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DETERMINATION OF THE BALLISTIC PERFORMANCE RAMIE-FIBER-REINFORCED EPOXY COMPOSITE-SiC CERAMIC IN MULTILAYERED ARMOR SYSTEM

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Multilayered Armor System (MAS) is being extensively studied around the world for its ability to retain ceramic fragmentation after a collision occurs. MAS consist of a ceramic layer placed at the front and supported by a composite layer of ramie-fiber-reinforced epoxy resin. Present study utilizes natural fibers of 50 % ramie fibers with epoxy resin as the matrix and Silicon Carbide (SiC) ceramic as the front panel. The ballistic testing in this study used 7.62×51 mm NATO Ball projectile with a firing distance of 15 m from the bullet panel. The velocity of projectile was detected using LIGHT SCREEN B471 type. The aim of the study is to conclude the optimal thickness of ramie fiber-epoxy and SiC ceramics MAS structure based on experiments which can withstand 7.62 NATO ball bullet penetration. To achieve this aim, the following objectives are accomplished: study the effect of SiC ceramic addition to ramie composite on BFS and study the effect of SiC ceramic addition to ramie composite on failure mode. Results show that the addition of the number of layers of SiC increases resistance of ballistic MAS marked by a decrease in the value of BFS clay. The 5SiC+10R is the optimal thickness in resisting the penetration of 7.62×51 mm bullets with 12 mm BFS clay. Failure phenomena found in this study were projectile fragments, matrix cracks, radial cracks, impact points, and ceramic fragments. Matrix crack formation appears on 5SiC+10R with mini deformation in rear side. Phenomenon of ceramic fragmentation in the shot causes the MAS structure to be damaged, so that the ramie fiber composite layer will face the bullet directly if it is subjected to a second shot. Ultra High Hardness Armor (UHHA) as first layer on the MAS structure is an attractive option for further research

Keywords: ballistic performance study, multilayered armor system, SiC, ramie, back face signature

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1. Introduction

Natural fibers application in Polymer Matrix Composites (PMCs) has shown great potentials as alternative material to substitute the existing synthetic fiber materials in the ballistic world [1]. Ramie fiber (Boehmeria Nivea) is one of the natural fiber material with qualified physical and mechanical properties. However, ramie strengthened composite panel has limitation in resistance of level III and IV NIJ standard sharp projectile.

The hard property of ceramics can absorb the energy generated by the impact of projectiles through deformation and erosion. Silicon Carbide ceramic (SiC) is the most popular material as ballistic ceramic, although the price is higher than alumina (Al_2O_3) but SiC ceramic has higher mechanical properties and lower density [1]. Shattering phenomenon appears in ceramics as ballistic material caused the material to be ineffective for multiple firing [2] as shown in Fig. 1.

Fig. 1. Shattered phenomena presented on B_4C ceramic [2]

MAS consists of a ceramic layer placed at the front and supported by a composite layer of ramie-fiber-reinforced epoxy resin. Lightweight MAS material is preferred bulletproof vest [3]. The shock wave impedance inequality that occurs between the ceramic front and the back layer, which has a low density, may cause ceramic fragmentation [4]. One of the back layer's functions in MAS is to reduce the kinetic energy of fragmentation. MAS structure can be one of a solution to overcome the ramie fiber and SiC ceramics disadvantages as sole ballistic resistance materials for a sharp tipped armor pierce. Therefore, research on MAS structure with ramie and SiC layer combined is relevant to solve the concern related to weight and ceramic fragmentation issue in ballistic material. SiC layer supported with ramie fiber reinforced epoxy resin will have prevent ceramics fragmentation and resulted in lightweight material for ballistic.

2. Literature Review and Problem Statement

The paper [5] shown that ramie fibers are one of natural fibers with excellent mechanical properties, such as having a density of about 1.30–1.45 g/cm^3 which made ramie fiber a lightweight material, furthermore the paper [6] showed that tensile strength range between 400 to 1620 MPa, Young Modulus 61–128 GPa. The paper [7] shown the decortication treatment without water is the best treatment to produce droptest strength, and Energy absorbed per effective linear thickness also increases significantly with the rising thickness and bulletproof panel density. Furthermore, the paper [8] has shown that ramie woven fiber reinforced bulletproof panel able to endure penetration of projectile with 380 m/s impact velocity in ballistic test. Then [9] shown that another ballistic test on 6, 9 and 12 layers epoxy ramie composite conducted with 240 m/s velocity before hit the panel and 80 m/s velocity after hitting the panel. Those ballistic test proofed that ramie-composite can endure the impact of projectile. Ramie fiber composites are known to have disadvantage of not being able to withstand NIJ standard Armor Pierce bullet penetration (level III and IV). An option to overcome the relevant difficulties can be seen in previous researches [10] showed that MAS with ceramic Al_2O_3 and the 20 vol % of fique fabric polyester matrix composite as a second layer was not perforation on the 7,62×51 mm NATO ball ballistic test, and the backface signature 28±3 mm, thus the paper [11] showed that MAS hexagonal Al_2O_3 ceramic with polyester composite reinforced within jute non-woven mat as second layer resisted penetration by 7.65×51 mm bullets with a BFS of 24±7 mm. Furthermore [12] ceramic Al_2O_3 and the curaua non-woven fabric composite is promising, since there was not perforation on the 7,62 mm NATO ball ballistic test, and the backface signature 28±3 mm then [13] showed that front layer ceramic plate backened with 30 % volume of mallow fiber have similar indentation as Kevlar for 7.62 ammunition ballistic test. The paper [14] mentioned that 30 % volume of curaua fibers with better strength and stiffness than aramid fabric showed trauma indentation on standard clay simulated as human body. Aramid fabric MAS was at higher cost than curaua fiber full MAS due to the high price of aramid fabric. Related to MAS indicated that ceramic material followed by natural fibers polymer matrix composites fulfill the standard ballistic test with 7,62 mm projectile. Natural fiber such as ramie in second layer of MAS has succeed in resisting the projectile impact compare to existing synthetic fiber materials. The paper [6] shown that Ramie epoxy composite 30 % shown better projectile penetration resistance than kevlar if it positioned behind Al_2O_3 ceramic on Multilayered Armor System (MAS) in level II 7.62 mm ballistic test NATO.

Back Face Signature (BFS) is one of the tests on ballistics with NIJ standards in self-protection [15]. The standards require projectile stoppage and its penetration to be intercepted by clay not more than 44 mm in thickness. A person could die when shot with a projectile resulting in a penetration depth of more than 44 mm. A low BFS indicates a good MAS performance [6].

Alumina base (Al_2O_3), silicon carbide (SiC) and boron carbide (B_4C) are the three types of popular ceramics ballistic material because of their high ballistic performance and price wise. But the paper [2] shown that SiC ceramic is the most popular as ballistic material for its higher mechanical properties and lower density [2]. All this allows to assert that it is expedient to conduct a study on SiC ceramic layer addition to ramie fiber composite as a MAS on the ballistic testing as bulletproof material potential.

3. The aim and objectives of the study

The aim of the study is to conclude the optimal thickness of ramie fiber-epoxy and SiC ceramics MAS structure based on experiments which can withstand 7.62 NATO ball bullet penetration. To achieve this aim, the following objectives are accomplished:

– to study the effect of SiC ceramic layer addition to ramie composite on BFS;

– to study the effect of SiC ceramic layer addition to ramie composite on failure mode.

4. Materials and Method

4. 1. Object and hypothesis of the study

The object of this study was MAS (Multilayered Armor System). with ceramic in the front layer. The Silicon Carbide (SiC) ceramic and ramie fiber-reinforced epoxy resin were used as the composite material to improve the quality of MAS (Multilayered Armor System) as the bulletproof material.

According to the literature review, the main hypothesis in this study was the Silicon Carbide (SiC) ceramic that used in the MAS (Multilayered Armor System) will be able to blunt and destroy the bullets since this material has greater hardness compared to other materials. While the mechanical property of ramie is high and will give contribution to reduce the weight of material. In addition, the number of Silicon Carbide (SiC) ceramic layer will affect the performance of MAS (Multilayered Armor System) through decreasing the value of Back Face Signature (BFS).

As the assumptions in the study was the physical and mechanical properties differences of every Silicon Carbide (SiC) ceramic and every ramie fiber will not have effect on the ballistic test results. So does the defects in both of the material and the production process. The previous shot will not change the physical and mechanical properties of roman plasticina clay. Only the standard will give the effect.

Simplifications adopted in the work are:

1) materials procurement in the form of Silicon Carbide (SiC) ceramic, ramie fiber, epoxy, and hardener;

2) production equipment procurement in the form of hydraulic molding machines and composite molding;

3) ramie fiber fabrication into woven ramie fiber;

4) manufacturing of ramie fiber epoxy composite with vf 50 percent and thickness value of 10 mm;

5) layering of Silicon Carbide (SiC) ceramic with ramie composite using numerous layer variations of 3,4,5, and 6;

6) ballistic testing;

7) data analysis.

4. 2. Materials

The MAS consisted of ceramic material and epoxy resin composite as the matrix, reinforced with 50 % of ramie fiber volume. Ramie plants are currently grown by farmers in Wonosobo, Indonesia, as shown in Fig. 2, *a*. The stems of the ramie plant were taken and then extracted into ramie fibers, as shown in Fig. 2, *b*. The extracted ramie stems were then sorted by quality by tying them into bundles. In order to achieve uniform ramie bundles, the fibers were cut with a uniform length of 150 mm, as illustrated in Fig. 3, *a*. The ramie fibers were soaked in 5 NaOH solution for two hours to remove the gum and pectin. The ramie fibers were then dried under the sun to reduce their moisture content for the weaving process, as shown in Fig. 3, *b*.

a *b*

Fig. 2. Ramie: *a* – ramie plants; *b* – ramie stems

a *b*

Fig. 3. Ramie fiber process result: *a* – extracted fiber bundles; *b* – ramie fiber weaving process

The material used was Silicon Carbide (SiC) with dimensions of 100×100×4 mm, as shown in Fig. 4. SiC ceramic from Sancera [16] commercial ceramics with 3,12 g/cm^3 density, hardness value of 2650 kg/mm^2 dan 400 MPa bending strength. During the process of making composite specimens with the epoxy resin matrix reinforced with 50 % of rami fibers, about 10 weaves used high pressure hydraulic tools and were pressed until the composites were dry. The pressing process applied at the time of manufacture is useful for preventing air voids and achieving a homogeneous thickness, as seen in Fig. 5, *a, b*. The resulting ramie composite materials had dimensions of 150×150×10 mm. The engineering process of the MAS placed ceramics as the frontmost layer ramie composite and each layer ceramic glued using epoxy glue. An illustration of MAS design is shown in Fig. 6.

Fig. 4. Silicon Carbide (SiC) material (100×100 mm in dimensions)

a *b*

Fig. 5. Composite molding process: *a* – hydraulic; *b* – ramie composite (150×150 mm in dimensions)

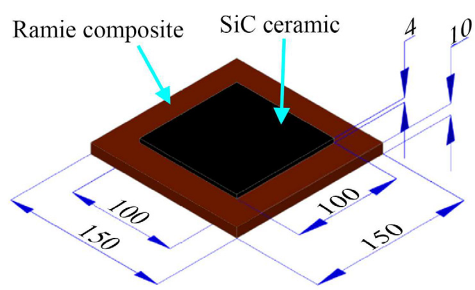


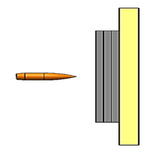
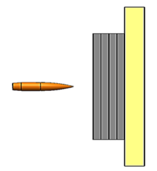
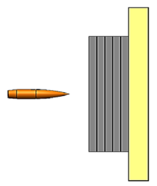
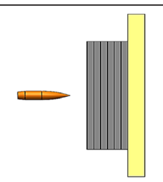
Fig. 6. Illustration of 1 layer SiC and ramie fibers composites in multilayered armor system (dimensions in mm)

An illustration of ramie fiber composite lamination was prepared with 10 layers (10R) along with SiC layer configurations, consisting of 3 layers (3SiC), 4 layers (4SiC), 5 layers (5SiC), and 6 layers (6SiC) using 7.62×51 mm NATO Ball, as seen in Table 1. The coding shows R code (ramie) and SiC code (Silicon Carbide). Detailed configurations and physical properties can be seen in Table 1.

Table 1 denoted the MAS geometry variation based on SiC layer addition. One SiC layer have 4 mm thickness with composite thickness 10 mm on average. The thickness of the glue layer also affects the total thickness of the MAS. The greater the amount of SiC, the thickness and weight of the MAS also increases.

Table 1

MAS Configurations

No.	MAS Geometry	Layer Code	Number of SiC	Ramie Layer	SiC Thickness (mm)	Ramie composite Thickness (mm)	Adhesive Thickness (mm)	Total Thickness (mm)	Total Weight (gr)
1		3SiC+10R	3	10	12	10.1	0.7	22.8	690
2		4SiC+10R	4	10	16	10.2	1	27.2	850
3		5SiC+10R	5	10	20	10.2	1.1	31.3	1015
4		6SiC+10R	6	10	24	10.1	1.3	35.4	1125

4. 3. Ballistic testing method

After the MAS was made the ballistic test carried out in Research and Development Department (Dislitbang) of The Indonesian Army of Land Forces, Bandung, Indonesia. Ballistic test performed using method based of 0101.06 National Institute of Justice (NIJ) standard [17]. Fig. 7, *a*, *b* illustrated the ballistic method used in this research.

MAS was mounted on a mannequin stand with roman plasticina clay installed in the middle section [18]. Projectile discharge directed at 0 degree angle through Light Screen B 471 velocity sensor with 12 m distance. The total shooting distance is 15 m from projectile panel utilize long-barreled riffle type as seen in Fig.8, *a* with 7.62×51 mm NATO ball Lead Core (type III), as shown in Fig. 8, *b*, *c*. The projectile velocity parameter used in the experiment was 850 m/s.

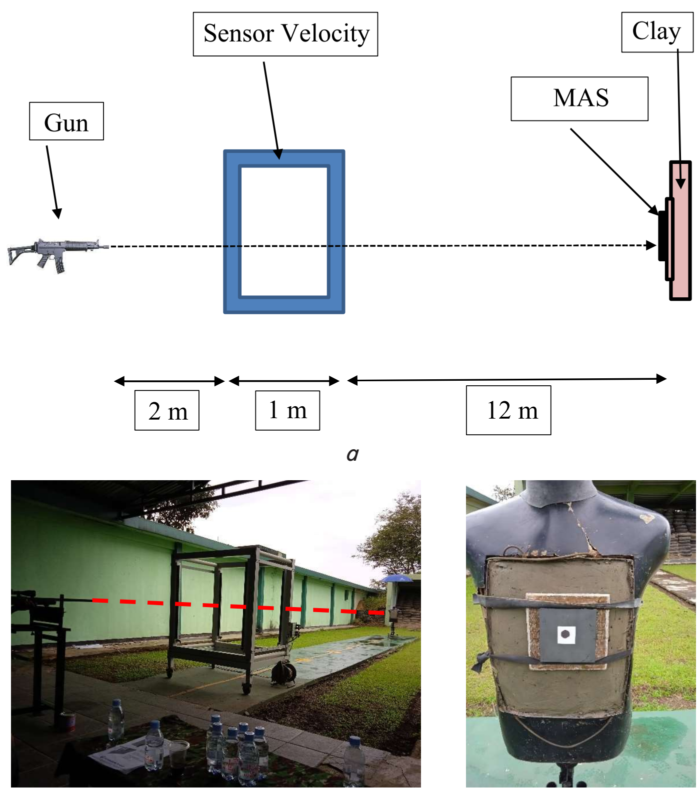
Table 2 shows the hardness test result for the projectile specimens. The hardness test method used for the projectile is Vickers method.

Table 2

Hardness testing result of the projectiles

Projectile specimen	Hardness test result			
	Point 1 (HV)	Point 2 (HV)	Point 3 (HV)	Average (HV)
7.62×51 mm NATO ball Lead Core (type III)	143	42.3	44.4	55.5

The trace of projectile with a certain depth level then measured. BFS depth level showed that total projectile energy distribute towards back of panel [19]. The projectile, which penetrate the panel, called perforation. The success of ballistics testing on composite MAS is determined by the occurrence of perforation or BFS.

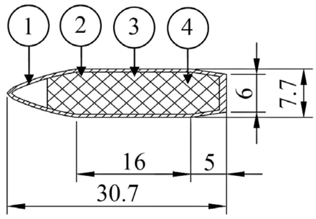


a

b *c*

Fig. 7. Ballistic experiment schematic: *a* – distance illustration; *b* – real experiment set up environment; *c* – multilayered armor system mounted on the mannequin

a



b

c

Fig. 8. Ballistic experiment firearm:
a – long-barreled riffle;
b – 7.62×51 mm NATO ball Lead Core (type III) geometry illustration projectile;
c – 7.62×51 mm NATO ball Lead Core (type III) projectile

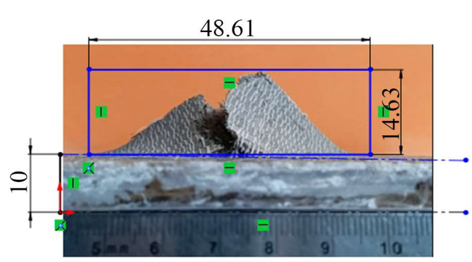
Back Face Signature (BFS) method was used to measure the ballistic test result. The projectile which cannot penetrate the panel will form a gunshot trace on the plasticina clay as shown in Fig. 9.

This research used two method in BFS measurement:

a) indirect measurement, shown at Fig. 9, *a* where the BFS measurement conducted in the clay;

b) direct measurement where the BFS measured directly on the MAS specimen utilized Safewear FEA as illustrated in Fig. 9, *b*.

a



b

Fig. 9. Illustration of back face signature measurement:
a – clay; *b* – multilayered armor system

5. Result of SiC ceramic addition Effect on Ramie Fiber Composite related to BFS and Failure Mode

5. 1. The effect of SiC ceramic coating addition to ramie composite on back face signature

All the MAS materials are subjected to ballistic testing using projectiles at a velocity of 738–841 m/s. Table 3 shows that the best ballistic test result is obtained from 3SiC+10R to 6SiC+10R. Ballistic strength is directly proportional to the increase in the amount of SiC ceramic addition layer. This can be seen from the phenomenon of whether or not the MAS penetrates and the decrease in the value of BFS Clay along with the increase in the amount of SiC. There are two terms, i. e. Perforation and non-perforation. Even though the BFS Clay perforation value is below the NIJ 0101 standard value, it is still considered a failure because it can injure the user. The lowest MAS result was observed in 3SiC+10R, where perforation was found with the Clay BFS 41 mm. The speed of the bullet could not be suppressed, so the projectile was able to perforate. The same phenomenon also happen for 4SiC+10R material. In 5SiC+10R and 6SiC+10R In 6SiC+10R MAS, no perforation occurred on the ramie composite, demonstrating that the resulting kinetic energy from the projectile at 826 m/s was absorbed optimally. The addition of 1 SiC did not have a significant effect. This indicates that at the optimal point, the addition of 1SiC did not have a significant impact on ballistic strength. So that the 5SiC+10R composite is the optimal thickness in resisting the penetration of 7.62×51 mm leadcore bullets. Table 3 denoted the ballistic test result related to BFS criteria. There was significant difference for the 3SiC+10R and 4SiC+10R with deviation 24.23 mm

The results show a quite significant deviation between the BFS results on the ramie composites and BFS on the clay as seen on Table 3. Clay BFS and Ramie BFS relationship are shown in Fig. 10.

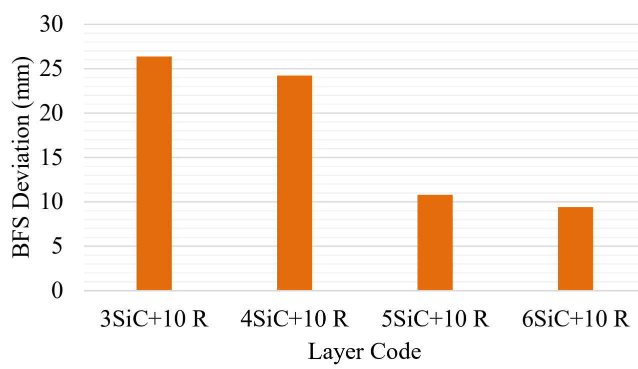
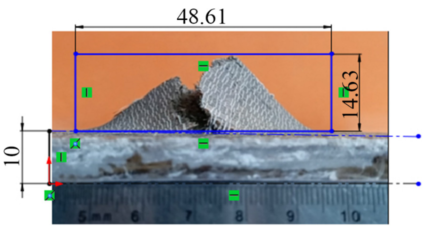
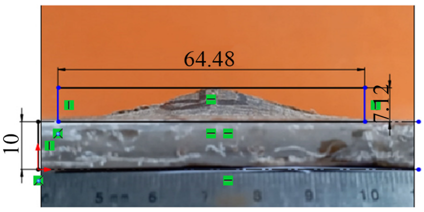
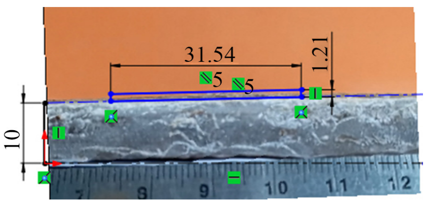
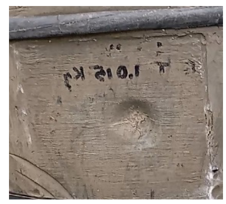
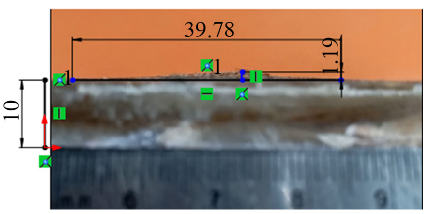


Fig. 10. Back face signature deviation

There are two terms of deviation and perforation phenomena group. First group is penetrated and second group is non-penetrated. First group is penetrated (3SiC+10R and 4SiC+10R) which has a high deviation between ramie fiber BFS and clay BFS, sized 26.37 mm and 24.23 mm, while group 2 is non-penetrated (5SiC+10R and 6SiC+10R) which has a low deviation of 10.79 mm and 9.42 mm. This shows that when an impact or explosion occurred on the ceramic, the remaining energy is transmitted backwards, so that the ramie composite experiences elastic strain. In that MAS, the shock wave reaction caused by the explosion of the projectile can be efficiently absorbed by the ceramic fragmentation [6].

Table 3

Ballistic result related to BFS

Layer Code	Velocity (m/s)	Results	Ramie	BFS Ramie (mm)	Clay	BFS Clay (mm)	Deviation (mm)
3SiC+10R	840.73	Perforation		14.63		41.00	26.37
4SiC+10R	838.28	Perforation		7.12		31.35	24.23
5SiC+10R	815.19	Non-Perforation		1.21		12.00	10.79
6SiC+10R	826.88	Non-Perforation		1.19		10.61	9.42

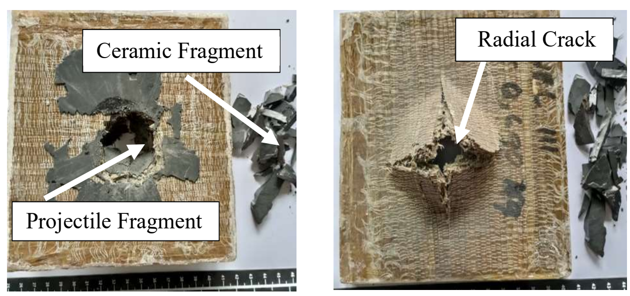
The MAS method represents an effort to provide better protection against any threat, including projectile attack threat. All tests were performed in accordance with the NIJ standards [20]. The results of the ballistics testing in this study are as follows.

5. 2. The effect of SiC ceramic coating addition to ramie composite on failure mode

Observations of the performance and absorption failure of ramie composites are shown in Fig. 11–14. The failure phenomena found in this study were projectile fragment, matrix crack, radial crack, impact point, and ceramic fragment. The most severe damage is shown in Fig. 11, showing that perforation occurred in this MAS, resulting in wide radial cracks on the ramie composite. Radial cracks seen in the 3SiC+10R MAS are caused by large compressive stresses on the inlet side and tensile forces when exiting, resulting in increased damage [21].

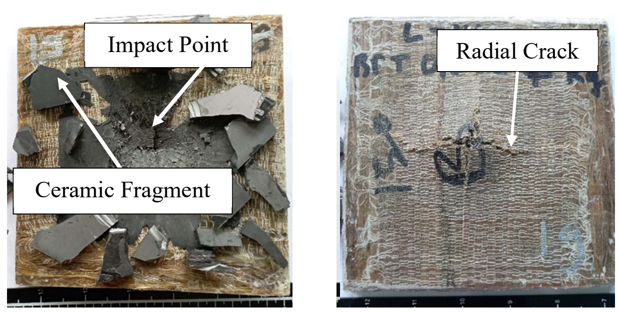
The damage to the MAS at parameter 4SiC+10R indicates the presence of ceramic fragmentation, so that the projectile can be suppressed but the perforation still occurs. However, the ramie composite still suffered plastic, hill-shaped deformation with radial crack damage, as seen in Fig. 12, *b*. Partial penetration of the projectile into the MAS lamination is thought to be the cause of the damage [18].

The absorption capability of MAS with parameters 5SiC+10R and 6SiC+10R seem efficient, evidenced by very minimal deformation of the plates in the ramie composite, not exceeding 2 mm.



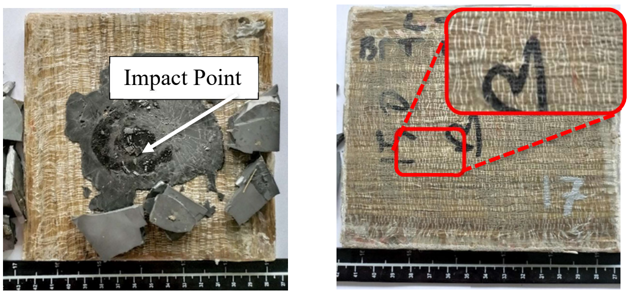
a *b*

Fig. 11. Macrostructure of 3SiC+10R: *a* – front side; *b* – rear side



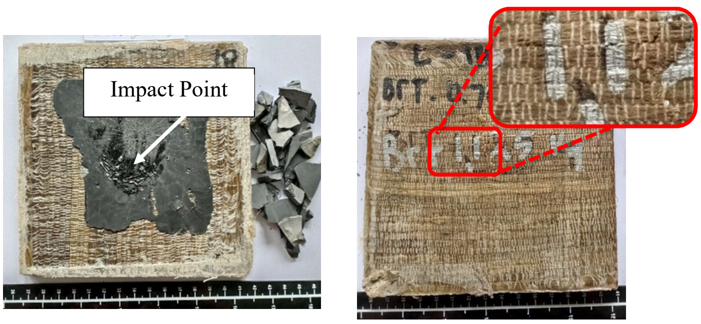
a *b*

Fig. 12. Macrostructure of 4SiC+10R: *a* – front side; *b* – rear side



a *b*

Fig. 13. Macrostructure of 5SiC+10R: *a* – front side; *b* – rear side



a *b*

Fig. 14. Macrostructure of 6SiC+10R: *a* – front side; *b* – rear side

6. Discussion of SiC ceramic addition Effect on Ramie Fiber Composite related to Back Face Signature and Failure Mode

In 5SiC+10R and 6SiC+10R MAS, no perforation occurred on the ramie composite, demonstrating that the resulting kinetic energy from the projectile at 826 m/s was absorbed optimally. One proof that the ceramic in front is able to optimally absorb energy is the very low BFS value of the ramie composite of 1.19 mm, as shown in Fig. 14. High fragmentation of the ceramics greatly affects effective energy absorption. The resulting kinetic energy from the projectile is well absorbed by the MAS, but the residual energy causes composite to break which shown in Fig. 12. These results prove that ramie composites are very efficient at absorbing energy in ballistic tests, in line with the study [22]. The results of the 7.62x51 mm Lead core bullet firing test showed that the ceramic fragmentation phenomenon appeared in all materials. The phenomenon of ceramic fragmentation in the shot causes the MAS structure to be damaged, so that the ramie fiber composite layer (second layer) will face the bullet directly if it is subjected to a second shot. This phenomenon also appears in several other studies using ceramic-composite MAS structures.

The paper [23] It is shown that phenomena ceramic fragmentation occurs at an optimal thickness which capable of withstanding 7.62×51 mm Lead core and 7.62×51 mm hard steel core penetration. This becomes a problem when the panel has been fired multiple times. In the second shot the MAS structure was unable to withstand bullet penetration. The solution offered by [24] is a layer of composite ramie fiber material must be created at the front before the tungsten carbide. This has a weakness if size of the ceramic used is large. The ceramic used is small in size to limit the crack propagation that occurs while at the same time covering another weakness, i.e. the limited shape of the body armor.

The development of this study is using Ultra High Hardness Armor (UHHA) for first layer substitute SiC. UHHA steel has now been developed and commercialized with various hardness levels Rolled Homogenous Armor (RHA) (210–410 HB), High Hardness Armor (HHA) (477–534 HB) Ultra High Hardness Armor (UHHA) (more than 570 HB). The high hardness and ductility of UHHA steel armor material become attractive properties in the ballistic world which can cover the disadvantages of using ceramics in MAS structures. More in the paper [24]. It is shown that testing the Ramor 500 steel with a thickness of 4.5 mm at an angle of 0° was unable to withstand 7.62×51 mm NATO Ball bullets (with a soft lead core) with the petalling phenomenon. The petalling phenomenon shows that fragmentation does not occur in UHHA materials. This is an attractive option for further research on the use of UHHA as the first layer (facing layer) on the MAS structure.

The damage to the MAS is almost invisible, and only with careful observation can damage be found on the identified of the ramie composite. In this MAS, ceramic as the front layer is able to absorb kinetic energy efficiently. Most of the energy absorption is also carried out by ceramic fragmentation, projectiles and ceramic spalling [2]. The fracture of the ramie fiber composite that occurs after the projectile penetration and ceramic fragmentation is the impact of the projectile collision from the front. In Fig. 13, after magnification, the fracture of the epoxy matrix is clearly visible, corroborating the study carried out [14].

The lowest MAS result was observed in 3SiC+10R, where perforation was found. The speed of the bullet could not be suppressed, so the projectile was able to perforate the ramie composite, as shown in Fig. 11. This MAS also had the highest BFS dimensions with 14.63 mm, indicating that the ramie composite is unable to suppress the velocity of the bullet. The result is in line with the study [25].

The results of this study showed that ramie composite is suitable for bulletproof panels, furthermore to be able to compete with popular synthetic materials such as kevlar, UHMWPE and aramid.

The limitation of this research is that ramie fiber layers are still produced manually so that in industrial applications where speed is prioritized it will be hampered. The industrialization of ramie fiber processing has faced challenges in the form of a lack of public confidence that it can compete with synthetic fibers.

The disadvantage of this research is that ceramic manufacturing uses high temperature so that production requires a high initial investment. The hexagonal ceramic shape is structurally better than the box shape, but due to limited availability, this study used boxes on the market.

7. Conclusions

1. The addition of the number of layers of SiC increases the resistance of ballistic MAS marked by a decrease in the

value of BFS clay. The 5SiC+10R is the optimal thickness in resisting the penetration of 7.62×51 mm leadcore bullets with 12 mm BFS clay.

2. The failure phenomena found in this study were projectile fragments, matrix cracks, radial cracks, impact points, and ceramic fragments. Matrix crack formation appears on 5SiC+10R with mini deformation in the rear side.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Manuscript has no associated data.

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