structure, and the numerical technique has become a powerful tool to recognize the process of penetration response. In the present manuscript, the response behavior of 7.62 APM2 impacting an AD995/5083-H116 target is simulated. The influence mechanisms of thickness ratio, lateral size and double-parameter coupling on the ballistic performance are clarified in detail based on V_{bl} . The simulations have successfully captured the crack propagation in ceramic, formation of the fracture cone, mass erosion of the projectile, and other important phenomena during the penetration process. Through the systematic analysis of simulation results, some important conclusions are obtained as follows:

- There is an optimal thickness ratio for ceramic/metal bi-layer armor, and the intrinsic mechanism may be explained as follows: for small R_c , the thin ceramic tile will cause the perforative damage of tile to be advanced, projectile/ceramic interaction time and dwell duration to be reduced, and fracture cone to be difficult to form or cone half-angle to be diminished. These factors are not conducive to the erosion of the projectile, which leads to the reduction of ballistic performance. For large R_c , a thin backplate fails to provide effective support for the tile, and, also implies less backplate materials participate in energy dissipation of projectile. Additionally, the reduction in cone half-angle will also bring about the decline in the ballistic performance.
- The increase of R_p (3.7 ~ 19.9) always improves the ballistic performance. On one hand, increasing R_p will enhance the self-restraint effect of tile and keep the ceramic fragments on the path of projectile to resist its penetration. On the other hand, it delays the tensile wave reflected from the lateral boundary.
- Based on the analysis of the effect of double-parameter coupling, it is suggested for R_c ranging from 1.1 ~ 3.0 and R_p ranging from 11.9 ~ 19.9, the bi-layer armor designed can demonstrate superior ballistic performance.

Of course, although the above conclusions provide an effective guide for design of the armor structure, in fact, different types of threats and oblique penetration will play a role in the structural response of armor and the final ballistic performance evaluation during the penetration event. However, this would complicate our numerical model, especially for the asymmetric characteristic caused by oblique penetration. Therefore, although it is necessary to pay attention to these research topics, it is beyond the scope of this paper, and more in-depth research in these fields can be left for the future.

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Disclosure statement

The authors declare that they have no conflict of interests.

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