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Ballistic Performance of ETİAL-171 (A360) Aluminium

ETİAL-171 (A-360) Alüminyum'un Balistik Performansı

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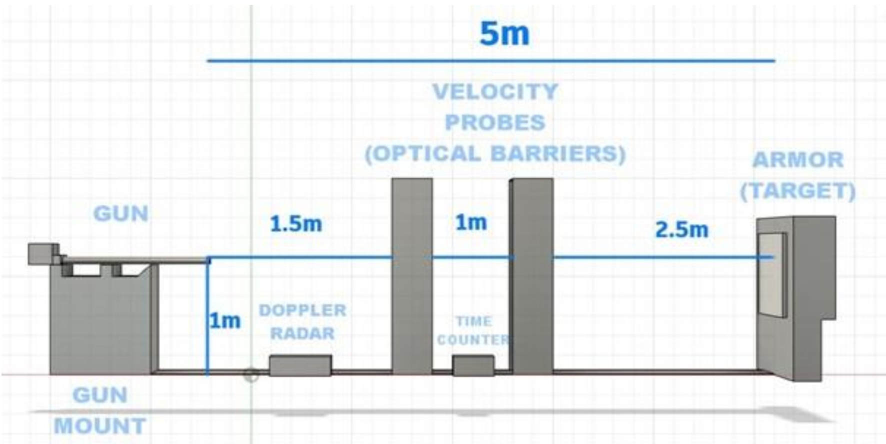
Önemli Noktalar / Highlights

ETİAL-171 (A-360) Alüminyum 9x19 mm mermilere karşı göreceli olarak güzel performans sergilemiştir. Fakat, FB3-Sınıfı şartları için gereksinimleri karşılamamaktadır. ANSYS ile yapılan sümülasyon testleri neticesinde, ETİAL-171 Alüminyum'un kafes zırhı olarak kullanılabileceği kanıtlanmıştır.

The ETİAL-171 (A-360) Aluminum performs relatively good performance against 9x19mm bullets. However, this performance did not satisfy the requirements of FB3-Class. It has been proven by the ANSYS data that the ETİAL-171 series can be used for cage armor.

Grafiksel Özet / Graphical Abstract



Abstract

This study was prepared to determine the ballistic protection capacity of ETİAL-171 (A360) series aluminum. The ballistic tests were divided into two parts, the amateur part which used 9x19 mm ammunition at a distance of 16 meters, and the professional part based on ballistic laboratory data using 357 magnum ammunitions. As a result of these tests, the ETİAL-171 aluminum was able to hold 3 out of 5 bullets based on 9x19 mm bullets, and it was not successful against 357 magnum bullets. When this resistance is evaluated, ETİAL-171 series aluminum cage armor can be used against chemical energy ammunition.

Özet

Bu çalışma ETİAL-171 (A360) serisi alüminyumun balistik koruma kapasitesini belirlemek amacıyla hazırlanmıştır. Balistik testler, 16 metre mesafede 9mm mühimmat kullanılan amatör kısım ve 357 magnum mühimmat kullanılan balistik laboratuvar verilerine dayanan profesyonel kısım olmak üzere iki kısma ayrılmıştır. Bu testler sonucunda ETİAL-171 alüminyum, 9mm mermiler baz alındığında 5 mermiden 3'ünü tutabilmiş, 357 magnum mermilere karşı ise başarılı olamamıştır. Bu direnç değerlendirildiğinde ETİAL-171 serisi alüminyum kafes zırh kimyasal enerjili mühimmatlara karşı kullanılabilmektedir.

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1. INTRODUCTION

Sectoral use of non-ferrous metals increases day by day on a world basis. In this respect, the nonferrous metals show widely varying projected growth rates; the growth rate for aluminum, 4.3 percent per year, is the largest [1]. One non-ferrous metal that has become increasingly important in the defense and military sectors is aluminum. Some series of aluminum are prominet in ballistic and aerospace applications such as 2000, 5000, 7000, and 8000 series aluminum. The first generation of ballistic aluminum armor is the 5000 series by U.S. Military Standards. Aluminum Alloy (AA) 5083-H131 has been used in systems such as the M1113, the M109, and the USMC Amphibious Assault Vehicle (AAV), in accordance with specification MIL-DTL-46027J [2]. This alloy is preferable because of its lighter weight, ease of weldability for manufacturing purposes, level of performance against fragmentation-based threats, and excellent corrosion resistance [2]. After that, the 7075-T6 aluminum alloy is being used as an armor for most of the combat vehicles. It is a heat treatable alloy provides improved protection at all angle and can have very good mechanical properties. Since the minimum weight for the given level of protection also comes into play to considerable mobility, 7075-T6 aluminum alloy armor plates are extensively used for armor vehicle [3]. Also, the 7075 series aluminum is suitable for different heat treatment methods to obtain better mechanical properties. For instance, a new heat treatment route was designed, and the effects of pre-deformation on the retrogression and re-aging (RRA) and 17500 h natural aging (NA) heat treatment were investigated [4]. The results showed that the hardness values, dislocation densities, and lattice strain of the pre-deformed RRA + NA specimens were increased compared to the pre-deformed RRA specimens [4]. Thus, 7000 series aluminum has become the optimum quality for armored vehicles and ballistic properties with different heat treatments and strengthening works. Moreover, some aluminum series have been reinforced with SiC, B_4C, Al_2O_3, and ceramic particles to produce functionally graded material (FGM) and hybrid composites for more resistant defensive materials. These works show that aluminum can be excellent additive with different ceramics for composite armor. For example, the hot-rolled FGM specimen reinforced with B_4C offered the lowest density. The microhardness was improved by 32% and 30.4% in the inner to outer regions of the SiC- and Al_2O_3-reinforced FGMs, respectively, while it was improved by 22.6% in B_4C-reinforced FGM. On the other hand, the tensile strength and elongation of the B_4C-reinforced FGM specimen were better than those of the SiC- and Al_2O_3-reinforced FGMs [5]. In addition, the highest ballistic protection was achieved with B_4C-reinforced laminated FGM at an impact speed of 664.25 m/s with a penetration depth of 14 mm, while the impact speeds of SiC- and Al_2O_3-reinforced FGMs were 500.88 and 435.23 m/s, respectively [5]. In addition, studies have also been conducted on a hybrid Al-matrix composite reinforced with both SiC and B_4C ceramic particulates. For example, the hybrid composite demonstrated a very high dynamic compressive strength (over 1.5 GPa), along with a good total strain of 11.7%, which readily reached an undiscovered strength area (far over 1.2 GPa) of typical composites [6]. The results showed that the hybrid composite was radially cracked with a small hole-mark and a few fallen-off debris, which indicated the higher ballistic properties than those of the SiCp- or B_4Cp-reinforced composite because of outstanding dynamic compressive strength and strain [6]. Lastly, the 2000 series aluminum has been developed for armored vehicles due to its high mechanical properties. The 2139-T8 has a higher ultimate tensile strength (~6% greater than 2519-T87, ~7% than 7039-T64, and ~30% greater than 5083-H131 when compared in the L direction), high hardness (~160 Brinell as compared with ~130-160 for alloys 7039 and 2519 and ~85 Brinell for alloy 5083) and is substantially tougher than all the other the tabulated aluminum alloys in all directions where they could be compared [7]. Furthermore, as with wrought aluminum grades, aluminum products produced by the casting process can also be used in military applications due to their required mechanical properties. The study aims to add the ballistic properties of cast ETİAL-171 (A-360) series aluminum against 9x19 mm and 357 magnum bullets to the literature and to evaluate it as cage armor with the help of ANSYS.

2. EXPERIMENTAL STUDIES

The ETİAL-171 aluminum plates required for this project were cast by the İnter Döküm in cubic 40x40x1 centimeter shapes. The casting process was carried out with green sand molding and an induction furnace with MgO lining at 700 °C. Figure 1 shows the image of the plate cast by the İnter Döküm. Figure 2 shows the composition of the elements that form the plate.

Figure 1: Aluminum cast plate.

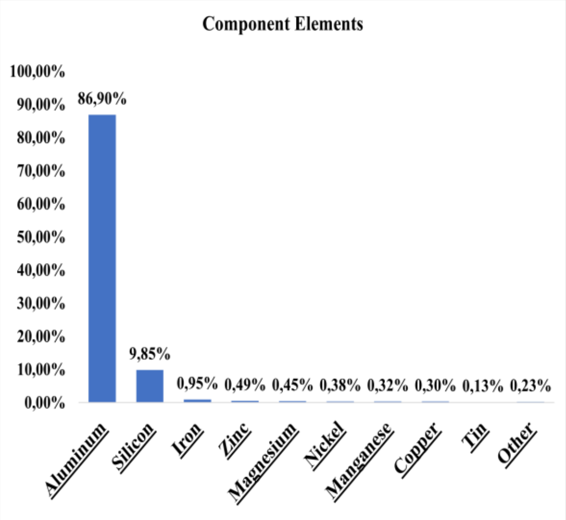

Figure 2: Component elements of cast plates. (Analyzed by inductively coupled mass spectrometry)

The component elements on the figure 2 were found and confirmed by the Thermo iCAP RQ device. Then, the mechanical properties of the plates were determined. These measurements are obtained from the Qness hardness test machine and the UTEST (UTM 4000 and UTC 4940) test machines. The values of the plates in terms of mechanical properties are given in Table 1.

Table 1: Mechanical properties of cast plates.

Hardness, Brinell (HB)	72
Ultimate Tensile Strength (MPa)	298
Tensile Yield Strength (MPa)	145
Elongation (%)	3.2
Shear Modulus (GPa)	22.5
Shear Strength (MPa)	167

Two different methods and two different ammunitions were preferred for the shots on the plates. The first method was carried out amateurishly using 9x19mm ammunition in such a way that there would be 5 shots in the open air from 16 meters without regard to angle. The second method was carried out in the KIM Technology ballistic laboratory by EN-1522-1523 standards by professionally using 357-magnum ammunition. After that, the testing of ETİAL-171 series aluminum as cage armor was carried out on a computer-based basis. The designs made in this study were created by the Fusion 360, and simulations were carried out with the ANSYS Explicit Dynamics.

2.1. ETİAL-171 Aluminum Plate Resistance Against 9x19mm Ammunition

ETİAL-171 series aluminum can be a very suitable alternative in the field of ballistics with its hardness above 70 HB and yield strength above 140 MPa. When these mechanical properties were evaluated, the suitability of low-caliber ammunition for testing was revealed. Low-caliber rounds are classified as ammunition with a core size of up to 7.62 mm and velocities below 1000 m/s. Considering the mechanical properties of the ETİAL-171 series plate and the effect of low-caliber ammunition, 9x19mm bullets have been preferred for firing. These munitions have an average velocity in the range of 360-420 m/s. Considering the weight of the projectiles and their speed, the energy of the projectiles varies in the range of several kilojoules (kj). The 9x19 mm ammunition has a complementary metal envelope and a rounded tip. This study was carried out in an amateur manner. A total of 5 shots were fired, and these shots were fired at a distance of 16 meters in an amateurish manner, with no attention to the angle. Figure 3 shows a photograph taken during the amateur shooting.

Figure 3: A photograph taken during the amateur shooting.

Five different shots were fired at the aluminum plate amateurishly. These shots were fired one after the other, 3 on the front side and 2 on the backside. The ETİAL-171 Aluminum Plate succeeded to hold 3 of 5 shoots on the surface. Figure 4 shows the plate after the amateur shots.

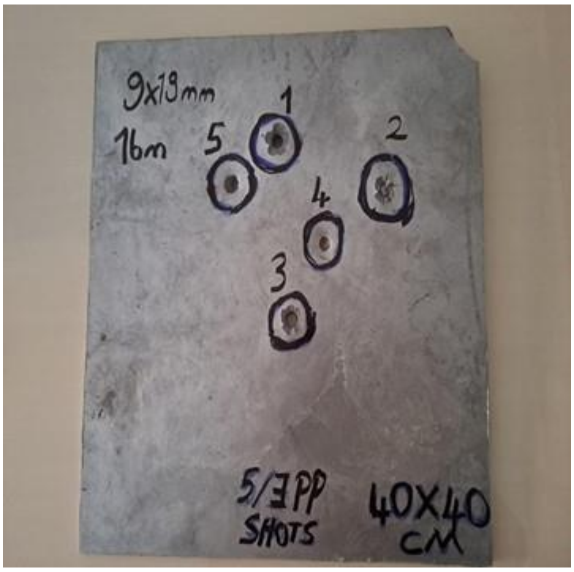

Figure 4: Plate after the amateur shots.

After these shots, the plate was professionally tested at the KIM Technology ballistic laboratory according to EN-1522-1523 standards.

2.2. ETİAL-171 (A-360) Aluminum Plate Resistance Against 357 Magnum Bullet in Accordance with EN-1522-1523 Standards

The work in this section has been carried out according to EN 1522 / 1523 Standards. This standard defines the requirements and classification that windows, doors, shutters, and blinds must satisfy when tested in accordance with EN 1523. Figure 5 shows a schematic exploded view of the FB3 Class ballistic setup.

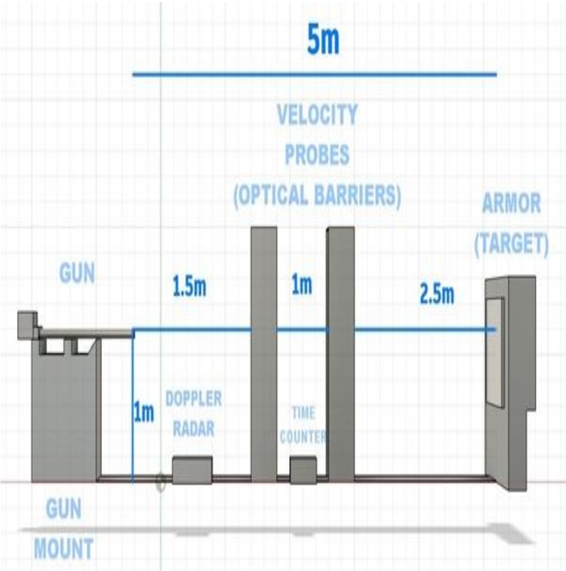

Figure 5: A schematic exploded view of the FB3 class ballistic setup.

This standard applies to attacks by handguns, rifles, and shotguns on windows, doors, shutters, and blinds complete with their frames and infills, for use in both internal and external locations in buildings. Shutters and Blinds must be tested separately and not in conjunction with a window or door, to achieve classification in terms of bullet resistance. When applying this standard, the FB3 Class was preferred instead of the FB2 Class. In the FB2 Class, the 9 mm Luger bullet had already been applied to the plate amateurishly. The effect of the 357-

magnum bullet with higher speed and weight on the plate would be more useful in determining the ballistic resistance of the ETİAL-171 plate. The characteristics and velocity values of the bullet are given in Table 2.

Table 2: Classification and requirements for testing with handguns and rifles (EN-1522-1998 Standards.).

Class	Type of Weapon	Caliber	Bullet		Test condition	
			Type	Mass (g)	Test range (m)	Bullet velocity (m/s)
FB1	Rifle	22LR	L/RN	2.6 ± 0.1	10 ± 0.5	360 ± 10
FB2	Hand gun	9 mm Luger	FJ^1/RN/SC	8.0 ± 0.1	5 ± 0.5	400 ± 10
FB3	Hand gun	357 Mag.	FJ^1/CB/SC	10.2 ± 0.1	5 ± 0.5	430 ± 10
FB4	Hand gun Hand gun (see note)	357 Mag. 44 Rem. Mag.	FJ^1/CB/SC FJ^2/FN/SC	10.2 ± 0.1 15.6 ± 0.1	5 ± 0.5 5 ± 0.5	430 ± 10 440 ± 10
FB5	Rifle	5.56 x 45*	FJ^2/PB/SCP1	4.0 ± 0.1	10 ± 0.5	950 ± 10
FB6	Rifle Rifle (see note)	5.56 x 45* 7.62 x 51	FJ^2/PB/SCP1 FJ^1/PB/SC	4.0 ± 0.1 9.5 ± 0.1	10 ± 0.5 10 ± 0.5	950 ± 10 830 ± 10
FB7	Rifle	7.62 x 51**	FJ^2/PB/HC1	9.8 ± 0.1	10 ± 0.5	820 ± 10

L Lead
FJ^1 = Full steel jacket (plated)

CB Conned bullet
FJ^2 = Full copper alloy jacket

FJ Full metal jacket bullet

FN Flat nose bullet

HC1 Steel hard core, mass (3.7 ± 0.1) g hardness more than 63HRC

PB Pointed bullet

RN Round nose bullet

SC Soft core (lead)

SCP1 Soft core (lead) with steel penetrator (type SS109)

* To achieve stated values for (5.56 x 45), the recommended barrel twist length = (178±10) mm.

** To achieve stated values for Class FB7, the recommended barrel twist length = (254±10) mm.

For this test, soft point ammo is used, and two of the three shots required have been successfully applied by the KIM Technology. The last shot was not fired. Figure 6 shows the performance of the plate after shots.

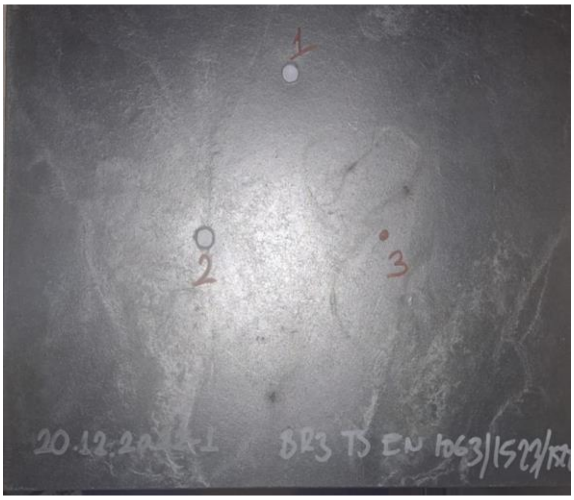

Figure 6: ETİAL-171 plate after 357-magnum shots.

The report generated within the scope of that test by the KIM Technology. Table 3 shows the ballistic test report data.

Table 3: Ballistic test report data.

Name of Ballistic Test Standard	TS EN 1522/1523	
Level of Ballistic Test Standard	FB3	
Date	20.12.2022	
Time	10:00	
Test Number	20122022-1	
Ambient Temperature (°C)	19,9	
Ambient Humidity (%RH)	50,2	
Sample Information		
Owner of Sample	Yıldırım Beyazıt Üniveristesi	
Name of Sample	20122022-1	
Serial Number	-	
Weight / Size	*/400x400 mm	
Test Equipment		
Shot Distance (m)	5	
Velocity Reading Distance (m)	2,5	
Barrel / Gun	.357 Mag	.357 Mag
Bullet Weight / Gunpowder Amount (gn)	157.4 gn	-
Backing Material		
Name	Temperature	
-	-	
Results of Drop Test	-	
- - - - -	Average	-

Shot No	Velocity (m/s)		Deformation	Penetration (CP-PP)
1	431,2	431,3	-	CP
2	432,8	432,9	-	CP
Notes: -				

(a): Low Velocity
(b): High Velocity
(Possible Velocity Interval): 430 ± 10 m/s
CP: Complete Penetration
PP: Partial Penetration

2.3. ETİAL-171 Aluminum Cage Armor Simulation

The densities of aluminum alloy vary between 2.66-2.84 g/cm^3. The aluminum alloy has good advantages with density values, and impact-damping capacity. They have been used as door struts, windshield frames, extruded turret armor, and forged turret rings in light armored vehicles. In heavily armored tanks, it is used in the form of cage armor against high explosives and RPG ammunition. Chemical energy munitions, such as RPG, high-explosive (HE), high-explosive anti-tank (HEAT), and high-explosive squash heads (HESH), are freely directed at the target on impact. Typically, the copper or aluminum metal wall material is conical in shape, with the inner side facing in the opposite direction, and with the explosion, all the energy is concentrated in the focus of the conical inner surface, forming a long jet directed at the target. In simple terms, this is a metallic mass directed toward the target at extremely high velocity and pressure. In a sense, the metallic conical wall has now become a penetrator, and the impact velocity reaches 7-9 km/s, compared to 1-2 km/s for typical penetrators. The metallic conical-shaped design is surrounded by explosives. With detonation, the explosives collapse into this conical structure, focusing it and compressing it with heat and detonation energy, creating a plasma jet of 8000-9000 m/s (25 Mach) [8]. The metallic layer is not molten but exhibits a fluid behavior under the influence of high pressure. Thus, when it hits the tank armor, the extremely high pressure deforms the armor, pushing the armor material and creating a penetration hole in front of the plasma jet. This type of explosive reaches stresses that exceed the mechanical strength of the armor in local areas of the armor with high pressure. Cage armor is used to minimize the effect of such explosives. Thus, it is aimed to lose the high pressure of the chemical energy ammunition detonated before it reaches the main armor. In this type of cage armor, 5083-H131, 7039-T64, 7075-T6, and 2519-T87 aluminum plates are used. In this section, the ETİAL-171 series aluminum is designed as cage armor with the help of the Fusion 360. Then, the resistance values that this design would be calculated against chemical-powered munitions were found with the help of the ANSYS Explicit Dynamics. Figure 7 shows the technical drawing of cage armor, ammunition, and main armor to describe the test design generated by the Fusion 360. In the simulation, the main armor is RHA, the cage armor is the ETİAL-171 Aluminum, the ammunition is 120 mm HE with a total of 4.5 kg TNT. Figure 8 shows the effect after detonation of the high explosive (HE) ammunition. Figure 9 shows the effect of the explosion on the ETİAL-171 aluminum.

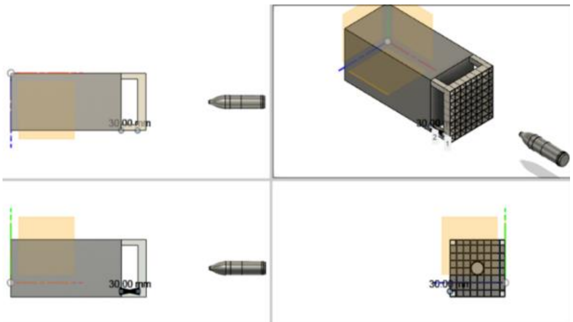

Figure 7: Technical drawing of the cage armor, ammunition, and main armor for test design.

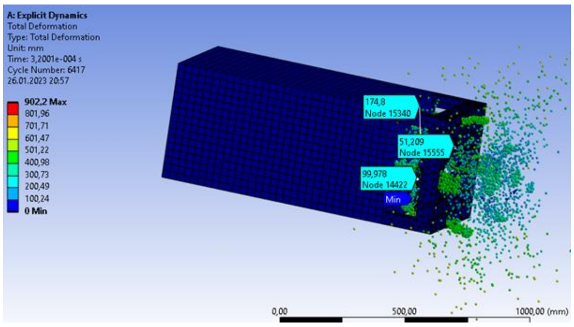

Figure 8: After detonation of the HE ammunition.

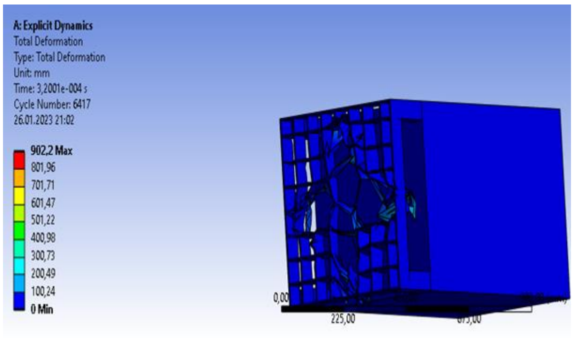

Figure 9: The Effect of the HE ammunition on the ETİAL-171 cage armor.

Then, these experiments were simulated again without cage armor. In order to better demonstrate the effect of the ETİAL-171 cage armor on the protection of the main armor. Figure 10 shows the impact and penetration of high explosive (HE) ammunition on the main armor without cage armor.

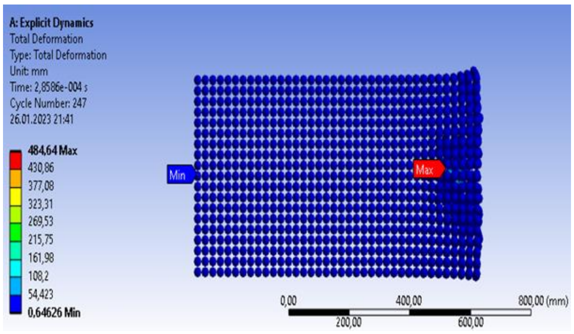

Figure 10: Impact and penetration of the HE ammunition on the main armor without cage armor.

High explosive ammunition, RPG, and various artillery shells reach very high values in terms of areal energy density. They create shock pressures during the explosion with the intensity level of energy density. Figure 11 shows blast wave and pressure difference during the explosion.

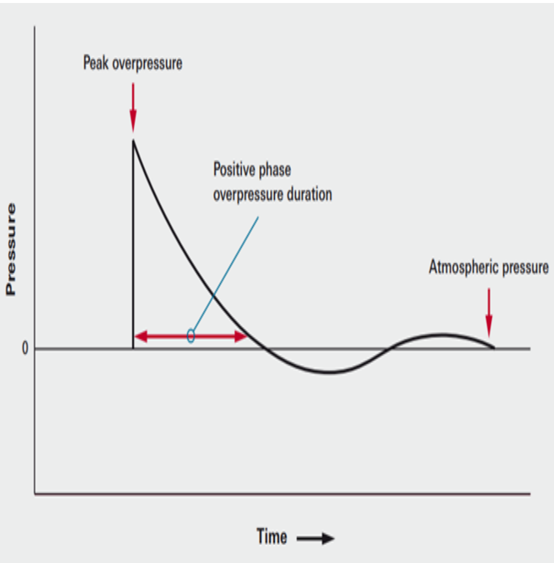

Figure 11. A visual representation of the blast wave, showing the pressure changes. [9,10].

Since it dampens and reduces this shock wave on the main armor, the ETİAL-171 aluminum stand outs as a cage armor.

3. RESULTS AND DISCUSSION

According to simulation data, in a system protected by the ETİAL-171 cage armor, the high-explosive projectile could not show any penetration characteristics on the main armor. ETİAL-171 series aluminum, in terms of hardness and other mechanical properties, had the effect of breaking the integrity of the projectile. The fact that the explosion took place in the atmosphere ensured that the armor did not show creep behavior under high pressure and temperature. The ETİAL-171 cage armor protection systems provide excellent protection against high explosive projectiles, even though its total deformation is two times greater than that of RHA steel. The 120 mm HE ammunitions can penetrate up to 200 mm into RHA steel without cage armor.

ETIAL-171 (A-360) series aluminum reaches very good values in terms of mechanical properties. Even, the plate suffered a 5% loss of mechanical properties due to the low quality of the raw material during the casting process in this project. The density value of A-360 Aluminum is between the 5083-H131 series aluminum and the 2219-T87 series aluminum. This aluminum series is not processed without any heat treatment, with excellent viscous behavior and high silicon content during casting. The ammunitions and the kinetic energy they are generate as follows:

$$E(kinetic) = \frac{1}{2} \times m \times v^2 \qquad (1)$$

$E_k\ of\ 9mm\ Luger$:

$$= \frac{1}{2} \times 8.0g \times 400^2 m^2/s^2 = 640Joule$$

$E_k\ of\ 357\ Magnum$:

$$= \frac{1}{2} \times 10{,}2g \times 430^2 m^2/s^2 = 943 Joule$$

The 357-magnum ammunition also has a different design in terms of its envelope and softness. With this bullet structure, it penetrates the plate in the form of plugging. When penetration in metallic armor is considered, there is a direct relationship with the thickness of the target. If expressed by the formula:

$$\boldsymbol{h} = \left(\frac{\boldsymbol{mv^2}}{\boldsymbol{\pi D^2}}\right) \times \frac{\boldsymbol{1}}{\boldsymbol{\sigma_0}} \quad (2)$$

"h" is the thickness of the target; "D" is the bore diameter (equal to the projectile diameter); "m" and "v" are the penetrator mass and velocity, "$\boldsymbol{\sigma_0}$" is the target strength.

ETİAL-171 series aluminum was able to hold 3 out of 5 shots fired from 16 meters using a 9x19mm bullet on the armor. For the 9x19mm Luger bullet, the armor plate with 72HB hardness showed that it did not have the strength to break the core of the bullet, but with its relatively high toughness value, it did not allow the bullet to pass through the armor with a success rate of 60%. Moreover, when we examined the data simulated as cage armor, we obtained the results that high-explosive chemical energy projectiles would apply the necessary pressure on the trigger mechanism for detonation in a way that minimizes the effect on the main armor. According to the simulations, we minimize the stress value of 484 MPa on the main armor with the cage armor. In addition, the maximum deformation data on the cage armor reaches a stress value of 902.2 MPa. This difference shows us the difference in strength between RHA steel and ETİAL-171 Aluminum. It is obtained from simulation data that it will be a useful alternative to cage armor. As a result of firing with 357-Magnum bullets, it was unsuccessful to keep the bullets on the armor. The 357-Magnum projectile was successful in penetrating the armor with its 943 Joules kinetic energy and round nose flat point made of high-strength metal. ETİAL-171 aluminum in its no heat-treated form was partially successful up to the FB3 projectile penetration class, but it is insufficient for the FB3 projectile penetration class. It shows insufficient performance as a personal ballistic protector. Resistance against FB3 class can be provided, by applying to quench, tempering heat treatments, and cold or hot work on this subject. However, it is an ineffective option, considering its weight and density. In addition, with these weight and density values, success can be achieved in accessories such as doors, window edges, aerospace material, and door handles in building protection systems. Moreover, it can show excellent backbone performance and shrapnel-damping capability with its toughness.

4. CONCLUSIONS

Armor technologies consist of advanced composites with developing material technology. With these composites, high mechanical properties are optimized with appropriate weight values. Aluminum is used in some protection systems and aerospace applications with its cheap production, easy shaping, and relatively good mechanical properties. While the A-360 aluminum series is ideal as cage armor, it is insufficient as individual protective equipment. Heat treatment can be applied to increase mechanical properties for different protection classes. However, the increasing core weight with the speed of the bullets reveals the inadequacy of aluminum together with the reports. Therefore, it is healthier to use this series of aluminum as a cage armor system, and shrapnel damping system.

5. LIMITATIONS OF THE PROJECT

The simulations performed within the scope of this project are carried out by the ANSYS Explicit Dynamics student version. This situation creates certain limitations. These limits are due to the use of the student version. Problem size limits are Structural Physics: 128K nodes/elements., The simulation data can be elaborated and repeated in more detail in different ways due to this situation. The simulation data used in this study were made in a way that can be compared with real data.

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AUTHORSHIP CONTRIBUTION STATEMENT

Baran ÖZDEMİR: Conceptual design, Data curation, Analysis, Funding acquisition, Research, Methodology, Project management, Resources, Software, Audit, Approval, Visualization, Writing-Draft, Writing-Reviewing, Editing, and Experimental studies.

CONFLICTS OF INTEREST

The author declares that he has no conflict of interest.

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