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Araştırma Makalesi / Research Article

Experimental Investigation of Ballistic Performance of Free Particle Armor Systems

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ABSTRACT: Recent armor studies generally rely on improving the single-shot capabilities of ceramic armors. In multi-shot studies, ballistics tests assume that there is a certain distribution, so these successive shots were not made from exact same point. With these shots, thus, the armor completely loses its effectiveness. In this study, the ballistic performance of damaged and undamaged free particle armor system in multiple hits from exact same and different points was experimentally investigated. The new armor system, consisting Al2O3 free ceramic balls, tested with 9 mm FMJ and 7.62 mm API ammunition. This armor system prevented perforation in multi-hits from the same point, and the depth of depression in ballistic clay was 9.42 mm and bullet deviation in trajectory was 27 mm. In the shots with dispersion, depression depth was limited to 3.52 mm and deviation increased with each shot. As a result, it has been found that the free particle armor system performs more ballistic efficiency than conventional armors even in the most challenging conditions. The ceramic balls, being more irregularly and densely spaced with each shot, increase the likelihood of the bullet hitting at larger angles and increase ricochet in direct proportion.

Keywords: Ceramic Armor, Al_2O_3, Free Spherical Particles, Terminal Ballistic, Multi-hits, Aramids, Ballistic Clay

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1. INTRODUCTION

The requirement for lighter armor materials for the purpose of using in military applications has given increasing value to the use of ceramic armor materials. Ceramic armors have greatly progressed over the decades as the mechanical properties have been optimized along with advancing technology (Crouch, 2016; Hazell, 2015). The seeking for enhancing the ballistic performance/areal density ratio and the need for protective and containment materials that can provide maximum ballistic resistance have led to the development of different armor combinations using ceramics (Bracamonte et al., 2016a). Ceramic armors, having high hardness and compressive strength together with the lightness advantage brought by their low density, have been developed for a high level of bullet resistance. Ceramics offer a great advantage over steel in weight reduction and over all metals in absorbing the impact energy. Therefore, they are considered as one of the most important materials for light armor applications with their high compressive strength, high hardness value and low densities (Gadow and Kern, 2014; Yang and Qiao, 2010).

Of primary importance are ceramic types such as Al_2O_3, B_4C, SiC and ceramic matrix composites (CMC) which are the most preferred and used in ballistic armor applications (Carter and Norton, 2007; Karandikar et al., 2009). Al_2O_3 has the best cost effectiveness among high-performance ceramics due to its easier manufacturing, lower cost, high elastic modulus, high refractoriness and high hardness compared to boron carbide and silicon carbide, which are highly covalent ceramics with high melting temperature (Biçer, 2022). However, Al_2O_3 has lower fracture toughness and flexural strength compared to SiC and B_4C in ballistic performance (Tressler, 2002). In addition, the ballistic performance of the ceramic materials can be improved by adding ceramic fiber to obtain CMCs or by adding tetragonal zirconia particles (Heimann, 2010; Orange et al., 1986).

Swab et al. compared ceramic armor designs with metal-based armor resistant to the same type of ammunition and showed that bullet mass can be significantly reduced using ceramic (Swab et al., 2005). Klement et al. have found that B_4C, Al_2O_3, Si_3N_4, SiC, TiB_2, Si and SiC (SiC – Si) etc. are prominent in ceramics for armor application. (Klement et al., 2008). Dresch et al., on the other hand, compared Al_2O_3, SiC and B_4C in terms of ballistic performance in their research. They reported that Al_2O_3 and B_4C gave similar results in performance against 7.62 mm caliber AP rounds. There is also an relationship between hardness and fracture toughness; They found that hardness causes the bullet to wear and break, while fracture toughness helps the ceramic withstand multiple impacts (Dresch et al., 2021). Both hardness and fracture are important in light armor applications. However, deciding which to improve and maintaining the balance between the two has always been a problem for designers of ceramic armor (Goh et al., 2017). Composite armor systems, which have different armor complications by showing different properties according to different reinforcement materials, are divided into three main groups as metallic reinforced, ceramic reinforced and fiber reinforced according to the type of reinforcement element used (Chi et al., 2013; Zaera and Sánchez-Gálvez, 1998). Fiber-reinforced polymer composites have been found to further reduce the weight of body armor and facilitate personnel movement compared to metallic materials (Guo et al., 2020). Materials with high strength, component integrity and high modulus of elasticity, such as Kevlar, have become a natural candidate for reinforcement material due to their lightweight structure, and have found widespread use in the development of "Soft Armor" armor systems (Cheng et al., 2004; Guo et al., 2021).

The ballistic performance of an armor system is determined by several parameters such as material properties, sample sizes, projectile geometry, projectile velocities and boundary conditions (Grujicic et al., 2012). It is often difficult to optimize these factors simultaneously. Most studies have generally relied on improving single-shot capabilities of ceramic armors rather than multi-hit performance. (Bhat et al., 2021; Wadley et al., 2013; Yungwirth et al., 2011). When an armor system is hit by a projectile, it easily breaks and fragments beyond the impact area, significantly reducing its multi-hit capability (Guo et al., 2020). One of the most important ways to increase multi-hit ability on is to be able to limit damage within a specific area. Hence, ceramics began to be used as tiles instead of a monoblock design (Medvedovski, 2010a). Nevertheless, in order to further increase the multi-hit performance, Medvedovski conducted tests using Al_2O_3 spherical ceramic particles on the front and inside of the armor and compared the results with a normal Al_2O_3 plate. As a result of this study, he showed that the ceramic spheres, which are stationary in the system, can provide protection against multiple hits (Medvedovski, 2010b). In the study by Zahraee and Sabet in which they compared traditional ceramic armor plate and hybrid armor that ceramic particles were embedded in a polymer matrix, it was reported that while there was no significant difference in ballistic limiting velocities for the two types of ceramic targets at impact, the results were at the same ballistic level for both. On the second impact, plates with ceramic particles showed a significant ballistic performance in terms of higher energy absorption, and it was reported that the armor could be easily repaired thanks to the ability of ceramic embedded plates to be replaced later (Zahraee ve Sabet, 2014). As a result of these developments, the "Free Particle Modular Armor", which is believed to show high performance on multi-hits (IŞIK, 2021). It was inspired by the sandbag and transformed into a more complex ballistic structure by placing free ceramic balls inside it, has been the research subject of this study.

Ballistic testing assumes that there is a certain dispersion in successive shots, so shots do not come from the exact same point. With these shots, the armor largely loses its effectiveness. In this study, an attempt was made to uncover the effect of repeated shots fired from the exact same point, which is rare in the literature, on the ballistic performance of the free particle armor system and its behavior on multiple hits with a specific dispersion. Within this framework, the armor system designed with Al_2O_3 free ceramic balls was tested according to the NIJ-0101.04 Level 2 (9 mm FMJ) and STANAG 4569 Level II (7.62 x 39 mm API BZ) standards, as well as with real-time shots. As a result of the tests, an attempt was made to explain the performance of the armor system with free spherical particles with repeated shots at the same and various points, how it minimizes the energy of the projectile, and the condition of the armor materials after the shots using SEM and optical microscope images.

2. MATERIALS AND METHODS

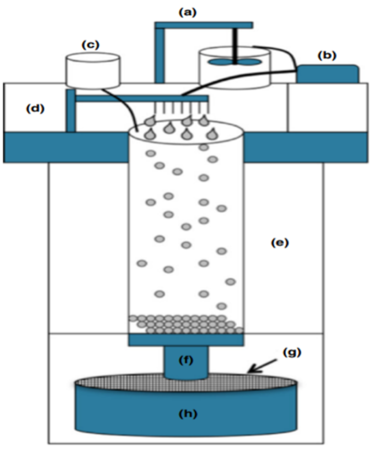
In the study, shots were fired with 9 mm FMJ rounds to investigate the effects of armor system design factors on ballistic performance, based on the NIJ-0101.04 standard II. protection level. In addition, the performance evaluation was carried out on multi-hit capability based on the penetration depths formed on the ballistic clay at the rear of the armor system. In the experimental setup, a marking was made with the help of the laser, the entry position of the projectiles from the front plate and the exit from the back plate were observed during firing, and the extent of the deflection in bullet trajectory was measured. Al_2O_3 ceramic balls with diameter of 10 mm were used in the armor system. First shots were fired at a thickness of 90 mm, the thickness was reduced until data was obtained on the rear surface of the armor configuration. Having obtained the data at a thickness of 40 mm, the experiments were carried out at this thickness. Using the data recorded on the ballistic clay, the energy absorption and the amount of deflection of the shots fired from the exact same point were studied.

Though, the system's reactions to shots arriving at different points of the same armor system were examined. In addition, additional tests were conducted using ceramic balls with diameter of 6 mm to check if larger diameter bullets that would hit the system were used to check, if there was ball flow from armor through the system would come the deformation of the front cover.

Moreover, the new concept of armor, developed using the example of layered armor systems, was studied and with the increase in the level of protection, the armor-piercing bullet 7.62 mm x39 API BZ according to STANAG 4569 Level II was used in the tests. Shots were fired from 30 m at a speed of 695 m/s and conclusions were drawn about its ballistic performance.

2.1. Alumina Ceramic Balls

The desire to produce ceramic balls with equivalent and homogeneous properties in ceramic products requires the use of more complex systems. One of the techniques currently used is the production of spherical ceramic beads of reproducible size and homogeneous properties using ceramic spherical bead forming equipment (Buaki-Sogo et al., 2013). As shown in Figure 1, the system includes a slurry mixer, slurry transport pump, intravenous tubing for ethanol, multi-nozzle system, nozzle position controller, 700 mm dripping column, metallic filter net, manual valve and collection container. The upper containers contain ceramic slurry and ethanol, which are two liquids.



a	Slurry Mixer
b	Slurry Transport Pump
c	Intravenous Tubing for Ethanol
d	Nozzle And Nozzle Position Controller
e	Drip Column
f	Manual Valve
g	Metallic Filter Mesh
h	Collection Cup

Figure 1. Diagram of Ceramic Spherical Bead Forming Equipment (Santos et al., 2013).

In this study, 99% pure Al_2O_3 ceramic balls manufactured by this method and supplied by "Civelek Porcelain" were used. Figure 2 shows the appearance and mechanical values of Al_2O_3 ceramic balls are given.

%99 Al_2O_3 Balls - Hardness (Rockwell 45N): 82 Density (kg/m3): 3,72		
Size (radius) (mm)	**Crush Strength (kg) (min.)**	**Surface Area (m^2/m^3)**
6	105	420
10	200	390

Figure 2. Mechanical Properties of %99 Al_2O_3 Balls

The ceramic balls used in the test procedure are 6 mm and 10 mm in diameter. The reason for choosing the diameters in this way is that the aim of the tests is to use larger and smaller diameter bullets than the 9mm and 7.62mm bullets. Therefore, it is planned to check whether smaller-diameter bullets flow out of the large-diameter bullet holes formed in the case of deformation in the front plates.

2.2. Armor System Configurations

The armor system, whose frame is formed by welding 20 x 20 mm square steel profiles, has a height of 200 mm, a width of 200 mm and a depth of 90 mm. A review of the literature and examination of the STANAG 4569 Level II one-piece ceramic armor currently on the market shows that their thickness varies between 40 and 50 mm. However, these models are manufactured as a whole. Since the armor model used in this study consists of free spherical particles, its density decreases. In order to be able to draw clearer conclusions when comparing the two armor models, the thickness of the armor model in question was calculated to be the same in density, using the ceramic density per m^3, and the armor thickness was adjusted to 90 mm for the first experiment. An image of the armor system design filled with ceramic bullets is shown in Figure 3.

Figure 3. Armor System Configuration

For the front and back covers of the armor design, Plexiglass® (Acrylic) sheet is used, since it does not require any specific properties except ductility, it is easy to find in the market, it is light and easy to process, and it allows observing the inside of the armor. Polymethyl methacrylate (PMMA), also known by the trade names and brands of Crylux, Plexiglass, Acrylic, Astariglas, Lucite, Perclax and Perspex, is a transparent thermoplastic developed as an alternative to glass with its lightweight and shatter resistant structure, and is generally in sheet form used (Gent, 2009).

Table 1. Mechanical Properties of Acrylic

Parameters	Value
Density (g/cm^3)	1.19
Hardness (Rockwell)	94-105
Tensile Strength (MPa)	75
Compressive Strength (MPa)	110-124

In the study, acrylic sheets were attached using screws through the holes drilled in the steel frame. The mechanical properties of acrylic material are listed in Table 1.

2.3. Experimental Setup

Due to the limited sharing of test setup images performed in CES Advanced Composites and Defense Technologies INC's ballistics laboratory, in accordance with the company's confidentiality policy, Figure 4 uses equivalent test setup images. The devices and setups in these images match the experimental setups in the laboratory where the experiments were carried out exactly.

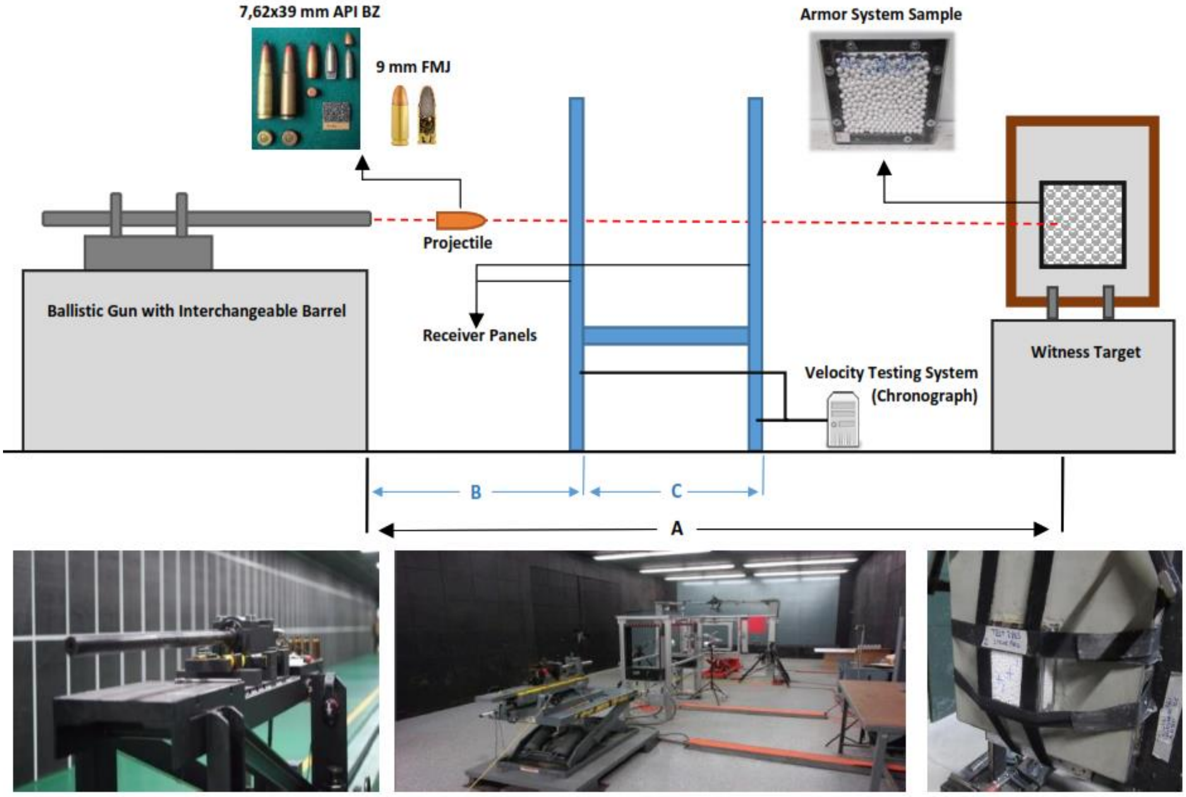


Figure 4. Schematic Illustration of Ballistic Experimental Setup

Different types of bullets are loaded in the fixed barrel shown in Figure 4, and the barrel and bullets are interchanged to achieve different muzzle velocities. In addition, the barrel-to-target distance can be adjusted according to different ballistic testing standards. Bullet velocity is measured between the panels to ensure full calibration during firing. The length A, the distance between the sample and the barrel, is fixed at 5 m for armor levels I, II, II-A and III-A. For level III and IV armors, it is increased to 15 m. The length B, the distance between the barrel and the first receiver, must be fixes at a minimum length of 2 m for armor levels I, II, II-A and III-A, and at least 12 m for armors levels III and IV. Length C, is the distance between the receivers, is adjusted between 0.5 m and 1.5 m.

The speed of the bullet passing the first and last receiver panels is measured by chronographs with each shot. This velocity measurement is made by dividing the distance between the panels by the time between the wave produced by the bullet on the oscilloscope when passing through the first receiving panel and the wave formed when passing through the last receiving panel. If the bullet velocity is not at the desired level, the shot is considered invalid. The distance between the receivers varies depending on different levels. Besides, the receiver panels must be covered with a protective layer due to fragments that will break from the armor and bullet. As can be seen in Figure 4, the sample, which is small in size and difficult to fix, was buried in ballistic clay by opening a pit with armor dimensions and a depth of 50 mm. In addition, the armor system has been tightened in such a way that it remains completely stable during the shootings, by connecting with the Velcro straps used as standard in the experiments. The same procedure was repeated for each sample. The distance between the barrel and the target was fixed at 5 m, the distance between the first receiver and the barrel to 2 m, and the distance between the receiver panels to 1 m, in accordance with the NIJ 0101.04 level II standard, and the system was made ready for testing.

2.4. Ballistic Clay

During the testing phase, ballistic clay was used to determine the damage to the armor backplate caused by the bullets. In order for the ballistic clay, which is “Sculpture House-Roma Plastilina No:1” and has a gray color, to be ready for use, it must be kept at a temperature of 29 ^{o}C and above for at least 3 hours. Figure 5 provides a visual of the ballistic clay preparation process.

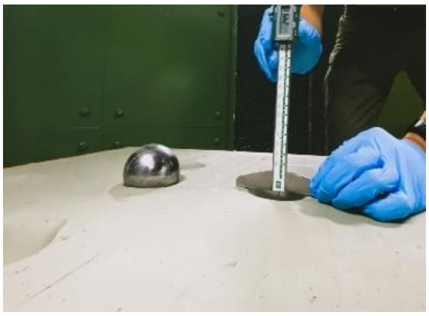


Figure 5. Free Fall Test with Steel Shots and Measurement of Pit Depths

To measure that the ballistic clay is ready for the testing process and can provide stable values, steel balls weighing 1043 ±5 grams and having a diameter of 63.5 ±0.05 mm are dropped onto the clay by free fall (Bozdoğan et al., 2015). From the holes of the 2 m high and previously prepared upper platform, 5 steel balls are dropped onto the clay in free fall and then the arithmetic mean of the depths of the formed pits is determined. If the arithmetic mean is 20 ±3 mm, it is understood that the ballistic clay is ready for the test. Additively, according to the NIJ-0101.04 standard, the net criterion of the level of ballistic protection is that the depth of deformation formed on the clay, taking the human body as an example, and is positioned behind the armor, should be less than 44 mm.

2.5. A Change of Concept Against Armor Piercing Bullet

A layered armor design has been developed to recognize the ballistic protective properties of free-particle ceramic balls against superior ammunition and to minimize the fragmentation and scattering that occurs with explosive ammunition working with the shaped charge principle. Accordingly, the armor system was divided into two parts with aramid fabric and filled with 10 mm Al_2O_3 balls on one side and 6 mm Al_2O_3 ceramic balls on the other. The new concept is schematized in Figure 6.

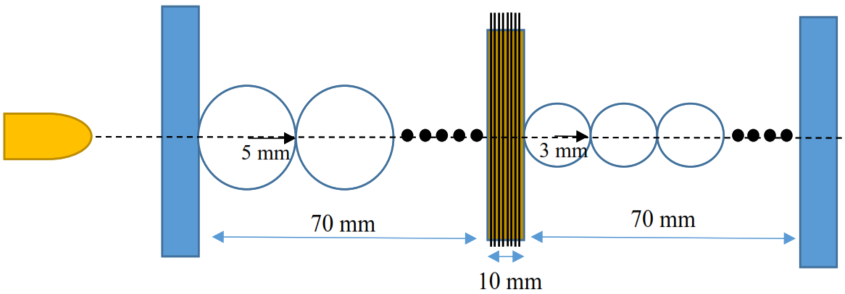


Figure 6. Schematic Illustration of the New Armor Concept

The first part of the armor system encountering the bullet was filled with 10 mm balls and adjusted to 70 mm thickness. A 10 mm thick aramid fiber fabric was then used. The second part of the armor was adjusted to a thickness of 70 mm and filled with 6 mm diameter ceramic balls. Thus, a new armor concept with an inner thickness of 150 mm was obtained. The purpose of this layered armor system is to increase the level of protection by taking the layered sandwich armor as an example and making a difference in concept. Hereby, two free layers are obtained, the interior of which is filled with balls in a dynamic and free state. It is assumed that the projectile, hitting balls with different diameters, will increase the angle of deflection and dwell time in the armor when it reaches the second part. It is also envisaged that bullet will lose its effectiveness as it penetrates the fabric. The thickness of an aramid (Kevlar®) fabric used as an intermediate layer is about 0.34 mm. A total of 30 layers of aramid fabric were used to achieve a thickness of 10 mm. The mechanical properties of aramid fabric are given in Table 2.

Table 2. Mechanical Properties of Aramid Fabric

Features	**Values**
Fiber Type	Aramid
Density	1.4 g/cm^3
Tensile Strength	2926 MPa
Elasticity Module	110 GPa
Thermal Degradation	>450 ºC

Along with the increase in the level of protection, the armor-piercing bullet 7.62 mm API BZ was used during the test in accordance with the STANAG 4569 Level II format. The bullet was fired from 30 m at a speed of 695 m/s.

2.6. Types of Ammunition

The tests used 9 mm FMJ 124-gram bullets conforming to NIJ 0101.04 standard level II and 7.62 mm x 39 API BZ bullets conforming to STANAG 4569 standard level 2. While 9 mm FMJ bullets reach a speed of 358 m/s, 7.62 mm x 39 API BZ bullets reach a speed of 695 m/s. Armor-piercing 7.62mm x 39 API BZ bullets consist of a hardened steel core surrounded by a copper jacket, while 9mm FMJ bullets consist of a soft lead core surrounded by a 70% copper and 30% zinc alloy brass jacket.

2.7. Scanning Electron Microscope (SEM)

A Jeol Neoscpae JCM-6000 brand SEM device located in the Mechanical Engineering Laboratory of the National Defense University was used (Figure 7) in this experiment. Even if Al_2O_3 ceramic spheres show fragmentation, they form a denser structure by filling the voids. In addition, these differently shaped pieces increase the irregularity and increase the probability of the bullet deviating from the trajectory in the armor. The shattered bullets were examined with the relevant device and evaluations were made after fragmentation.

Figure 7. Jeol Neoscpae JCM-6000 SEM Device

The images obtained with the device, as well as the crack propagation and surface images seen on the ceramic balls after the shots, were examined and the images obtained are presented in the following section.

2.8. International Test Standards

NATO AEP-55 STANAG 4569 is a NATO Standardization Agreement covering the levels of protection for occupation in logistics and light armored vehicles standards. Standard covers attacks from kinetic energy, artillery and IED explosions (Craig, 2009). In this study, shots were made based on level 2. Table 3 shows the levels of this standard.

Table 3. STANAG 4569 Test Standards

Level	Ammunition	Velocity	Range
1	5.56mm x 45 M193	937 m/s	30 m
1	5.56mm x 45 NATO SS109	900 m/s	30 m
1	7.62mm x 51 NATO	833 m/s	30 m
2	7.62mm x 39 API BZ	695 m/s	30 m
3	7.62mm x 51 AP	930 m/s	30 m
3	7.62mm x 54R B32 API	854 m/s	30 m
4	14.5mm x 114 API/B32	911 m/s	200 m
5	25mm x 137 APDS-T, PMB 073	1258 m/s	500 m

In this study, 9 mm FMJ bullets were fired according to the NIJ 0101.04 level II standard, which is used to evaluate the performance of armor systems, and the shots are set at 5 m. The scope of the standard is limited to ballistic resistance only and does not address different types of threats, such as knives and cutting tools (Craig, 2009). Additionally, these standards must be considered for the use of ballistic clay. Table 4 shows the levels in this standard.

Table 4. NIJ 0101.04 Test Standards

Level	Ammunition	Required Min. Velocity	Max. Deformation
I	38 Special RN Lead	259 m/s	44 mm
I	22 LRHV Lead	320 m/s	44 mm
II-A	357 Magnum JSP	381 m/s	44 mm
II-A	9 mm FMJ	332 m/s	44 mm
II	357 Magnum JSP	425 m/s	44 mm
II	9 mm FMJ	358 m/s	44 mm
III-A	44 Magnum Lead SWC Gas Checked	426 m/s	44 mm
III-A	9 mm FMJ	426 m/s	44 mm
III	7.62 mm (308 Winchester) FMJ	838 m/s	44 mm
IV	30-06 AP	868 m/s	44 mm

3. RESULTS AND DISCUSSION

3.1. Experiments on the Armor System Using Al_2O_3 Balls with a Diameter of 10 mm

In the first test setup, after determining the ballistic limit value as the thickness of the armor system, the goal was to observe the reactions of the armor system and the change in resistance to multiple shots fired on the same armor system through the depressions formed on the ballistic clay. Because of this, the armor thickness was gradually reduced with each shot until the result was obtained on ballistic clay. 9 mm FMJ bullets were fired at a speed of 358 m/s from a total distance of 5 m, on the armor filled with 10 mm ceramic balls and measuring 200 mm x 200 mm x 90 mm in these tests. The visuals obtained as a result of the test shots are shown in Figure 8.

Experiment	: 1
Armor Thickness	: 90 mm
Radius of Al_2O_3 Balls	: 10 mm
Bullet Type	: 9 mm FMJ
Number of Shots	: 2

Experiment	: 2
Armor Thickness	: 70 mm
Radius of Al_2O_3 Balls	: 10 mm
Bullet Type	: 9 mm FMJ
Number of Shots	: 2

Experiment	: 3
Armor Thickness	: 40 mm
Radius of Al_2O_3 Balls	: 10 mm
Bullet Type	: 9 mm FMJ
Number of Shots	: 4

Figure 8. Experiments on the Armor System Using Al_2O_3 Balls

No damage was observed on the back cover as a result of the shots fired in Experiment 1, which used the 90 mm armor system, and no deformation could be observed on the ballistic clay. Therefore, shots were fired by reducing the thickness of the armor system to 70 mm and 40 mm, respectively, by laying Styrofoam (10 and 20 mm thick) in front of the back cover until a depression formed on the ballistic clay. After each decrease in thickness, the front and back covers, as well as Al_2O_3 balls, were replaced with new ones. After any deformation is observed on ballistic clay, Experiment 3 was launched with an armor thickness of 40 mm.

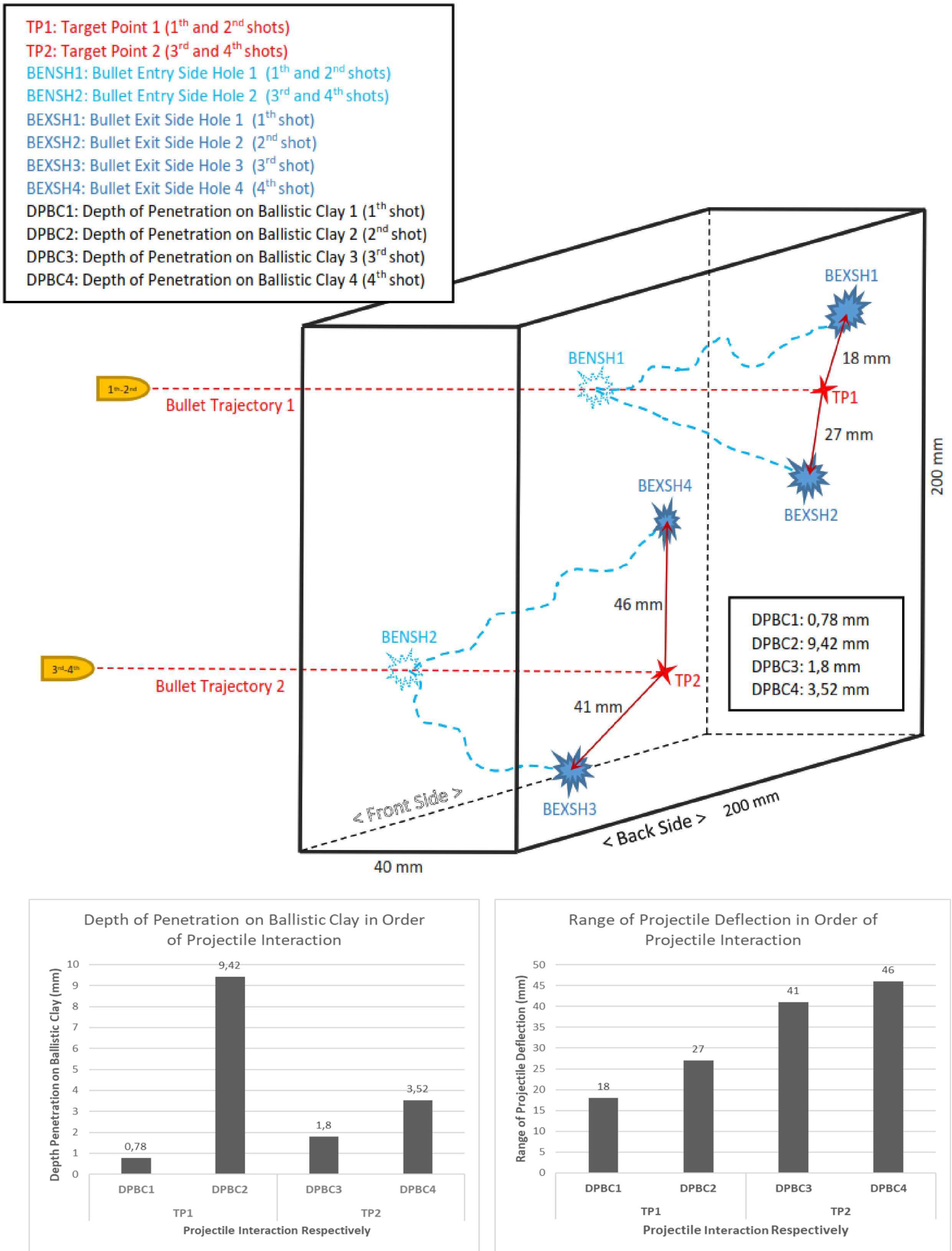


Figure 9. Detail of Experiment 3

In Experiment 3, shown schematically in Figure 9, the back side of the armor was damaged in the 1st shot aimed at the targeted point (TP1), and a small penetration deformation was formed on the ballistic clay. While the bullet entered the armor system from the BENSH1 point and was defeated within the armor system, it was determined that there was a deviation between the TP1 and the damage caused by the bullet on the back side of the armor system (BEXSH1).

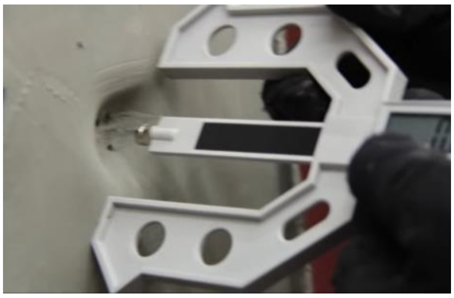


Figure 10. Measuring Depth of Penetration on Ballistic Clay

As a result of the 1st shot, the depth of penetration into the ballistic clay (DPBC1) was measured with a digital depth caliper as seen in Figure 10 and was 0.78 mm. In addition, the deviation between TP1 and BEXSH1 was measured at 18 mm by looking at the red laser pointer, which indicated the projectile motion and the firing point on the armor. After data acquisition on ballistic clay, TP1 was re-targeted, and the 2nd shot was fired. Therewith, while the DPBC2 value was 9.42 mm, the deviation between TP1 and BEXSH2 was found the increase to 27 mm. It is aimed to measure the response of the armor system with these two shots targeted TP1 (multiple shots fired from the same point on the armor system), which do not appear in the literature.

To determine the reaction of the "damaged armor system" in multiple shots from the same point, 3rd and 4th shots were fired at the TP2. The TP2 point is randomly positioned according to international standards, with a distance distribution of 40 mm between it and TP1. Although the depth of penetration was expected to increase as a result of the 3rd shot, it was determined that DPBC3 decreased to 1.8 mm and the amount of deviation between BEXSH3 and TP2 increased to 41 mm. In the 4th shot, where the TP2 was again aimed, the DPBC4 increased slightly to 3.52 mm, while deviation between BEXSH4 and TP2 increased to 46 mm.

Consequently, it is considered that the main reason for the high rate of increase between DPBC1 and DPBC2 is that the balls that first encounter the bullet after firing cannot be filled in exactly the same order by other balls after fragmentation. Because the ceramic balls, which are in a tight order in the first shots, disperse after the interaction and are randomly positioned on the same route with the effect of the deformed particles, reducing the armor density. Thus, it is seen that the depth of depression on the clay increases in shots made from exactly the same point. In the 3rd and 4th shots to the TP2, the depth of penetration DPBC4 increased approximately twice that of DPBC3. It is thought that the reason for obtaining different values from the shots fired at the TP1 is due to the irregular breaks in the balls and the fact that the bullet becomes much more unstable due to the irregular structures formed as a result of spallation.

Previous studies have almost exclusively focused on firing from different points on the armor not exactly the same point. The reason for this is that the bullet distribution seen on the target in a possible conflict is always irregular and the probability of hitting the armor system over exactly the same point is low. In addition, armor systems greatly lose their effectiveness when hit from the same point. In this study, it was observed that from ballistic point of view, the protection of the free particle armor system persists and prevents the formation of the perforation mechanism, even in the conditions where the protection of the free particle armor system is the lowest from exactly the same point. At the same time, it is believed that it can form a scientific basis in the literature by obtaining original test results from multi hits at the same point.

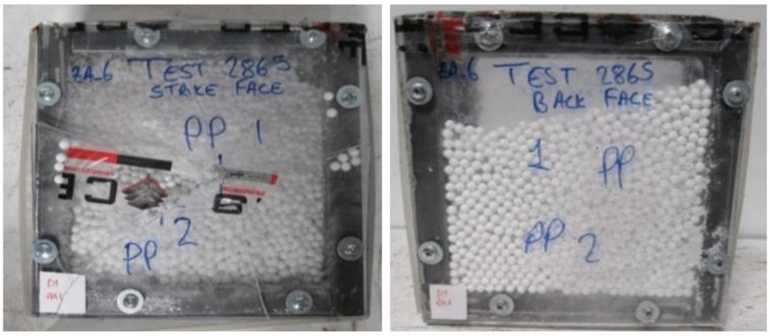
The deviation increases regularly for all shots fired at TP1 and TP2. If one compares the deviation in the 1st and 2nd shots to TP1, an increase of 50% can be observed. There was also a 50% increase between the 2nd shot in TP1 and the 3rd shot in TP2. An increase in the deviation of 12% was determined for the 4th shot. Although armor performance decreased as expected, it was found that this decrease was not as great as in conventional armors and continued to provide protection. The deviation increased with each shot, so the time it took the bullet to penetrate the armor naturally increased. In conventional metal armors, hydrodynamic behavior is observed in the contact area with the ammunition due to the sudden heat and high pressure, and the armor permeability increases. In addition, mechanical properties change in a certain interaction area after contact. Radial crack propagation, conoid fracture and comminution are observed in monoblock ceramic armors; performance on multi-hits drops significantly. In the armor system of this study, while the hardness of the ceramic armors was exploited, the fragmentation situation was turned from a disadvantage to an advantage. By utilizing the spherical geometry of the ceramic, the movement of the bullet in the armor is deflected and aggravated. Even though Al_2O_3 ceramic spheres exhibits fragmentation, they form a denser structure by filling the voids, similar to the carbon atoms that fill the interatomic spaces in the steel alloy and give steel strength. In addition, differently shaped ceramic pieces increase the irregularity and increase the probability of the bullet deviating from the trajectory in the armor.

Comparing the data obtained with the literature shows that it is seen that they are consistent with the experimental study by Grujicic et al. (2012). This study shows that for 4 shots fired at different locations on the transparent armor, bullet dwell time in the armor increases by about 60% with each shot. In the same study, it was reported that the data from two bullet types fired at 893 m/s and 682 m/s achieved approximately the same rate of increase. Correspondingly, the propagation of cracks and their irregularities in the fragile armor system prolong the dwell time of the bullets in the armor (Grujicic et al., 2012).

3.2. Experiments on the Armor System Using Al_2O_3 Balls with a Diameter of 6 mm

In the second experimental setup, an armor system filled with 6 mm diameter Al_2O_3 ceramic balls was used as a sample. It is aimed to determine whether the balls will flow from the deformation area that will be created on the front plate by bullets with a larger diameter than ceramic balls and to see the reaction of the front plate made of ductile material.

Front Side Back Side



Armor Thickness	: 90 mm
Radius of Al_2O_3 Balls	: 6 mm
Bullet Type	: 9 mm FMJ
Number of Shots	: 2

Figure 11. Experiments on the Armor System Using Al_2O_3 Balls

Two shots were fired at 358 m/s with 9 mm FMJ bullets from a distance of 5 m on the armor, which is 200 mm x 200 mm x 90 mm in size and contains 6 mm ceramic balls, as seen in Figure 11.

These shots were made with a dispersion margin of 4 cm between each shot. As a result of the experiment, the armor was not fully penetrated, and no damage occurred on the back cover. In addition, due to the inward bending of the plexiglass plate after the shot, the ceramic balls did not spill through the holes drilled on the plates and the armor continued to protect effectively. Hereby, it is also evaluated that the surface roughness of the ceramic balls is high and thus it is difficult to slide and move between the balls.

3.3. Ballistic Behavior of Free Particle and Layered Armor against Armor Piercing Bullet

In the experiment on the new armor concept with an internal thickness of 150 mm, armor-piercing 7.62 mm API BZ bullets according to STANAG 4569 Level II format were used. The shots were fired at a speed of 695 m/s from a distance of 30 m. The first part of the armor system to resist the bullet was filled with 10 mm balls and adjusted to 70 mm thickness. A 10 mm thick aramid fiber fabric was then used. The second part of the armor was adjusted to thickness 70 mm and filled with 6 mm diameter ceramic balls. This resulted in a new armor concept with an internal thickness of 150 mm. The changes in the armor system after firing are shown in Figure 12.

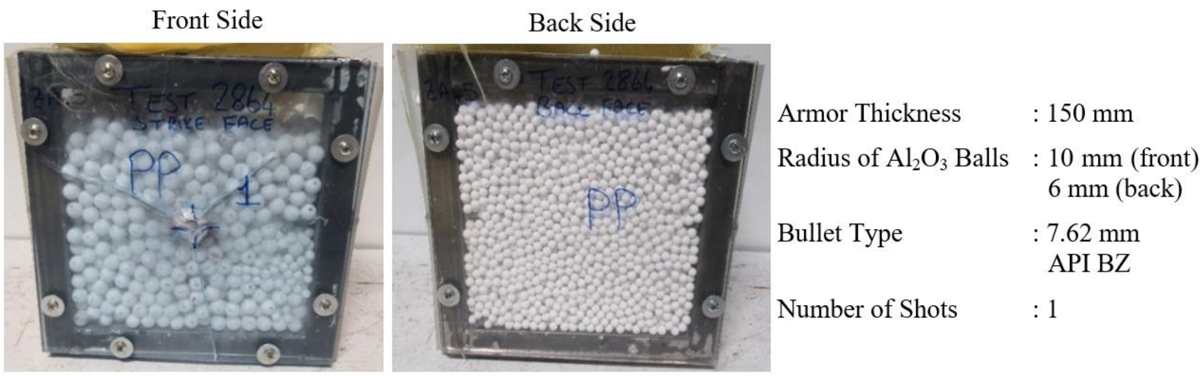


Figure 12. Deformation of Front and Back Covers After Shooting

As a result of the experiment, it was found that the bullet, which could not pass the first layer of 70 mm thickness, was mostly defeated within the first layer (containing 10 mm balls). It was observed that the last part of the energy remaining on the bullet reached the aramid fiber fabric, and the bullet fragments hit the first 5 layers of the aramid fabric and were completely stopped. No deformation or traces of contact were found in the 6th layer of the aramid fiber fabric. No matter how ballistic effective the aramid fabric was, due to its soft structure, it flexed inward at the end of the first shot and led to a deterioration in the armor system's structure. For this reason, further recordings were not carried out because stable results could not be obtained. The images and amounts of deformation obtained as a result of the examination made by separating the layers of the subject aramid fiber fabric are shown in Figure 13.

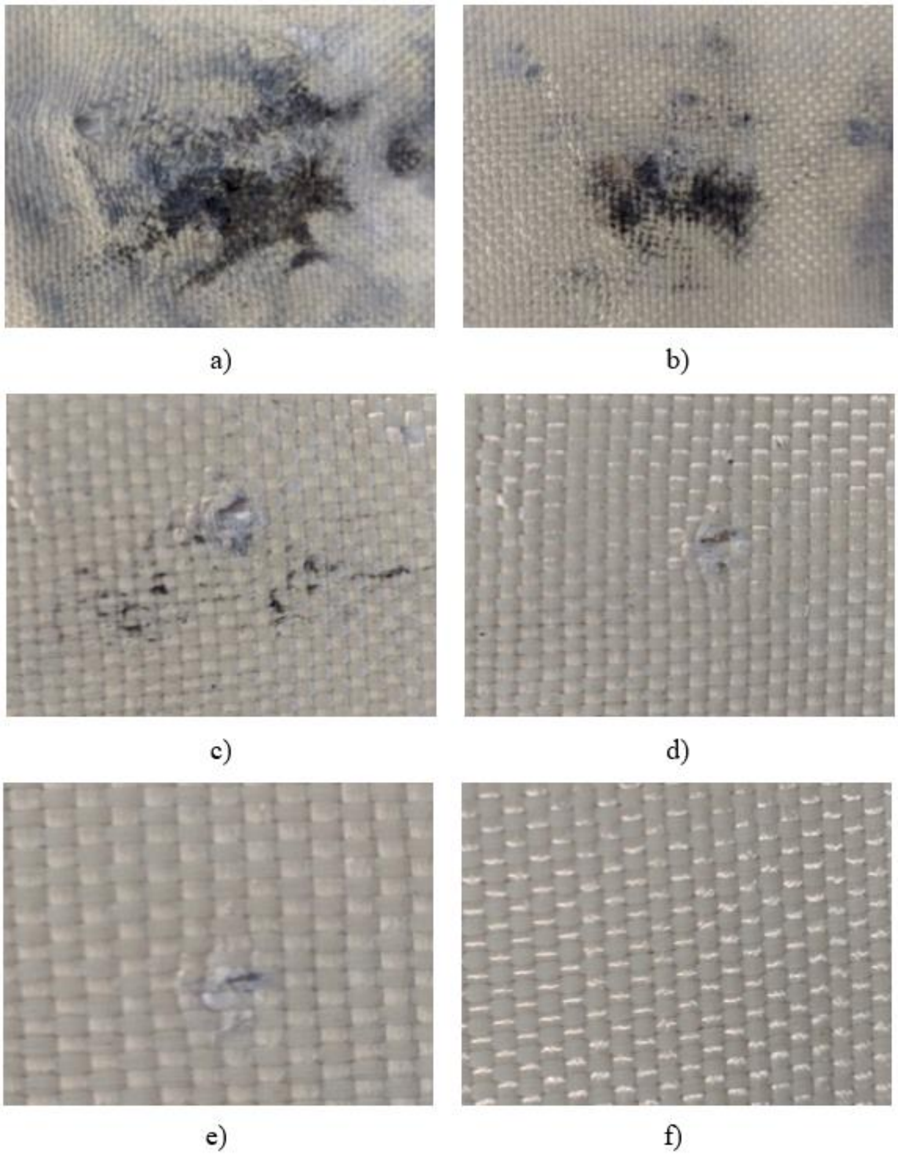


Figure 13. Aramid Fiber a) Layer 1 b) Layer 2 c) Layer 3 d) Layer 4 e) Layer 5 f) Layer 6

Figure 13 shows that the first layer is irregularly deformed. It is believed that the main reason for the deterioration of this irregular deformation in several places is that the armor-piercing bullet, which began to disintegrate by absorbing its energy in the armor, loses its integrity and impacts the aramid fabric from different points in the form of smaller particles. It can be seen that the similar penetration mechanism, albeit decreasing, also occurs in the aramid fabric layers in b and c. It was observed that the majority of the armor piercing bullet fragments were repelled in the first three layers of the aramid fiber fabric, and only attempted to penetrate as a single particle in the fourth and fifth fabric layers. It was found that the damping is completed with the tearing of the fibers in the fifth layer, which is seen in minimal size.

As can be seen, the energy of the armor-piercing bullet, which does not fully penetrate the layers, is absorbed, and prevented from entering to the second part of the armor system. Aramid fabric with a high modulus of elasticity also overlaps with the study by Guo et al. [19]. Accordingly, thanks to this property, aramid fabric, which has a high modulus of elasticity, greatly absorbs the energy of the bullet at the moment of interaction with the bullet.

Aramid fabric deforms vertically and horizontally under ballistic impact. If the bullet velocity stays within the ballistic limits of the aramid fabric, the deformation in the fabric propagates outward. When the bullet velocity exceeds the ballistic limit, the bullet perforates the fabric (Karahan et al., 2008). The layers of aramid fabric have a limited energy absorption capacity. The propagation speed of the shock wave formed in the ballistic plane during the ballistic interaction is related to the energy absorbing ability of the fabric layers. The ability of the fabric layers to absorb energy and prevent the propagation of shock waves depends on the tensile modulus of the fibers and yarns.

The aramid fabric used in the study was flexed inward after interaction, which degraded the configuration of the armor system. In future studies, it is evaluated that using harder materials such as carbon fiber blocks instead of aramid fabric will make free particle ceramic balls more stable. Thus, the damaged blocks can be easily replaced later, and their shape will not be deformed during the shots, which will ensure the protection of the layered structure of the armor.

3.4. Investigation of Ceramic Ball and Bullet Deformation

Structural changes in the ceramic balls as a result of the tests were examined. Accordingly, it has been observed that ceramics, depending on the different deflection angles of projectile, fractionate in different forms and lose their integrity. The images obtained as a result of the collecting and examining of the parts are given in Figure 14.

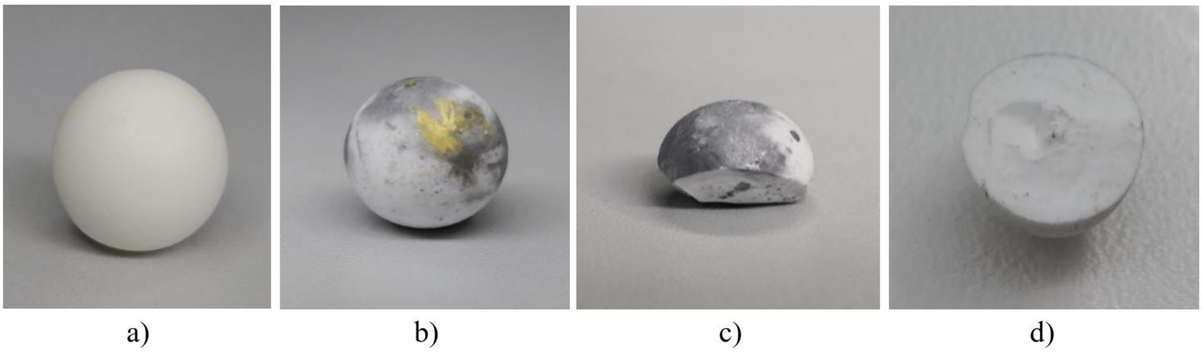


Figure 14. a) Undamaged Ceramic Ball b) Non-Fractured Ball Smeared on its Surface c) Fractured Ball d) Broken Ball (Inner surface)

The high temperature created by the high-velocity interaction of the bullet cores with the armor particles causes the core to exhibit hydrodynamic behavior. Because of this hydrodynamic behavior, it was observed that the bullet core material was plastered on the surface of the ceramic balls and this plastering/smearing occurred in almost all the balls in contact with the bullet. It is expected that the energy of the penetrator mass is not only absorbed by the fracture seen in the ceramic balls, but that some of the energy may also be absorbed due to the mass reduction with this plastering process. The fact that this plastering event affected a large number of balls was considered as an indicator of the distribution of the bullets hitting at different angles by liquefaction from the interstices of the ceramic balls and dispersed to different points. SEM and optical microscope images of damaged ceramic balls are shown in Figure 15.

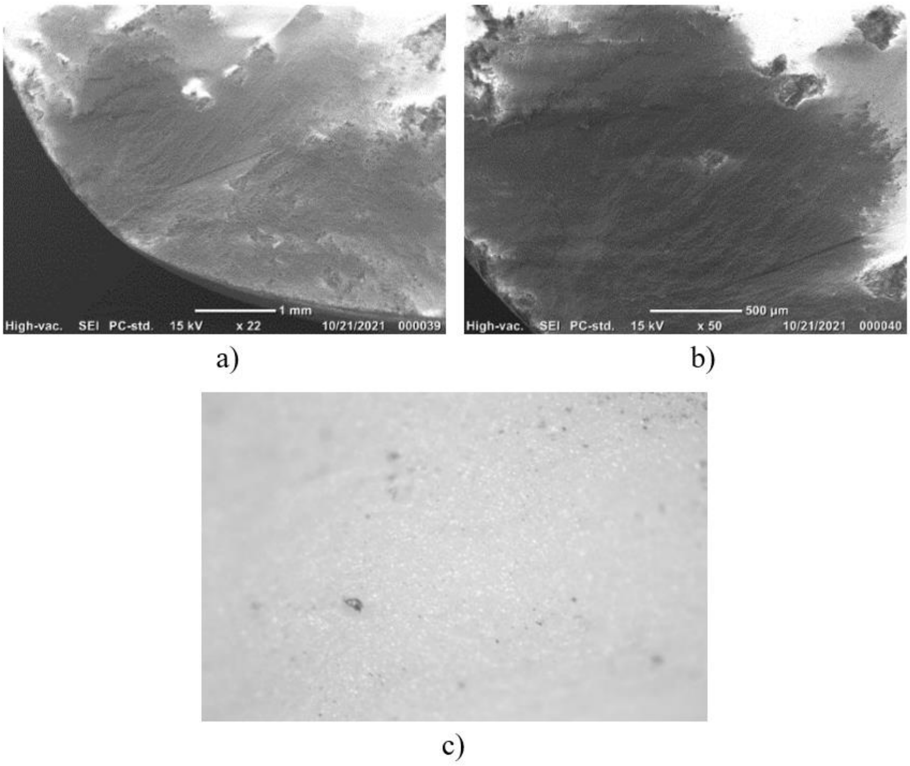


Figure 15. Ceramic Surface with Radial Crack (SEM) b) Ceramic Surface with Radial Crack (SEM) c) Ceramic Surface with Radial Crack (Optical Microscope)

Ceramic balls that interacted with the bullet generally showed a regular crack path in two dimensions, starting from the point of interaction, resulting in well-shaped ceramic fractures. Radial cracks running in the direction of the bullet cut the ceramic balls by a plane. As cab be seen in Figure 15 parts a and b, almost crack-free surfaces were obtained. Thus, these cleanly formed ceramic parts demonstrate that they can continue to provide protection against multiple hits, allowing for longer-term protection than expected.

There have been numerous studies to investigate the continuation of protection of ceramic pieces that have broken and disintegrated. In their study, Goh et al. covered the Al_2O_3 ceramic plate with AISI 4340 steel from all sides. Even when the covered ceramic plate exhibited fragmentation and comminution from multiple hits, it continued to provide protection as it was confined to a specific area (Goh et al., 2019). Bracamonte et al. found in their study that the protection of an environmentally covered ceramic plate remained almost constant in multiple hits. They explained that the main reason for this is that, there is no loss in ballistic performance after interaction by preventing the covered ceramic plates from disintegrating (Bracamonte et al., 2016b).

As a result of the tests, an attempt was made to evaluate the deformation characteristics of the ammunition after interaction. Accordingly, images of deformed bullets (9 mm FMJ and armor-piercing 7.62 mm API BZ) and their finds are sown in Figure 16.

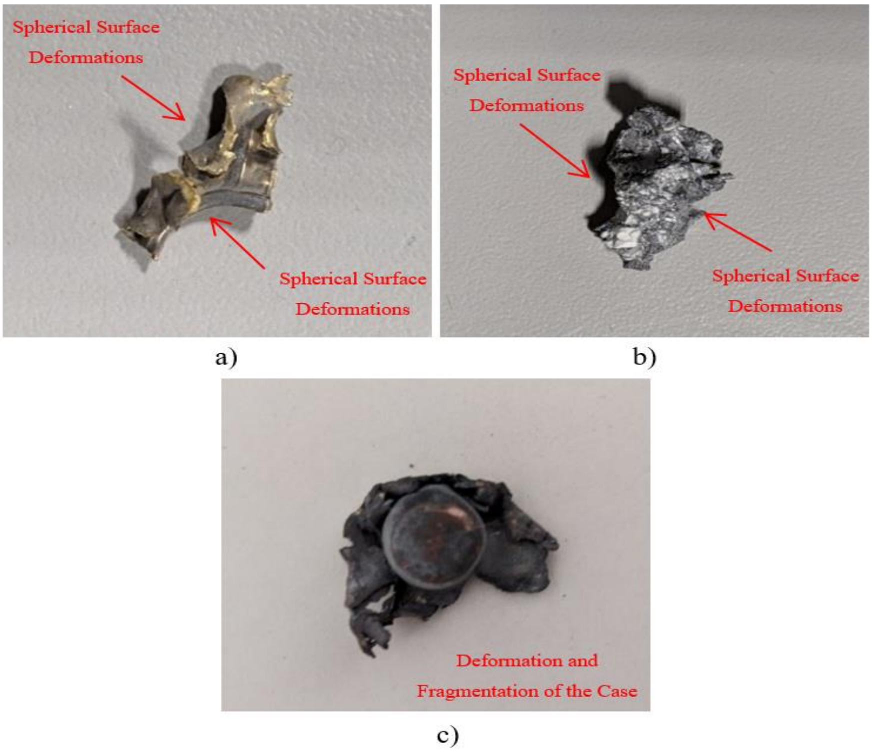


Figure 16. a) 9 mm Bullet Core Outer Shell (Jacket) b) 7.62 Bullet Inner Core c) 7.62 Bullet Outer Shell (Jacket)

As can be seen in the figure, all types of ammunition have their inner core and outer casing separated and fragmented. It has been observed that the ammunition cores lose mass by plastering on ceramic surfaces due to the thermal effect created by the high pressure and the resulting collision energy. Spherical tracks are observed to form in the core that have been deformed by hitting more than one spherical surface (Figure 16).

In his study, Helliker says that jacketed bullets like the 9mm FMJ and 7.62mm API exhibit deformation when interacting with the target. Accordingly, the amount of deformation increases according to the deceleration of the bullet seen in the target armor. The possibility of deformation and fragmentation increases with the effect of rapid deceleration, in the high hardness materials. He also explains that with the deformation of the bullet, extrusion can occur along the bullet shell and often the inner core can be thrown out by splitting of the jacket (Helliker, 2016). In the images obtained as a result of the experiments, it is judged that a same mechanism, seen in the previous studies, occurs and that the processes of same penetration and deformation occur.

3.5. Comparison of Mass Efficiency of Free Particle Armor System with Conventional Armor Systems

The fact that armor systems do not have sufficient hardness and metal-structured armors in particular behave like a liquid by exhibiting hydrodynamic characteristics under high temperature and pressure, allowing high-temperature airflow to pass through the armor with the bullet, and having a high weight due to high density create weakness. In Table 5, a comparison of conventional armor systems is made based on the density/volume/mass values of the free particle armor system.

Table 5. Mass Comparison of Conventional Armor Systems (MIL-A-12560:H "Armor Plate, Steel, Wrought, Homogeneous (For Use in Combat-Vehicles and for Ammunition Testing)", 2009; Patnaik, 2002)

Material	**Density**	**Volume**	**Mass**
MIL-A-12560 Armor Steel	7.8 g/cm^3	1600 cm^3	12.48 kg
Aluminum Plate (5083)	2.56 g/cm^3	1600 cm^3	4.096 kg
Al_2O_3 Ceramic Plate	3.72 g/cm^3	1600 cm^3	5.952 kg
Al_2O_3 Free Particle Armor System (*Ball Diameter: 10 mm, Armor Frame Weight Not Included*)	3.72 g/cm^3	1600 cm^3	2.3-2.9 kg

Metal armors are widely used in vehicle armors owing to their ready availability and machinability. However, when the density factor comes into play, it boasts higher weight ratings compared to its alternatives. Comparing the masses of armor systems in the same volume in Table 5, an average armor steel reaches about 3 times the weight of aluminum plates, while it corresponds to about 2 times that of Al_2O_3 ceramic plates. Although aluminum plates are preferred due to their lightness, they have inferior mechanical and ballistic properties. This situation causes it to lose its effectiveness especially against kinetic energy ammunition. Metal-based armors such as steel and aluminum can exhibit different ballistic behaviors under different conditions. These are brittle fracture, ductile hole enlargement, radial cracking, plugging, fragmentation and petalling (Backman, 1976). This behavior of metal armor under different conditions affects a specific area and causes a significant reduction in ballistic performance in multiple shots, especially getting into this area.

Ceramic, on the other hand, shows effective performance against kinetic energy ammunition due to its high hardness. These brittle materials absorb a large part of projectile's energy as the crack propagation. The fracture mechanism of ceramics under impact shows different physical properties compared to other armor steel materials due to the brittleness caused by the hardness of the ceramics. Particularly, comminution, fragmentation and many cracks cause the need to be supported by other materials (Swab et al., 2005).

Although ceramic plates are almost 50% lighter compared to armor steels, they are 31% heavier than aluminum plates. In terms of ballistic performance, they offer better protection than other type of armors. Nevertheless, it can be clearly seen that the weight of Al_2O_3 ceramics, which is very preferred in armor systems, is high enough even with small volumes such as 1600 cm^3. This situation increases the need to research various armor designs, including body armor. Thanks to the free-particle armor system with the advantages of the design, almost the same performance is achieved with particles with the same hardness as the ceramic plate, with up to 50% lower weights, and there is no performance loss with multiple shots. The design offers comfort to the user due to its wide range of use and modularity.

4. CONCLUSION

In this study, the ballistic performance of the free particle modular armor system was investigated. Findings obtained as a result of the experimental study are presented below;

- Ballistics tests assumes that there is a certain distribution in successive shots, so shots are not made from exactly the same point. With these shots, thus, the armor completely loses its effectiveness. In this study, in contrast to recent studies, it has been revealed that the armor system maintains its protection even though the ballistic performance decreases in multiple hits from exact the same point. In addition, it was noted that when moving through the armor system, the bullet deviated from its trajectory in these multiple shots fired at the same and different points. It was observed that the ceramic balls placed in a certain order before the test, the damaged ball particles during the shots were gathered in a more dispersed order each time with the effect of the energy from the bullet, and the armor system became denser as random-sized small particles filled in the gaps. It has been found that these ceramic balls, being more irregularly and densely spaced with each shot, increase the likelihood of the bullet hitting at larger angles and increase the risk of ricochet in direct proportion, also minimizing the drop in performance by multiple shots. This shows that the ballistic performance of the free particle modular armor system is higher than conventional armor systems.

- Penetration time of an armor is important in increasing ballistic efficiency. Sometimes, to increase the duration, the armor is positioned at an oblique angle, and sometimes the method of increasing the thickness of the armor is applied. The free particle armor system, on the other hand, exploits the spherical nature of the ceramic balls in the armor system without increasing the thickness and therefore the weight, causing the bullet to deviate from its natural axis. Penetration time of the armor thereby increases
- It has been found that even when larger diameter ammunition is used than ceramic balls in the armor system, the ductile cover materials are deformed inward along the bullet interaction area, preventing escape of smaller diameter balls. In addition, since ceramic balls provide sufficient protection, there is no need for ballistic resistance on the front and back cover. Instead of reacting to the bullet, it is desired to pass the bullet as much as possible and not disperse in the meantime.
- It has been revealed that upon impact to high-hardness material at high-velocity, the bullet's core smears on the bullet's surface, significantly reducing the bullet's mass and facilitating energy absorption.
- As a result of the weight comparison, it has been appointed that the free particle armor system is both lighter and outperforms conventional metal-based armors.
- Although the thickness of this armor system affects the level of protection linearly, it tends to disperse and loses its effectiveness against area-of-effect weapons such as Barrett and RPG. For this reason, this vulnerability can be prevented by creating an armor system with 2 or more layers and panels arranged one behind the other. It is believed that the number of layers can be increased to prevent armor spallation, especially against RPG ammunition.

Although further investigations are needed, the present study contributes to a better characterization of free particles which is used in armor systems. Future studies will evaluate that by using harder materials such as carbon fiber blocks instead of aramid fabric, more stable layered armor can be achieved. In addition, the damaged blocks can be easily replaced later, the system is not be disrupted during the interaction, and the disintegration of the armored layered structure will be prevented.

Table 6. List of symbols and abbreviations

Symbol/ Abbreviation	Meaning	Symbol/ Abbreviation	Meaning
Al_2O_3	Alumina	BENSH1	Bullet Entry Side Hole 1
B_4C	Boron Carbide	BEXSH1	Bullet Exit Side Hole 1
SiC	Silicon Carbide	TP1	Target Point 1
ZrO_2	Zirconium Oxide	BENSH2	Bullet Entry Side Hole 2
Si_3N_4	Silicon Nitride	BEXSH2	Bullet Exit Side Hole 2
TiB_2	Titanium Diboride	TP2	Target Point 2
CMC	Ceramic Matrix Composites	DPBC1	Depth of Penetration on Ballistic Clay 1
PMMA	Polimethyl Methacrylate	DPBC2	Depth of Penetration on Ballistic Clay 2
FMJ	Full Metal Jacket	DPBC3	Depth of Penetration on Ballistic Clay 3
API BZ	Armor Piercing Incendiary	DPBC4	Depth of Penetration on Ballistic Clay 4
		SEM	Scanning Electron Microscope

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6. CONFLICT OF INTEREST

Author(s) approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

7. AUTHOR CONTRIBUTION

Emre AYTAV contributed to the determination and execution of the conceptual and experimental design processes of the study, the execution of shooting tests in accordance with international standards, the design and writing of the article and the interpretation of the data. Abdullah Mahir IŞIK contributed to the preparation of the samples, execution of the shooting tests, writing of the article and interpretation of the data.

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