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DAMAGE FORMATIONS OF RAMIE FIBER COMPOSITES MULTILAYER ARMOUR SYSTEM UNDER HIGH-VELOCITY IMPACTS

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Multilayer armour system (MAS) becomes the best choice in reinforcing protection for military officers against projectile attack which has a high velocity of up to 7.62×51 mm nato ball lead core (projectile level III NIJ standard) or AP 7.62×51 mm hard steel core (projectile level IV NIJ standard). This study aimed to analyze the damage formation of wolfram carbide (WC) ceramic and ramie fiber composites. The front-most MAS uses WC ceramic and is enveloped by a back layer of ramie fiber composites with epoxy resin reinforcing material as the matrix. Ballistic testing was carried out in this study using a long-barreled rifle to determine the resistance of the MAS from projectile impact. The speed meter in ballistic testing uses a velocity sensor type light screen B 471 and clay witness is used to measure back face signature (BFS). The results show that 7.62 lead core and hard steel core projectiles were unable to penetrate the 3-layer ceramic MAS in the front. The results are marked by a relatively low BFS value of 1.45 and 1.17 mm, so that the energy in the MAS with 3 ceramic layer is absorbed efficiently but with the phenomenon of rupture ceramic failure. Ceramic rupture failure needs to be overcome by bonding several layers of ramie so that MAS can be used in the next stage. MAS with 1 and 2 ceramic layers are unable to withstand projectile level III and level IV NIJ standard. From these results it is known that the MAS limit can withstand the projectile level III and IV NIJ standard, namely MAS with 3 ceramic layers. The damage formation of ceramic was rupturing ceramic failure. Therefore, it is necessary to design a ceramic binder by placing some ramie fibers in front of the ceramic

Keywords: multilayer armour system, wolfram carbide, ramie fiber, back face signature

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1. Introduction

Protection against projectile shrapnel from firearms is a matter of personal safety protection, especially for law enforcement or military officers. Protection against high-velocity projectiles, like 7.62 mm caliber projectile, depends on the use of steel or ceramic plate material as personal protection [1].

Heavy materials used for ballistic protection present new problems, namely impaired mobility [2]. There are other ballistic armors based on materials such as steel plate, where alloy steel plate at a certain thickness is able to stop the projectile in its way, even though material thickness will also affect the weight of a material [3]. It might find better use in vehicles, but not as personal protection. One of the characteristics of ceramic materials is that they are stiff and hard so that they can deform and erode the tip of the projectile and are able to absorb the kinetic energy of a projectile. Composite materials can absorb a significant portion of the energy and collect fragments of the ceramic coating and projectiles.

A combination of lightweight materials that have high physical or mechanical strength is the best choice. MAS method typically consists of ceramic material at the front and composite reinforcing material with high strength and resilience at the back [4, 5]. A system of combining the specific characteristics of a material synergistically contributes to the efficiency of global protection [6].

Synthetic fiber materials that have high strength but lightweight are often used as composites or laminates on the second, third or other layers as MAS [7, 8]. Fibers such as aramid (twaron^{tm} and kevlar^{tm}) and others have been used as synthetic composite materials as a defense material [9]. Natural fibers such as giant bamboo [10], ramie [11], sisal [12], curaua [13], tucum (palm tree) [14], cyperus malaccensis, and bagasse [12] display good properties to replace aramid and non-aramid-based engineered synthetic fibers for ballistics. One of the researchers who studied bullet-proof polymer composites was [15]. Researchers also used polypropylene as a matrix and reinforced it with ramie fibers [16].

Several natural fibers extracted from the ramie plant (*boehmeria nivea*) are developed almost all over the world. In the last decade, ramie fibers have been extensively studied as a composite reinforcement [17, 18]. Ramie fibers are one of natural fibers with excellent mechanical properties, with a density of around 1.30–1.45 g/cm^3 as well as tensile strength between 393 and 800 MPa. In addition, it also possesses an indentation depth of around 17+1 mm [9, 19]. In ballistic armour testing, composites are engineered to be placed in front of or between two steel plates or other materials. In terms energy absorption, sandwiched steel or composites have advantages over neat materials and plain fiber composites. Energy absorption analysis of epoxy resin-ramie composites showing a 71 % increase compared to pure epoxy-ramie composites [20]. Other studies also demonstrated that ramie fiber composites are more efficient compared to aramid composite with ballistic testing [11]. Research has also been carried out which demonstrated that jute can provide good protection compared to Kevlar fiber [21].

Ceramic material chosen as the protection material plays an important role in the performance of MAS for the reason that ceramic functions as an absorber of energy resulting from projectile collision. The ceramic layer at the front can withstand the compressive stress of the projectile, eroding the tip of the projectile and spreading the impact energy across the material [22]. Overall, the MAS method can stop a projectile and distribute the energy minimally to the back panel [23].

Most studies utilized natural fibers as the main material of MAS to absorb energy resulting from the impact of projectile level III and level IV NIJ standard. Therefore, research on the damage formation of ramie fiber composite ballistics with epoxy matrix as MAS and ceramic multilayer front layer to absorb energy resulting from projectile level III and level IV NIJ standard is relevant.

2. Literature review and problem statement

Ramie fiber with the addition of polymer or polypropylene as a matrix and reinforced can withstand standard level II and IIIA NIJ projectiles [24]. However, it is unable to withstand standard NIJ level III and IV projectiles.

In order to be able to withstand NIJ standard level III and IV projectiles, a first strike layer of hard material must be given to dull the projectile. Projectiles that have been blunt are easily snared by the fibers. To withstand high-velocity projectiles such as 7.62 mm or 5.56 mm, MAS is the best choice. Experimental studies on MAS with front Al_2O_3 ceramic tiles followed by jute and kevlar composites reinforced with an epoxy matrix have been studied. The results of the analysis have met the performance requirements as determined by NIJ level III and IV. It was found that all MAS with double ceramic tiles had successfully defeated projectiles with observed maximum BFS of 28.70 mm each. In the case of a single monolithic ceramic, 35.12 mm is the maximum BFS observed against projectiles [9]. The ballistic performance of the investigated ceramics has been explored in relation to their structure, characteristics, armour system design, and projectile type. Armour systems may be created in a variety of designs and weights based on the best ceramic materials and backing, depending on the needs for ballistic protection. It has been shown through demonstrations how to create lightweight armor systems with appropriate ballistic performance, including satisfactory multi-hit performance [5].

The use of ramie fiber added with a hard first strike layer whose composition is called MAS has not been carried out. What material and how the composition of the first strike layer needs to be investigated. The form of damage to the MAS when it is hit by a level III and IV NIJ standard projectile has also not been done.

As the second layer of a MAS, the ballistic performance of plain-woven jute fabric-reinforced polyester matrix composites was examined. Orth phthalic polyester was combined with volume fractions of jute fabric up to 30 % vol % to create laminate composites. High velocity 7.62 mm ammunition was used in the ballistic tests. According to the international standard, the MAS ballistic performance was assessed using the bullet's depth of penetration in a block of clay witness that represented a human body. After tests, scanning electron microscopy was used to investigate the shattered materials. The findings showed that when used as MAS second layers with the same thickness, jute fabric composites function similarly to the much stronger Kevlar^{tm}, an aramid fabric laminate [14].

A sandwich composite made of natural fibers including jute, epoxy, and rubber was studied for its potential to absorb ballistic energy [20]. These composites' energy absorption and residual velocities are assessed analytically and through finite element analysis (FEA). JE plates are subjected to FEA for various thicknesses. To determine residual velocity and energy absorbed, JE plates and JRE sandwiches of equal thickness are created and evaluated. With a maximum error of 9 %, the analytical results are determined to be in good agreement with the FEA results. According to the research on JE composite plates, thickness affects how much energy is absorbed. JRE sandwiches have better energy absorption than JE plates, according to experimental and FEA research. A JRE sandwich absorbs energy 71 % more efficiently than JE plates. Damage estimates from testing and FEA are quite consistent. Composites failed by fiber rupture and fragmentation, according to SEM examination.

Natural fibers are currently being developed as basic materials for bulletproof panels because they are more environmentally friendly [10]. One of the potential natural fibers is ramie fiber [17]. Starch-based batters containing either jute or flax fibers were effectively baked inside a heated mold to create starch-based composite foams (SCFs). Investigations were done on how moisture content affected the mechanical characteristics of SCFs. With the addition of 5–10 % by weight of the fibers, both the flexural strength and the flexural modulus of elasticity appeared to be noticeably enhanced. Both the flexural strength and the flexural modulus of elasticity were discovered to rise with increasing aspect ratio of the fibers at a fixed fiber content of 10 % by weight. Scanning electron micrographs of the SCF fracture surface showed that the improvement in the mechanical characteristics of SCFs was due to the strong contact between fibers and the starch matrix. Jute fibers demonstrated a stronger reinforcing impact than flax fibers did in jute- and flax-reinforced SCFs. Both the flexural strength and the flexural modulus of elasticity of SCFs were found to be strongly influenced by the orientation of the fibers, with the maximum values being noted on specimens having fibers orientated in the longitudinal direction (fibers oriented perpendicularly to the crack propagation direction) [17].

To ascertain the impact of injury on people wearing bulletproof panels, a BFS study of MAS following a bullet strike is required. Additionally, the bulletproof panels developed for this investigation need to have the MAS damage formation evaluated.

3. The aim and objective of this study

The aim of the study is to identifying regularities damage formation ramie fiber composite-MAS.

To achieve this aim, the following objectives are accomplished:

– the ballistics analysis of back face signature;

– the damage formation failure of MAS with projectile level III NIJ standard;

– the damage formation failure of MAS with projectile level IV NIJ standard.

4. Materials and methods of research

4. 1. Materials

The materials used to design the MAS were ceramic and ramie fiber with epoxy resin as the matrix [25]. The ramie fibers were taken directly by farmers from the Wonosobo area of Indonesia. Ramie fibers are a threaded weave that uses natural fibers after being extracted from the stems, as shown in Fig. 1.

Fig. 1 shows the process of ramie fiber weave, starting from stem of ramie-to-ramie fiber weave. The stems of ramie were selected, Fig. 1, *a*. The china grass was taken through a decortication method using a waterless machine, Fig.1, b. Only quality fibers were chosen to achieve uniformity in a single layer. A bundle of ramie fibers was cut to a length of 170 mm and to achieve uniformity in a single layer, each bundle of ramie fibers weighed around 5–6 g, Fig. 1, *c*. The process of making ramie fiber composites with an epoxy resin matrix starts with soaking the ramie fibers in 5 % NaOH solution for 2 hours to remove gum and pectin. After that, they were dried in the sun to reduce the liquid content of the fibers when woven, in Fig. 1, *d*.

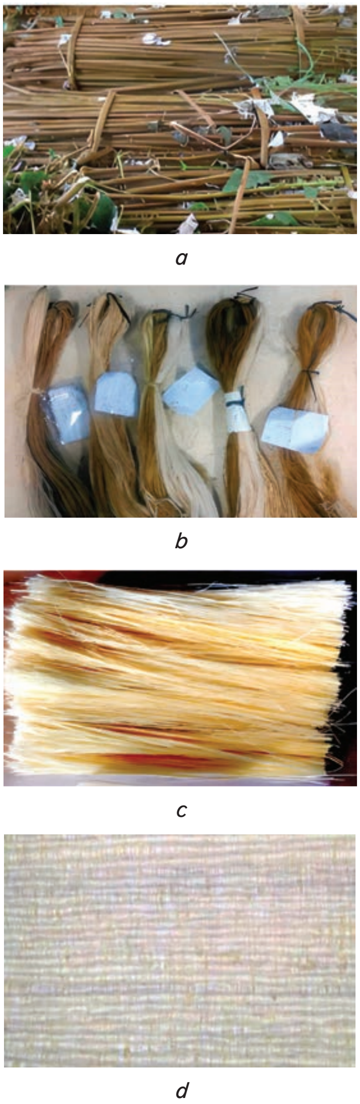

a
b
c
d

Fig. 1. Ramie fiber weave: *a* – stem of ramie; *b* – china grass; *c* – ramie fiber; *d* – woven

Composite molding with an epoxy resin matrix was carried out using a hydraulic press machine while holding until the composite was dry. The pressing was intended to prevent any air cavity from forming and to achieve uniform thickness, in Fig. 2.

Hydraulic press machine was operated in hot conditions. In varied numbers of laminae, the composite volume fraction employed in this investigation was 60 % [26]. The ramie surface was then covered with the epoxy mixture and pressed using a press machine to achieve the desired thickness. Fig. 2, *a* show the hydraulic press machine. The supporting layer is made of ramie fiber composite with dimensions of 150×150×10 mm, in Fig. 2, *b*.

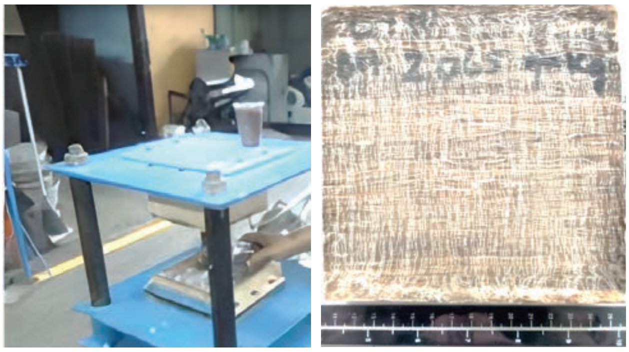
The type of ceramic used was WC with dimensions of 100×100×4 mm and placed on the front, in Fig. 3. The number of WC starts from 1–3, and so on until it can hold bullets.

An illustration of ramie fiber composite lamination was drawn up with 10 layers (10R) and WC layer configurations of 1 layer (1WC), 2 layers (2WC) and 3 layers (3WC) using projectile level III NIJ standard and projectile level IV NIJ standard, in Fig. 4. The coding shows code R (ramie) and code WC (wolfram carbide). Detailed configurations and physical properties can be seen in Table 1.

Table 1

Detailed configurations and physical properties of composite layers

Layer Code	Number of WC	Ramie Layer	Ramie Thickness (mm)	WC Thickness (mm)	Total Thickness (mm)	Total Weight (gr)
LIII+1WC+10R	1	10	10	4	14	875
LIII+2WC+10R	2	10	10	8	18	1480
LIII+3WC+10R	3	10	10	12	22	2065
LIV+1WC+10R	1	10	10	4	14	870
LIV+2WC+10R	2	10	10	8	18	1440
LIV+3WC+10R	3	10	10	12	22	2025



a *b*

Fig. 2. The process of molding the composites: *a* — hydraulic press machine; *b* — ramie composites

Fig. 3. Wolfram carbide material

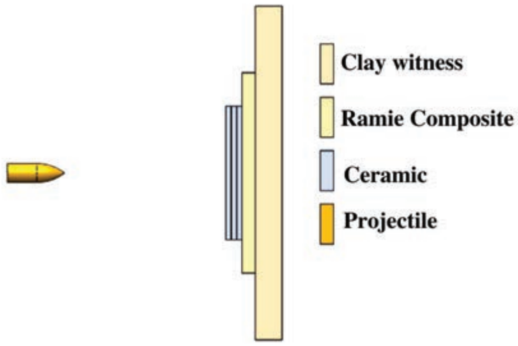
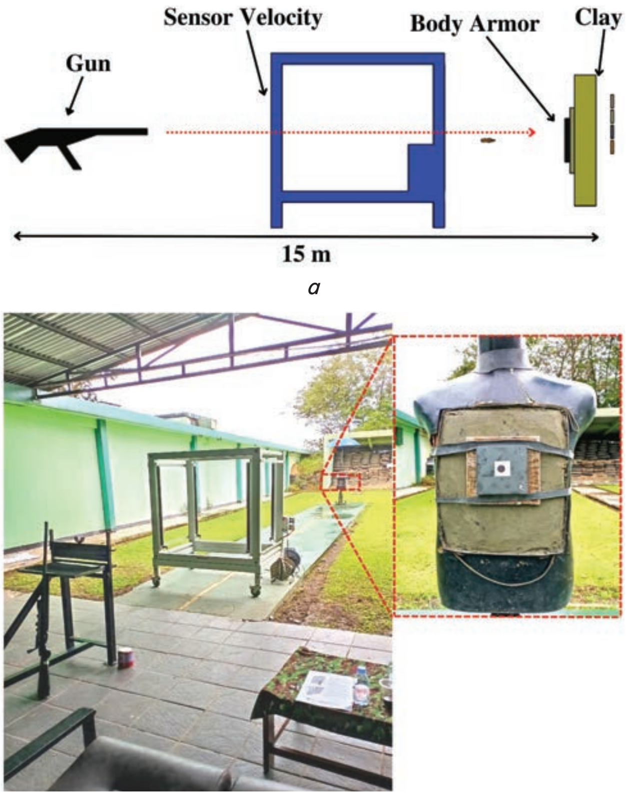


Fig. 4. Multilayer armour system configuration and projectile direction

Each composite layer configuration has different physical properties. At the same amount of tungsten carbide, level III and IV projectiles have the same total thickness, but have different weights.

4. 2. Ballistic Testing method

The ballistics testing was performed at the Research and Development Department of the Indonesian Army, Batudjajar, Bandung. The ballistics testing method refers to the National Institute of Justice (NIJ) standards 0101.06 [27]. An illustration or schematic of the ballistics test is shown in Fig. 5.



a

b

Fig. 5. Ballistic test: *a* — ballistics experimental schematic; *b* — test equipment preparation

Fig. 5, *a* show the distance MAS and the gun was 15 m. The tst equipment preparation consists of the gun, sensor velocity, body armour, and clay. The sensor velocity was put in between the gun and body armour to measure bullet velocity before attract the MAS.

In the illustration, the bullet panel is mounted on plasticina roman clay, as previously [9]. The angle of attack of the bullet is directed 90 degrees through the light screen B 471 type velocity sensor with a distance of 10 m from the bullet panel. The total shooting distance is 15 m from the bullet panel using bullet level III NIJ standard and bullet level IV NIJ standard caliber projectiles with a speed of 878 m/s, in Fig. 6 [28].

All materials were subjected to shooting testing using a long-barreled rifle. If the projectile failed to penetrate the panel, it will form a gunshot indentation on the clay. This gunshot indentation with a certain depth is called Back Face Signature (BFS). Fig. 7 shows how to measure BFS. The BFS depth level shows the total projectile energy distributed towards the back of the panel [29].

The projectiles that can penetrate the panel are called perforations or holes. The success of ballistics testing on composite MAS is determined by the occurrence of perforation or BFS. The maximum depth of BFS is 48 mm that may be used on bulletproof panels without killing the user.

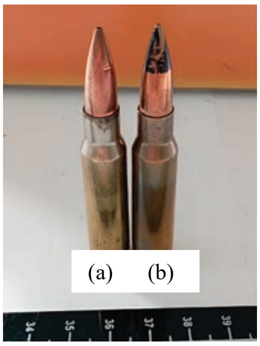


Fig. 6. Projectile: *a* – 7.62×51 mm nato ball lead core (level III); *b* – AP 7.63×51 mm hard steel core (level IV)

Fig. 7. Back face signature measurement illustration

5. Result of studying damage deformation of ramie fiber composites Multilayer armour system under high-velocity impacts

5. 1. Ballistics analysis of back face signature

Table 2 shows the results of MAS performance against BFS. BFS on clay witness measured using digital caliper, in ballistics testing using 7.62×51 mm nato ball lead core projectiles, the best result was observed on the 3WC+10R MAS, which proves the ramie composite is not penetrated or perforated. These results show that MAS is not only able to stop projectiles but is also very efficient in reducing kinetic energy during collisions. The MAS and the velocity of the bullet cannot be suppressed, thus the projectile is able to perforate the ramie composites, as shown in Fig. 8.

In the testing, the 1WC+10R MAS also had the highest BFS dimensions, demonstrating that the ramie composites failed to suppress the projectile velocity, as shown in Fig. 8, *a*. In the next result, 2WC+10R MAS showed no perforation. Two ceramics with the WC type can absorb the kinetic energy resulting from the projectile, even though there is residual energy that causes the composite panel to break, as shown in Fig. 8, *b*. The results are corroborated by the dimensions of the BFS of 1.45 mm, as shown in Fig. 8, *c*. The lowest MAS result was observed on 1WC+10R, where perforation occurred.

The ballistics testing used 7.62×51 mm hard steel core AP projectiles. The damage formation test result of 1WC+10R, 2WC+10R, and 3WC+10R of MAS Fig. 9.

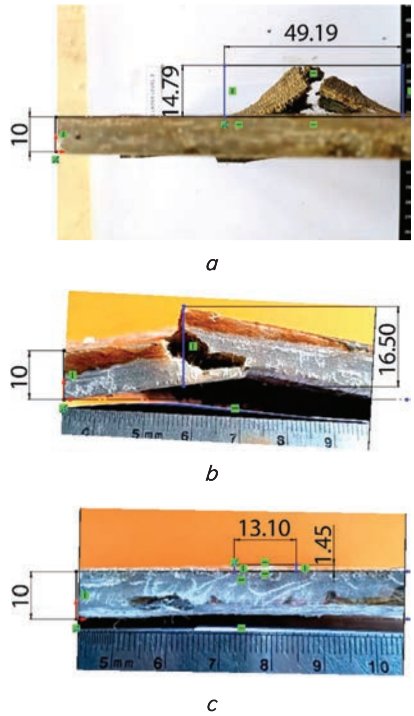


Fig. 8. Back face signature dimensions: *a* – 1WC+10R; *b* – 2WC+10R; *c* – 3WC+10R (7.62×51 mm nato ball projectiles)

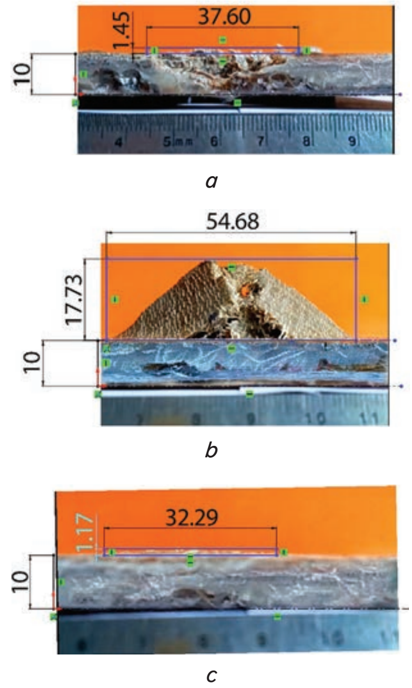


Fig. 9. Back face signature dimensions: *a* – 1WC+10R; *b* – 2WC+10R; *c* – 3WC+10R (AP 7.62×51 mm hard steel core)

Table 2

Ballistics Testing Results

MAS	Results	Lead Core level III Projectile		Results	Hard Steel Core level IV Projectile	
		Velocity, m/s	BFS, mm		Velocity, m/s	BFS, mm
1WC+10R	Perforation	847.16	–	Perforation	875.66	–
2WC+10R	Non-Perforation	832.25	15.62	Perforation	877.18	63.58
3WC+10R	Non-Perforation	831.73	1.45	Non-Perforation	869.79	4.84

The test results showed that 1WC+10R and 2WC+10R MAS suffered perforations with BFS dimensions of 1.45 mm and 17.73 mm, respectively, as shown in Fig. 9, *a*, *b*. The perforations occurred because of the large kinetic energy and the hard steel core material carried by the 7.62×51 mm AP projectiles; thus, 1 to 2 layers of ceramic are not sufficient to withstand the projectile's velocity and impact. For 3WC+10R, no perforation was observed with a BFS of 1.17 mm, as shown in Fig. 9, *c*.

5. 2. Damage formation failure with projectile level III NIJ Standard

The macroscopic phenomenon of composite panel breakdown mode and failure are presented in Fig. 10–12. The figures show damage to the front and rear surfaces of the MAS. Various modes of damage occurred in the MAS such as projectile fragment, matrix crack, radial crack, impact point, ceramic fragment. Ceramic is the material of the first layer on the MAS mode and as a barrier material, most of the kinetic energy absorption is done by ceramic fragmentation.

The compression stress that occurs at the inlet side and the tensile stress that occurs at the exit cause minor damage to the inlet side, while the damage to the exit side is more intensive. From this phenomenon, it is seen that there is an increase in damage for 1WC+10R, as shown in Fig. 10, *a*. The macrostructure of ceramic rupture for 1WC+10R. Damage to the panel on the outside caused by the impact of the projectile resulted in a matrix crack, in Fig. 10, *b*. The tensile and compressive forces from the impact of the projectile are intensive enough to make the ramie fibers deform and even break.

The phenomenon, it is seen that there is a damage for 2WC+10R, as shown in Fig. 11, *a*. Projectile pressure partially into the MAS lamination could plastically deform the composite, forming a mountain-like shape and causing plastic deformation and radial cracking s, as seen in Fig. 11, *b*.

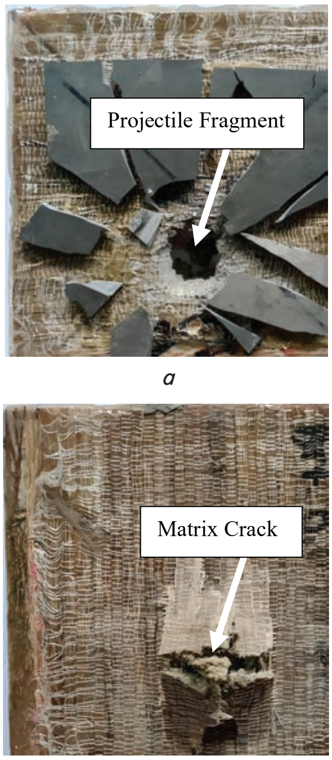


Fig. 10. Macrostructure of 1WC+10R: *a* — front side; *b* — rear side hard steel core

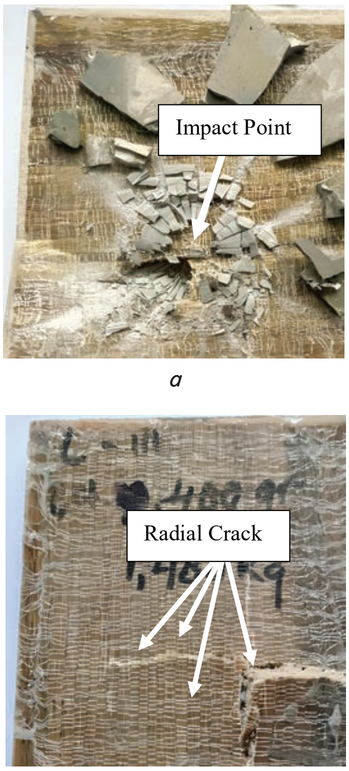


Fig. 11. Macrostructure of 2WC+10R: *a* — front side; *b* — rear side hard steel core

Fig. 12. Macrostructure of 3WC+10R: *a* — front side; *b* — rear side hard steel core

The phenomenon, it is seen that there is a damage for 3WC+10R, as shown in Fig. 12, *a*. But projectile couldn't penetrate the MAS lamination, as seen in Fig. 11, *b*.

5. 3. Damage formation failure with projectile level IV NIJ Standard

Fig. 13–15 shows the damage that occurred during ballistic impact testing with projectile level IV NIJ standard. The damages include projectile fragments, ductile hole formation, ceramic fragments, and impact point.

Fig. 13, *a* show the damage rupture of ceramic 1WC+10R. Damages occurred in Fig. 13, *a* are because the projectile compressive force is smaller, and the tensile force is greater. Fig. 13, *b* shows a ramie damage and causing ductile hole formation because of failed to withstand the projectile.

Fig. 14, *a* show the rupture of ceramic 2WC+10R. The damage to the rear side is greater and matrix crack damage is formed, as seen in Fig. 14, *b*.

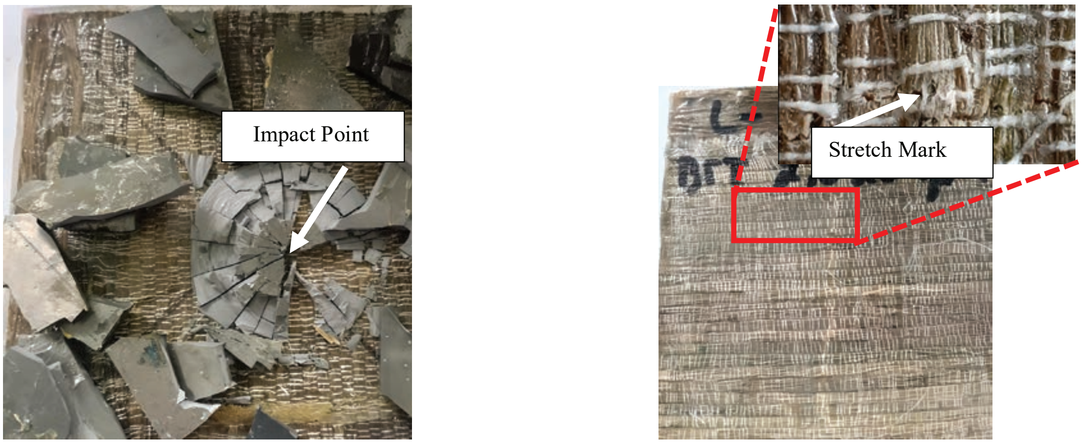
Fig. 15 shows that no damage occurs, but, upon closer inspection, there are actually stretch marks on the back panel, as seen in Fig. 15, *b*. The damage occurred because the kinetic energy of the projectile was able to be absorbed by the ceramic MAS and the remaining energy resulted in stretch marks on the back panel.

a *b*

Fig. 13. Macrostructure of 1WC+10R: *a* – front side; *b* – rear side

a *b*

Fig. 14. Macrostructure 2WC+10R: *a* – front side; *b* – rear side



a *b*

Fig. 15. Macrostructure of 3WC+10R: *a* – front side; *b* – rear side

As shown in this study with ballistic testing, composites with epoxy resin matrix reinforced with ramie arranged in layers can support ceramics as the first layer. Although in almost all ballistic tests the ceramics experienced fragmentation, the ceramic layer at the front can absorb most of the kinetic energy resulting from the projectile collision. Ceramic fragmentation is evidence of major energy absorption and as a buffer in general.

6. Discussion of studying damage deformation of ramie fiber composites multilayer armour system under high-velocity impacts

MAS result was observed on 1WC+10R and 2WC+10R, where perforation occurred both for projectiles level III and IV NIJ standard. The MAS and the velocity of the bullet cannot be suppressed; thus the projectile is able to perforate the ramie composites. In the testing, the 1WC+10R MAS also had the highest BFS dimensions, demonstrating that the ramie composites failed to suppress the projectile velocity. Two ceramics with the WC type can absorb the kinetic energy resulting from the projectile, even though there is residual energy that causes the composite panel to break. The result is in line with the previous study [30], that the rami composite is not able to withstand the impact of the projectile. The best result was observed on the 3WC+10R MAS, which proves the ramie composite is not penetrated or perforated. These results show that MAS is not only able to stop projectiles, but also very efficient in reducing kinetic energy during collisions [9]. These results are corroborated by the dimensions of the BFS of 1.45 mm.

Various modes of damage occurred in the MAS such as projectile fragment, matrix crack, radial crack, impact point, ceramic fragment. The compression stress that occurs at the inlet side and the tensile stress that occurs at the exit cause minor damage to the inlet side, while the damage to the exit side is more intensive. From this phenomenon, it is seen that there is an increase in damage, as has been observed in previous studies [31], as shown in Fig. 10, *a*. Damage to the panel on the outside caused by the impact of the projectile resulted in a ductile hole. The tensile and compressive forces from the impact of the projectile are intensive enough to make the ramie fibers deform and even break. The presence of brittle composite matrices such as epoxy resins can increase energy or absorb traces in ballistics [32].

Ceramic is the material of the first layer on the MAS mode and as a barrier material, most of the kinetic energy absorption is done by ceramic fragmentation. The absorption of kinetic energy from the largest projectile is ceramic spallation. Projectile pressure partially into the MAS lamination could plastically deform the composite, forming a mountain-like shape and causing matrix and radial cracks. Partial penetration occurred in the MAS lamination caused plastic deformation and radial cracking.

The damage that occurred during ballistic impact testing with projectile level III and level IV NIJ standard. The damage occurred because the kinetic energy of the projectile was able to be absorbed by the ceramic MAS and the remaining energy resulted in stretch marks on the back panel. As shown in this study with ballistic testing, composites with epoxy resin matrix reinforced with ramie arranged in layers can support ceramics as the first layer. Although in almost all ballistic tests the ceramics experienced fragmentation, the ceramic layer at the front can absorb most of the kinetic energy resulting from the projectile collision. Recent studies highlight how several methods may explain the main function of a second layer in MAS [33]. Ceramic fragmentation is evidence of major energy absorption and as a buffer in general.

The bulletproof panels here are square panels, not shaped according to the shape of the human body. The focus of research is on perforation or non-perforation panels and the formation of damage to the panels.

MAS with a composition of 3WC+10R is able to withstand projectiles. However, tungsten carbide as the first strike causes damage, namely rupture. It can only be used once as a bulletproof panel. It is impractical to use it as a bulletproof panel. In order to solve this issue, a layer of composite ramie fiber material must be created at the front before the tungsten carbide in order to prevent rupture.

7. Conclusions

1. BFS for 1WC+10R is infinity, 2WC+10R is in the condition of injuring the user of the bulletproof panel, and 3WC+10R is safe for users of bulletproof panels because there is almost no BFS for both kind of bullets.
2. The damage formation of tungsten carbide was rupture failure i. e., projectile fragment, impact point, and impact fragment.
3. The damage formation of ramie fiber composite was matrix crack, radial crack, ductile hole formation, and stretch mark.

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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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