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Enhancing laminate composites: Investigating the impact of kevlar layering and titanium carbide nanoparticles

Adinda Oktaviani[1], Anne Zulfia[1*] and Dieter Rahmadiawan[2,3]

[1] Department of Metallurgy & Materials Engineering, Universitas Indonesia, Depok, **INDONESIA**
[2] Department of Mechanical Engineering, National Cheng Kung University, Tainan, **TAIWAN**
[3] Department of Mechanical Engineering, Universitas Negeri Padang, Padang, **INDONESIA**

* Corresponding Author: anne@metal.ui.ac.id
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Abstract: The quest for innovative and superior materials is a challenge in the realm of materials science and engineering. Traditional materials often fall short in meeting the demands of modern industries, especially in the military. Technological developments in the military domain are still progressing, one of which involves a new material for combat vehicle applications: a laminated composite. In this research, a composite consisting of AA7075 sheet metal and kevlar with epoxy resin and TiC nanopowder were prepared. A test was conducted to assess its performance in absorbing ballistic energy from projectiles. Solid Thickening Fluid (STF) was created by mixing TiC nanopowder with PEG-400 through 2 hours of stirring. The laminate composite structure was prepared using the hand layup method, followed by a drying process at room temperature. The addition of kevlar layers yielded promising results in the ballistic and impact tests, as the diameter of the perforation decreased progressively with each additional kevlar layer. The IK sample impact test value improved by 35.7% compared to the unimpregnated one. The production process of this material also consumes minimal energy, which suggest a potential for environmental sustainability.

Keywords: Composite; Titanium Carbide; Kevlar; Nanoparticle.

1. Introduction

A tank is an armored fighting vehicle that utilizes chain-shaped wheels. It is a versatile weapon capable of destroying targets with good mobility. Typically, tanks are constructed with steel bodies, which possess a high density of approximately 7.85 g/cm^3, providing considerable strength. However, tanks often exhibit poor maneuverability during operations [1]. Excessive weight in land vehicles reduces their mobility, presenting a weakness in combat vehicles. This limitation hampers the vehicle's ability to evade enemy attacks, thereby compromising the safety of the driver and passengers. Moreover, combat vehicles are known to consume significant amounts of fuel for propulsion, resulting in the emission of exhaust gases with high combustion levels, contributing to environmental pollution [2].

The production of steel, commonly used as a protective material in bullet-proof vehicles, requires substantial energy. The use of non-renewable energy sources in steel manufacturing contributes to pollution and may pose environmental risks [3][4]. A viable alternative to steel as the primary material for combat vehicle bodies is composite materials. Composites are formed by combining two or more materials with distinct properties [5]. Among various types of composites, hybrid composites have the potential to replace steel in combat vehicles. The primary material in this composite is 7075 aluminums, in the form of a low-density plate with a density of approximately ±2.7 gr/cm^3 and varying mechanical strengths depending on the addition of alloying elements. The reinforcing material used is kevlar cloth, which enhances the tensile and bending strength of the composite.

Before the manufacturing process, kevlar fibers are impregnated with a liquid known as Shear Thickening Fluid (STF). STF is a mixture of PEG-400 powder, ethanol, and nano TiC [6]. Nanoparticles possess remarkable properties such as thermal, mechanical, and electrical characteristics, high reactivity, and large specific surface area [7]–[9]. They also show potential in the treatment of muscle and prostate tumors [10]. Recently, the development of nanomaterials known as MXenes, which are two-dimensional inorganic compounds with layers just a few atoms thick, has garnered significant attention from researchers [11]–[13]. Researchers are now exploring the feasibility of using both synthetic and natural fibers in hybrid composites for military applications to achieve a better environmental impact. For instance, Meliande et al. developed a laminated hybrid composite with aramid woven fabric and curaua non-woven mat. The composite comprises 15 layers of aramid and one layer of curaua, with the ballistic limit about 15% lower compared to the neat composite [14]. Furthermore, Tsirogiannis et al. investigated a hybrid composite comprised of carbon nanotubes (CNT) for armored vehicles. The addition of CNT proved to increase the hardness of the composite by approximately 23% [15].

In this research, we prepared laminated composites by incorporating TiC nanoparticles. As far as the author is aware, work related to laminated composites using nanoparticles is very scarce [16]. TiC, known for its excellent mechanical strength, particularly its high hardness, significantly influences the ballistic properties of the material. Kevlar, an aramid fiber, boasts low density, high strength, and excellent energy absorption capabilities [17]. The impregnated kevlar will be layered using manual lay-up, accompanied by epoxy resin, and curing agent. Once the assembly is complete, the 7075 aluminum and kevlar layers will be compressed. The production process of this material consumes minimal energy, thus exhibiting potential for environmental sustainability. This study investigates the effect of adding TiC nanopowder to kevlar reinforcement with AA7075 as the matrix. It examines the ballistic performance, impact resistance, and microstructure of hybrid laminate composites.

2. Material dan methods

2.1 Material

Figure 1 illustrates the preparation steps for the laminate composite. AA7075 aluminum sheet metal and Kevlar fibers were locally sourced (Jakarta, Indonesia), while TiC nanoparticles (98% purity) and PEG-4000 were obtained from Alibaba (Shanghai, China). The production process of laminated composite materials commences with the preparation of the necessary components. The aluminum plate was cut into dimensions of 7.5x15 cm (for ballistic testing) and 5.5x1 cm (for impact testing), and the surfaces were thoroughly cleaned and sanded. Each of the three samples comprised 8, 16, and 24 layers of unimpregnated aramid, respectively. For each number of Kevlar layers used, the impregnation material was prepared in a mass ratio of 1:2, with TiC to PEG-400 solution. Concurrently, the shear-thickening fluid (STF) was prepared using PEG-400, ethanol, and TiC nano powder.

First, the TiC nano powder was weighed, and the required volume of PEG-400 was measured to prepare the STF based on the number of aramid layers to be impregnated. Subsequently, the mixture was stirred using a magnetic stirrer at room temperature and a speed of 1200 RPM for 1 hour. Then, ethanol was added to the mixture, and stirring was continued for another hour under the same conditions.

Next, the kevlar impregnation process was carried out using the STF. The kevlar cloth was soaked in the STF for a calculated period of time to ensure impregnation. The kevlar cloth was completely submerged in the liquid during impregnation. Afterward, the kevlar cloth was dried for 72 hours at room temperature to allow for complete evaporation of the ethanol. Once the kevlar was impregnated, the subsequent step involved preparing the structure of the hybrid laminate composite. During the preparation of the laminate composite, each surface of the kevlar or 7075 aluminum was coated with an adhesive substance, using an epoxy resin and hardener ratio of 2:1. The sample without STF is denoted as UK, while the sample incorporating STF is referred to as IK.

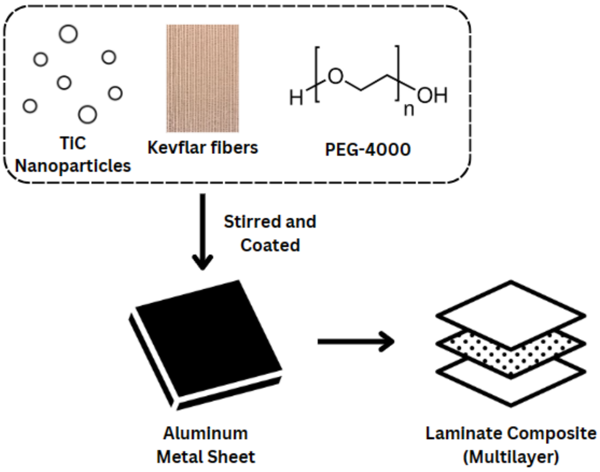

Figure 1: Laminate composite preparation

2.2 Methods

The morphology of the composite was examined using a scanning electron microscope (SEM) (Inspect F50, USA) at the Center for Material Processing and Failure Analysis, Universitas Indonesia. The observed section focused on the fibers (Kevlar and STF). To determine the diameter of the Kevlar fibers, the acquired SEM image was analyzed using ImageJ software. Approximately 10 measurements were conducted to calculate the average diameter of the Kevlar fibers. The FTIR analysis was conducted using a Spectrum Two-UATR instrument (Perkin Elmer, United States), which is equipped with a MIR TGS detector for spectrum detection. The scanning range of the measurements spanned from 500 to 4000 cm^{-1}, with a scanning speed of 0.2 cm/s.

The ballistic impact experiment involved the use of two types of projectiles, namely level II and level III, consisting of 9 × 19 mm MU1-TJ and 5.56 x 45 mm MU5-TJ caliber bullets (Pindad, Indonesia), respectively. The samples were positioned at a distance of 15 meters from the firing point. Each sample was subjected to impact following the NIJ (National Institute of Justice) standards for body armor systems, specifically meeting the requirements for Type IIIA in armor level [18]. The diameter of the perforation caused by the projectiles was measured using a digital caliper. The test was conducted with no repetitions, and 6 total samples were tested.

The impact test was performed according to the ASTM E-23 standard using the Charpy impact tester (Tinius Olsen, USA) [19]. The test specimens were prepared with a V-shaped notch having an angle of 45°, a radius of curvature of 0.25 mm, and a depth of 2 mm. The dimensions of the samples were 10x10x55 mm. The energy absorbed by the test specimen was measured in Joules and could be directly read from the indicator scale on the testing machine. The test was conducted with 2 repetition and 12 total samples were tested.

3. Results and discussion

3.1 SEM Analysis

SEM observation was conducted to examine the uniform dispersion of TiC nanoparticles on the Kevlar fibers and evaluate the viability of this method as a reinforcement technique in the specimen, aiming to enhance structural strength and increase energy absorption capacity during ballistic testing. Figure 2 presents SEM images captured at magnifications of 1000x and 5000x. This image is from our previously published research work [14]. The images reveal that a portion of the TiC nanopowder adhered to the finest kevlar fibers. Figure 2 (a and b) displays the kevlar fibers, which are about 7 µm. The TiC nanoparticles can be seen in Figure 2d pointed by orange arrow. However, it can be observed that some TiC nanofillers agglomerate on the smaller kevlar fibers. This phenomenon aligns with the findings of Foratirad et al., who conducted research on the dispersibility of TiC. According to their study, the addition of PEG 400 had minimal impact since PEG is a non-ionic substance that does not affect the charge or potential on the surface of TiC [20].

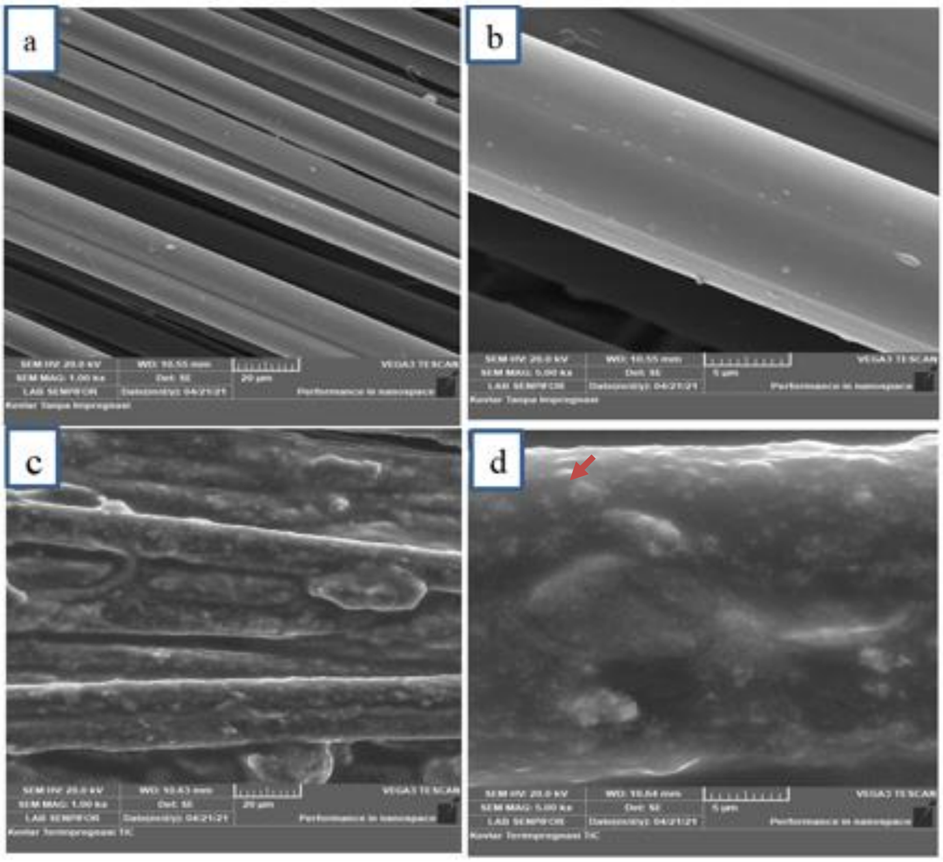

Figure 2: SEM test results on unimpregnated kevlar with (a)1000x and (c)5000x magnifications and TiC nano-impregnated kevlar with (b)1000x and (d)5000x magnifications [14]

3.2 FTIR Analysis

Based on the FTIR results, the wavenumber analysis revealed several characteristic vibrations. The presence of an O-H stretching vibration was indicated by a broadband exhibited at 3383 cm^{-1}. Additionally, a narrow band observed at 1065 cm^{-1} indicated a C-O stretching vibration. The broadband exhibited at 3450 cm^{-1} corresponds to the spectrum of the PEG-400 solution and signifies the O-H vibration [21]. Furthermore, stretching vibrations were observed at 2870 cm^{-1}, indicating C-H stretching. In the FTIR spectrum of the as-received nano TiC, a peak at 476 cm^{-1} can be attributed to the Ti-C vibration, which is consistent with previous research findings [22].It can be seen that when kevlar fiber is coated with STF, the 3450 cm $^{-1}$ peak intensity is significantly drop, and 2870 cm^{-1} peak is not visible. The absence of this peak in the IK sample suggests that the impregnation or coating process with PEG and TiC nanoparticles might have altered or masked the aliphatic C-H bonding in the kevlar fiber. Furthermore, the lower intensity of 3450 cm $^{-1}$ peak suggests that the impregnation process may have influenced the hydrogen bonding environment or altered the accessibility of hydroxyl groups on the kevlar fiber surface. The presence of PEG, which is known for its hydrophilic nature, and TiC nanoparticles could modify the surface interactions and water absorption characteristics.

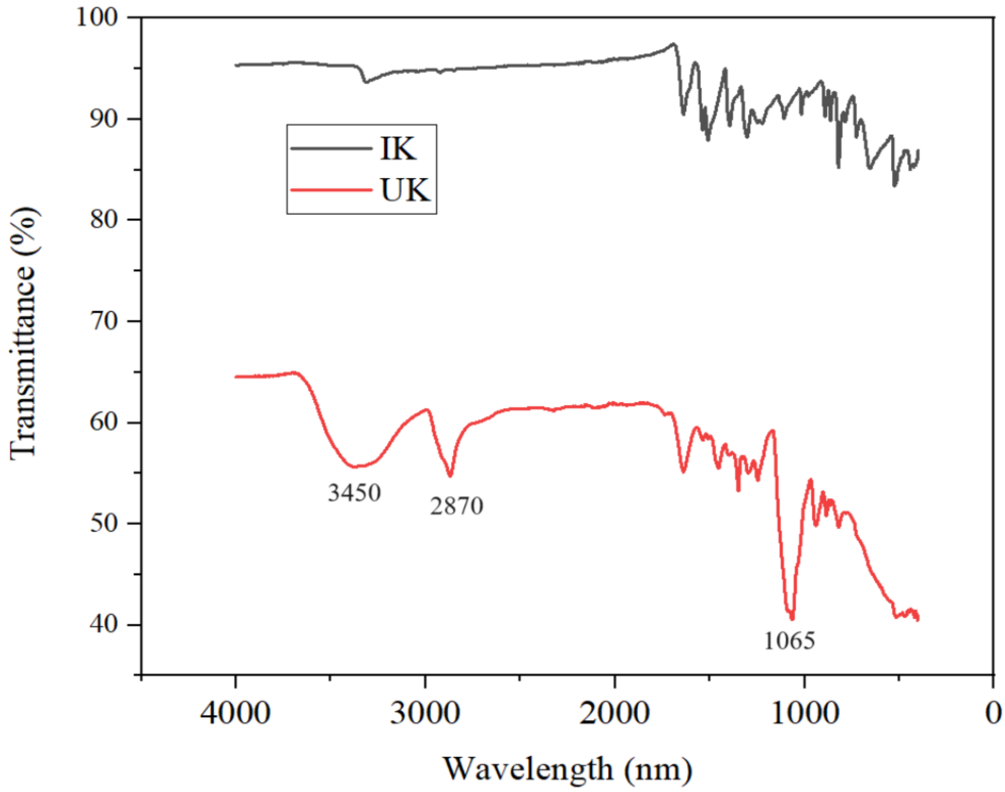

Figure 3: FTIR Spectra of UK and IK samples

3.3 Ballistic Testing Analysis

Three types of laminates were not impregnated with STF (referred to as UK), while the other three types were impregnated with STF (referred to as IK). Each type of laminate was prepared with three different thicknesses: 8 layers, 16 layers, and 24 layers. Figure 4 presents the perforation diameter obtained from all samples. The results show that the perforation diameter decreases as the number of kevlar layers increases for both UK and IK samples. Specifically, for UK samples, the perforation diameter was 15.45 mm for 8 layers of kevlar, 13.33 mm for 16 layers of kevlar, and 11.42 mm for 24 layers of kevlar.

On the other hand, for IK samples, the perforation diameter was 12.5 mm for 8 layers of kevlar, 10.78 mm for 16 layers of kevlar, and 10.05 mm for 24 layers of kevlar. Notably, the perforation diameter of IK samples is consistently lower compared to the UK samples. Figure 4 displays the UK samples after undergoing the ballistic test. All three samples exhibited delamination, characterized by the separation of layers, as a result of being pierced by bullets. This delamination phenomenon can be attributed to the adhesive used, namely epoxy resin and hardener. The adhesive layer in the laminated composite, possessing higher stiffness compared to aluminum and kevlar, becomes more susceptible to energy transfer from the bullet, leading to delamination [23].

Furthermore, in parts (c-d) of the specimens, a failure indicating a spalling phenomenon was observed. Spalling refers to the failure of tensile strength caused by the reflection of a transient energy wave, often occurring when the specimen is subjected to explosive stress. In this condition, the sample appears to have scabbing, but due to the presence of inhomogeneous forces, failure occurs due to surface deformation [24]. Figure 5 and 6 show the results of ballistic testing of IK samples. It can be a phenomenon called petalling is highlighted with a red circle. Petalling occurs due to strength inhomogeneity, causing the plate material to be pushed forward and form a bending moment in front of the striker. This phenomenon is often accompanied by permanent flexure. Furthermore, inhomogeneity can be observed in the petalling phenomenon.

Petalling is typically followed by permanent flexure [25]. In Figure 5d, there is delamination shown by the detachment of the aluminum plate from the kevlar layer. This is because when the projectile presses a specific contact area. The energy transferred by the projectile will be transferred in all directions to the target. The target area with the weakest bond will experience matrix crackin In Figure 5d, delamination is shown by the detachment of the aluminum plate from the kevlar layer. This occurs when the projectile applies pressure to a specific contact area. The energy transferred by the projectile is then dispersed in various directions within the target. The area with the weakest bond experiences matrix cracking [26].

Additionally, another failure observed in the IK samples is the back face deformation (BFD) phenomenon, which results from imperfect penetration of the projectile. This occurs because as more layers of kevlar are used, increased friction takes place during the bullet penetration process, dissipating more energy [27]. However, the presence of nano TiC tends to increase the distance between each kevlar layer slightly. This increased distance affects the adhesive layer between the kevlar layers, making the sample thicker compared to the UK samples [28].

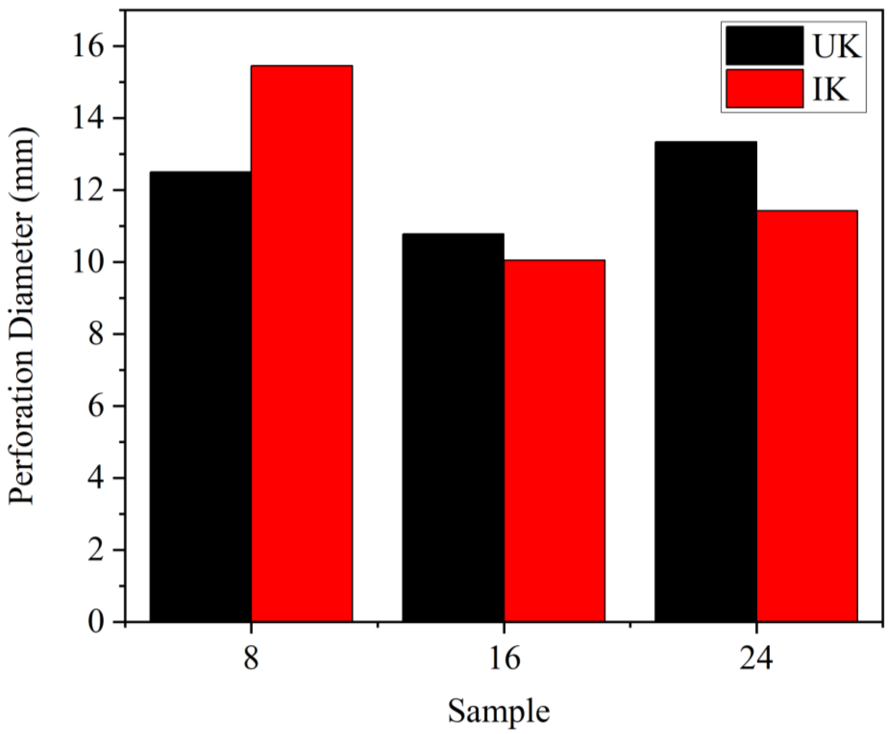

Figure 4: Comparison of ballistic testing perforation diameters

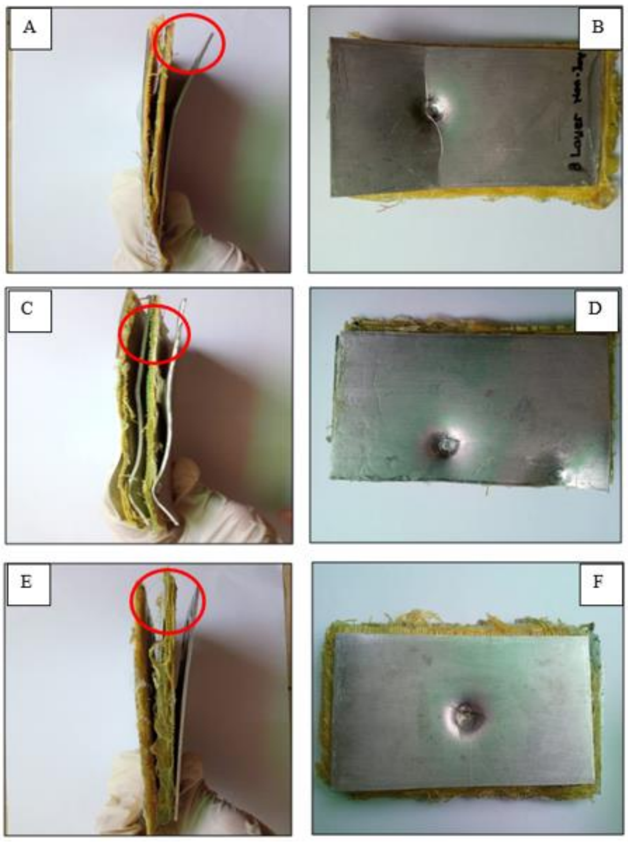

Figure 5: UK ballistic test results of (a-b) UK8; (c-d) UK16; and (e-f) UK24

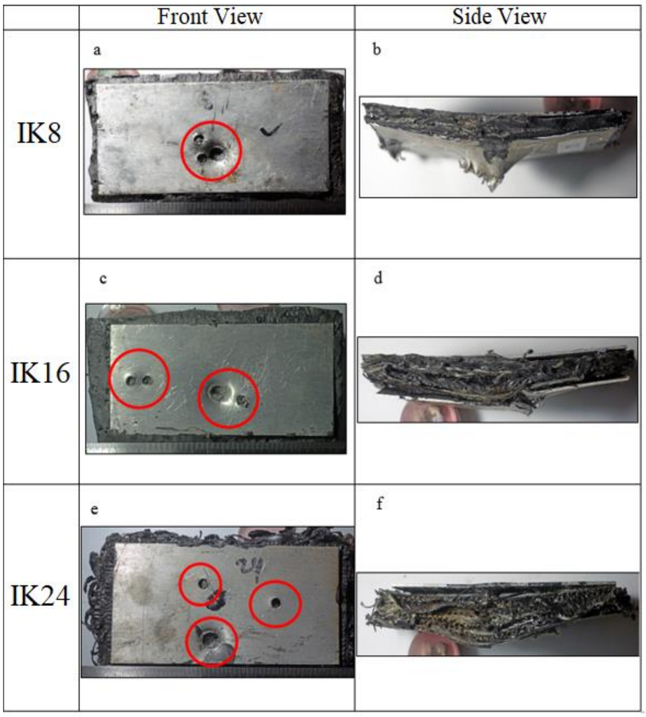

Figure 6: Ballistic test results of (a-b) IK8; (c-d) IK16; (e-f) IK24

3.4 Impact Testing Analysis

In Figure 7, the impact values of UK and IK samples are presented. It is evident that there is an improvement in the Impact Value as the number of layers increases. For the UK samples, the impact values for UK8, UK16, and UK24 are 0.26, 0.27, and 0.28 joules/mm^2, respectively. On the other hand, the impact values for IK8, IK16, and IK24 are 15.3%, 33.3%, and 35.7% higher compared to the UK samples.

This improvement in impact resistance in the IK samples can be attributed to the increase in the number of kevlar layers. When more kevlar layers are present, a greater number of threads become dislocated due to the impact of the pendulum, allowing for better energy absorption [29]. Consequently, by using more kevlar in the composite, the capacity to absorb impact energy increases, resulting in increased resistance to deformation.

In addition, Figures 8 and 9 provide a comparison between the bending forms of UK and IK samples. It can be seen that the composite with most layer has the lowest bend, and in Figure 9, cooperating STF could lead to prevent the delamination damage.

Delamination damage in laminated composites occurs when the bond between layers, formed by the adhesive, breaks down. The adhesive is responsible for transferring the energy received from the impact on the first layer of the laminate shortly after being impacted by the pendulum [8]. The transferred energy reaches the subsequent layer, where the absorbed energy approaches the threshold of the adhesive strength to bond with neighboring layers, leading to the delamination process. The presence of gaps or voids in laminated composites can also be attributed to the manufacturing process [30].

Furthermore, the presence of a limited amount of kevlar in the composite contributes to the mechanism where the material absorbs a minimal amount of energy. Consequently, the unabsorbed energy becomes concentrated in the adhesive layer, serving as the initiation site for delamination. In Figure 9 above, the presence of delamination phenomena can be observed in all samples. This occurrence may be attributed to the untreated surface of the aluminum plate. Additionally, the quantity of impregnated kevlar can influence the wetting behavior of the adhesive on both the aluminum and kevlar plates. Increased impregnation of kevlar with STF results in a higher concentration of TiC powder within the laminated composite. As a consequence, the adhesive's ability to wet the surfaces of the aluminum and kevlar plates is impeded, thereby reducing its effectiveness in withstanding impact loads [8].

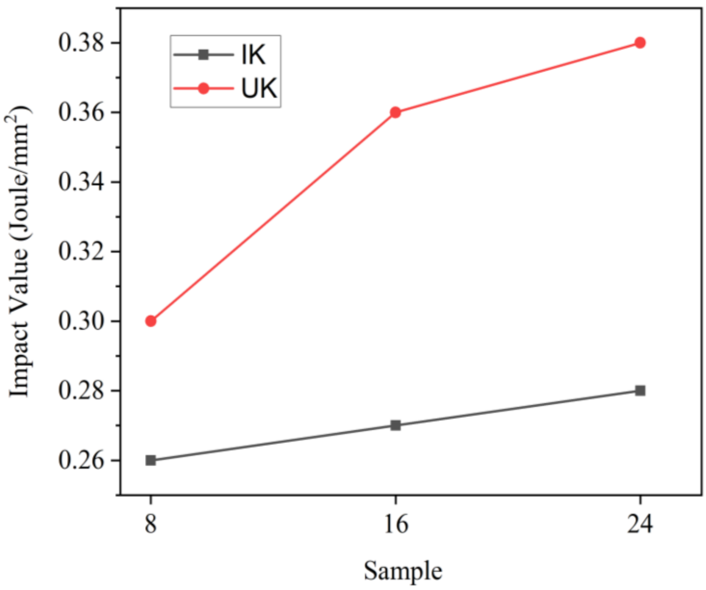

Figure 7: Comparative graph of impact value and number of kevlar layers

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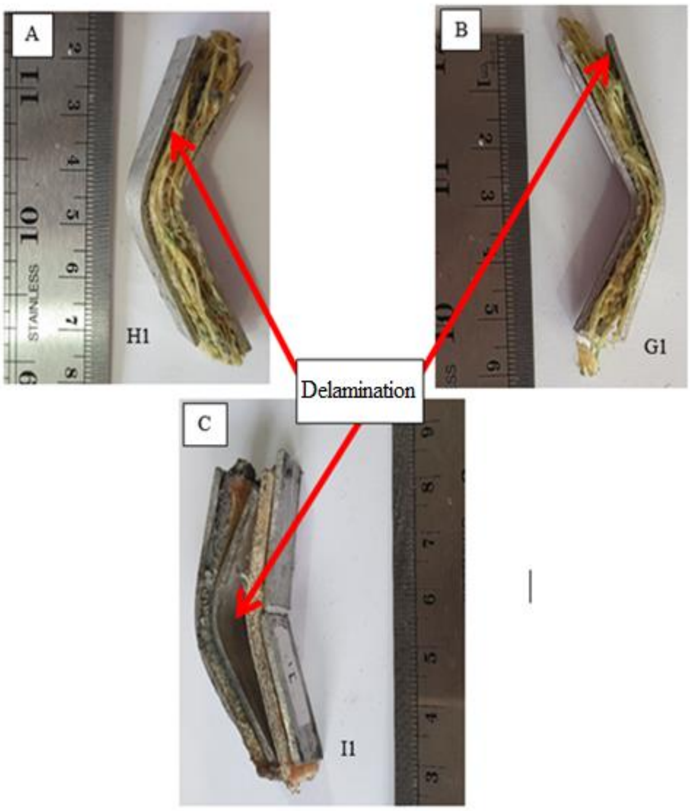

Figure 8: Laminated composite impact test results of (a) UK8, (b) UK16, and (c) UK24

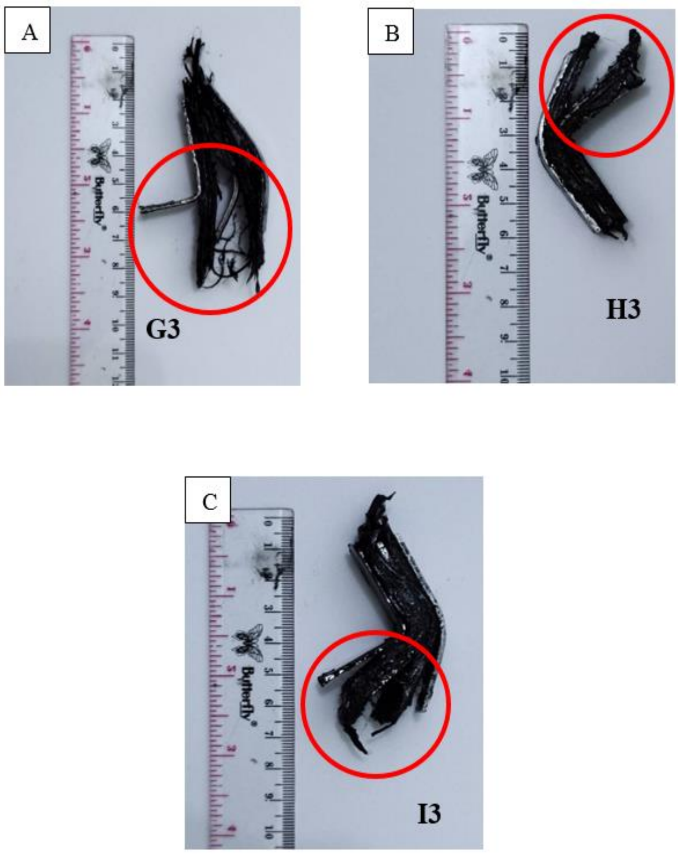

Figure 9: Impact test results of (a) IK8, (b) IK16, and (c) IK24

4. Conclusion

Based on the conducted research and the data analysis, several conclusions can be drawn:

1. The addition of kevlar layers in laminated composite components enhances their ballistic resistance. The perforation diameter decreases as more kevlar layers are added. Impact tests also reveal that increasing the number of layers improves the impact resistance at lower velocities. Furthermore, the morphological analysis of the composites demonstrates that damage decreases with an increase in the number of kevlar layers. This is attributed to the greater energy absorption capacity of the composite with a higher amount of kevlar.
2. The inclusion of STF in kevlar has a significant effect on the microstructure of the kevlar surface. SEM results for the untreated kevlar samples show empty spaces between the kevlar yarns. However, when TiC nano impregnation is applied to kevlar, the empty spaces become filled with TiC particles.
3. The destruction-test analysis reveals the occurrence of delamination in the interphase layer between different materials during both ballistic and impact tests. When the energy surpasses a certain threshold, it leads to matrix cracking and initiates delamination. The weak adhesive bond between different materials, particularly caused by inadequate surface preparation of the aluminum layer, is identified as a factor contributing to suboptimal adhesive strength and its inability to effectively bond and withstand energy transfer during pendulum or projectile impact.

These conclusions highlight the positive influence of kevlar layers on ballistic resistance, the impact of STF impregnation on the microstructure, and the importance of strong adhesive bonds to prevent delamination in laminated composites.

Author contribution

Adinda Oktaviani: Writing – original draft; Investigation; Formal analysis. Anne Zulfia: Supervision; Writing – review & editing; Methodology. Dieter Rahmadiawan: Writing – review & editing; Visualization.

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Competing interest

No potential conflict of interest was reported by the author(s).

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