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Recent developments in ballistics

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Abstract

Ballistics, the science of projectile motion, encompasses the study of objects such as bullets, missiles, and rockets from launch to impact, divided into internal, external, terminal, and forensic ballistics. This paper explores recent advancements in ballistic materials, methods, and sustainability challenges. Traditional and self-healing materials, including microcapsule-based, bio-inspired, and metallic self-repairing systems, are examined for their applications in armor, projectiles, and thermal protection.

Experimental techniques like light gas guns and high-speed photography, alongside numerical simulations such as finite element analysis (FEA) and smoothed particle hydrodynamics (SPH), are compared for their efficacy in ballistic research. High-velocity projectiles exceeding Mach 5, including hypersonic and kinetic energy penetrators, are analyzed for their aerodynamic and material challenges, with future directions pointing toward AI-guided systems and 3D-printed materials.

The study also highlights green ammunition innovations, such as lead-free bullets and biodegradable cartridges, to address environmental concerns like toxic propellants and heavy metal contamination. Sustainability efforts focus on resource efficiency, including recycled composites and additive manufacturing, while military and civilian applications explore hypersonic swarms and non-lethal munitions.

The paper concludes with future perspectives, emphasizing digital twins in forensics, space ballistics, and closed-loop ammunition recycling. By integrating experimental and computational approaches, this research aims to advance ballistic technologies while addressing ecological and ethical challenges in the field.

Keywords: ballistics, armor, projectiles, sustainability

1. Introduction

Ballistics is the science of projectile motion, encompassing the behavior of objects such as bullets, missiles, and rockets from launch to impact. Ballistics can be divided into three categories: internal ballistics, external ballistics, and terminal ballistics. Internal ballistics examines the internal processes of a weapon, such as thrust, pressure, and muzzle dynamics. External ballistics examines the bullet's flight, trajectory, drag, and wind effects. Terminal ballistics examines penetration, fragmentation, and tissue damage.

Types of ballistics can be categorized as interior ballistics, exterior ballistics, terminal ballistics, and forensic ballistics. The types of ballistics, focus areas, and key factors are shown in Table 1. In addition, Table 2 shows the application sectors, usage patterns, and sample technologies [1], [2].

Ballistics studies are used in the military, forensics, aviation and space, and counterterrorism. For example, the use of self-guided sniper rounds in the military and the controlled landing of a spacecraft under changing aerodynamic forces in aviation are examples of ballistics [3], [4], [5], [6], [7].

In this study, traditional and self-repairing materials used in ballistic applications were examined. In addition, experimental and numerical simulation methods used in ballistic research were examined. Then, the traditional and high-speed bullets used in ballistics were mixed. Traditional and green ammunition, intelligent and guided ammunition were examined.

The environmental effects encountered in ballistic sustainability and difficulties, such as resource efficiency, were examined in this research, and solutions to these difficulties were investigated. Tables 1 and 2 below show types of ballistics, focus area, and key factors, as well as application areas, use cases, and example technologies investigated.

Table 1. Types of ballistics, focus area, and key factors

Type	Focus Area	Key Factors
Internal	Inside the barrel	Propellant burn rate, pressure curves, barrel harmonics
External	Projectile in flight	Drag coefficients, Coriolis effect, gyroscopic stability
Terminal	Target impact	Penetration depth, energy transfer, wound ballistics
Forensic	Crime investigation	Bullet matching, gunshot residue (GSR) analysis

Table 2. Application areas, use cases, and example technologies

Field	Use Case	Example Technologies
Military	Long-range sniping, missile guidance	EXACTO smart bullets, hypersonic glide vehicles
Law Enforcement	Crime scene reconstruction	3D bullet trajectory mapping (FARO systems)
Aerospace	Rocket staging, re-entry vehicles	SpaceX’s reusable rocket ballistics
Sports	Archery, shooting sports	Aerodynamic arrow designs, precision rifles
Medical	Ballistic trauma research	FBI’s wound ballistics studies

2. Materials

Various materials are used in ballistics. These materials can be divided into general materials and self-healing materials. Here, we will examine the general materials as projectile materials, armor materials, cannon materials, and thermal protection materials [3], [4], [5].

2.1 General

Detailed comparison tables of materials used in ballistic applications, including projectiles, armor, railgun components, and thermal protection systems, are provided below. Projectile materials are listed in Table 3, armor materials in Table 4, railgun materials in Table 5, and thermal protection materials in Table 6.

In Table 3, projectile materials comparison is given for high-speed kinetic penetrators, hypersonic vehicles, and railgun slugs. In Table 4, armor materials comparison is specified for defeating high-speed projectiles, fragmentation, and shaped charges.

In Table 5, railgun materials comparison is given for rails, armatures, and structural components in electromagnetic launchers. In Table 6, thermal protection materials are conferred for hypersonic projectiles, re-entry vehicles, and railgun components [1].

Table 3. Projectile materials comparison

Material	Density (g/cm^3)	Melting Point (°C)	Strength (MPa)	Advantages	Disadvantages	Applications
Tungsten Carbide (WC)	15.6	2,870	500–1,200	Extreme hardness, high density	Brittle, expensive	APFSDS rounds, penetrators
Depleted Uranium (DU)	19.1	1,132	1,000–1,600	Self-sharpening, pyrophoric	Toxic, radioactive	Tank penetrators
Titanium Alloy (Ti-6Al-4V)	4.43	1,650	900–1,100	Lightweight, strong	Lower density than tungsten	Aerospace projectiles
Steel (4340 Alloy)	7.85	1,425	1,000–1,500	Cost-effective, tough	Heavy, lower performance	General-purpose ammo
Carbon-Carbon Composite	1.8–2.1	3,000 (sublimes)	200–500 (flexural)	Light, heat-resistant	Low impact resistance	Hypersonic vehicle nose tips

Table 4: Armor materials comparison

Material	**Hardness (HV)**	**Density (g/cm^3)**	**Advantages**	**Disadvantages**	**Applications**
Rolled Homogeneous Armor (RHA Steel)	300–400	7.85	High toughness, cost-effective	Heavy, limited vs. DU penetrators	Tanks, armored vehicles
Ceramic (Al_2O_3, SiC, B_4C)	2,500–3,500	3.2–3.5	Extreme hardness, lightweight	Brittle, multi-hit issues	Body armor, vehicle add-on
UHMWPE (Dyneema, Spectra)	-	0.97	Lightest armor, stops fragments	Weak vs. high-velocity AP	Bulletproof vests
Aramid (Kevlar, Twaron)	-	1.44	Flexible, good for fragmentation	Degrades under UV/heat	Helmets, soft armor
Reactive Armor (Explosive Sandwich)	-	Varies	Defeats shaped charges	One-time use, dangerous to nearby troops	Tank protection

Table 5: Railgun materials comparison

Material	**Conductivity (MS/m)**	**Melting Point (°C)**	**Advantages**	**Disadvantages**	**Applications**
Copper (Cu)	58	1,085	High conductivity	Low strength, erodes quickly	Traditional rails
Copper-Chromium-Zirconium (CuCrZr)	45–50	1,080	Better wear resistance	Still erodes under plasma	Advanced railgun rails
Tungsten (W)	18	3,422	Extreme durability	Poor conductivity, heavy	Rail liners
Graphene-Enhanced Copper	~60 (estimated)	1,085+	High conductivity, reduced wear	Expensive, experimental	Next-gen railgun rails
Plasma Armature (Aluminum Plasma)	-	N/A (ionized gas)	No solid wear	Energy loss due to heat	Ultra-high-speed launches

Table 6: Thermal protection materials

Material	**Max Temp. (°C)**	**Thermal Conductivity (W/m·K)**	**Advantages**	**Disadvantages**	**Applications**
Carbon-Carbon (C/C)	3,000+	50–150 (anisotropic)	Light, reusable	Expensive, oxidizes above 450°C in air	Hypersonic leading edges
Ultra-High-Temp Ceramics (ZrB_2-SiC)	2,500+	60–120	Excellent ablation resistance	Brittle, hard to machine	Nose cones, scramjet parts
Tungsten (W)	3,422	170	Extreme melting point	Heavy, oxidizes	Railgun projectiles
Phenolic Impregnated Carbon Ablator (PICA)	1,700+	0.1–0.5	Lightweight, ablative	Single-use, chars away	Spacecraft heat shields
Hafnium Carbide (HfC)	3,900+	20–30	Highest known melting point	Extremely expensive	Experimental hypersonics

2.2. Self-healing

High-velocity projectiles, hypersonic vehicles, and spacecraft face extreme conditions. This is why, for example, hypersonic missiles experience temperatures of up to 3,000°F. Similarly, microcracks form in railgun barrels and rocket nozzles due to repeated stress. Therefore, materials that can autonomously repair damage are needed to extend lifespan.

Self-healing materials in ballistics can be divided into four categories: microcapsule-based healing, bio-inspired healing, intrinsic self-healing polymers, and metallic self-healing [3].

Microcapsule-based healing uses small polymer capsules (50–200 μm) filled with healing agents such as dicyclopentadiene embedded in composites. When cracked, the capsules rupture, releasing polymerized liquid to seal the gaps. They are also used as heat shields in the thermal protection systems of SpaceX spacecraft and in self-healing coatings on weapon barrels to reduce wear.

In bio-inspired healing, the mechanism mimics human blood vessels; hollow channels in the material deliver healing agents upon damage. For example, in military use, they prevent fatigue cracks in turbine blades in jet engines.

In intrinsic self-healing polymers, reversible hydrogen bonds recombine under heat/light. For example, polyurethane-elastomer composites are used in missile wings.

Metallic self-healing involves the use of Ni-Ti shape-memory alloys, which fill cracks when heated. For example, self-healing metals are being tested for artillery shells [3].

3. Methods

Both experimental and numerical simulation methods are used in ballistic research. Detailed comparison information covering the principles, advantages, limitations, and applications of experimental methods and numerical simulations used in ballistic research is provided in Tables 7-9.

It is seen from Table 7 that experimental methods in ballistics, their description, advantages, disadvantages, and applications are given.

Numerical simulations in ballistics are also given, namely in Table 8 via their definitions, advantages, limitations, as well as application areas.

Comparison of experimental vs. numerical approaches in ballistics is given in Table 9, for different criteria, including cost, time, accuracy, scalability, as well as limitations.

Table 7: Experimental methods in ballistics

Method	Description	Advantages	Limitations	Applications
Light Gas Gun (LGG)	Uses compressed hydrogen/helium to launch projectiles at **Mach 6+**	Extremely high velocities, controlled environment	Limited projectile size, single-shot	Hypervelocity impact studies, armor testing
Split-Hopkinson Pressure Bar (SHPB)	Measures dynamic material properties under high strain rates	Accurate stress-strain data for materials	Limited to small samples, not full-scale	Penetrator/armor material characterization
Ballistic Gel Testing	Fired projectiles into calibrated gelatin blocks	Simulates tissue damage, standardized testing	Not fully representative of human tissue	Terminal ballistics, wound ballistics
High-Speed Photography	Captures projectile flight/impact at **>1,000,000 fps**	Visualizes deformation, fragmentation	Expensive, requires precise timing	Fragment analysis, impact dynamics
Flash X-ray Imaging	X-ray pulses capture internal projectile/armor interactions	Sees through obscuration (smoke/debris)	Limited to a few frames, radiation hazards	Penetrator behavior behind armor
Doppler Radar (e.g., Weibel, RAdar)	Tracks projectile velocity and deceleration in flight	Real-time velocity data, long-range	Expensive, requires a clear line of sight	Exterior ballistics, drag coefficient validation

Table 8: Numerical simulations in ballistics

Software/Method	Description	Advantages	Limitations	Applications
Finite Element Analysis (FEA) (e.g., ANSYS, LS-DYNA)	Solves material deformation under impact using mesh-based methods	Handles complex geometries, material nonlinearity	Computationally expensive, mesh dependency	Armor penetration, fragment simulation
Smoothed Particle Hydrodynamics (SPH)	Meshless Lagrangian method for extreme deformations	No mesh distortion issues, good for fractures	High computational cost, less accurate for elasticity	Hypervelocity impacts, explosive fragmentation
Computational Fluid Dynamics (CFD) (e.g., Fluent, OpenFOAM)	Models aerodynamics, shockwaves, and heat transfer	Captures hypersonic flow physics	Requires high-fidelity turbulence models	Drag/wave drag optimization, thermal analysis
Molecular Dynamics (MD)	Simulates atomic-scale interactions under impact	Reveals material failure mechanisms	Limited to nanoscale, extreme computational cost	Novel material design (e.g., graphene armor)
Coupled Eulerian-Lagrangian (CEL)	Combines fluid (Eulerian) and solid (Lagrangian) modeling	Ideal for fluid-structure interaction (e.g., shaped charges)	Complex setup, long solve times	Explosively formed penetrators (EFPs), blast effects
Discrete Element Method (DEM)	Models granular materials (e.g., sand, ceramic fragmentation)	Simulates brittle fracture, particulate flow	Limited to granular systems, calibration needed	Ceramic armor failure, soil penetration

Table 9: Comparison of experimental vs. numerical approaches

Criteria	Experimental Methods	Numerical Simulations
Cost	High (equipment, ammo)	Lower (after software acquisition)
Time	Slow (setup, repetition)	Faster (parametric studies)
Accuracy	High (real-world physics)	Depends on model fidelity
Scalability	Limited (physical constraints)	Highly scalable (virtual prototypes)
Data Output	Direct measurements (e.g., velocity, damage)	Full-field data (stress, temp., etc.)
Limitations	Safety risks, material costs	Requires validation, assumptions
Best For	Validation, terminal effects	Parametric optimization, conceptual design

4. High-speed projectiles

In ballistics, high-velocity projectiles refer to objects launched at speeds significantly higher than conventional ammunition, typically exceeding 1,700 m/s (Mach 5). These projectiles are analyzed for internal ballistics (inside the weapon), external ballistics (flight dynamics), and terminal ballistics (impact effects) [4], [5].

High-velocity projectiles can be divided into hypersonic projectiles, kinetic energy penetrators, and hypervelocity impactors. Hypersonic projectiles are used in advanced military applications such as railguns and scramjet-assisted projectiles. Kinetic energy penetrators are used in tank ammunition, such as armor-piercing and finned projectiles. Hypervelocity impactors are used in space exploration.

High-speed projectiles present challenges such as aerodynamic heating, drag, and stability. For example, at speeds of Mach 5+, air friction causes extreme temperatures (1,000-3,000°C), requiring advanced materials such as tungsten, ceramic, or carbon composites. Shock waves also disrupt flight; specialized shapes, such as thin nose cones, improve efficiency. Furthermore, spin stabilization can fail; fins or homing systems are typically used. Propulsion methods such as chemical thrusters and electromagnetic railguns are used to address these challenges.

High-velocity projectiles can be used in military and civilian applications. For example, these high-velocity projectiles are used in military applications, long-range precision-strike hypersonic missiles, and to penetrate modern tank armor. In space and science, high-velocity projectiles are also used to simulate high-velocity impacts on satellites and to test asteroid deflection via hypervelocity impact.

Future developments of high-velocity projectiles can be envisioned as follows: the use of guided hypersonic projectiles for AI-assisted mid-range corrections, the use of energy-efficient railguns to overcome power and barrel wear issues, and the use of 3D-printed materials to develop heat-resistant alloys for sustained hypersonic flight [1], [2].

5. Ammunition

Ammunition is a term that encompasses all spare parts and ammunition necessary for warfare that are not fixed assets. Ammunition, on the other hand, is any explosive or penetrating material prepared for firing from firearms. There are many different types of ammunition. This section will focus solely on green ammunition and smart ammunition.

Green ammunition is used in environmentally friendly ballistics to reduce toxicity, pollution, and resource consumption in firearms and artillery. Green ammunition includes lead-free bullets, biodegradable cartridges, and clean propellants.

Lead poisoning harms wildlife and contaminates shooting ranges. Non-toxic W-Cu alloys, lightweight polymer-composite bullets, and ammunition that fragments on impact and does not ricochet can be used as solutions. These are examples of lead-free ammunition.

Brass/steel cartridges take decades to decompose. This creates environmental pollution. Biodegradable cartridges can be used as a solution to this problem. Examples of this include PHA-based polymers and seed-embedded hives. PHA-based polymers decompose within 1-2 years, and seed-embedded hives are destroyed and then planted. Nitrocellulose gunpowder emits carcinogenic substances. Alternatively, nitroamine-based propellants, which have lower toxicity and higher energy efficiency, are used, or electric ignition, which eliminates the chemical encapsulation.

Smart and guided munitions can be divided into two categories: self-guided projectiles and AI-assisted targeting. Self-guided projectiles have demonstrated real-time course correction. Self-guided projectiles have demonstrated real-time course correction. Machine learning increases hit probability for snipers and artillery by taking into account wind, humidity, and target movement. Machine learning, used in AI-assisted targeting, increases hit probability for snipers and artillery by accounting for wind, humidity, and target movement.

6. Sustainability

The field of ballistics is facing increasing scrutiny regarding environmental impact, resource efficiency, and ethical concerns, while also advancing with the latest technologies. Below is a breakdown of sustainability challenges [4], [5].

Sustainability challenges in ballistics can be divided into two categories: environmental impacts and resource efficiency. Environmental impacts include toxic propellants, heavy metals, and ammunition contamination. For example, traditional gunpowder (nitrocellulose) and lead-based bullets contaminate soil/water. Green ammunition, known as lead-free bullets (W or Cu composites), could be used as a solution. Biodegradable cartridges (plant-based polymer cartridges) could also be a potential solution.

Ammunition pollution is another factor affecting the environment. Unexploded ordnance, such as landmines and artillery shells, damages ecosystems. Research is underway on self-degrading mines as a solution to this problem. Furthermore, AI-powered cleaning drones are being used to detect and destroy old ammunition. Another challenge in sustainability is resource efficiency. Resource efficiency can be explored in terms of rare earth material dependency and energy-intensive systems. Tungsten is a combat material used in armor-piercing projectiles. As an alternative to this heavy metal, some recycled composites, such as depleted uranium alternatives, can be used. Additive manufacturing (3D printing) can also be used to reduce waste in projectile production. Rail guns and hypersonic missiles also require tremendous power. Energy sources such as portable fusion reactors are being explored as alternative solutions [8], [9].

7. Future perspectives

Future perspectives and innovations can be briefly examined in four groups: military and defense, forensics and law enforcement, space and aviation, and civilian applicati**ons** [6], [7]**.** Various trends, their application examples, and sustainability angles for military and defense are shown in Table 10.

Table 10. Military & defense applications and sustainability

Trend	Example	Sustainability Angle
Hypersonic Swarms	AI-coordinated micro-missiles	Reduced collateral damage
Energy Weapons	Laser interceptors (e.g., *HELIOS*)	No physical ammunition waste
Bio-Inspired Design	Shape-changing projectiles (DARPA)	Improved aerodynamics = less fuel use

Forensics and law enforcement, topics such as digital twins and non-lethal smart munitions can be discussed. In preparing digital twins for crime scene problems and supporting critical decision-making processes, 3D simulated bullet trajectories reduce laboratory waste. Furthermore, fatalities can be minimized by using electroshock bullets, a type of non-lethal smart munition. In space and aviation, research is underway for future use in self-orbiting satellites and planetary defenses [10], [11].

Finally, for civilian applications, sustainable hunting ammunition and sport shooting can be discussed. Regarding sustainable hunting ammunition, it can be noted that Federal's non-toxic shot (steel/bismuth shot) is gradually replacing lead. Furthermore, studies on the construction of solar-powered shooting ranges and the use of recycled brass materials in sport shooting can be reported. Various areas, including green ammunition, space ballistics, and sustainability, are shown in Table 11 between 2025 and 2030 as well as beyond 2030 [4], [5], [6], [7], [8], [12], [13].

Table 11. Future outlook for different areas between 2025 and 2030.

Area	2025–2030	Beyond 2030
Green Ammo	Mandatory lead bans (EU/NATO)	Bio-fabricated "living bullets"
Space Ballistics	Hypersonic missile treaties	Lunar railgun launches pads
Sustainability	Range cleanup drones	Closed-loop ammo recycling

Recently, experimental and numerical investigations have been done about the ballistic impact on polymer-based composite materials as well as metallic systems [14], [15], [16], [17], [18]. In polymeric-based composite metals [14], [15], various guns were used from a certain distance to the target, and their impact performance was determined (Figure 1). Also, various design in metallic systems (Figure 2) was employed and their impact performance was investigated via experimental as well as numerical systems [16], [17]. It is predicted that some more investigations can be done about the ballistic impacts of different materials and composites to better understand of the ballistic performance via experimental as well as numerical studies.

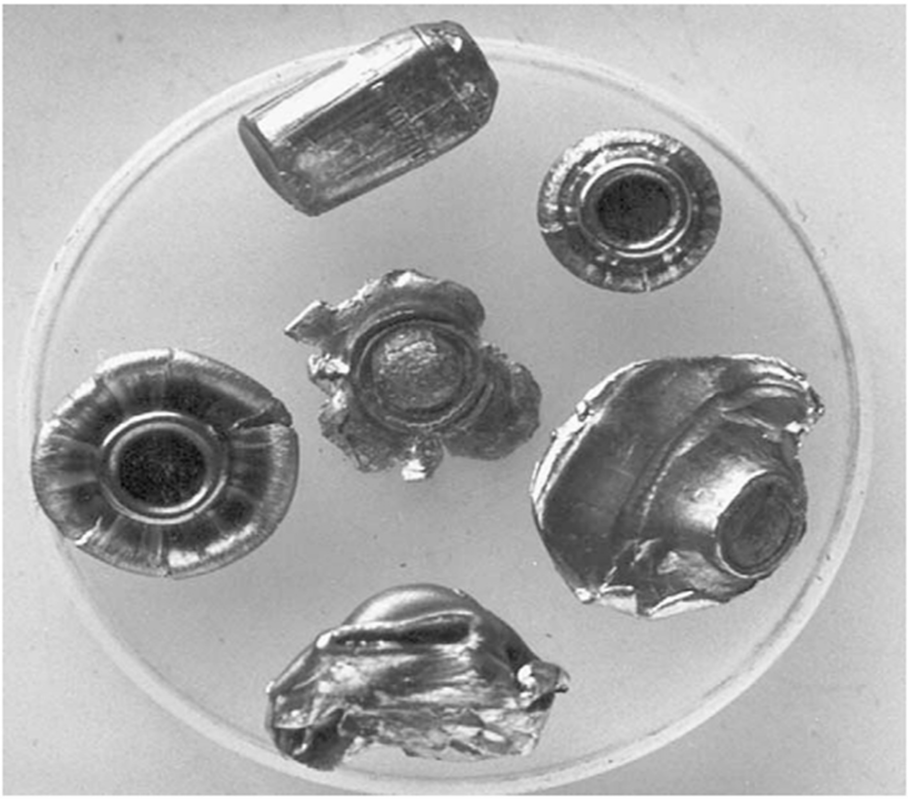

Fig. 1 An illustration of deformed bullets following a firearm test [15]

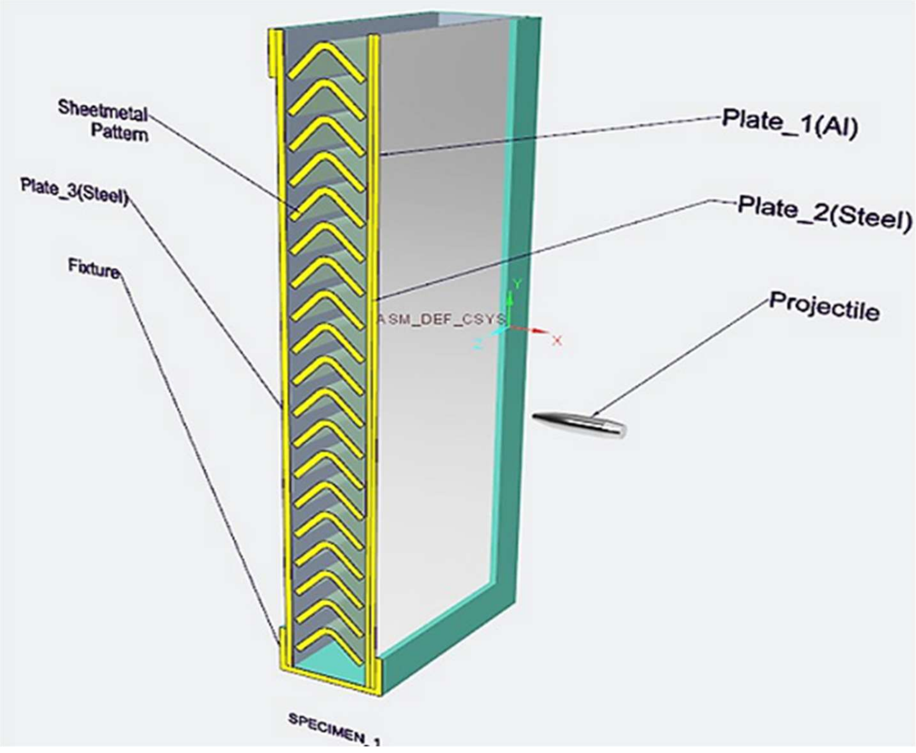

Fig. 2 CAD model of the armor system designed using CREO Parametric software [16]

8. Conclusions

The following conclusions can be drawn from the previous investigation for ballistic perspectives:

- Ballistics is the science of projectile motion, encompassing the behavior of objects such as bullets, missiles, and rockets from the moment of launch to the moment of impact. Ballistics studies are used in military, forensic science, aviation and space, and counterterrorism. The use of self-guided sniper rounds in the military and the controlled descent of a spacecraft under changing aerodynamic forces in aviation are examples of ballistics.
- To extend the lifespan of ballistics, self-healing materials are needed. These materials can be divided into four categories: microcapsule-based healing, bio-inspired healing, intrinsic self-healing polymers, and metallic self-healing.
- Both experimental and numerical simulation methods are used in ballistic research. The experimental methods used in ballistic research are very informative, but they require a long time to prepare the materials, and these materials are quite expensive. Therefore, it is recommended to model the study in a virtual environment before the experiment and solve it in a simulation environment using various methods such as FEM.
- In ballistics, high-velocity projectiles refer to objects launched at speeds significantly higher than conventional ammunition, typically exceeding 1,700 m/s (Mach 5). These projectiles are analyzed for internal ballistics (inside the weapon), external ballistics (flight dynamics), and terminal ballistics (impact effects). High-velocity projectiles can be classified as hypersonic projectiles, kinetic energy penetrator projectiles, and hypervelocity impactor projectiles.
- Ammunition is any explosive or penetrating substance designed to be fired from a firearm. Green ammunition is used in environmentally friendly ballistics to reduce toxicity, pollution, and resource consumption in firearms and artillery. Green ammunition includes lead-free bullets, biodegradable cartridges, and clean propellants. Smart and guided munitions can be divided into two categories: self-guided projectiles and AI-assisted targeting. Self-guided projectiles have demonstrated real-time course correction.
- Sustainability challenges in ballistics can be divided into two categories: environmental impacts and resource efficiency. Environmental impacts include toxic propellants, heavy metals, and ammunition contamination. Green ammunition, also known as lead-free ammunition (W or Cu composites), can be used as a solution. Ammunition contamination is another factor affecting the environment. Unexploded ordnance, such as landmines and artillery shells, damages ecosystems. Research is ongoing on self-destructing mines as a solution to this problem.
- In forensics, preparing digital twins for crime scene problems and supporting critical decision-making processes, 3D-simulated bullet trajectories reduce laboratory waste. Furthermore, fatalities can be minimized by using electroshock bullets, a type of non-lethal smart ammunition. Examples include sustainable hunting ammunition for civilian applications and sport shooting. It's worth noting that non-toxic shot (steel/bismuth shot) is increasingly replacing lead when it comes to sustainable hunting ammunition.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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