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BALLISTIC SIMULATION AND EXPERIMENTAL TEST OF 14.5 MM ARMOR PIERCING PROJECTILE IMPACT ON COMPOSITE ADD-ON ARMOR WITH A DOUBLE-LAYERED HIGH HARDNESS STEEL

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ABSTRACT
In this study, the ballistic performance of composite add-on armor with double-layered high-hardness steel which was impacted by a 14.5 mm armor-piercing projectile at a velocity of 900 m/s was investigated both experimentally and numerically. The armor system in this study consists of composite add-on armor and a backing plate. The composite add-on armor includes advance alumina-zirconia ceramic which was produced by cold-isostatic pressing (CIP) at a high pressure of 300 MPa and sintered at a high temperature of 1700 oC. The sintered advance ceramics pellets was combined with polyurethane rubber by the casting process. The high-hardness steel plate was installed with composite add-on armor that was designed as a backing plate by double-layered 6.0 mm thick which Bisalloy HHA500 was chosen.

The numerical simulation results showed the kinetic energy of the projectile, velocity of the projectile, kinetic energy absorption. The results showed that the initial velocity of the projectile decreased when impacted the composite add-on armor. The kinetic energy absorption versus time of composite add-on armor and backing plate were numerically explained by using explicit finite elements also. Both numerical simulation and experiment results was indicates a good agreement and the results are close to other experiments in the literature. The agreement between finite element analysis and experimental results is a crucial aspect of validation in engineering and scientific research. It enables engineers and researchers to rely on numerical simulations as cost-effective and efficient tools for analyzing and optimizing design, without solely relying on physical testing.

Index Terms – Ballistic Simulation, Composite add-on Armor, Advance Alumina-zirconia Ceramic, Bisalloy HHA500

INTRODUCTION
Composite add-on armor is commonly used in military vehicles to enhance their protection against various threats encountered in combat situations. Military vehicles, such as tanks, armored personnel carriers, and tactical vehicles, often require additional shielding to withstand ballistic projectiles, shrapnel, and explosive devices. The purpose of composite add-on armor is to provide an extra layer of defense to the vehicle's existing structure, reinforcing its ability to withstand attacks [1]. This supplemental armor is typically designed to be modular, allowing it to be added or removed based on mission requirements or threat levels. The materials used in composite add-on armor for military vehicles are selected for their ability to withstand and defeat specific threats. Common materials utilized in composite add-on armor include ceramics, absorber materials, high-hardness steel, and fiber-reinforced materials [2]. These materials are combined to create a multifunctional armor system, leveraging the unique properties of each component to achieve optimal performance. However, these materials offer different levels of protection against ballistic which choice of materials depends on factors such as weight constraints, desired level of protection, and cost considerations [3].

The principles governing the functionality of composite add-on armor systems for ballistic protection can be broadly classified into two categories: (1) absorption of impact energy and (2) redistribution of impact energy. An effective composite armor system must possess the capability to efficiently absorb and redistribute the energy generated upon projectile impact, preventing its complete penetration through the ceramic layer and into the backing plate [4]. Additionally, numerical simulations have been employed to analyze the intricacies of the penetration process and to quantitatively assess changes in projectile energy. These simulations have proven to be highly valuable tools for examining the influence of material composition and structural design on ballistic performance. By utilizing such simulations, researchers can gain insights into the effects of various materials and architectural factors on the overall effectiveness of the armor system [5-7].

This study focused on investigating the ballistic performance of a composite add-on armor with a double-layered high-hardness steel configuration. The composite add-on armor was designed based on the composition of advance alumina-zirconia ceramic pellets were then combined with polyurethane rubber using the casting process. The double-layered high-hardness steel plate, specifically 6.0 mm thick and utilizing Bisalloy HHA500, was selected and integrated as the backing plate. The armor system was subjected to impacts from a 14.5 mm armor-piercing projectile traveling at a velocity of 900 m/s. The investigation encompassed both experimental and numerical analyses to comprehensively assess the armor's response to the ballistic threat. By numerical simulations data such as the velocity of the projectile, kinetic energy of the projectile, and kinetic energy absorption of composite add-on armor and the backing plate with experimental results, a thorough understanding of the armor system's performance under these specific conditions was obtained.

MATERIALS AND METHODS

2.1. Advanced ceramics preparation

In this present study, Zirconia Toughened Alumina (ZTA) was utilized. The ZTA powder materials obtained from the powder mixed process were prepared through a series of steps, which included mixing, baking, crunching, and sieving. Afterward, they were subjected to compression molding at a pressure of 25 MPa, resulting in the formation of a "Green compact" product. Subsequently, the "Green compact" was subjected to an additional compression process known as cold-isostatic pressing, applying a pressure of 300 MPa. This further compression step enhances the density and integrity of the green compact. Finally, the advanced ceramic material went through sintering at a high temperature of 1700°C for a soaking time of 3 hours is shown in Figure 1.

Table 1. The physical and mechanical properties of advance ceramic.

Properties	Value
Density (kg/m^3)	3945
Hardness (GPa)	19.03
Flexural Strength (MPa)	204.20
Young's Modulus (GPa)	7.04

This sintering process facilitates the consolidation and densification of the material, resulting in a dense of high-performance ceramic component for using in the composite add-on armor. The measured mechanical properties of the advance ceramic are given in Table 1. The XRD data on high purity alumina showed only peaks corresponding to single phase α-alumina, and for ZTA specimen peaks corresponding to α-alumina, and tetragonal zirconia phases were found along with little amount of monoclinic zirconia (Figure 2). The microstructure of ZTA specimen was observed by a scanning electron microscope (SEM) is given in Figure 3. The microstructure reveals distinct phases of alumina and zirconia, with the grey region representing alumina and the white region representing zirconia.

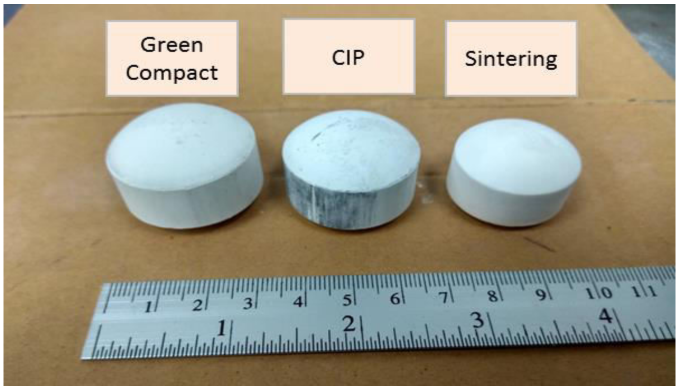

Figure 1. The advanced ceramic material has successfully completed each stage of the process.

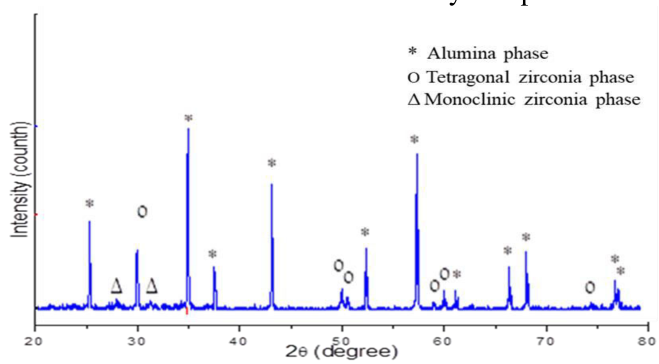

Figure 2. The XRD pattern of the sintered advanced ceramic material used in this study.

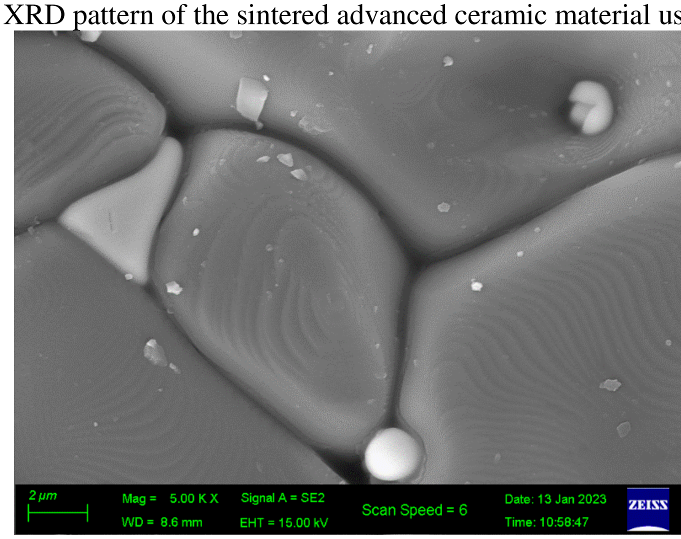

Figure 3. SEM photo of microstructure of the sintered advanced ceramics material

2.2. Composite add-on armor preparation

The composite add-on armor investigated in this study consists of advanced ceramics assembled using multiple ceramic pellets. Each pellet average size of 26.2 mm in diameter and 20.0 mm in height. These ceramic pellets are arranged in a hexagonal close-packed pattern, interconnected with polyurethane rubber using a resin casting process at curing temperature of 180 ^{o}C. The finished sample of composite add-on armor with the size 500 x 500 x 25 mm. was shown in Figure 4 which was used for ballistic tests. The measured mechanical properties of the polyurethane rubber are given in Table 2.

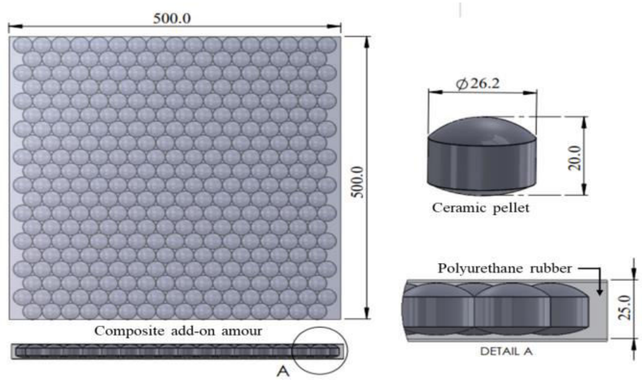

Figure 4. The schematic diagram of the designed composite add-on armor.

Table 2. The physical and mechanical properties of polyurethane rubber.

Properties	Value
Density (kg/m^3)	1093
Hardness (Shore A)	81
Tensile strength (MPa)	20.79
Flexural strength (MPa)	3.09

2.3. Ballistic test methodology

Ballistic tests were performed on the targets composed of composite add-on armor with along double-layered of high hardness steel. Bisalloy HHA500 of 6.0 mm thick of 2 layers that high hardness steel was used as reference backing material in all these ballistic experiments. Typical mechanical properties of the backing material are given in Table 3. The chemical composition of the Bisalloy HHA500 contains C (0.32), P (0.025), Mn (0.80), Si (0.50), S (0.005), Ni (0.50), Cr (1.20), Mo (0.30) and B (0.002). The composite add-on armor and backing plate were firmly clamped to the testing frame was shown in Figure 5.

Table 3. The mechanical properties of Bisalloy HHA500

Properties	Value
Hardness (HBW)	500
Yield strength (MPa)	1300
Tensile strength (MPa)	1640
Elongation (%)	10

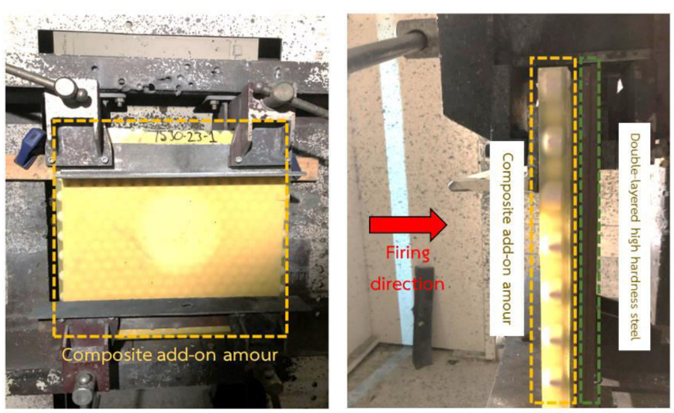

Figure 5. The composite add-on armor, along with a double-layered high hardness steel, was placed on the target for a ballistic experimental test.

The ballistic tests were carried out by using a 14.5x114 mm API/B32 type projectile in a ballistic laboratory of Ballistic & Mechanical Testing Ltd. (BMT), Australia. Prior to each firing test, the firing equipment was meticulously aligned to ensure accuracy and consistency. The velocity measuring equipment was employed to measure the impact velocity of the projectile during each test. The schematic diagram of the ballistic testing setup as shown in Figure 6. The standard velocities of the projectiles were recorded at an average of 911±20 m/s. The firing range for the tests was set at a distance of 25 m. A witness plate made of 0.5 mm thick aluminum grade 2024 T3 was utilized. Following the ballistic testing, a thorough investigation of composite armor failure was conducted through visual inspection, enabling the assessment of any visible signs of damage or penetration.

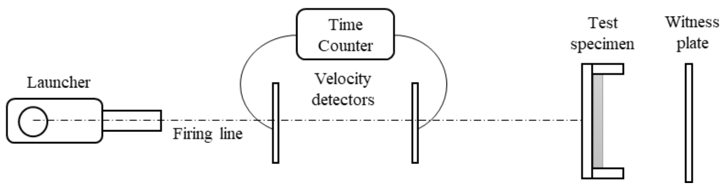

Figure 6. The schematic diagram of the ballistic testing setup shows the arrangement of the target specimen placed downrange from the launcher.

2.4. Numerical simulations

The penetration process was analyzed and the ballistic behavior and distribution of kinetic energy were investigated using numerical simulations conducted in ANSYS/Explicit. These simulations focused on examining the impact of both the composite add-on armor and the backing plate on the ballistic performance. By utilizing ANSYS/Explicit, the study aimed to gain insights into the interaction between the projectile and the composite armor system, as well as evaluate the effectiveness of both the composite add-on armor and backing plate in mitigating penetration and dissipating kinetic energy. For the analysis using numerical simulations, the dimensions of the composite add-on armor and double-layered backing plates were set at 120 mm x 120 mm x 25 mm and 150 mm x 150 mm x 6.0 mm, respectively. These specific dimensions were selected to ensure an appropriate representation of the armor system and facilitate accurate simulation of the ballistic behavior and energy distribution. The finite element model was shown in Figure 7.

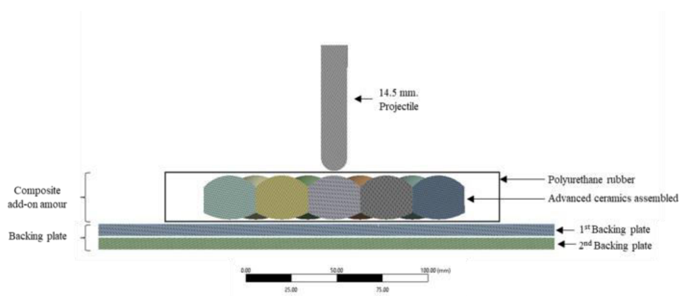

Figure 7. The finite element model of the ballistic simulation.

The projectile configuration for the numerical simulations is illustrated in Figure 3. The projectile configuration assumed for the numerical simulations consists of a length of 52 mm and a diameter of 14.5 mm. The mass of the projectile is calculated to be 64 g throughout the numerical analysis, an incident velocity of 900 m/s was applied as the projectile velocity setting.

The Johnson-Holmquist-2 model was as the constitutive model which comprises of three parts – strength, pressure and damage. The intact and fractured ceramic material strengths were evaluated as nonlinear functions of normalized pressure (P), tensile strength (T) and the normalized total incremental strain rate [6] as in equation (1) and (2):

$$\sigma_i = (P^* + T^*)^N (1 + C \ln \dot{\varepsilon}^*) \quad (1)$$

$$\sigma_f = \sigma_{HEL} B (P^*)^M (1 + C \ln \dot{\varepsilon}^*) \quad (2)$$

Where i and f are intact and fractured ceramic strengths.

σHEL is an equivalent stress at the Hugoniot elastic limit and A, B, C are the Johnson–Holmquist parameters. The initial hydrostatic pressure P is formed from the polynomial equation of state as in equation (3):

$$P = K_1 + K_2 u^2 + K_3 u^3 \quad (3)$$

The Johnson-Cook damage model for projectile and backing plate material were also used. In this model, the equivalent stress is expressed as equation (4):

$$\sigma_{eq} = (A + B\varepsilon_{eq}^{n})\left(1 + \varepsilon_{eq}^{\dot{n}}\right)^{c}(1 - T^{*m}) \quad (4)$$

Where σ_{eq} is the equivalent stress, ε_{eq} is the equivalent plastic strain A, B, n, C and m are the material constants and $\varepsilon^{\dot{}}*_{eq} = \dot{\varepsilon}_{eq} / \dot{\varepsilon}_0$ is the dimensionless strain rate where it is a ratio of the strain rate and a user-defined strain rate. T^{*m} is the homologous temperature and is given by (5)

$$T^{*m} = (T - T_r)(T_m - T_r) \quad (5)$$

Where T_r and T_m represent the room temperature and the melting temperature, respectively.

RESULTS AND DISCUSSION

3.1. Finite element analysis results

The simulation evolutions of ballistic testing, the behavior of the projectile and composite armor system during impact can vary depending on various factors such as the projectile's characteristics, the properties of the ceramic material, and the design of the armor system. Generally, when the projectile strikes the ceramic layer, it experiences a sudden deceleration due to the resistance offered by the ceramic material. The initial impact can results in a transfer of the momentum and kinetic energy from the projectile to ceramic layer. After that, the projectile may undergo deformation upon impact. The interaction with the ceramic layer can cause the projectile to deform, flatten, or fragment, depending on its design and velocity of projectile [8-10]. However, if the ceramic layer fails to stop the projectile, it may penetrate though the ceramic layer and continue into subsequent layers of the armor system.

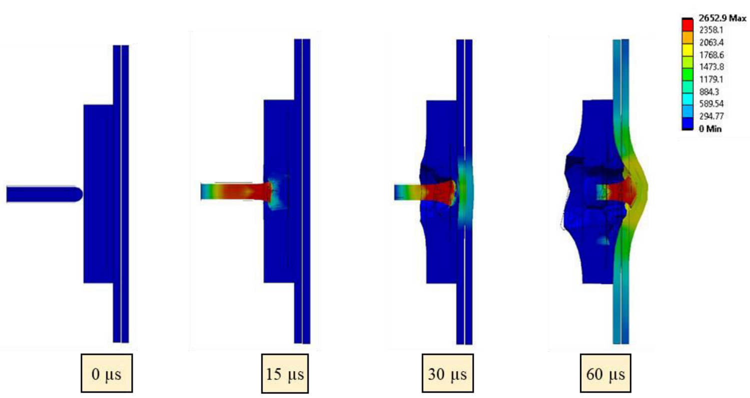

Figure 8. The penetration process during the impact of the composite add-on armor, along with a double-layered high hardness steel, is examined in numerical simulation.

In this case study, the finite element of 14.5 mm armor piercing projectile impact on composite add-on armor with a double-layered of high hardness steel. The results shown penetration process during impacted as Figure 8. When the projectile makes contact with the ceramic layer, the high stress was occurred in area of ceramic. The projectile continues to penetrate the ceramic layer, it creates a localized region of plastic deformation on the surface. This deformation occurs due to the immense pressure exerted by the projectile on the ceramic material. During this process, the kinetic energy of projectile is transferred to the ceramic layer. Ceramic layer will absorbed thorough kinetic energy and high pressure lead to ceramic cracks and fracture propagation. Typically, ceramic fragments helps to disperse and dissipate the energy, reducing the penetration capability of the projectile [11]. After that, the remaining kinetic energy of projectile though ceramic layer was absorbed by a double-layered of high hardness steel. The high hardness steel plate was damage lead to bends slightly along with projectile fully stop.

The variation of the projectile residual velocity and kinetic energy versus time graph was shown in Figure 9. It is indicated to the termination time about 80 us that enough time to complete the projectile to succeed to a full stop and also short enough to prevent dispensable solution times. During the initial stage, the projectile impacts a composite add-on armor consisting of polyurethane rubber, resulting in a slight reduction in its velocity. Moving into the second stage, the projectile strikes the advanced ceramic layer, causing the projectile head to deform and mushroom. This deformation dissipates most of the kinetic energy and resists further penetration. Consequently, the projectile's velocity rapidly decreases from its initial velocity of 900 m/s to 220 m/s. Finally, in the last stage, the banking plate absorbs the remaining kinetic energy from the projectile, resulting in the projectile's velocity dropping to 0 m/s.

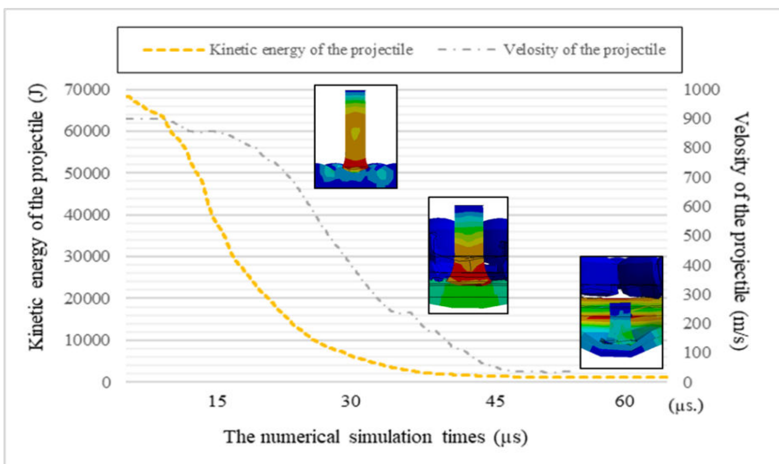

Figure 9. The relationship between the kinetic energy and velocity of the projectile over time in numerical simulation.

The efficiency of an armor system in terms of kinetic energy refers to its ability to effectively absorb and dissipate the kinetic energy of incoming projectiles, thereby minimizing the damage inflicted on the protected target [12, 13]. A high efficiency armor system maximizes the energy absorption capacity while minimizing the energy transferred to the target. The variation of the kinetic energy absorption of composite add-on armor and kinetic energy absorption of backing plate versus time graph was shown in Figure 10. The composite add-on armor is capable of absorbing energy, as indicated by a peak value of 6115 J reached at 13 microseconds when the projectile impacts it. Following this, the residual kinetic energy of the projectile is progressively absorbed by the backing plate. The first backing plate absorbs up to 4017 J of kinetic energy by 25 microseconds, while the second backing plate absorbs up to 2000 J of kinetic energy by 25 microseconds. As time progresses, the remaining kinetic energy of the projectile continues to decrease as it is absorbed. This process continues until all the kinetic energy is fully absorbed, reaching a value of 0 J.

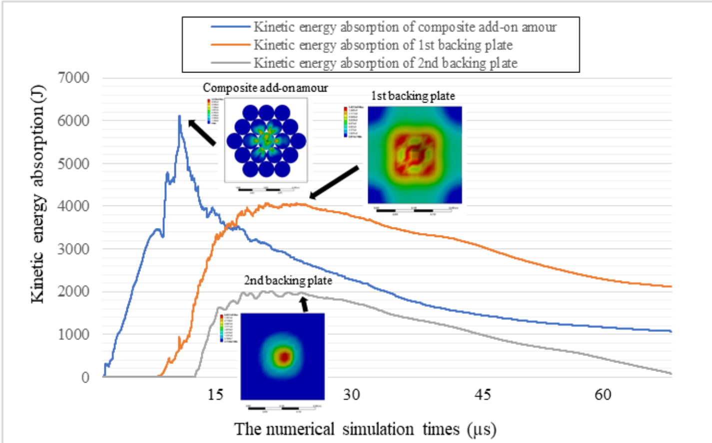

Figure 10. The relationship between the kinetic energy absorption of composite add-on armor, 1st backingplate and 2nd backing plate in numerical simulation.

Base on finite element results shown when the projectile strikes the composite add-on armor, it undergoes deformation and undergoes a reduction in kinetic energy. The layers of the armor system, including the composite add-on material and the high hardness steel backing plate, work together to absorb and dissipate the projectile's kinetic energy. The high hardness steel backing plate as Bisplate500 known for its exceptional strength and toughness. Using double layer of backing plate further enhances the energy absorption capacity. It resists penetration by deforming plastically, which dissipates the remaining kinetic energy of the projectile.

3.2 Ballistic experimental results

In this study, a total of 4 shots were fired in the ballistic experimental test at a 0-degree impact angle. The velocity of the projectile was measured at 2 points, and the average results are presented in Table 4. The witness plate remained in perfect condition after the ballistic experimental test. The composite add-on armor and backing plate, after being impacted by a 14.5 mm armor-piercing projectile, were shown in Figure 11. The figure includes images illustrating the front of the composite add-on armor, the first backing plate, and the second backing plate. Upon examining the composite add-on armor, it can be observed that the ceramic layer has suffered breakage, resulting in the formation of small fragmented pieces. The first backing plate exhibits indications of both ceramic and projectile fragments, indicating their interaction during the impact. Furthermore, the second backing plate displays a slight sunken mark where the shot was fired. Overall, the experimental results demonstrate the effectiveness of the composite add-on armor with double-layered high hardness steel in effectively defending against the 14.5 mm projectile.

Table 4. The velocity of the projectile and the penetration of the witness plate in the ballistic experimental test.

Shot No.	Impact angle	Velocity Chrono 1 (m/s)	Velocity Chrono 2 (m/s)	Velocity average (m/s)	Witness plate penetration
1	0^o	905.6	905.6	905.6	No
2	0^o	894.0	894.0	894.0	No
3	0^o	900.0	900.4	900.2	No
4	0^o	901.0	901.4	901.2	No

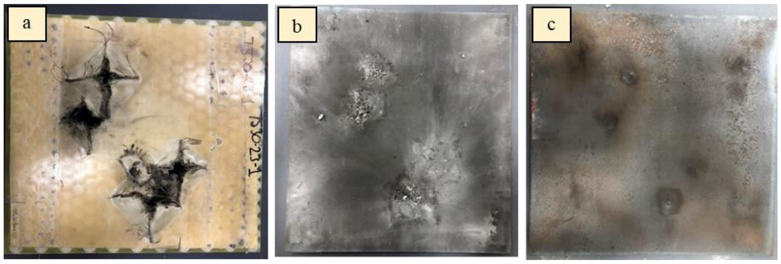

Figure 11. Digital images of the front of (a) Composite add-on armor, (b) 1st backing plate and (c) 2nd backing plate.

CONCLUSIONS

Computational analysis and simulations are crucial for optimizing the design and performance of the armor system. We chose composite add-on armor along with a double-layered of high hardness steel which Bisplate500 as backing plate. The configuration demonstrated a high level of ballistic performance. It defeated 14.5x114 mm armor piercing projectile. Prediction of impact behavior through numerical simulation has been done and experimentally validated. Finite element methods used in computational analysis can demonstrate the behavior of projectiles and armor systems, aiding in material selection and enhancing efficiency in terms of kinetic energy absorption. The analysis of the kinetic energy occurring during ballistic testing with the composite add-on armor and high hardness steel backing plate provides valuable insights into the performance and protective capabilities of the armor system. By understanding the energy transfer and absorption mechanisms, its can optimize the design and materials used in armor systems to enhance their ability to withstand high-velocity impacts and protect against armor-piercing threats. Using composite add-on armor along with double layer of backing plate that incorporating a high hardness steel backing plate in the armor system can improve efficiency by providing additional resistance and energy absorption. The backing plate can deform plastically, effectively reducing the kinetic energy transferred to the target.

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