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Effect of Ceramic Properties and Depth-of-penetration Test Parameters on the Ballistic Performance of Armour Ceramics

Fengdan Cui[!], Guoqing Wu[!,*], Tian Ma[#], and Weiping Li[#]

[!]*School of Materials Science and Engineering, Beihang University, Beijing - 100 191, China*
[#]*The Quartermaster Research Institute of the General Logistics Department of the PLA, Beijing - 100 082, China*
[*]*E-mail: guoqingwu@buaa.edu.cn*

ABSTRACT

Through an analysis on the relationship among ceramic properties, the depth of penetration (DOP) test parameters and the ballistic performance of armour ceramics based on literatures, the effects of ceramic type, tile thickness and projectile velocity on the ballistic performance of different kinds of ceramics were investigated systematically. The results show that the ballistic performance of different armour ceramics mainly depends on its density, and by using thin ceramic tiles or under high velocity impact, the ceramic composite armour could not provide effective ballistic protection. Furthermore, the differences in the ballistic performance of armour ceramic are found due to the different ballistic performance criteria and DOP test conditions. Additionally, the slope of the depth of penetration (not include tile thickness) (P_a) versus tile thickness has negative correlation with flexural strength of ceramics, indicating the flexural strength can be one of the criteria to evaluate the performance of armour ceramics.

Keywords: Armour ceramics; Ballistic performance; Mechanical property; Quantitative analysis

1. INTRODUCTION

Nowadays, the development of military weapons and increasing capability of modern anti-armour threats require highly effective composite armour systems. Due to the low density, high compressive strength and hardness[1-23], ceramics play an important role in improving the ballistic performance of composite armours, and have been extensively utilised for lightweight armour applications such as personal body armour, fighting vehicles and helicopters[1-4]. To further improve the ballistic performance of armour ceramic now has become one of the focuses in ceramic composite armour systems[5,6].

The parameters possibly having an influence on the ballistic performance of armour ceramics include geometry, size and backing material as well as the shape, size and velocity of projectiles[7-11]. In addition, the ballistic performance of different armour ceramic may vary in a wide range according to their manufacturing processes and the depth of penetration (DOP) test conditions[7,12-14]. However, due to experimentation limitations, experimental results are not always reproducible, and thus it is difficult to evaluate the ballistic performance of ceramic tiles from different reference sources for a same type ceramic[15,16]. Based on the comparison of ceramic types, Moynihan[17], *et al.* pointed out the boron carbide (B_4C) tiles had higher ballistic efficiency than both silicon carbide (SiC) and alumina (Al_2O_3) tiles. However, the research carried out by Kaufmann[18], *et al.* proved that SiC tiles had higher ballistic efficiency than B_4C, Al_2O_3 and modified Al_2O_3 tiles. It was also reported[19] that SiC and B_4C tiles behaved similarly when considering the areal densities, whereas B_4C tiles performed worse than SiC and TiB_2 tiles at the same thickness. Based on the comparison of tile thickness, the ballistic efficiency for a given velocity was found to decrease with the increase in tile thickness for 99.5 per cent Al_2O_3 tiles, while for 95 per cent Al_2O_3 tiles, it was found to increase with the increase in tile thickness[8]. Savio[20], *et al.* discovered that as B_4C tile thickness increased, the ballistic efficiency did not change significantly. Moreover, according to the comparison of projectile velocity, Madhu[8], *et al.* and Zhang[21], *et al.* showed that the ballistic efficiency of Al_2O_3 tiles increased with the increase in projectile velocity. However, according to Woolmore[22], *et al.*, SiC and Al_2O_3 tiles both showed a similarly linear decrease in the ballistic efficiency of the ceramic armour system when the projectile velocity increased. Additionally, many efforts have been put to correlate the ballistic performance of ceramic tiles to the key material properties such as density, hardness, strength, Young's modulus and fracture toughness since the 1960s[4,7,18,23]. Several fundamental mechanical properties, such as the dynamic compressive strength, hardness and Young's modulus, have been used to guide the selection of ceramics for light armours[24,25]. The damage mechanism of ceramic layer in the whole ceramic composite armour against the projectile was analysed in previous studies[9,26]. However, few reports focused on the mechanism of ballistic protection for different ceramic layers were published. Therefore, particular attention needs to be paid to the relationship between ceramic properties and the ballistic performance.

However, it is difficult to investigate the ballistic performance of armour ceramics systematically due to the

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high costs (human and material resources). There are many contradict information of the ceramic ballistic efficiency in literatures concerning the ceramic type, tile thickness and projectile velocity. The authors did not necessarily use the same ceramic compositions, manufacturing processes and DOP test conditions. These differences can make sense if we incorporate the parameters that are listed.

Through an analysis on the ballistic performance of armour ceramics based on the literatures published from 1988 to present, the effects of ceramic properties and DOP test parameters on the ballistic performance were investigated systematically. The effects of monolithic ceramic types (Al_2O_3, SiC, B_4C and TiB_2) on the differential efficiency factor (Δe_c) and the depth of penetration (not include tile thickness) (P_a) were investigated. Additionally, the effects of tile thickness and projectile velocity on the Δe_c and P_a were investigated.

2. METHOD

In this study, earlier published literatures were investigated with information about the ceramic properties, DOP test parameters and the ballistic performance (P_a, $P_a/(P_a+t_c)$ and Δe_c) of different ceramic tiles (Tables 1-4). All the work reported in this study entirely relied on the literature data. The schematic diagram of DOP test configuration is as shown in Fig. 1. All the DOP tests were performed at room temperature under normal impact.

Table 1. The published DOP test parameters and ballistic performance of Al_2O_3 ceramic tiles from different resources.

Studies	ρ_c (g/cm^3)	t_c (mm)	Projectile		P_a (mm)	$P_a/(P_a+t_c)$ (%)	Δe_c
			Type	v (km/s)			
Madhu[8], *et al.*	3.85	6-8	7.62 mm AP	0.83	1-2	18-35	3.8-5.0
	3.68-3.85	10-14	12.7 mm AP	0.50-0.83	0-38	2-53	1.8-4.2
Moynihan[17], *et al.*	3.7	1.3-6.4	Caliber.30 APM2	0.84	0-42	0-97	1.9-5.8
Woolmore[22], *et al.*	3.89	18	14.5 mm AP	0.75-1.10	\	\	1.7-3.2[a]
Savio[30], *et al.*	3.91	3-6	7.62 mm AP	0.82	5-34	47-92	4.7-5.6
Rozenberg and Yeshurun[31]	\	6-10	12.7 mm AP	0.92	\	\	4.2-5.0
			14.5 mm AP	0.98	\	\	3.6-5.3
Reaugh[10], *et al.*	3.40-3.75	10-60	W rod	1.35-2.60	0-39	0-83	0.9-2.0[a]
Zhang and Li[21]	3.54	50	W rod	1.0-1.5	22-49	27-48	1.9-3.0
Li[27]	3.62	6-30	W rod	1.50-2.50	37-60	57-91	2.1-4.9
Anderson and Morris[28]	3.60	28, 42	W rod	1.50	\	\	1.7-2.2[a]
Anderson and Royaltimmons[33]	3.90	25.9	W rod	1.53 -1.78	20-63	55-69	1.4-3.5
Hohler[32], *et al.*	3.85	20-80	W rod	1.25-3.0	12-78	15-88	1.4-2.0[a]
Sun[29]	3.5	30	Fe rod	1.1-1.3	7-32	20-51	2.0-2.6

'a' Calculated or measured by the authors; 'AP' represents armor piercing projectile; 'W rod' represents tungsten rod projectile; 'Fe rod' represents 35CrMnSi rod projectile.

Table 2. The published DOP test parameters and ballistic performance of SiC ceramic tiles from different resources

Studies	ρ_c (g/cm^3)	t_c (mm)	Projectile		P_a (mm)	$P_a/(P_a+t_c)$ (%)	Δe_c
			Type	v (km/s)			
Moynihan[17], *et al.*	3.2-3.3	1-5	Caliber.30 APM2	0.84	0-42	0-96	2.6-8.9
Roberson and Hazell[19]	3.14-3.15	6-8	7.62×51 mm NATO	0.97	2-14		6.2-6.6
Woolmore[22], *et al.*	3.18	18	14.5 mm AP	0.75-1.1	\	\	3.5-5.0[a]
Rozenberg and Yeshurun[31]	3.07-3.17	6-10	12.7 mm AP	0.92	\	\	6.9
			14.5 mm AP	0.98	\	\	7±0.3
Flinders[34], *et al.*	3.14-3.22	6.35	7.62×51 mm M993	0.91	4-17	40-72	5.9-7.6[a]
Tong[36]	3.16	6	12.7 mm API	0.82	15-22	29-55	5.5-8.2
Reaugh[10]	3.16	10-60	W rod	1.35-2.6	0-18	0-58	1.4-5.8[a]
Cao[35]	3.09-3.14	26-29	W rod	1.3-1.4	12-13	30-33	4.1-5.6
Rosenberg[37], *et al.*	3.15	20-80[a]	W rod	1.70	3-40[a]	\	1.2-2.6[a]

'a' Calculated or measured by the authors; 'AP' represents armor piercing projectile; 'API' represents armor piercing incendiary projectile; 'W rod' represents tungsten rod projectile.

Table 3. The published DOP test parameters and ballistic performance of B_4C ceramic tiles from different resources

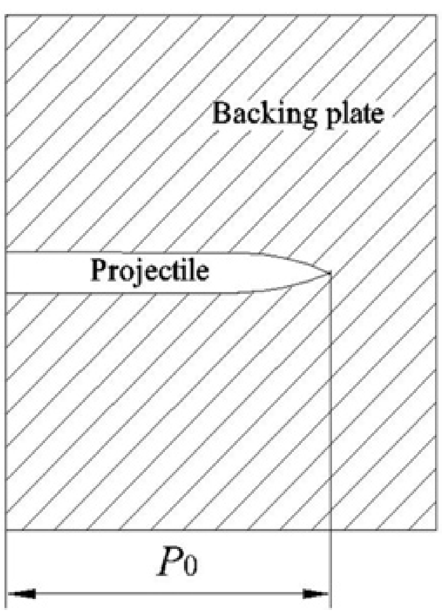
Studies	ρ_c (g/cm^3)	t_c (mm)	Projectile		P_a (mm)	$P_a/(P_a+t_c)$ (%)	Δe_c
			Type	v (km/s)			
Savio[20], *et al.*	2.31-2.49	5-10	7.62 mm AP	0.6-0.8	0.5-30	5-80	3.0-8.5
Roberson and Hazell[19]	2.5	5-8	7.62×51 mm NATO	0.97	18-26	71-81	5.6-6.9
Sun[38]	2.47	8	12.7 mm API	0.82-0.85	17-19	68-69	4.3-4.5[a]
Rozenberg and Yeshurun[31]	2.51	6-10	12.7 mm AP	0.92	\	\	7.8[a]
			14.5 mm AP	0.98	\	\	8.3
Moynihan[17], *et al.*	2.49	1-4	Caliber.30 APM2	0.84	0-42	0-96	2.7-10.4
Reaugh[10], *et al.*	2.51	10-60	W rod	1.2-2.6	0-28	0-73	1.4-6.2[a]
Rosenberg[37], *et al.*	2.5	48.45[a]	W rod	1.70	32.0[a]	\	1.1[a]
		84[a]			7.5[a]	\	2.04[a]

'a' Calculated or measured by the authors; 'AP' represents armor piercing projectile; 'API' represents armor piercing incendiary projectile; 'W rod' represents tungsten rod projectile.

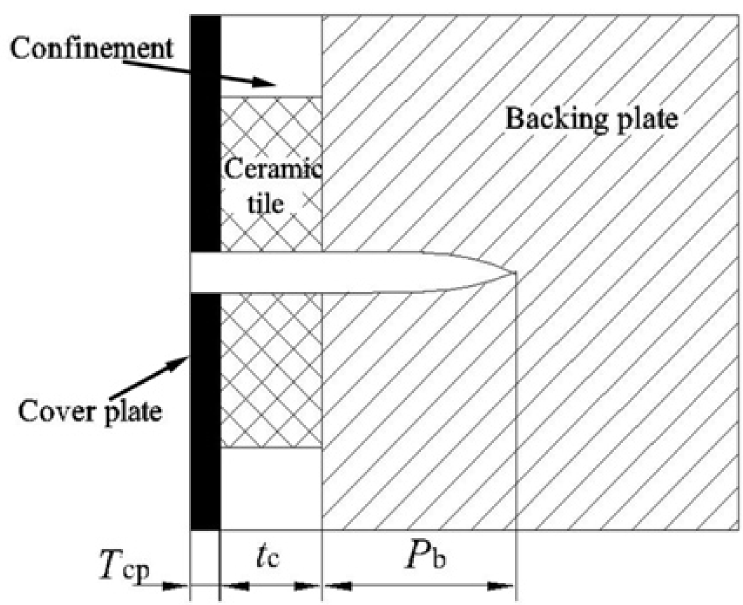
Table 4. The published DOP test parameters and ballistic performance of TiB_2 ceramic tiles from different resources

Studies	ρ_c (g/cm^3)	t_c (mm)	Projectile		P_a (mm)	$P_a/(P_a+t_c)$ (%)	Δe_c
			Type	v (km/s)			
Roberson and Hazell[19]	4.5	5-8[a]	7.62×51 mm NATO	0.97	2-10[a]	23-64	4.2-4.5[a]
Rozenberg and Yeshurun[31]	4.46	6-10	12.7 mm AP	0.92	\	\	5.05
			14.5 mm AP	0.98	\	\	>5.2
Song[39]	4.5	18-20	14.5 mm API	0.99	5-7	21-28	2.9-3.2
Reaugh[10], *et al.*	4.49	8-40	W rod	1.3-2.7	0-34	0-68	2.1-7.1[a]
Rosenberg[37], *et al.*	4.45	20-70[a]	W rod	1.70	0-36[a]	\	1.7-2.4[a]

'a' Calculated or measured by the authors; 'AP' represents armor piercing projectile; 'API' represents armor piercing incendiary projectile; 'W rod' represents tungsten rod projectile.



(a)



(b)

Figure 1. Schematic diagram of DOP test configuration: (a) Reference depth of penetration (P_0) in backing plate without ceramic tiles and (b) Residual depth of penetration (P_b) in backing plate.

In this study, the Δe_c and P_a were used to rank the ceramic tiles based on their ballistic performance[25]. The reference DOP value (P_0) was obtained on the bare backing plate and the residual DOP value (P_b) was obtained on the same backing plate after penetration of the ceramic tile in front.

$$\Delta e_c = \frac{\rho_b \times (P_0 - P_b - T_{cp})}{\rho_c \times t_c} \quad (1)$$

$$P_a = P_b + T_{cp} \quad (2)$$

where ρ_b and ρ_c are the density of the backing material and ceramic, respectively. P_0 is the reference depth of penetration in the bare backing material. P_b is the residual depth of penetration in the backing material. T_{cp} and t_c are the thickness of cover target and ceramic tile respectively. P_a is the depth of penetration (not include tile thickness).

Most of the Δe_c and P_a could be obtained from literatures, but the ones that were not given clearly were calculated using Eqns (1) and (2). All these calculated data were labelled as 'a' in Tables 1-4. If the tile density or thickness published in literatures was in a range, the average value was used to calculate the Δe_c.

3. RESULTS

3.1 Effect of Ceramic Type

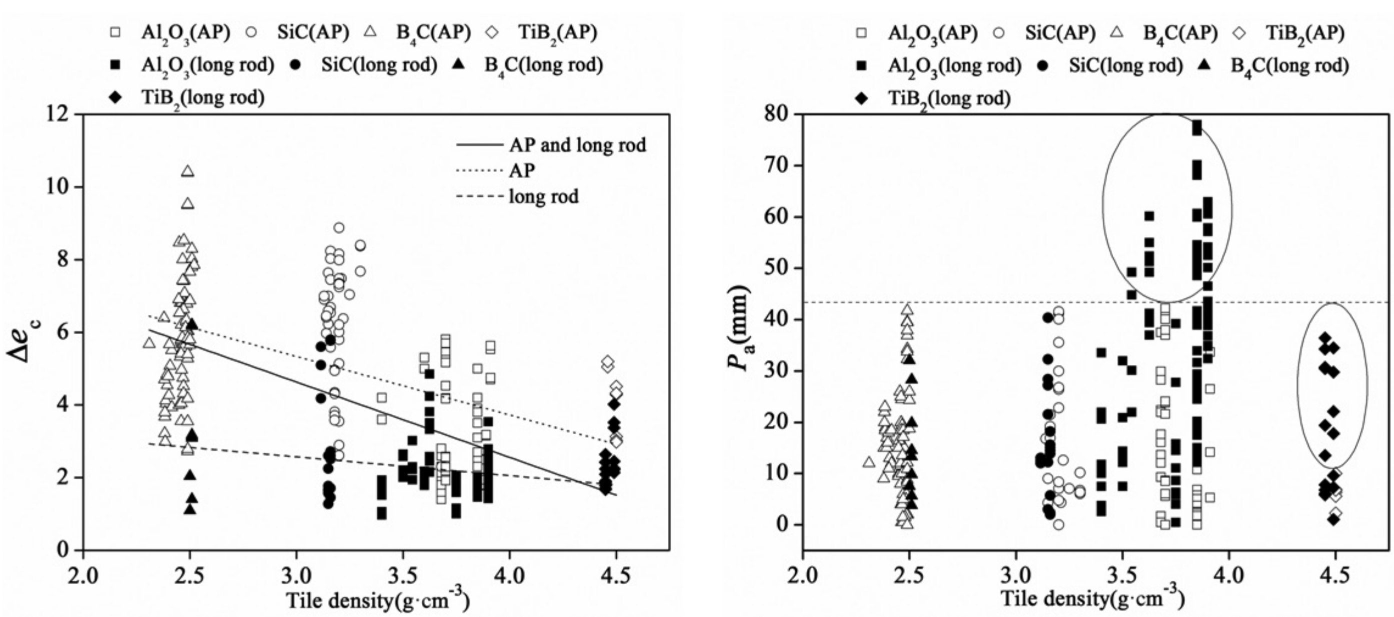
According to the different tile densities, the ballistic performance of four typical armour ceramics subjected to the impact of armour piercing (AP) projectiles and long rod projectiles is presented in Fig. 2. As it can be seen, most data shows a linear relationship. The Δe_c of different ceramic tiles decreases in the order of B_4C, SiC, Al_2O_3 and TiB_2 tiles when impacted by AP projectiles as well as long rod projectiles (Fig. 2(a)). Significant differences are found with respect to the Δe_c of different ceramics in the case of AP projectiles rather than long rod projectiles. For P_a (Fig. 2(b)), the data is approximately within the range of 0-44 mm and most P_a of Al_2O_3 tiles are higher than 44 mm, and this is closely related to thin ceramic tiles or high impact velocity, which indicates that ceramic composite armours could not provide effective ballistic protection with relatively thin ceramic tiles or at high impact velocity. There is no sufficient data to draw general trend for DOP tests of TiB_2 tiles against AP projectiles, which might be related to limited applications due to its high density. In a word, P_a shows no obvious difference among different ceramic tiles.

The Δe_c is very sensitive to tile density, which are not coincided with P_a, and with a higher tile density, a lower Δe_c could be obtained, which is in agreement with the results observed by Wilkins[40], *et al.* It needs to be further considered that when investigating the armour ceramics with long rod projectiles, DOP test conditions such as the backing material and confinement can influence the ballistic performance of ceramic tiles, which causes the ballistic performance of ceramic tiles against long rod projectiles less obvious than using AP projectiles. Therefore, ballistic performance criteria and DOP test conditions should be chosen carefully.

3.2 Effect of Tile Thickness

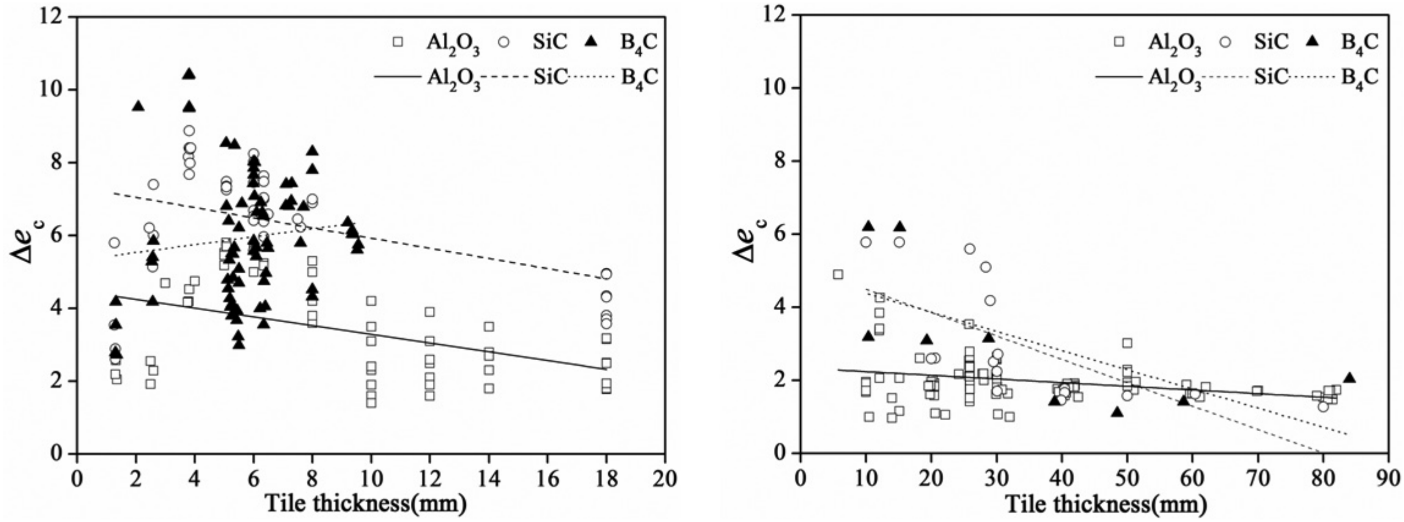
The effects of tile thickness on the Δe_c of three armour ceramics are as shown in Fig. 3. As it can be seen, most data exhibits a linear relationship. It can be observed that the Δe_c of the Al_2O_3 and SiC tiles increases as the tile thickness increases, no matter the AP projectiles or long rod projectiles are used. However, with the increase in tile thickness, the Δe_c of B_4C tiles is found to increase when using AP projectiles but decrease when using long rod projectiles, which may be related to the limited ballistic data for thick ceramic tiles or the large scatter of the existing data. It should be noted that the ballistic performance of TiB_2 tiles is not analysed here due to the lack of data.

Figure 4 gives the correlations between P_a and tile thickness of three armour ceramics against AP projectiles and log rod projectiles. A decrease in P_a is observed with the increase in tile thickness by both using the AP projectiles



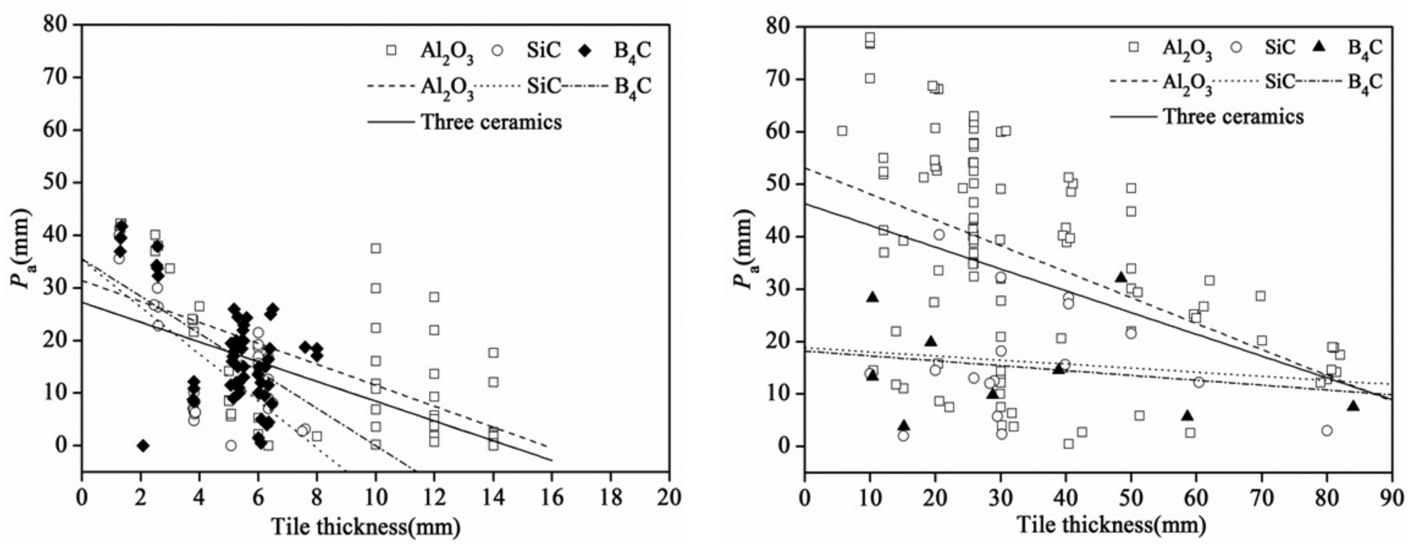
(a) (b)

Figure 2. The effect of ceramic types on the ballistic performance of armour ceramics: (a) Δe_c and (b) P_a.



(a) (b)

Figure 3. The effect of tile thickness on the Δe_c of armour ceramics impacted by (a) the AP projectiles and (b) the long rod projectiles.



(a) (b)

Figure 4. The effect of tile thickness on P_a of armour ceramics impacted by (a) AP projectiles and (b) long rod projectiles.

(Fig. 4(a)) and long rod projectiles (Fig. 4(b)). A linear fitting equation is given as follow:

$$P_a = kt_c + b \tag{3}$$

the slopes and intercepts of the linear fits for Al_2O_3, SiC, B_4C and above three ceramic tiles are listed in Table 5. It can be evidently found that for AP projectiles impacting ceramic faced armours the intercepts, namely the reference DOP, have smaller deviations (with the maximum deviation of 8.24 mm), when compared to that for long rod projectiles (with the maximum deviation of 27.5 mm). This also proves that there are some limitations when investigating the ballistic performance of armour ceramics with long rod projectiles. Generally, the Δe_c decreases as the tile thickness increases, which is similar to the results when considering of P_a.

Table 5. Linear fitting results for Al_2O_3, SiC, B_4C and above three ceramics

Parameters	Al_2O_3	SiC	B_4C	Three ceramics
Slope, *k*	-1.99	-4.46	-3.55	-1.88
Intercept, *b*	31.42	35.29	35.49	27.25

3.3 Effect of Projectile Velocity

Due to the limitations of using long rod projectiles discussed above, this study only focuses on analysing the effects of tile thickness on the ballistic performance of three armour ceramics against AP projectiles, as shown in Fig. 5. An increase in the Δe_c is first observed as the projectile velocity increases from 0.50 km/s to 0.80 km/s and then it decreases by further increasing the velocity after 0.90 km/s (Fig. 5(a)) as well as P_a (Fig. 5(b)) with the maximum Δe_c for AP projectiles is achieved at the impact velocity of 0.80 km/s - 0.90 km/s. Overall, both the Δe_c and P_a, as function of projectile velocity, have similar trend.

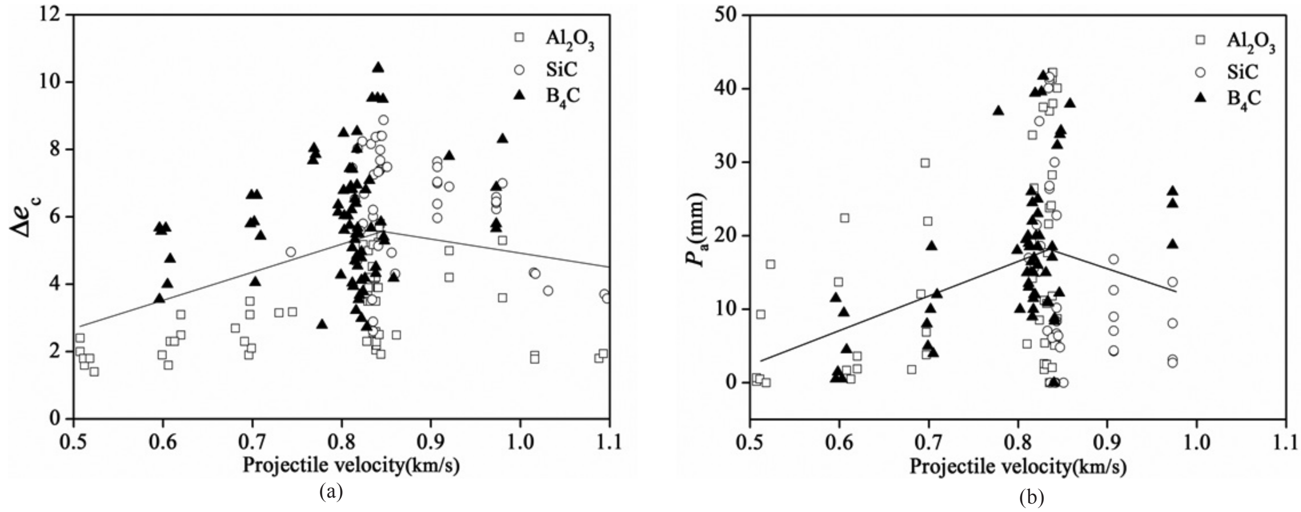


Figure 5. The effect of projectile velocity on the ballistic performance of armour ceramics: (a) Δe_c and (b) P_a.

3.4 Discussion

The primary mechanical properties of each armour ceramic vary widely among literatures. Generally, B_4C and SiC exhibit high hardness and flexural strength, and Al_2O_3 displays high fracture toughness but low Young's modulus. In this study, the correlations between the ballistic performance and ceramic material properties, such as flexural strength, Knoop hardness, Young's modulus, and fracture toughness, have been considered. The mechanical properties are taken from Karandikar[23], *et al.* based on CAP-3, SiC-N and Ceralloy-546 4E. With the increase in tile density, a decrease in Knoop hardness, Young's modulus, a slight increase in fracture toughness and insignificant change in flexural strength are found in Fig. 6. In addition, with the increase in tile density, the slope (k) of P_a versus tile thickness has negative correlation with flexural strength (Fig. 6(a)), while it has no direct relationship with Knoop hardness (Fig. 6(b)), Young's modulus (Fig. 6(c)) and fracture toughness (Fig. 6(d)), which indicates that the flexural strength can be one of the criteria to evaluate the performance of ceramics in armours.

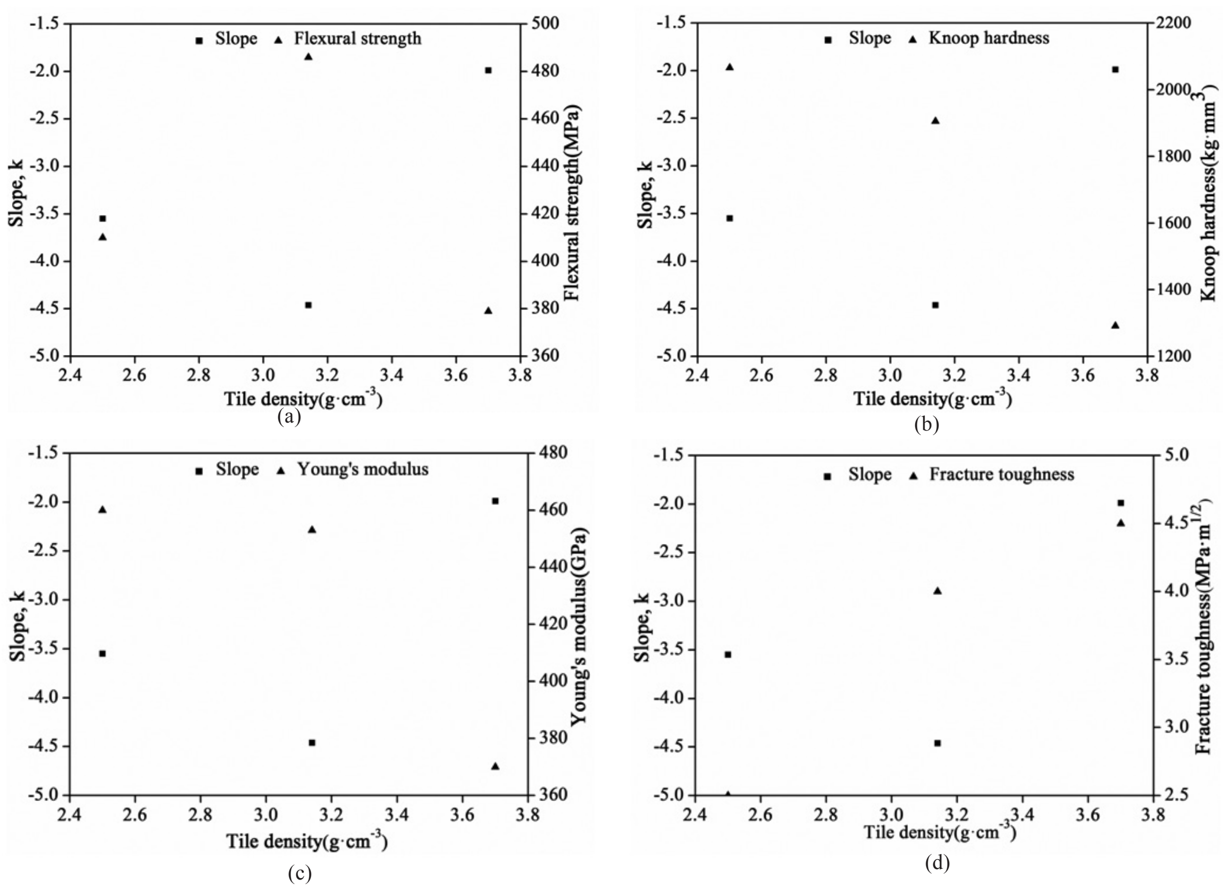


Figure 6. Relationships among tile density, slope (k) of P_a *vs* tile thickness and (a) flexural strength, (b) Knoop hardness, (c) Young's modulus and (d) fracture toughness.

4. CONCLUSIONS

Through an analysis on ceramic properties, DOP test parameters and the ballistic performance of armour ceramics which dated from 1988 to present, the effects of ceramic type, tile thickness and projectile velocity on the ballistic performance were investigated systematically. Based on these analyses, the following conclusions are as follows:

(i) The ceramic type, tile thickness and projectile velocity have significant influence on the ballistic performance of armour ceramics. The ballistic performance of different armour ceramics mainly depends on its density. The differential efficiency factor (Δe_c) of different ceramic tiles decreases in the order of B_4C, SiC, Al_2O_3 and TiB_2 tiles and P_a shows no obvious difference among different ceramic tiles. The Δe_c decreases as the tile thickness increases, which is similar to the results when considering depth of penetration (not include tile thickness) (P_a). In addition, the Δe_c and P_a increase at first then decrease with the increase in projectile velocity. And the maximum ballistic efficiency for AP projectiles is achieved at the impact velocity of 0.80 km/s - 0.90 km/s.

(ii) Ballistic performance criteria and DOP test conditions should be chosen carefully. The differential efficiency factor is very sensitive to tile density, which is not coincided with P_a. In addition, when investigating the ballistic performance of armour ceramics with long rod projectiles, the effects are less remarkable than that of using AP projectile.

(ii) Mechanical properties have significant correlations with the ballistic performance of armour ceramics. With the increase in tile density, the slope of P_a versus tile thickness has negative correlation with flexural strength, which indicates that the flexural strength can be one of the criteria to evaluate the performance of armour ceramics.

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CONTRIBUTORS

Ms Fengdan Cui received her BS (Material Science and Engineering) from Jiangsu University, China, in 2014, and MS (Material Science and Engineering) from Beijing University of Aeronautics and Astronautics, in 2017. Her area of expertise is : Design and manufacture of ceramic and composite armour. In the current study, she collected and processed the literature data and prepared the manuscript.

Dr Guoqing Wu received his MS (Material Science and Engineering) from Xian Jiaotong University, China, in 2000, and PhD (Material Science and Engineering) from Beijing University of Aeronautics and Astronautics, in 2003. Currently, he is working as an Associate Professor at the Department

of Material Science and Engineering, Beijing University of Aeronautics and Astronautics. His research interests include: relationship among process, microstructure and property of Ti alloy, design and manufacture of ceramic and composite armour.
In the current study, he provided initial idea for the study and prepared the manuscript.

Dr Tian Ma received his MS (Materials processing engineering) from Xian Jiaotong University, China, in 2000, and PhD (Material Science and Engineering) from Tsinghau University, in 2004. Currently, he is working as senior engineer in the Quartermaster Research Institute of the General Logistics Department of the PLA. His research interests are in the areas of development and characterisation of ceramic armour materials and design, manufacture and application of composite materials in armours.
In the current study, he provided initial idea for the study and prepared the manuscript.

Ms Weiping Li received her BS (Material Science and Engineering) from Liaocheng University, China, in 2010, and MS (Material Science and Engineering) from Beijing Institute of Technology, in 2013. Currently, she is working as engineer in the Quartermaster Research Institute of the General Logistics Department of the PLA. Her area of expertise is manufacture and application of composite materials in armours.
In the current study, she processed the literature data and prepared the manuscript.