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Ceramic Faced Stand-Alone Hybrid Armor Design for Civilian (Hidden Armored) Vehicles

Sivil (Gizli Zırhlı) Araçlar için Seramik Yüzlü Münferit Hibrit Zırh Tasarımı

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Sivil araç

Özet

Bu makalede, sivil araç zırhlaması üzerine yapılan araştırmalar ve bu alanda kullanılmak üzere tasarlanan seramik kompozit bir zırhın balistik test sonuçları sunulmuştur. Günümüzün farklı mühimmat tehdit seviyelerine karşı askeri araçlarda olduğu gibi sivil araçlarda da zırhlama çok önemli bir konu haline gelmiştir. Ayrıca ağırlığın önemli bir tasarım kriteri olması nedeniyle hafif zırh sistemlerine olan talep de artmaktadır. Ağırlık, aracın yakıt tüketimini, motor gücünü ve ilgili diğer sistem gereksinimlerini artırır ve manevra kabiliyetini azaltır. Çalışmada sunulan bağımsız zırh, sivil araçlarda kullanılmak üzere geliştirilmiş ve zırh panelinin ağırlık kazancı, Ultra Yüksek Sertlikli (UHH) zırh çelikleri (Armox 600T ve Armox Advance) ile karşılaştırılmıştır. Geliştirilen zırh, darbe yüzünde alümina (Al_2O_3) seramik karolardan ve son katmanda Ultra Yüksek Moleküler Ağırlıklı Polietilen (UHMWPE) kompozit destek plakasından oluşmaktadır ve 7.62 mm x 51 M61 AP mermiye karşı test edilmiştir. Hafif zırh panelinin beş atıştan sonra yapısal bütünlüğünü koruduğu gözlemlenmiştir. Geliştirilen zırh panelinin sivil zırhlı araçlar için 7.62 mm zırh delici mühimmatlara karşı hafif ve uygun maliyetli çözüm sağlayacağı değerlendirilmektedir.

Abstract

In this paper, researches on civilian vehicle armoring and ballistic test results of a ceramic composite armor designed to be used in this field are presented. Armoring has become a very important issue in civilian vehicles as well as in military vehicles against today's different ammunition threat levels. Also, there is an increasing demand for the lightweight armor systems since weight is important design criterion. The weight increases fuel consumption, engine power and other related systems requirements of the vehicle and decreases the maneuverability. The stand-alone armor in the study was developed for use in civilian vehicles and weight saving of the armor panel was compared with Ultra-High Hardness (UHH) armor steels (Armox 600T and Armox Advance). The armor developed consists of alumina (Al_2O_3) ceramic tiles in the strike face and Ultra High Molecular Weight Polyethylene (UHMWPE) composite backing plate in the end layer and it was tested against 7.62 mm x 51 M61 AP (Armor Piercing) projectile. It was observed that the lightweight armor panel protected its structural integrity after five shots. It is evaluated that developed armor panel provides lightweight and cost effective solution against 7.62 mm Armor-Piercing projectiles for civilian armored vehicles.

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1. INTRODUCTION

Today, with the developing technology, light and innovative armor systems are needed against increasing ammunition threat levels (Göde, 2020). When examined in this context, ceramic composite armor systems draw attention in terms of advanced material production techniques, improved ballistic protection level against kinetic and chemical energy projectiles, and high mass and volume efficiency. Advanced technology offered by ceramic composite systems is used in Germany's Leopard II, England's Challenger, America's Abrams and Israel's Merkava main battle tanks.

In armor design, lightweight armor systems are very important for ballistic protection because weight factor has become a very important criterion. In the past, armors were composed of metals (Bürger, Faria, Almeida, Melo and Donadon, 2012, pp. 63-67). However, these metallic materials used in armor applications increase considerably the weight of the total vehicle or system which affects fuel efficiency, their transportability/deployability, mobility and mechanical/structural failures (Grujicic, Pandurangan, and d'Entremont, 2012, pp. 380-393).

Due to the need for lightweight materials, ceramics were considered for the armors. With the combination of the backing plate which is energy absorbing layer, ceramics have better ballistic performance. Hybrid armor systems had been developed with use of this combination (Kaufmann, Cronin, Worswick, Pageau and Beth, 2003, pp. 51-58).

The ceramics used on the front surface (impact surface) of armor systems, with their high hardness, compression strength and abrasion resistance, prevent full penetration of the bullet into the structure, thanks to the high energy absorption ability of the composite in the back layer, which provides structural integration.

As in military vehicles, there is a big demand for armors against various threats in civilian vehicles. This study mainly focuses on to develop lightweight stand-alone armor for civilian vehicles. In this paper, researches on civilian vehicle armoring and ballistic test results of a ceramic composite armor designed to be used in this field are presented. The usability of stand-alone ceramic composite armor analysis instead of armor steels, which are widely used in civilian vehicle armoring activities, was investigated. The stand-alone armor solution was compared with armor steels of various hardnesses. It has been determined that the armor analysis, which was subjected to the destructive test in the case of multiple shots, showed successful results.

1.1 Ceramic-Composite Armors

Ceramic-based armors have been extensively used in protective structures such as helicopter seats, helicopter floor plates, engineering vehicles, armored fighting vehicles, body armor and so on. The first use of ceramic armor technology was during Vietnam War in helicopters (Hazell, 2015; Rolston, Bodine, and Dunleavy, 1968, pp. 55-63). Ceramic armor was used in UH-1 and AH-1 Cobra helicopter seats against 7.62 mm AP ammunition in 1965. The first monolithic ceramic body armor vest was issued to the helicopter crews in 1966 (Dunstan, 1984; Hazell, 2015).

When ceramic armors are used, it saves up to 65% in weight compared to conventional steel armor plate, as shown in Figure 1 (Roberson, 1995).

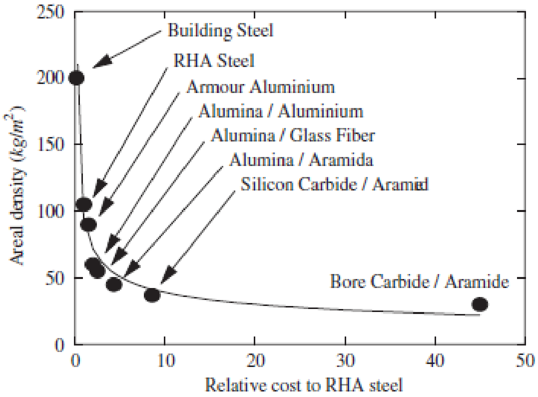


Figure 1: A Comparative Study to Assess the Areal Density of Several Armor Solution Against 7.62 mm AP projectile with velocity of 840 m/s
(Source: Lopez-Puente, Arias, Zaera, and Navarro, 2005, pp. 321-336; Roberson, 1995).

In the hybrid armor systems, the ceramic plates are used to blunt and fracture incoming projectiles and the residual kinetic energy of the fragments are absorbed by the backing (rear) plate (Marx, Portanova and Rabiei, 2018, pp. 652-661). A ceramic-based armor system is shown in Figure 2.

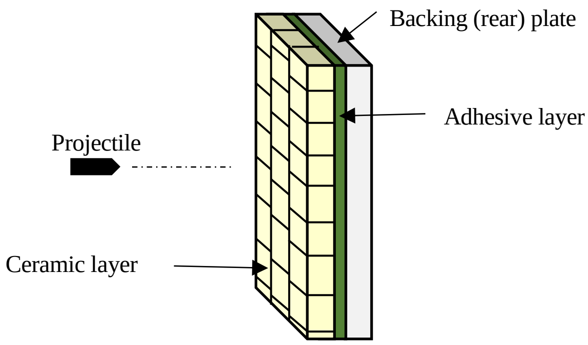


Figure 2: A Lightweight Ceramic-based Armor Layout (Modified from
(Source: Marx et al., 2018, pp. 652-661).

Generally, armor panels are used with a ballistic material such as armor steel, aluminum alloys, spall liners etc. But, this kind of an additional ballistic protection material is not needed with the use of stand-alone armor panels. Stand-alone armor panels provide ballistic protection on their own without any material or system. In the present study, ballistic performance of standalone armor system consisting of alumina ceramic tiles which provide cost effective solution and Ultra High Molecular Weight Polyethylene (UHMWPE) composite backing plate which is lightweight ballistic material was investigated for civilian armored vehicles against 7.62 mm x 51 M61 AP projectiles. Armor panel was coated with polyurea/polyurethane based material for the structural integrity of the armor and multi-hit impact resistance

1.2 Civilian Vehicle Armoring

Today's hybrid threats are now aimed at civilians as well. Similarly, the target spectrum has expanded in ballistic threats. The main reason for this is the changes that states and societies go through, and the economic and social risks. Increasing crime rates around the world, security problems due to terrorist incidents, instability and personal security concerns have increased the interest and need for armored civilian vehicles that have the same appearance as vehicles of the same brand and model, in other words, hidden armored vehicles (Yogiata, S., & Kriti, K., n.d.). Unlike military armored vehicles, a civilian armored car is designed to be inconspicuous and similar to its factory version (Wikipedia, 2023). Depending on the protection level, these vehicles are much heavier than their regular variants and special training for driving is recommended for them (Alpine Armoring, n.d.c). End users of civilian armored vehicles include government customers such as prime ministers, president and diplomats etc., non-governmental organizations, law enforcement agencies, corporate users from different industries such as oil&gas, construction, mining and banking sector and VIP’s (Very Important Person) (Yogiata, S., & Kriti, K., n.d.). An armored Mercedes-Benz W221 used by the President of Germany and Queen Elizabeth II's Bentley State Limousine are presented in Figure 3 and Figure 4, respectively, as examples of armored VIP vehicles.

Figure 3: Armored Mercedes-Benz W221
(Source: Wikipedia, 2023)

Figure 4: Bentley State Limousine
(Source: Wikipedia, 2023)

The diversification of hybrid threats, the easier access of non-state actors to highly destructive ammunition and weapon systems have increased the need for higher ballistic protection and lighter armor solutions in hidden armored vehicles (Göde, 2020). Weight is the main design issue for armoring engineers when armoring a vehicle originally designed for civilian use. A subsequently armored vehicle will carry more weight than it was designed for, as well as a change in the center of gravity. These changes will adversely affect the vehicle's engine power, transmission, fuel consumption, acceleration, braking performance and distance, and maneuverability (Teoman et al., 2022, pp. 547-557).

Mobility, firepower and armor protection are three conflicting requirements in the design of any modern armored vehicle. The balance between ballistic protection and vehicle mobility should be considered during the design process. An armored vehicle whose ballistic protection level was determined at the design stage and designed accordingly is more stable than a vehicle designed for civilian use and subsequently armored (Kamel, 2017, pp. 1-12). Also, some vehicle parts, such as suspension rear springs, shocks, etc. can be upgraded to prevent the performance loss caused by the additional weight that comes with the armoring (Universal Defense for Military Equipment, n.d.). The effect of armoring equipment on a subsequently armored civilian vehicle is shown in Figure 5 (Kamel, 2017, pp. 1-12).

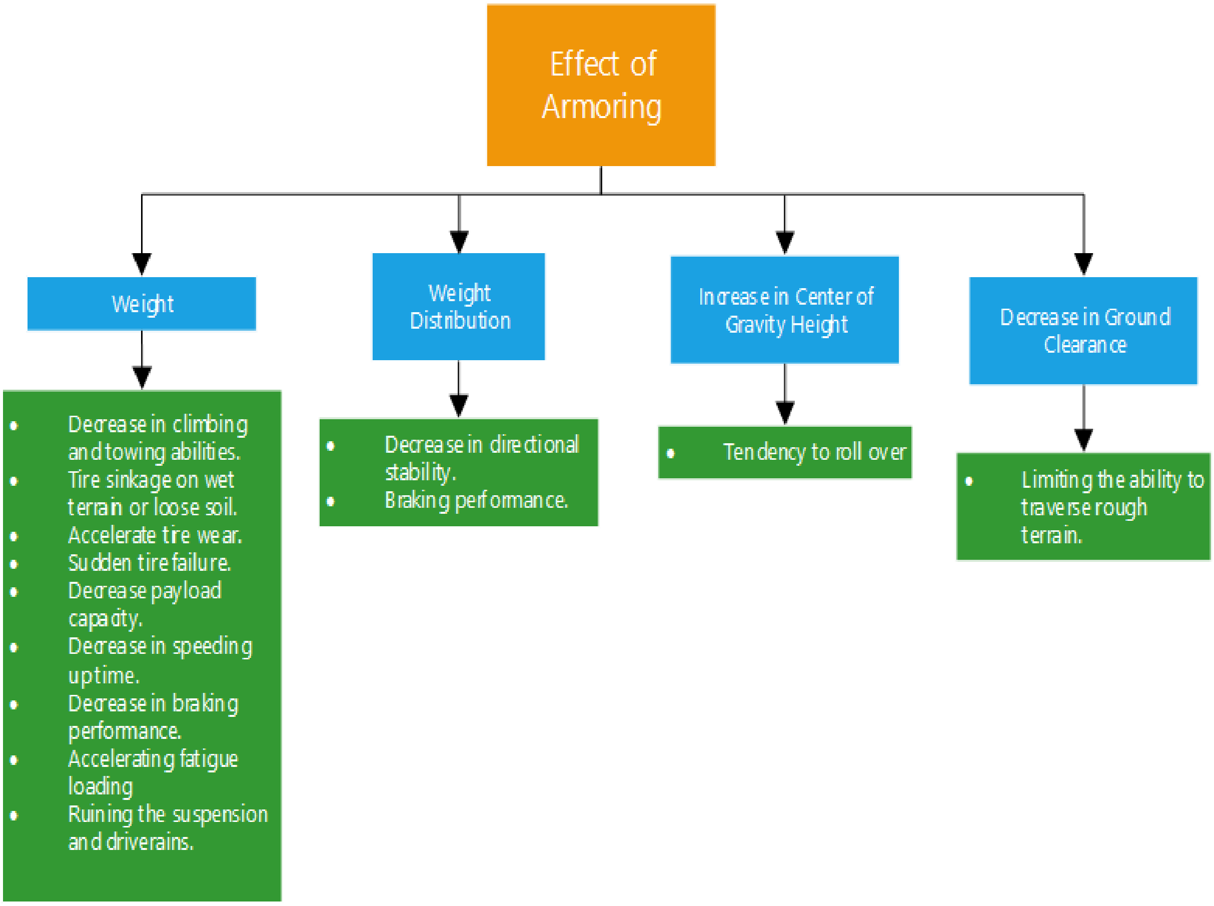


Figure 5: Effect of Protection on Vehicle Mobility
(Modified from Kamel, 2017, pp. 1-12).

Many terrorist incidents occur in the world and each new terrorist act necessitates the evaluation of technologies used for ballistic protection. For this reason, information about attack events should be carefully examined (Teoman et al., 2022, pp. 547-557). In the terrorist incident that took place in Sanaa, the capital of Yemen, in 2014, in the attack on the secret armored vehicle belonging to the German Embassy, 17 bullets from the side passenger compartment in the front hit the vehicle, and the punctures were observed at some points (Figure 6). This incident, which resulted in the injury of one of the diplomats in the vehicle, once again revealed the importance of ballistic protection (Solms-Laubach, 2014).

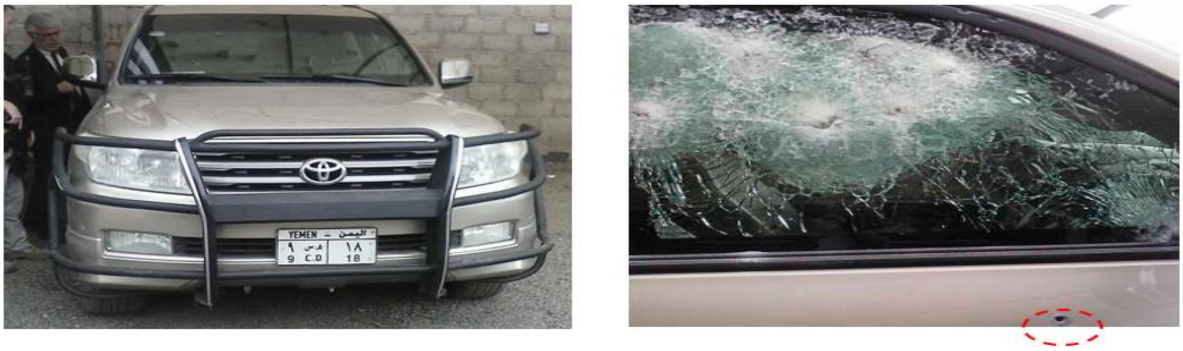


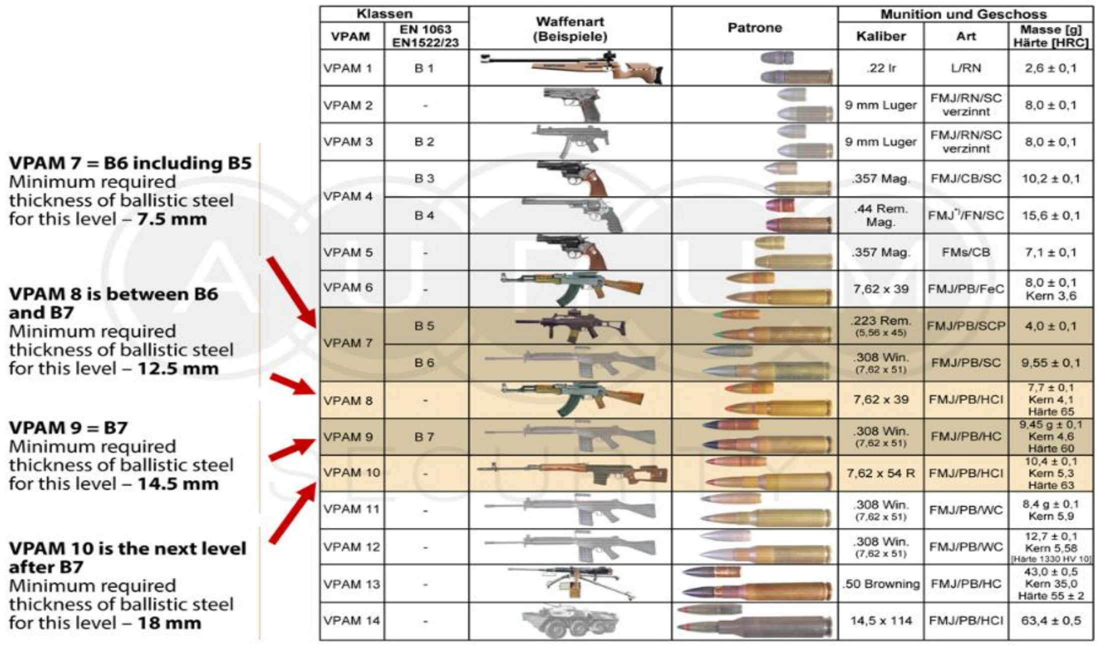
Figure 6: Image of the Vehicle after the Attack
(Source: Aurum Security, n.d.a).

At the end of 2016, Afghan Deputy Fakuri Beheshti was injured and his bodyguard died as a result of the explosion of a roadside explosive in the terrorist incident that took place in Kabul, the capital of Afghanistan (Aurum Security, 2017a). Images of the explosion are given in Figure 7.

Figure 7: Images of the Vehicle after the Explosion
(Source: Anadolu Ajansı, 2016).

In 2017, approximately 80 people lost their lives and more than 400 were injured when an explosive device, which was placed in a parked vehicle in the diplomatic area in Kabul, a few meters away from the German Embassy, was detonated during the rush hour. Such terrorist attacks have once again demonstrated the importance of armored vehicles produced in accordance with quality and safety standards (Aurum Security, 2017b).

Hidden armored vehicles are vehicles that can be lightly or heavily armored according to the threat and protection level, and are not suitable for tactical or combat use (United States Goverment Accountability Office, 2017). Euronorm 1522/1523 (for opaque armor such as body) and Euronorm 1063 (for optical armor such as vehicle glass) and VPAM BRV standards are the widely used protection classes for hidden armored vehicles (Aurum Security, n.d.c; Yogiata, S., & Kriti, K., n.d.). Class B2 can withstand a 9 mm, Class B3 can withstand .357 Magnum rounds or lesser threats, and Class B4 can withstand a .44 Magnum rounds or lesser threats. B5 is capable of withstanding a .357 Magnum at 5 meters and B6 can withstand 7.62 x 39 rounds from Kalashnikov rifle. B6 is used for relatively high level protection against threats such as threats ranging from 7.62x51 (.308) up to 30.06 AP (Armor Piercing) and penetrator rounds. Armored SUV's like police car or ambulance can provide a B5, B6 or B7 level of protection. Vehicles armored at B5, B6, B7 class have good explosion protection (Aurum Security, n.d.c). The correspondence of VPAM levels to the 7 levels of EN 1522 / EN 1063 is shown in the Figure 8.



Klassen		Waffenart (Beispiele)	Patrone	Munition und Geschoss		
VPAM	EN 1063 EN1522/23			Kaliber	Art	Masse [g] Härte [HRC]
VPAM 1	B 1			.22 lr	L/RN	2,6 ± 0,1
VPAM 2	-			9 mm Luger	FMJ/RN/SC verzinnt	8,0 ± 0,1
VPAM 3	B 2			9 mm Luger	FMJ/RN/SC verzinnt	8,0 ± 0,1
VPAM 4	B 3			.357 Mag.	FMJ/CB/SC	10,2 ± 0,1
	B 4			.44 Rem. Mag.	FMJ*)/FN/SC	15,6 ± 0,1
VPAM 5	-			.357 Mag.	FMs/CB	7,1 ± 0,1
VPAM 6	-			7,62 x 39	FMJ/PB/FeC	8,0 ± 0,1 Kern 3,6
VPAM 7	B 5			.223 Rem. (5,56 x 45)	FMJ/PB/SCP	4,0 ± 0,1
	B 6			.308 Win. (7,62 x 51)	FMJ/PB/SC	9,55 ± 0,1
VPAM 8	-			7,62 x 39	FMJ/PB/HCI	7,7 ± 0,1 Kern 4,1 Härte 65
VPAM 9	B 7			.308 Win. (7,62 x 51)	FMJ/PB/HC	9,45 g ± 0,1 Kern 4,6 Härte 60
VPAM 10	-			7,62 x 54 R	FMJ/PB/HCI	10,4 ± 0,1 Kern 5,3 Härte 63
VPAM 11	-			.308 Win. (7,62 x 51)	FMJ/PB/WC	8,4 g ± 0,1 Kern 5,9
VPAM 12	-			.308 Win. (7,62 x 51)	FMJ/PB/WC	12,7 ± 0,1 Kern 5,58 [Härte 1330 HV 10]
VPAM 13	-			.50 Browning	FMJ/PB/HC	43,0 ± 0,5 Kern 35,0 Härte 55 ± 2
VPAM 14	-			14,5 x 114	FMJ/PB/HCI	63,4 ± 0,5

Figure 8: The Correspondence of VPAM Levels to the 7 Levels of EN 1522 / EN 1063
(Source: Aurum Security, n.d.c)

The passenger compartment, defined as the living space, is expected to provide 360-degree protection against ballistic threats. The most important element of protection is that hidden armored vehicles are not noticed during use (United States Goverment Accountability Office, 2017). While determining the brand and model of the vehicle to be armored, first of all, the standard and level of protection the vehicle will be armored with, the type of mission the vehicle will be used for (personnel transport, transportation of important persons, etc.), and the ground conditions in which the vehicle will be used are determinants. Today, SUV (Sports Utulity Vehicle) or off-road type pickup trucks are mostly preferred in order to have a wide range of use for the vehicle model to be selected (Figure-9) (Teoman et al., 2022, pp. 547-557).

Figure 9: Hidden Armored Pickup Truck (Left) and Hidden Armored Passenger Vehicle (Right)
(Source: Türk Savunma Sanayii Ürün Kataloğu, n.d.)

Armor integrated into conventional military vehicles is part of the design or construction while for most hidden armored vehicles; the armoring material is mounted on the vehicle body and structural elements after production (Teoman et al., 2022, pp. 547-557). There are also vehicle companies that produce armored vehicles from the factory such as the Audi Security Vehicles (A6 and A8 models), Lincoln Town Car BPS, Hyundai Equus, BMW Security series (3 Series, 5 Series, 7 Series and X5 models), the Mercedes Benz Guard vehicles (E, ML, GL, G & S Class) (Wikipedia, 2023). These armoring methods (in production or after production) are very effective in the price of armored vehicles. While the price of an armored vehicle with B6 protection class is about $1.27 million more as compared to a non-armored variant, the retrofit manufacturers offer a similar vehicle at a much reduced price of around $50,000 plus the cost of the base vehicle (Yogiata, S., & Kriti, K., n.d.). In Figure 10, a typical hidden armored civilian vehicle and a typical military armored vehicle are presented. The various armors on a hidden armored civilian vehicle are shown in Figure 11.

Figure 10: Typical Armored Commercial Passenger-Carrying Vehicle (left) Compared with Tactical Vehicle (right)
(Source: United States Goverment Accountability Office, 2017)

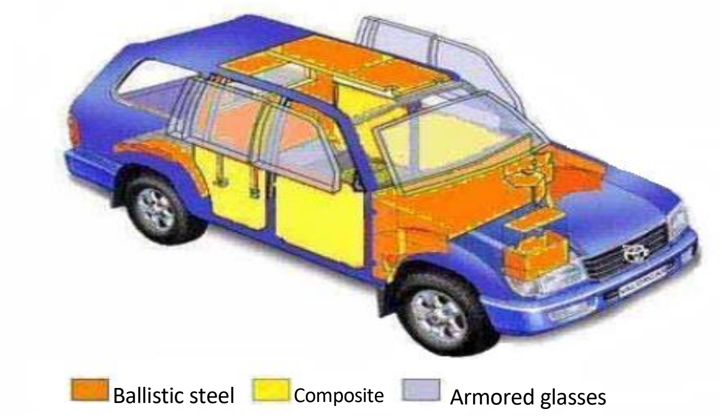


Figure 11: Various Armors on a Civilian Vehicle
(Modified from Universal Defense for Military Equipment, n.d.)

Some hidden armored cars may be one-off unique vehicles with no standard equivalent, such as the Presidential state car of the USA which is built on a medium-duty truck platform styled like a Cadillac (Figure 12) (Wikipedia, 2023).

Figure 12: Presidential State Car of the United States, Also Known as Cadillac One
(Source: Wikipedia, 2023)

Hidden armored civilian vehicles can provide regional ballistic protection against high kinetic energy threats, as well as generally protect against grenades or low-impact hand-made bombs, with the internal cladding method. For hidden armored vehicles that are subsequently armored, armoring the entire body of the vehicle is not preferred due to weight. Primarily, armoring of the vehicle's living area (capsule) and critical areas that will cause the vehicle to lose its mobility during the attack is done (Teoman et al., 2022, pp. 547-557).

Since armored vehicles are not produced according to the additional loads brought by the armoring, they are also subjected to driving safety and performance tests in addition to ballistic protection tests. Examples of these tests are hot-cold test, rain test, brake test, handbrake test, run-flat test and engine compartment fire extinguishing tests (Teoman et al., 2022, pp. 547-557).

The hidden armoring process is not only applied to passenger cars or pickup trucks; It is also applied to multi-purpose vehicles (Figure 13), vans (Figure 14), midi buses and buses (Figure 15) (used for personnel dispatch in regions with a high risk of attack) (Teoman et al., 2022, pp. 547-557).

Figure 13: Armored Multi-Purpose Vehicle
(Source: Türk Savunma Sanayii Ürün Kataloğu, n.d.)

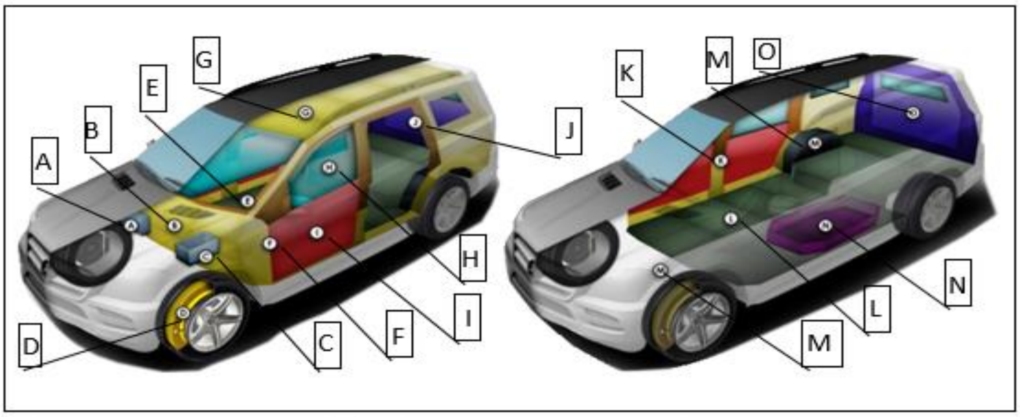
Figure 14: Armored Van
(Source: Plasan, n.d.)

Figure 15: Armored Bus
(Source: Türk Savunma Sanayii Ürün Kataloğu, n.d.)

The interest in hidden armored civilian vehicles has led to the establishment of many companies doing post-armoring around the world and the emergence of an important economy. The mechanical and structural characteristics of the vehicle to be armored and the threat level are important factors in determining the material and technology to be used in armoring. In general, advanced technological materials and material combinations such as ballistic armor steel, composite and ceramic impact surface hybrid armors are used. For example, Aurum Security Company operating in Germany armors SUV type vehicles against various ballistic threats with 500 HB and 600 HB armor steels (Teoman et al., 2022, pp. 547-557). Companies such as BMW and Anadolu ISUZU manufacture hidden armored civilian vehicles (BMW, n.d.). Dew Engineering and Development, based in Ottova, Canada, is the largest and most advanced designer, integrator and manufacturer of cutting-edge add-on armor in North America. DEW is a wholly owned subsidiary of CoorsTek, Inc., which manufactures technical ceramics in the USA (DEW Engineering and Development, n.d.b). Dew Engineering and Development company manufactures ballistic door panels against various armor-piercing and non-armor-piercing ballistic threats for police vehicles using metallic and composite type materials (DEW Engineering and Development, n.d.a). Figure 16 shows a ballistic door panel produced by this company.

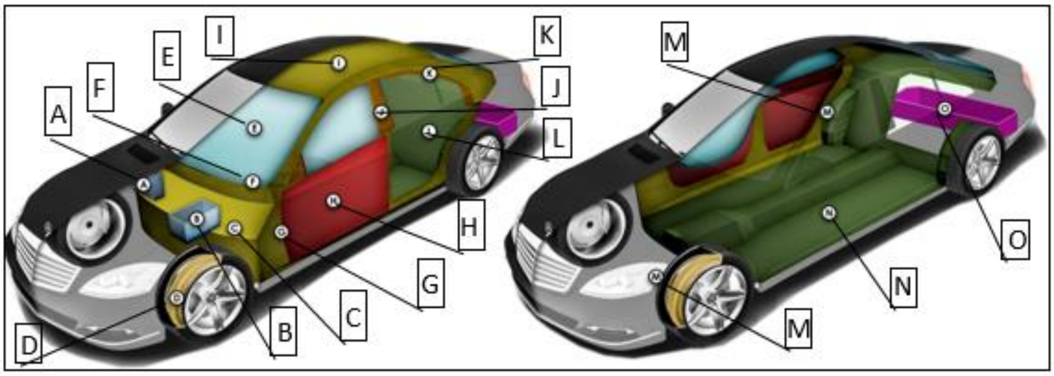
Figure 16: Ballistic Door Panel Produced by Dew Engineering and Development Company
(Source: DEW Engineering and Development, n.d.a)

Alpine Armoring Company, operating in the USA, armors various types of vehicles (Alpine Armoring, n.d.b) using composite, ultra-high molecular weight polyethylene, ballistic steel and ceramic-faced hybrid armor against various ballistic threats (Alpine Armoring, n.d.a). The armoring schematic views of SUV and sedan type vehicles are given in Figure 17 and Figure 18.



A	Battery Protection	F	Heavy-Duty Door	K	Pillar Protection
B	Firewall Protection	G	Roof Protection	L	Floor Protection
C	Engine Computer	H	Transparent Armor	M	Whell Well Protection
D	Composite Run-Flats	I	Door Protection	N	Fuel Tank Protection
E	Window Anchors	J	Steel Door Overlaps	O	Rear Partition Armored

Figure 17: Schematic View of Typical Armoring of a SUV (Modified from (Source: Teoman et al., 2022, pp. 547-557).



A	Engine Computer	F	Window Anchors	K	Steel Door Overlaps
B	Battery Protection	G	Heavy-Duty Door	L	Rear Seat-Back
C	Firewall Protection	H	Door Protection	M	Wheel Well Protection
D	Composite Run-Flats	I	Roof Protection	N	Floor Protection
E	Transparent Armor	J	PillarProtection	O	Fuel Tank Protection

Figure 18: Schematic View of Typical Armoring of a Sedan (Modified from (Source: Teoman et al., 2022, pp. 547-557).

It is seen that hybrid systems with ceramic impact faces have the potential to be used in structures such as security door protection and rear compartment armored doors (Teoman et al., 2022, pp. 547-557). The general approach to standards for armoring a civilian vehicle is given in Figure 19.

Figure 19: Armoring of a Civilian Vehicle
(Source: Shield Armoring, n.d.)

When Figure 19 is examined, some basics about vehicle armoring can be seen:

- Ballistic armored security compartments provide maximum protection for the passengers in the vehicle.
- The protection of the armored walls and ceiling against the explosion of two DM 51 grenades at the same time was taken into consideration.
- Reinforced protected door hinges and alignment supports are designed.
- For maximum protection during the attack, wide door closing areas are placed under ballistic protection.
- The suspension system is strengthened to meet the additional weight that comes with armoring.
- Fuel tank is armored.
- There are ballistic glasses that can be operated optionally.
- Run-flat wheel attachments designed to keep the vehicle moving under attack are seen (Shield Armoring, n.d.).

After the armoring process, the vehicle is subjected to detailed tests (Figure 20, Figure 21).

Figure 20: An off-Road Test after Armoring
(Source: Universal Defense for Military Equipment, n.d.)

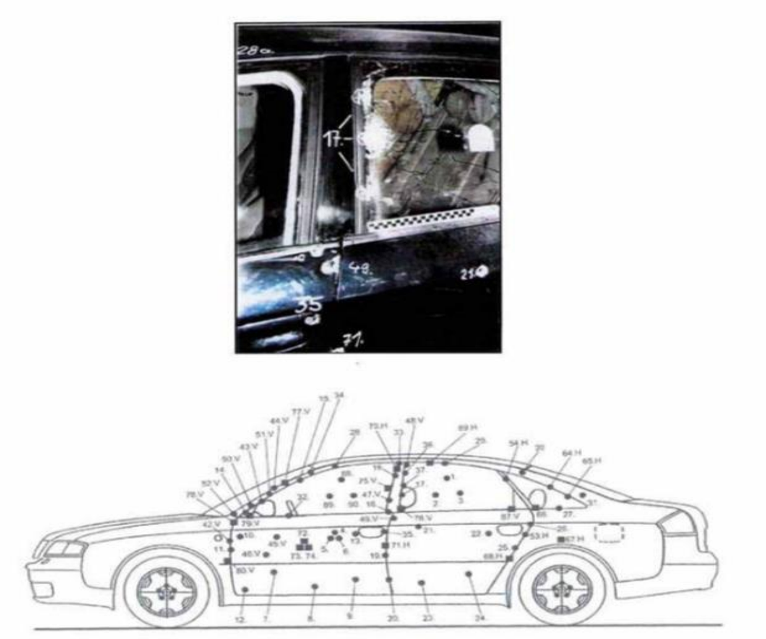


Figure 21: An Ballistic Test after Armoring
(Source: Universal Defense for Military Equipment, n.d.)

2. EXPERIMENTAL STUDY (BALLISTIC TEST AND RESULTS)

The armor panel developed consists of four layers. Schematic diagram of the panel is shown in Figure 22. The strike face of the armor panel consists of alumina ceramic tiles. The projectile hits the ceramic layer first. UHMWPE composite plate was used as the backing plate to absorb the remaining kinetic energy of the projectile. Alumina ceramic tiles and UHMWPE composite plate were bonded with polyurethane based adhesive. Finally, the armor panel was coated with high performance aromatic polyurea/polyurethane hybrid spray elastomer system for the structural integrity of the armor and multi-hit impact resistance. After the ballistic test, ceramic pieces are scattered towards the direction of arrival (towards the outside of the armor) of the ammunition. Thanks to the elastomer coating used to prevent this scattering, the ammunition can still be deformed with the help of the ceramic parts in the confined fracture area and the multi hit resistance of the armor increases.

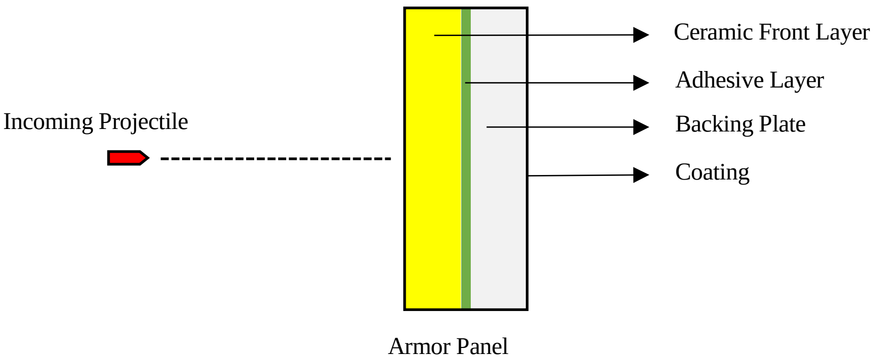


Figure 22: Layers of the Armor Panel.

Standalone armor system was installed to a specific fixture which secured armor panel (Figure 23). Then, ballistic tests were performed for the developed armor configuration.

Figure 23: Standalone Armor System in Fixture.

7.62 mm x 51 M61 AP bullet used in ballistic test has a core weight of 9.45 ± 0.15 g. The velocity of the 7.62 mm M61 AP bullet at 23 meters is 838 ± 9.1 m/s. (Makine ve Kimya Endüstrisi Inc, n.d.). The surface area of the core of the relevant bullet is approximately 45.7 mm^2 and the average kinetic energy density of the bullet is 70.02 j/mm^2.

7.62 mm M61 AP bullet has a similar penetrating capacity to the heavier 7.62 x 63 mm M2 AP and 7.62 mm x 54 AP-I/B32 bullet due to the 7.62 mm M61 AP bullet's AP core form, like the arrowhead form, that prevents the core from being fragmented (Crouch, 2017, pp. 1-54; Stewart, Netherton, 2020, pp. 503-513).

The defined 7.62 mm P80 ammunition in the VPAM PM 2006 standard is similar to the 7.62 mm M61 ammunition. It is the 7.62 mm M61 AP USA version and the 7.62 mm P80 NATO version. 500 HB Armor steel with an areal density of 114 kg/m^2 is required to stop 7.62 mm P80 AP ammunition defined in Level 9 of the VPAM PM 2006 standard, while 500 HB armor steel with an areal density of 126 kg/m^2 is required to stop 7.62 mm x 54 AP-I/B32 ammunition defined at Level 10 (ArcelorMittal, n.d.).

Ballistic set up is shown in Figure 24. The fixture holding the armor panel is heavy enough to perform ballistic tests. There are two clamps providing equal holding force for the armor panel. Target is secured by two bolts located on the clamps. The distance between the rifle barrel and the armor panel is 25 m. A chronograph which measures projectile impact velocity was installed next to the target. Steyr SSG (Scharfschützengewehr) rifle was used for shootings.

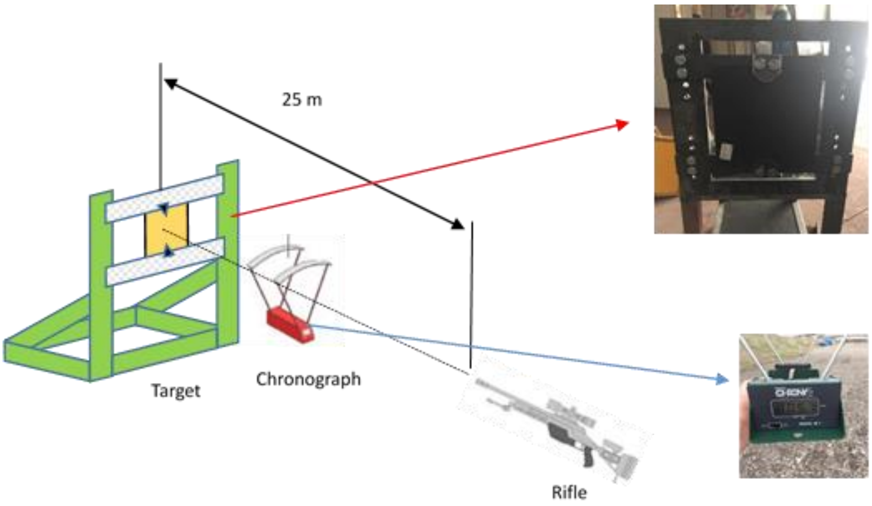


Figure 24: Ballistic Test Set-Up.

Ballistic test was performed against 7.62 mm x 51 M61 AP projectile for the ceramic composite armor panel. The standalone armor system defeated five projectiles without complete penetration. Ballistic test results for the armor panel are shown in Table 1.

Table 1: Ballistic Test Results for the Ceramic Composite Armor Panel

Shooting Number	Projectile Strike Velocity (m/s)	Result
1	825	Partial penetration
2	821	Partial penetration
3	818	Partial penetration
4	827	Partial penetration
5	824	Partial penetration

The standalone ceramic composite armor system view (front face) after ballistic test is seen in Figure 25. Damaged areas created by projectiles are shown with red circles. After five shootings, armor panel protected its structural integrity without perforation.

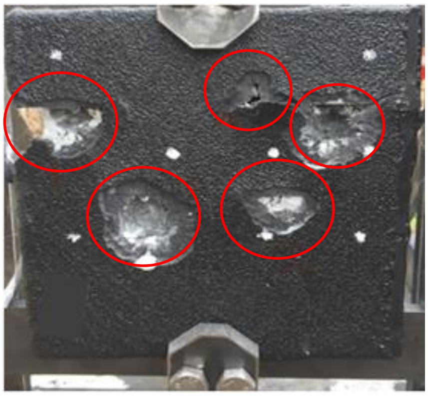


Figure 25: Standalone Ceramic Composite Armor System View after Ballistic Test.

Various armor configurations can be used in civilian vehicle armoring. When ceramic composite armors are used instead of traditional monolithic metallic armors, they provide a significant weight advantage. It is possible to do this with ceramic-based hybrid armors with approximately 50% of the steel weight used to eliminate 7.62 AP ammunition (Khan and Iqbal, 2022, pp. 26147-26167; Lopez-Puente et al., 2005, pp. 321-336; Roberson, 1995).

Table 2: Weight saving compared to UHH armor steels

	Armox Advance	Armox 600T
Approximate Weight Saving over Armor Steels	30%	45%

It is not enough to just eliminate the threat in vehicle armoring. At the same time, multi-shot resistance is expected to be high. Most weapons are automatic or semi-automatic. Therefore, it may not be enough to defeat 3 shots, as in armor solutions made according to the Euronorm 1063 ballistic standard (Teoman et al., 2022, pp. 547-557). According to statistics, 80% of shots are aimed at glass during attacks (Aurum Security, n.d.b). Considering this situation, the transparent armor of the vehicle can be made at a higher level than the opaque armor (Teoman et al., 2022, pp. 547-557).

In vehicle qualification tests, the most challenging conditions affecting the vehicle should be applied. The angle of attack on the target should be selected, taking into account the possibility of maximum ammunition penetration. Necessary tests must be carried out in potentially weak areas such as glass edges and door frames. Since ballistics is a science that includes statistics, a sufficient number of tests should be done for qualification (Aurum Security, n.d.b).

3. CONLUSION

Research results on civilian vehicle armoring, ballistic test results of developed stand-alone ceramic-composite armor and evaluations have been presented in this study and the following results have been reached:

(1) Civil vehicle armoring should be done without losing the desired performance characteristics of the vehicle with the use of appropriate materials according to the threat level.

(2) In this study, 7.62 mm x 51 M61 armor-piercing bullet manufactured in accordance with MIL-C-60617A standards with an average impact energy of 3200 joules was successfully stopped. The average kinetic energy density of the bullet is 70.02 j/mm^2. Armor panel structural integrity was good enough for multi-hit resistance after shootings. Al_2O_3 ceramics used in armor design were divided into large pieces and did not leave the area. For this reason, it can provide ballistic resistance to other threats that may come to the same region.

(3) It is evaluated that this armor configuration with low areal density can be used effectively as a standalone armor for ballistic protection without any additional vehicle or system ballistic structure necessity. As seen in Table 2, the developed armor system saves about 30% weight compared to Armox Advance armor steel and about 45% weight compared to Armox 600T providing the same protection levels.

(4) The developed armor system has a high potential for use in armored military ambulances, naval platforms, civilian armored vehicles, armored containers etc. If the developed armor is used in civilian vehicle armoring, the resulting weight savings provide increase in the maneuverability and in the mobility of the civilian armored vehicle and less wear of the civilian armored vehicle's mechanical parts.

(5) It is obvious that weight saving in a vehicle by using ceramic-composite armor system will bring many advantages – increased payload, better stability and handling, smaller brake path, better acceleration, increased operation life, decrease in fuel consumption.

(6) Up to 5% less fuel consumption can be achieved in armor upgrading activities using high-hardness steel. It is evaluated that there will be a further reduction in fuel consumption with the use of ceramic composite armor.

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