

Analysis of Ballistic Capability in Making Bulletproof Multilayers Using Woven Ramie Fiber, Hardfacing Metal with Epoxy Matrix for Bulletproof Vests

Rizal Wahyu Permana^{1,2*}, Syamsul Hadi¹, Bima Cahya Maula Dana¹

¹Department of Mechanical Engineering, State Polytechnic of Malang, Jalan Soekarno Hatta No. 9, Malang, East Java 57139, Indonesia

²Department of Mechanical Engineering, Army Polytechnic (Poltekad), Jalan Anggrek No. 1, Batu, East Java 65321, Indonesia

*Corresponding author: theenginemachine22@gmail.com

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ABSTRACT

Bulletproof material in level III bulletproof vests must be created using hard and soft materials to prevent bullet penetration. Kevlar and SiC + PE are imported materials used as armor in bulletproof vests. The use of Kevlar and SiC is very dependent on foreign sources with high prices. An innovation was carried out by making bulletproof material using cheaper multilayer methods involving metal from hardfacing welding as a hard layer and ramie fiber as a soft layer with an epoxy matrix. To see the level of penetration and surface morphology structure in the specimens, 9 variations were made: 3 layers of hardfacing welding and 3 epoxy volume fractions (40%, 45%, 50%). Ballistic test using NIJ 0101.06 level III standards with AK-47 of 7.62 mm x 39 mm bullets and the morphology of bulletproof multilayer material after impact was observed using SEM. The results showed all specimens failed to withstand bullet penetration at a distance of 15 meters. Meanwhile, at 50 meters, the S2-C specimen with a 60% epoxy volume fraction was able to withstand bullet penetration with a BFS value of 25.85 mm. This value is < 44 mm; thus, it complies with the NIJ 0101.06 body armor standard. According to SEM, most of the failures occurred because the resulting adhesion force was weak. It was necessary to add reinforcing material so that the adhesion force between the metal, ramie fiber, and adhesive increases; the materials must also have very light density to prevent the effectiveness reduction of the multilayer.

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Keywords: Bulletproof multilayer, bulletproof vest, epoxy, hardfacing, ramie fiber woven

I. Introduction

Bulletproof vests are required equipment worn by army personnel on battlefields. The bulletproof vests used today contain materials such as Kevlar as a soft layer and Silicon Carbide as a hard layer that is still imported with expensive prices and complicated manufacturing processes. Bulletproof vests are used to protect the human body from negative impacts of colliding projectiles by absorbing and dispersing their kinetic energy [1]-[3]. The ballistic impact of small arms projectiles such as handguns and rifles must be prevented by body armor [4]. The basic goal of bulletproof vest research is to develop a clothing system that is lightweight, resistant to ballistic impacts, and low-cost [5].

The development of industrial revolution, technological advances, new materials and production techniques allow the creation of more effective bulletproof vests. Composite materials have excellent mechanical and physical properties which are currently used in all engineering



applications such as aviation, automotive, electronics, marine, etc. [6]. This is due to its weight characteristics. The overview of structural solutions and materials for ballistic inserts currently used in bulletproof vests utilizes multilayer material systems [1]-[3], such as aramid fiber [7]-[9], ceramic [10],[11], and kevlar [12]-[14].

Kevlar is commonly used as armor to protect against bullets used in pistols and assault weapons because of its impact resistance, high strength, and low weight. The promising performance of Kevlar has been widely applied in various ballistic and bulletproof applications, including bulletproof helmets, vests, and other armored parts, providing an acceptable range of protection for soldiers [15]. These properties make Kevlar an ideal material for bulletproof vests compared to others [16]. Bulletproof vests made from Kevlar have good performance and mobility. However, the price of Kevlar armor vests is very high and unavailable domestically [17]. Moreover, the disposal of used Kevlar products will also disrupt the ecosystem and pollute the environment [15]. Replacing Kevlar with natural fibers with improved absorption and dissipation of kinetic energy is a significant effort to improve the ballistic performance of composite structures with environmentally friendly and renewable resources [15].

With the abundance of natural fibers and relatively cheap prices, various research has been developed to study the replacement of synthetic fibers with natural ones in composite fabrication [16]. In addition, this fiber has a low density and mechanical properties that are good enough to be applied in bulletproof vests [18]. In recent years, there has been increasing interest in exploring sustainable and high-performance materials for the manufacture of ballistic vests [19]. One of these materials is ramie fiber [20], which exhibits outstanding mechanical properties that can be supported by reinforced epoxy composites [21]. Ramie composites are known for their excellent tensile strength, lightweight properties, and environmentally friendly characteristics [22],[19]. Incorporating ramie fabric into ballistic vest designs has the potential to offer a more cost-effective and sustainable alternative to traditional materials while maintaining the required level of protection [23].

Polymers have been widely used in aerospace, automation, civil engineering, marine engineering and other fields [24]-[26]. Epoxy resin has excellent mechanical properties, easy molding process, and better bond strength with other media, which can be used in resin matrices, interface adhesives, and coatings for repair and strengthening of engineering structures [27],[28]. However, the three-dimensional network structure of epoxy resin causes poor fracture toughness, which easily leads to cracks and concentration under complex loading conditions, resulting in fatigue damage and ultimate failure [29],[30]. At the same time, the hydroxyl groups in the molecular structure easily react with water molecules, leading to a decrease in durability, such as hydrolysis and plasticization [31],[32]. Compared to thermoset resin, thermoplastic resin has excellent fracture toughness, moisture, thermal and fatigue resistance [33].

Natural fibrous materials are considered as a new alternative for polymer composite reinforcement [34]. Natural fiber, such as ramie materials, has a highly damage-resistant structure which protects the user from threats and attacks while remaining light and allowing mobility [35]-[38]. The ballistic performance of natural fibers can be strengthened with a polymer composite armor system called multilayer armor system (MAS) [39]-[42]. MAS consists of at least two layers when used against high-energy ammunition, such as 7.62 mm rounds. The front layer of hard ceramic material crushes the bullet and absorbs most of its kinetic energy. In the second layer, a fiber-reinforced polymer composite dissipates residual impact energy by capturing shrapnel and the front ceramic layer [3]. Polymer composites

using epoxy resin can increase the bending elastic modulus [43], compressive strength, and compressive modulus of elasticity [44]. An effective method to strengthen epoxy resin can be adopted through continuous fibers to prepare fiber-reinforced epoxy composites [45][46]. Fibers have high tensile strength; adding them to epoxy can produce high-performance composites [47].

Considering the background of the study, an analysis of the effect of ballistic penetration was carried out on the manufacture of bulletproof multilayers from metal resulting from hardfacing welding, woven ramie fiber (*Boehmeria nivea*) with an epoxy matrix for bulletproof vests. The resulting multilayer was then subjected to a ballistic test in accordance with NIJ 0101.06 standards using an AK-47 weapon with a 7.62 mm x 39 mm caliber bullet to see the specimen's resistance to bullets. The impact of bullet penetration on the multilayer panel was observed using a Scanning Electron Microscope (SEM) test to determine the surface structure of the resulting specimen.

II. Materials and Methods

1. Materials

The raw materials were 3 mm in thick of ST-37 low carbon steel base metal, hardfacing electrode wire (Edzona-290) with chemical composition as shown in Table 1. There was ramie fiber with mechanical properties as shown in Table 2, epoxy Bisphenol A (Eposchson) with the chemical composition as shown in Table 3, and the hardener Cycloaliphatic Amine (EPH 555) as well Sodium hydroxide (NaOH) with the details as shown in Table 4. This NaOH solution was for alkaline treatment on ramie woven. The tools used in this research were digital scales to measure the weight of the materials, vernier calipers to measure the depth of impact from bullet penetration, welding (SMAW) and grinding to make metal layers, and wooden molds to make bulletproof multilayer specimens.

Table 1. Detailed information of the electrode

Type Product	Specification	Chemical Composition							Hardness
		C	Mn	Cr	Si	Fe	V	W	
Edzona-290	E10-UM-60	4.5	2	24	0.3	Bal	1	2	58/72 HRC

Table 2. Mechanical properties of ramie fiber

Fiber	Density (g/cm ³)	Elongation (%)	Tensile Strength (MPa)	Modulus Young (GPa)
Ramie	1.5	3.6-3.8	850	61.4-128

Table 3. Detailed information of the epoxy Bisphenol A (Eposchson)

Properties	Unit	Value
Viscosity	MPa	13±2
Epoxy number	%	22.7 ± 0.6
Epoxy equivalent	g/equiv.	189 ± 5
Epoxy value	equiv./100 g	0.53 ± 0.001
Total Chlorine content	%	< 0.2
Hydrolyzable chlorine content	%	< 0.05
Density	g/cm ³	1.17 ± 0.01

Table 4. Detailed information of NaOH

Properties	Unit	Value
Sodium Hydroxide	%	100
Density	g/cm ³	2.13
Soluted in	Water	Yes
Melting point	°C	323

2. Methods

Two research stages were carried out, they were the manufacturing process for making bulletproof multilayers for bulletproof vests and ballistic testing according to the Ballistic resistance of body armor NIJ standard - 0101.06. Ballistic testing is shown in the schematic diagram in Figure 1.

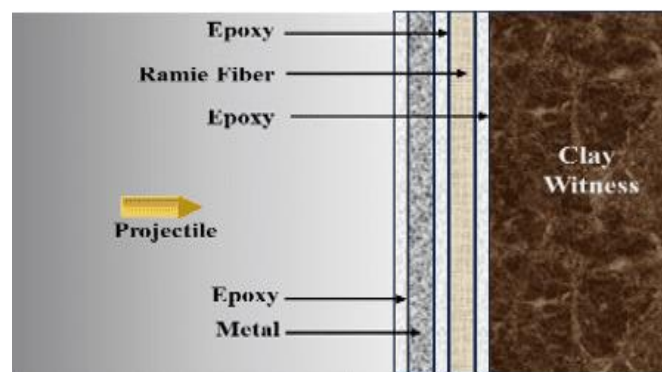


Fig. 1. Schematic diagram of ballistic tests on bulletproof multilayer specimens against 7.62 mm x 39 mm bullet penetration

The manufacturing process of bulletproof multilayers for bulletproof vests used metal layers resulting from welding hardfacing, woven ramie fiber, and an epoxy matrix. In order to make 9 combinations of composition variations, 9 specimen molds with the dimension of 105 mm x 100 mm were required. There were three stages in preparing the materials to make the multilayer.

The first stage was preparing the base metal by cutting the low carbon steel base metal according to the mold dimension and carrying out the welding/ hardfacing process to the base metal in a vertical direction with variations of 1, 2, and 3 layers using Edzona-290 hardfacing electrode wire with the composition. The welding with the current of 150 A and the voltage of 220 V produced hardfacing metal welding as shown in Figure 2.

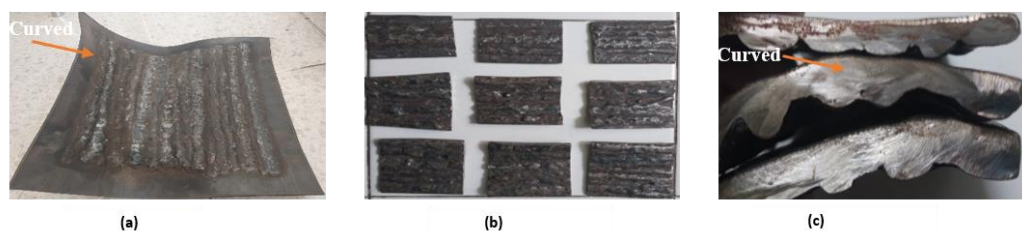


Fig. 2. (a) Hardfacing welding results using the Edzona-290 electrode with variations of 1, 2, and 3 layers (b) Results of cutting the specimen (c) side view of the thickness of the hardfacing welding results

In the second stage, ramie fiber was woven using a non-machine loom, treated using 0.5% alkali for 4 hours, and then dried under the sunlight (Figure 3).

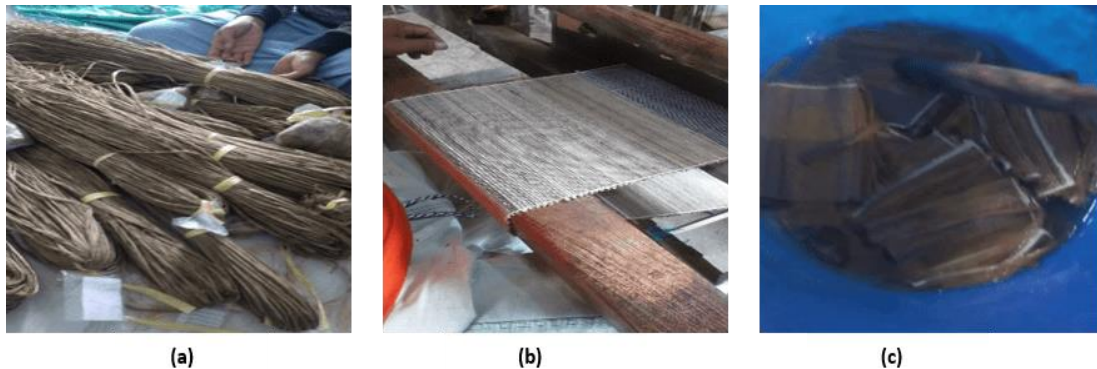


Fig. 3. (a) Ramie fiber; (b) Handloom weaving process; (c) 0.5% alkali treatment process

After all the multilayer materials were ready, in the third stage, the available specimen molds were cleaned and evenly coated using wax. This process was important so that when removing the specimen from the mold, the composite specimen did not stick to it. Variations in the composition of the specimens used in this study are shown in Table 5. The process for making bulletproof multilayers in this research is depicted in Figure 4.

Table 5. Composition of variations in multilayer specimens

Specimen Series	Welding Hardfacing (layers)	Mass (g)	Welded Metal (%)	Ramie Layer (sheet)	Mass (g)	Ramie (%)	Epoxy (g)	Epoxy (%)	Total Mass (g)
S1	A	124	44.93%	4	41	14.86%	111	40%	276
	B	124	41.20%	4	41	13.62%	136	45%	301
	C	124	37.24%	4	41	12.31%	168	50%	333
S2	A	200	50.13%	4	41	10.28%	158	40%	399
	B	200	45.56%	4	41	9.34%	198	45%	439
	C	200	41.75%	4	41	8.56%	238	50%	479
S3	A	201	49.51%	4	41	10.10%	164	40%	406
	B	201	45.48%	4	41	9.28%	200	45%	442
	C	201	41.27%	4	41	8.42%	245	50%	487

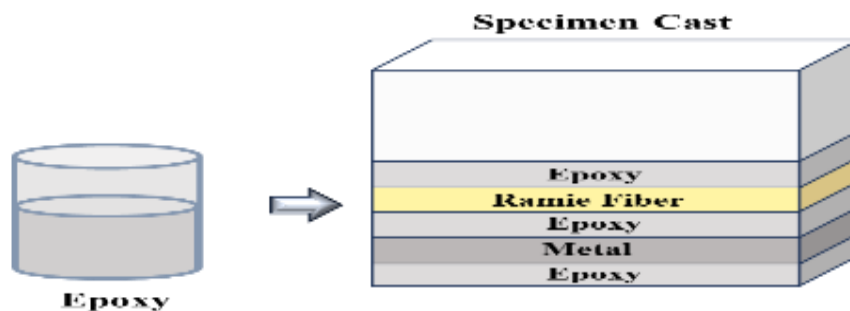


Fig. 4. The process of making Kevlar using metal and a ramie fiber/epoxy composite

Ballistic testing was carried out according to the NIJ 0101.06 level III standard using an AK-47 weapon with a 7.62 mm x 39 mm caliber bullet at a distance of 15 m. If it failed or the multilayer panel was penetrated by a bullet, the shot would be carried out again at a distance of 50 m. Weapons, bullets, and a shooting gallery, as well as ballistic tests, were provided by PT. Pindad Turen which already had international standards (Figure 5).

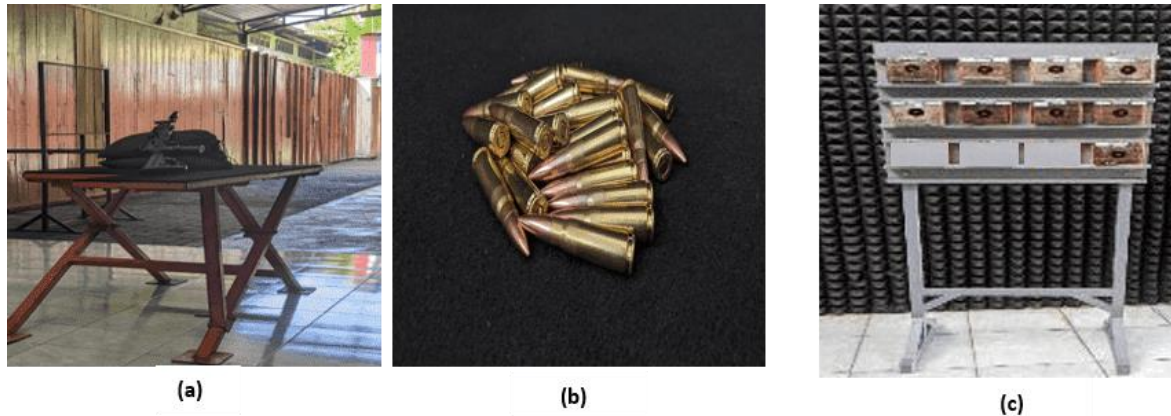


Fig. 5. (a) AK-47 weapon (b) 7.62 mm x 39 mm caliber ammunition (c) 9 ballistic test specimens with variations in bulletproof multilayer composition

The success standard of a bulletproof material for a bulletproof vest was that the specimen did not penetrate bullets and the Back Face Signature (BFS) on the plasticine placed behind the specimen must be <44 mm [48]. To see the BFS, a vernier caliper was used as in Figure 6.

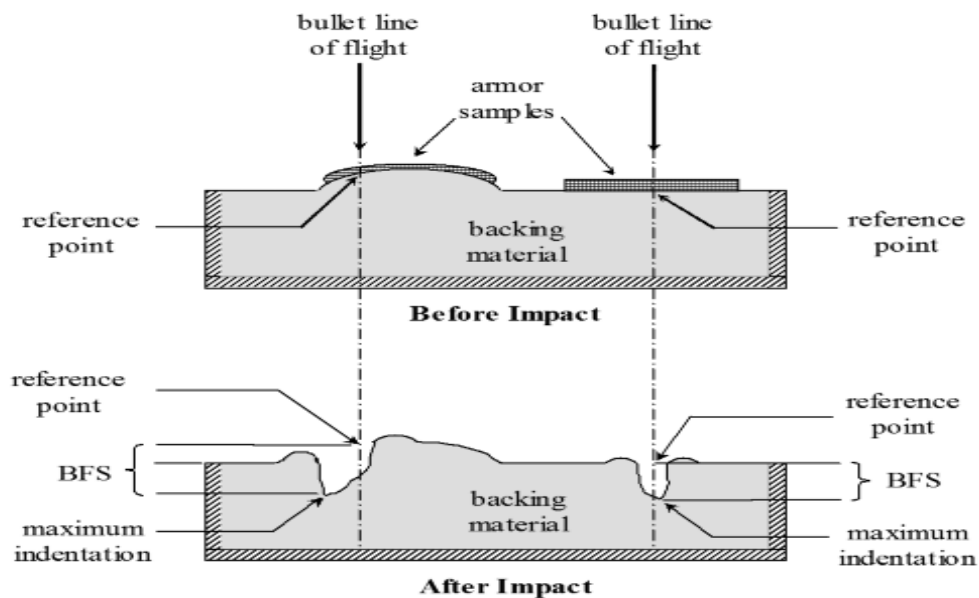


Fig. 6. Back Face Signature (BFS) [48]

The impact of the penetration of the 7.62 mm x 39 mm bullet from the AK-47 weapon resulted in deformation of the multilayer panel, which was analyzed using SEM test. The SEM characterization was needed to determine the surface structure of the resulting specimen in order to understand the morphology of this bulletproof multilayer

III. Results and Discussions

Body armor is used in both civilian and military scenarios to prevent penetrating injuries from high-velocity projectiles. An important aspect of body armor's performance is its ability to withstand non-penetrating ballistic impacts, which can result in rapid armor displacement and deformation. This transfer results in a large amount of energy being dispersed and distributed throughout the plates and underlying tissues, including the transmission of energy to organs that are not directly beneath the body's armor [49].

The characteristics between protection and mobility of bulletproof vests must be considered. The main factors in ballistic impact mechanisms include thickness, toughness, strength, ductility, density, and projectile parameters of the target material. Kinetic energy absorption, penetration depth, and residual velocity are parameters that influence the performance of natural fiber composites used in armor systems [50],[51]. Ballistic protective materials work based on two basic principles, namely impact energy absorption and impact energy redistribution [52]. The projectile energy must be absorbed by the protective material before it can penetrate panel [53]. Body armor provides protection in three ways. The first method is that ballistic projectiles are stopped by reducing their speed and losing their kinetic energy when they hit the armor. The second method, armor reflects the projectile completely, which is very rare. The third method is the combination between method one and two [53].

In general, high-performance fibers must be converted into different application phases. For example, the fibers are converted to yarns, textiles, or related textile reinforcing composites [54]-[58] to provide greater strength and protect against various ballistic impacts. Many mechanisms must be considered in addition to the unique qualities of the material (fiber) to improve the ballistic performance of the finished ballistic target. Adding extra layers in various settings during the manufacture of ballistic panels is a common way to increase ballistic protection against ballistic impacts in addition to selecting the appropriate material quality [59]-[63]. Factors that influence the ballistic performance of the fiber used are the physical properties of the fiber, the type of twist in the yarn, the resistance of the fiber in the warp and weft directions, the fabric weave pattern, yarn degradation during the weaving process, and the operations carried out after weaving [64]. Material, geometry, and projectile primarily influence ballistic impact response. Understanding the response of materials to ballistic impacts is a complex phenomenon. The level of complexity increases with impact speed, projectile geometry, manufacturing technique, matrix composition, and reinforcement [65], etc. This complexity causes limited research on the ballistic performance of natural hybrid composites. The material response to ballistic impacts combines predominantly local and global responses [66].

Projectile velocity is a parameter that differentiates the local and global response of materials to ballistic impacts. Damaged target panels experience various modes, including fiber tensile failure, fiber shear, matrix cracking, indentation, delamination, etc. The extent to which these failure mechanisms are observed is a function of material properties, impact velocity, projectile geometry, and so on. and targets [67]. In low-velocity impact events [68], global energy absorbing systems are usually dominant due to sufficient time to transfer and spread energy over a wide target area. The local response of the target material refers to the behavior of the target close to the point of contact of the projectile [65]. The results of the ballistic impact after the shot that occurred on 9 variations in the composition of multilayer bulletproof specimens at distances of 15 meters and 100 meters are shown in Table 6.

Table 6. Deformation results of ballistic penetration impact of 7.62 mm x 39 mm bullet

Specimen	Series	Welding Hardfacing (layers)	Welded Metal (%)	Ramie (%)	Epoxy (%)	Total Mass (g)	Deformation Width Front (mm)	Deformation Width Behind (mm)	BFS (mm) 15 m	BFS (mm) 50 m
S1	A	1	44.93%	14.86%	40%	276	22.60	22.60	Perforated	Perforated
	B	1	41.20%	13.62%	45%	301	19.55	17.85	Perforated	Perforated
	C	1	37.24%	12.31%	50%	333	18.35	16.90	Perforated	Perforated
S2	A	2	50.25%	10.30%	40%	398	18.42	18.42	Perforated	Perforated
	B	2	45.56%	9.34%	45%	439	17.25	15.45	Perforated	Perforated
	C	2	32.89%	6.74%	60%	608	7.40	4.60	Perforated	24.85
S3	A	3	49.51%	10.10%	40%	406	15.40	9.55	Perforated	Perforated
	B	3	45.48%	9.28%	45%	442	14.40	8.60	Perforated	Perforated
	C	3	41.27%	8.42%	50%	487	12.50	6.60	Perforated	Perforated

Table 6 displays the impact of ballistic penetration that occurred on 9 variations in the composition of multilayer bulletproof specimens, which caused the bullet to penetrate the entire panel in the first shot at a distance of 15 meters, as shown in Figure 7. In contrast, in the second shot at a distance of 50 meters, only one specimen was able to withstand bullet penetration with a BFS of 24.85 mm, namely in the S2-C series specimens. In panels with a weld layer composition of 1 and 2 layers and epoxy with a volume fraction of 40%, the bullet penetrated perfectly without narrowing the deformation width at the front and back of the panel. It indicated that the bullet did not experience significant resistance in this specimen. Meanwhile, for the composition of 2 and 3-layer welds with fractions with 45% and 50% epoxy volumes, there was a narrowing of the deformation width, which means that there is resistance to the bullet



Fig. 7. Multilayer panel specimens not able to withstand bullet penetration

In making this multilayer bulletproof specimen, the 10% epoxy composition was added from the existing 50%. It was noticeable that the material making up the multilayer bulletproof in the S2-C specimen was not completely covered in epoxy. This was due to one of the hard facing welding layers being concave or curved, leaving a cavity requiring more

epoxy filling. The depression in the hardfacing layer was caused by the 3-mm-thick ST-37 steel base metal material not being able to withstand the heat from the welding process as shown in Figure 2a and 2c. Therefore, 367 grams of epoxy or 60% volume fraction was added to the S2-C test specimen which had a total mass of 608 grams. It turned out that S2-C was the only specimen that was able to withstand bullet penetration (no perforated) and had the smallest deformation among the 9 combinations of bulletproof multilayer variations, although it only used 2 layers of hardfacing welding. This proves that the hardfacing metal only functions as a bullet tip breaker. Meanwhile, ramie-epoxy functions as a buffer for blunt bullets and absorbs the remaining energy from the bullet's impact. This shows that even 3 layers of hardfacing were used, yet the epoxy weight fraction was less than 60%, and the blunt bullets, due to colliding with the hardfacing, still could not be dampened with ramie-epoxy. These results are better than previous research using the same method with hardfacing hybridized on a ramie woven composite with an Epoxy matrix, which failed to prevent penetration from long-barreled rifle bullets and was only able to withstand penetration from pistol bullets [69]. The composition after the first ballistic test and the specimen was able to withstand bullet penetration at a distance of 50 meters with a BFS value of 24.85 mm, which was still below the maximum BFS value of < 44 mm as seen in Figure 8.

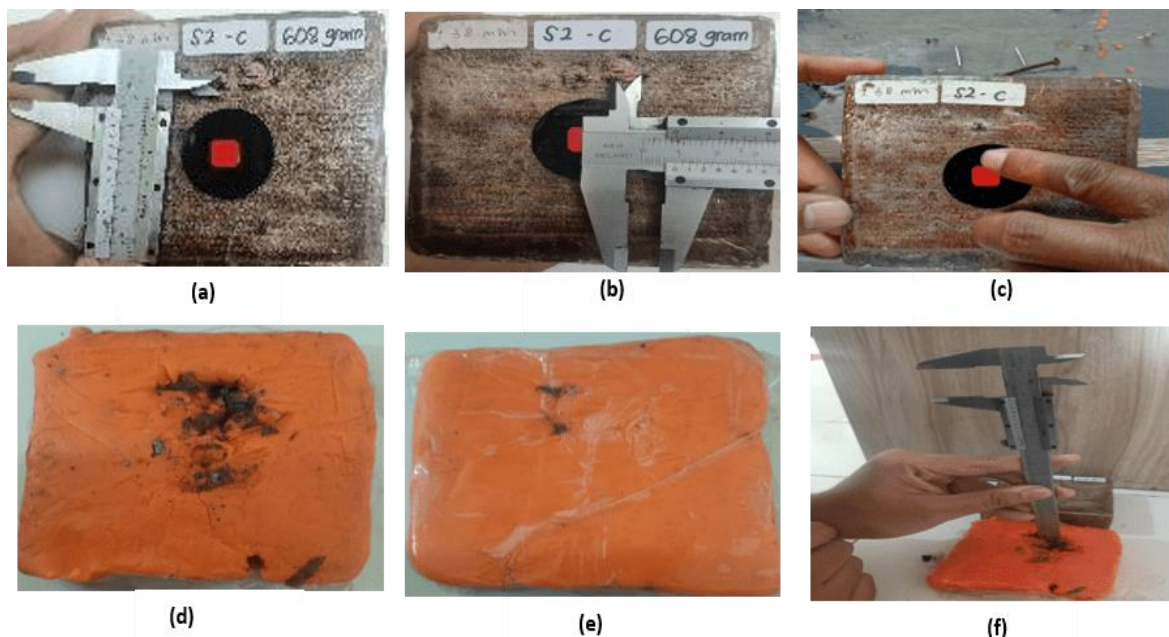


Fig. 8. (a) Deformation of first shot bullet at S2-C (b) Deformation of second shot bullet at S2-C (c) Backing board not perforated by the bullet (d) Front Side of plasticine had deformation (e) Back Side of plasticine was not perforated by the bullet (f) BFS measurements using calipers with a value 24.85 mm

When the projectile hits a ballistic target, the middle layer made of natural fiber-reinforced polymer composite exhibits a ballistic perforation mechanism. When a ballistic projectile hits the middle layer, the following failure mechanisms occur such as fiber pulling, delamination, fiber cracking, and matrix cracking. The ballistic limits of the intermediate layers of fiber-based protective systems are almost identical to those of aramid fiber composites. The striking layer of the protective system is made of ceramic layer to resist sliding blockage, and the backing layer is made of aluminum alloy to resist Tensile deformation [50].

Figure 8 shows that the increasing thickness of the bulletproof multilayer causes the resulting penetration width to decrease. This is because as the epoxy layer increases, the tensile modulus of the epoxy-based fiber composite increases [70]. The smaller the resulting penetration, it proves that the level of specimen resistance is greater. The most optimum results were found in the S2-C specimen with a deformation width of 7.4 mm at the face of the panel and 4.6 mm at the back of the panel. Based on the results of the ballistic impact test, the projectile was still able to penetrate the specimen. The reason why the projectile is still able to penetrate the specimen can be analyzed based on the results of the morphological structure in Figure 9.

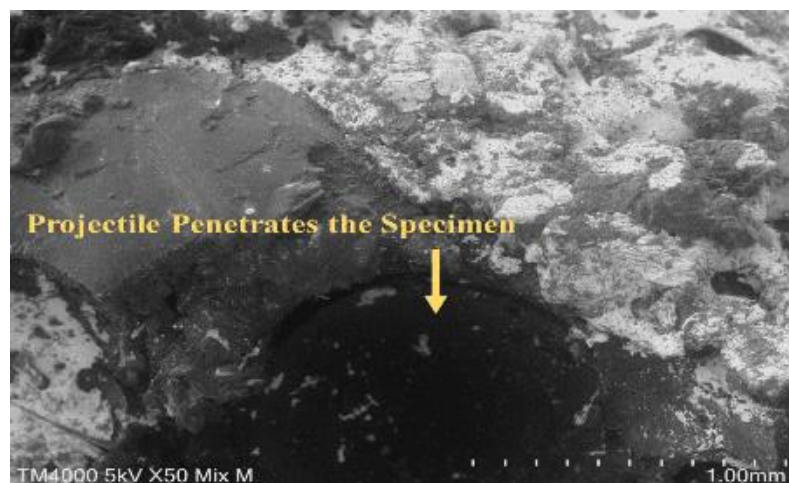


Fig. 9. Surface morphology structure of the S2C variation specimen due to penetration of the 7.62 mm x 39 mm AK-47 bullet

Figure 9 shows that the morphological structures in the specimen are evenly distributed. However, based on the morphological structure of the S2-C specimen, it shows poor interfacial adhesion between the epoxy resin and ramie fiber. This is why the specimen is still unable to withstand the projectile. It is necessary to add reinforcing material to an epoxy mixture so that the adhesion force between metal, ramie fiber, and adhesive is stronger as Hollow Glass Microsphere, which has good toughness and stiffness and a small density for it has holes. It is suitable for reducing the force of impact and bending [71].

IV. Conclusions

Epoxy is the material composition that mostly influences the bulletproof multilayer for bulletproof vests. It is known that as the volume fraction of epoxy increases, the deformation width due to bullet penetration becomes smaller. The best results on the S2-C with a composition of 60% specimen weight were obtained with the smallest deformation of 7.4 mm in the first shot and were able to withstand bullet penetration with a BFS value of 24.85 mm in the second shot. This value is < 44 mm therefore, it complies with the NIJ 0101.06 body armor standard.

Meanwhile, the addition of a hardfacing weld layer did not have much of an effect because after the shot test was carried out, it was revealed that the hardfacing served as a bullet tip breaker. This caused the hardfacing in layers 1, 2, and 3 to be broken. The role of ramie-Epoxy was to withstand blunt bullets; 60% epoxy weight fraction was able to withstand bullet penetration. In specimen S2-C, only with the 2 layers of hardfacing had better results than S-3C with 3 layers of hardfacing. The hardfacing welding process on the

ST 37 lace carbon steel base metal with a current of 150 A and a voltage of 220 V resulted in the base metal becoming curved, thereby reducing the mechanical properties of the welding results. Thus, it was necessary to carry out further studies on hardfacing welding.

As a result of the bullet shot, the specimen experienced delamination. This was confirmed by the SEM photos on the surface of the specimen as a result of the bullet shot. To avoid delamination, it is important to add additional materials to epoxy mixture that has strong adhesion, good toughness, and stiffness and has a small density with a hollow morphology. This additional material must be able to reduce impacts and banding forces as Hollow Glass Microsphere does.

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