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Additive manufacturing in armor and military applications: research, materials, processing technologies, perspectives, and challenges

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ABSTRACT

This review systematically examines the use of additive manufacturing (AM), also known as 3D printing (3DP), in the various aspects of military applications such as firearms, armor and ballistic resistant structures, including those bioinspired. The main goal is to provide a comprehensive exploration of AM in armor and military applications. The materials and structures created using AM technologies are analyzed and reported. Dynamic loading, and impact via Charpy and Izod tests were also explored in the search, although not considered in the armor results to be tests typically conducted at low strain rates, far from a real ballistic solicitation. Recently, an increase in military applications has been found, particularly gun prototypes fabricated in diverse materials with AM. Although the innovation, low costs, and manufacturing are clear advantages of these devices via 3D printing, there are limitations, such as the worrying panorama of unclear regulations that prevent these weapons from eventually reaching ordinary citizens. Current perspectives, opportunities, and challenges are discussed.

1. Introduction

Additive manufacturing (AM) [1], commonly known as 3D printing, is a fabrication technology that has expanded very fast in many areas due to its many advantages, such as adaptability [2], availability, and cost-effectiveness on the process when compared to the implementation of complex traditional fabrication methods. Many industrial and technical sectors have experienced a total innovation revolution [3] with startups, patents, and research elsewhere. It was initially seen by many as only a prototyping technology, but soon it was clear that could be down to a new level, changing the traditional factory concept to a broader type of manufacturing, from large scale in the factory to low scale at homes.

AM has been a complete revolution in materials science, from ceramics [4], composites [5], plastics [6], metals [7], recycled materials [8], construction [9], and more. Almost any synthetic material and many materials from natural origins have been 3D printed. In terms of engineered materials, thermoplastics using filaments and photocurable resins dominate the market [10], for several reasons but mainly because of the low cost and the simplicity of the technology. Ceramics are also very popular, particularly based on extrusion methods able to print clays [11] and cement [12,13], and more technical methods for engineered ceramics that sinter the materials directly in the printer. Metals printers are spreading very rapidly with an increase in the applications and quality of the printers. Sustainability related to AM is also a topic that has been increasing [14], as 3D printing can be associated with less materials waste and recycling, as strategies to decrease pollution in many sectors, including education [15].

AM has many different technologies based on different fabrication principles. ASTM [16] classifies AM into seven technologies: material extrusion [17], material jetting [18], binder jetting [19], vat photopolymerization [20], powder bed fusion [21], direct energy deposition [22], and sheet lamination [23]. There are many diversifications in each method and a considerable number of inventions to improve the resolution, speed, scalability, material property, and reduced costs of the fabrication, which are issues considered to be current limitations of the AM.

A very innovative area involves 4D printing, which combines

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creative designs and structures with intelligent materials which can change size, color, or any other property with external stimulus but without cables or circuits [24]. Among these designs are structures that include metamaterials [25], cellular structures [26], biomimetics design [27], and other areas object of intense research.

Current armor applications involving AM include an increasing number of components many of them in experimental evaluation for small arms [28], body armor [29], helmets [30], field equipment [31], and large-scale apparatus [32]. Fig. 1 shows a general overview of possibilities for AM in this industry, where vehicles, aircrafts, vessels, and drones could be the goal of this market.

There is an increasing use of AM in armor and military applications [33], with very positive developments brought about by technological advantages such as the manufacture of complex shapes, the availability of materials and technologies, the research of materials under extreme load conditions, as well as the development of new materials and technologies [34], among others. However, there are also concerns because of the increasing number of illegal and uncontrolled fabrication of guns in many countries by civilians and criminals [35], and even concerns about AM use by experts and the military, which have led to studies on ethics [36]. Fig. 2 shows some examples of prototypes of diverse guns found on the web.

This article explains how AM is used in the arms and military industry, the main by discussing the main concerns, research trends, materials, technologies, advantages, and limitations.

2. Application of 3D printing in military applications

The integration of 3D printing into military applications has spurred a revolution in the defense sector. Table 2 highlights the diverse applications of 3D printing technology, showcasing its transformative impact on various aspects of military operations and equipment. It delves into the myriad applications of 3D printing in military contexts, exemplifying its versatile role in advancing military technology, logistics, and operational efficiency. Each application serves as a testament to the transformative potential of 3D printing, paving the way for a more agile and innovative future in the realm of defense.

3. Historical perspective

Throughout history, armor and military equipment have played a crucial role in warfare, protecting soldiers, and influencing the outcome of battles. Over the centuries, the development and use of traditional manufacturing methods have been fundamental to producing armor and military tools. However, techniques have evolved to meet changing needs [79].

In ancient civilizations such as the Egyptians, Greeks, and Romans, armor and weapons were forged using traditional blacksmithing techniques [80]. Skilled blacksmiths were highly valued craftsmen who meticulously crafted pieces of armor to ensure protection on the battlefield. They hammered, riveted, and welded to shape metal plates and create functional armor.

During the Middle Ages, armor production reached its peak with the introduction of plate armor, which gained popularity in Europe. This type of armor consisted of interlocking metal plates that covered the body from head to toe. Skilled armorers employed techniques such as shaping, tempering, and fitting to create custom armor that offered increased protection. The process involved heating the metal plates, hammering them into shape, and finally polishing and decorating the armor [81].

As firearms became more prevalent in warfare, traditional manufacturing methods were adapted to produce military weapons. Casting and machining techniques were employed to create cannons, muskets, and other firearms. These methods involved melting metals and pouring them into molds, as well as using lathes and other machines to shape and refine the firearms [82].

The Industrial Revolution of the 18th and 19th centuries brought significant advances in traditional methods of armor making and military applications. The advent of steam-powered machinery made mass production techniques possible, leading to the production of standardized military equipment on a large scale. Assembly lines were implemented to efficiently manufacture items such as helmets, body armor, rifles and cannons [83].

In the 20th century, rapid advances in manufacturing technology revolutionized the production of armor and military equipment. Techniques such as stamping, forging, and welding were perfected, facilitating the mass production of military vehicles, tanks, aircraft and ships. In addition, the introduction of new materials, such as hardened steel alloys and composite materials, expanded the capabilities of traditional manufacturing methods, resulting in stronger and more versatile military equipment [84].

However, despite their historical importance and efficiency, traditional manufacturing methods often involve labor-intensive processes and face limitations in terms of design complexity and customization. As a result, there has been a growing exploration and adoption of AM, as a promising alternative in armor and military applications [85].

Understanding the historical background of traditional manufacturing methods in armor and military applications allows us to appreciate the evolution of techniques and challenges that have driven the exploration of AM. This innovative approach holds immense potential for producing advanced military equipment with increased customization, reduced costs, and greater operational efficiency. By

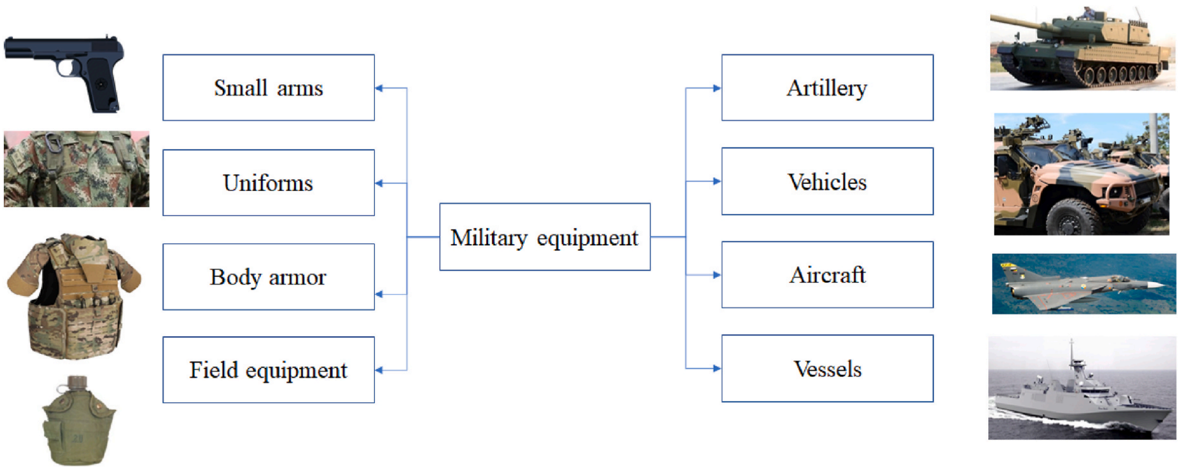

Fig. 1. Possibilities of AM in military equipment.

Fig. 2. Fabrication of guns with additive manufacturing.

building on the fundamentals of traditional manufacturing, AM is poised to reshape the landscape of military armor and production, equipping the military with cutting-edge solutions for the future.

The purpose of the article is to provide a comprehensive exploration of AM in armor and military applications. The scope of the article encompasses various aspects, including research, materials, processing technologies, perspectives, and challenges associated with AM in the context of armor and military equipment production.

4. Emergence and evolution of AM in armor and military applications

The emergence and evolution of AM have revolutionized various industries, and the defense sector is no exception [86]. In the realm of armor and military applications, AM has emerged as a promising technology with the potential to transform the way armor and military equipment are designed, manufactured, and utilized [87]. This section explores the significant milestones in the adoption of AM in this field, highlighting its transformative impact on armor and military technology.

Traditionally, the production of armor and military equipment relied on conventional manufacturing methods, such as forging, casting, and machining. These methods have been proven effective over centuries, providing soldiers with reliable protection on the battlefield [81]. However, as the complexities of modern warfare have evolved, the demand for more advanced, customized, and lightweight armor solutions has grown exponentially [88].

AM, with its unique ability to fabricate complex geometries layer-by-layer directly from digital designs, offers a revolutionary approach to armor and military equipment production [89]. The flexibility and design freedom offered by AM allow for the creation of intricate structures and customized components tailored to specific requirements, enhancing the performance and functionality of armor systems.

One of the key breakthroughs in the adoption of AM in this field was the development of high-strength materials suitable for armor applications. Research and advancements in materials science have led to the formulation of specialized alloys, composites, and ceramics optimized for AM processes, providing armor systems with improved resistance to impact, blast, and ballistic threats [90].

The integration of advanced materials with AM technologies has also enabled the incorporation of additional functionalities within armor and military equipment. The ability to embed sensors, communication devices, and energy-harvesting technologies directly into the structure of armor components creates "smart" armor systems capable of real-time monitoring and enhanced situational awareness for soldiers [91].

Moreover, AM has contributed significantly to the concept of modular and scalable armor systems. The ability to rapidly iterate designs and produce prototypes on demand facilitates the development of adaptable armor solutions that can be quickly customized for varying mission requirements and threats. This agility in design and production ensures that military forces can remain responsive and agile in rapidly changing environments.

As AM continues to advance, new frontiers are being explored in the field of armor and military applications. AM techniques are being employed to fabricate large-scale components for armored vehicles, aircraft, and naval vessels, further expanding its potential in the defense sector.

However, challenges remain, including the need for standardization, certification, and quality control in AM-produced armor and military equipment. As technology matures, addressing these challenges will be crucial to ensuring the reliability, performance, and safety of AM-enabled defense systems.

5. Brief overview of AM technologies and their significance in the military industry

Over the years, AM technologies have attracted significant interest in a variety of industries, including aerospace, automotive, healthcare and, more recently, the military. The unique capabilities of AM have the potential to transform traditional supply chains, reduce lead times and enable on-demand production of complex parts and components. In the military sector, AM holds great promise for addressing critical challenges and enhancing operational capabilities. Below is a brief overview of some key AM technologies and highlights their importance in the military.

5.1. 3D printing of continuous carbon fiber reinforced thermoplastics

The integration of continuous carbon fibers into 3D-printed thermoplastic structures offers both structural reinforcement and self-monitoring capabilities [92]. This technology can be applied to the development of high-performance shielding materials with enhanced mechanical properties and real-time damage detection. The use of continuous carbon fibers in thermoplastics has demonstrated improvements in tensile and flexural strength, making it an attractive option for lightweight but robust military applications.

5.2. Biomimetic artificial muscles using microfluidic micro-capacitors

The combination of microfluidics, 3D printing, and electrostatic actuation enables the creation of biomimetic artificial muscles with various applications, such as military exoskeletons and underwater propulsion systems [93]. These 3D printable artificial muscles can help soldiers carry heavy loads, improve mobility and potentially increase the effectiveness of military missions.

Table 1
3D printing applications in military contexts.

Application	Description	Refs
Weapon Prototyping and Development	3D printing enables rapid prototyping of weapons, allowing for quick iteration and testing of designs before mass production.	[37,38]
Spare Parts Production	Military units can 3D print spare parts on-demand, reducing dependence on traditional supply chains and logistics.	[39,40]
Unmanned Aerial Vehicles (UAVs)	3D printing enables the fabrication of lightweight, complex components for UAVs, improving performance and maneuverability.	[41,42]
Drones and Robotics	3D printing allows for the creation of intricate and lightweight drone components, enhancing agility and endurance.	[43,44]
Body Armor and Protective Gear	3D printing can produce custom-designed body armor and protective gear, offering better fit and enhanced protection.	[45,46]
Camouflage and Concealment	3D printing allows for the creation of adaptive camouflage patterns, enhancing stealth capabilities on the battlefield.	[47,48]
Military Vehicle Components	Critical parts for military vehicles can be 3D printed, reducing downtime and costs associated with traditional manufacturing.	[49,50]
Ammunition and Munitions	3D printing offers the potential for rapid production of specialized ammunition and munitions tailored to specific missions.	[51,52]
Field Medical Devices and Prosthetics	Soldiers can benefit from on-site 3D printing of medical devices and prosthetics, improving medical care in remote locations.	[53,54]
Communication and Sensor Equipment	3D printing facilitates the production of lightweight communication and sensor devices, enhancing situational awareness.	[55,56]
Base Infrastructure and Shelters	Military bases can deploy 3D printed structures and shelters, increasing operational flexibility and reducing construction time.	[57,58]
Underwater Equipment and Submarine Components	3D printing allows for the creation of waterproof components for underwater equipment and submarines, optimizing performance.	[59–61]
Satellite and Space Technology	3D printing supports the construction of small satellites and space technology components, reducing launch costs and lead time.	[62–64]
Military Training and Simulation Tools	3D printing can produce realistic training models and simulation tools, enhancing training effectiveness and cost-efficiency.	[65,66]
Electronic Warfare Equipment	3D printing facilitates the fabrication of intricate components for electronic warfare equipment, enhancing capabilities.	[67,68]
Energy Storage and Power Systems	3D printing enables the creation of efficient and lightweight energy storage and power systems, optimizing mission duration.	[69,70]
Landmine Clearance and Explosive Disposal Equipment	3D printing allows for the creation of specialized tools for landmine clearance and explosive disposal, increasing safety.	[71,72]
Military Vehicles and Armor	3D printing aids in the fabrication of lightweight, yet strong, components for military vehicles and armored personnel carriers.	[73]
Aerial Reconnaissance and Mapping Drones	3D printing enables the construction of precise and lightweight components for aerial reconnaissance and mapping drones.	[74]
Anti-Drone Systems	3D printing contributes to the development of anti-drone systems, improving security against unmanned aerial threats.	[75,76]
Battlefield Robotics	3D printing aids in the creation of advanced robotic systems for use on the battlefield, enhancing tactical capabilities.	[77,78]

Table 2
Search algorithms.

Search	All results	Only filter 1 (article or review)	Only filter 2 (last 5 years)	Tow filters
TITLE-ABS-KEY (((“Additive manufacturing” AND “armor”) OR (“3D Printing” AND “armor”) OR (“3D Printing” AND “ballistic”) OR (“Additive manufacturing” AND “ballistic”) OR (“Additive manufacturing” AND “shock loading”) OR (“3D Printing” AND “shock loading”) OR (“Additive manufacturing” AND “Izod”) OR (“3D Printing” AND “Izod”) OR (“Additive manufacturing” AND “charpy”) OR (“3D Printing” AND “charpy")))	341	247	250	–
TITLE-ABS-KEY (((“Additive manufacturing” AND “armor”) OR (“3D Printing” AND “armor”) OR (“3D Printing” AND “ballistic”) OR (“Additive manufacturing” AND “ballistic")))	134	88	82	55

5.3. *Standardization efforts*

In the military sector, standardization of AM technologies is crucial to ensure reliability and interoperability [94]. Organizations such as ASTM and ISO have been active in establishing standards for AM in the military and aerospace industries. The development of these standards encourages greater adoption of AM in military applications, enabling consistent, high-quality production of components and equipment.

5.4. *Droplet-based metal printing*

Droplet-based AM is a novel method for making dense metal parts by adding material drop-by-drop on a manufacturing platform [95]. This technology enables the manufacture of metal components with intricate geometry and tailored properties, making it ideal for producing customized military equipment and spare parts on demand.

5.5. *Titanium-based layered armor elements*

AM has been applied to create titanium-based triple-layer plates with superior ballistic protection [96]. By 3D printing Ti–6Al–4V and CP-Ti layers on a T110 substrate, the resulting material exhibits strong inter-layer bonding and promising resistance against high-energy projectiles. This advance in armor materials holds great potential for improving the protection of military personnel and vehicles.

5.6. *Validation of propellant formulations*

AM has extended its reach into the field of propellant development for military applications [97]. 3D printing has been used to manufacture propellants with polyurethane-acrylic acid resin as a binder and hexanitrohexaazazaisowurtzitane (CL-20) as an energetic filler. The ability to 3D print propellants allows precise control of geometry and composition, which improves combustion behavior and energy content. This technology could pave the way for customized and optimized propellants in various military systems.

6. Searching methodology

For this review, bibliographic searches were carried out in the Scopus database, with searches in the areas of AM, 3D printing, and other mechanical dynamic applications typically related to armor, see Table 1. The initial search included topics of AM traditionally related to military and armor applications such as ballistic applications, shock loading, and impact tests such as Charpy and Izod. These revealed 341 documents, of which 241 were articles and review papers, and 250 were from the last 5 years, (2019–2023. Removing these last tests, because they are low strain rate and speed, 134 documents were found, resulting in 88 regular papers and reviews, and 82 final documents in the last 5 years, which will be the center of this analysis.

Further analysis of these and other papers was implemented to classify the materials, structure, AM technologies involved, the applications, drawbacks, advantages, and opportunities of AM over this sector, very important for countries and industry elsewhere. Carrot2 software open-source search clustering engine was also used to understand the areas found in the search.

In addition, several websites were explored for uncontrolled guns and other developments associated with armor and military applications, but not reported on academic websites.

7. Results and analysis

Fig. 3 shows some of the search statistics obtained from Scopus, where the number of documents in the last years increased significantly, Fig. 3a; the dominant country in research is the USA, Fig. 3b; and the main research areas are engineering and materials science, see Fig. 3c.

Fig. 4 shows a tree map generated by the tool carrot2, with 53 results classified in clusters of modeling (7), development (6), and complex geometries (5), propellants and ballistic applications (both with 4), among others.

8. Research in AM for armor and military applications

As aforementioned emphasized, in recent years, AM has garnered significant attention and investment across various industries. The defense sector, including armor and military equipment production, has witnessed remarkable advancements in the utilization of AM technologies. This wide review explores recent research studies and notable advancements in the application of AM for armor and military equipment, highlighting the key developments and their implications.

Current and ongoing research studies have focused on optimizing the mechanical properties of armor and military components produced by AM. Commins et al. [99] investigated the influence of surface preparation and polymer support properties on the energy absorption capabilities and ballistic performance of ceramic-polymer composite armor during ballistic impacts, with the goal of improving understanding and contributing to the development of advanced armor materials and designs. Garcia-Avila et al. [100] explored composite metal foam (CMF), a lightweight, high-strength porous material. CMF panels, fabricated by powder metallurgy with hollow steel spheres in a steel matrix, were combined with a ceramic plate to create a lightweight composite armor system. The armor system was subjected to ballistic load testing to optimize its design and performance by analyzing material behavior, failure mechanisms, and ballistic performance. In addition, Medvedev

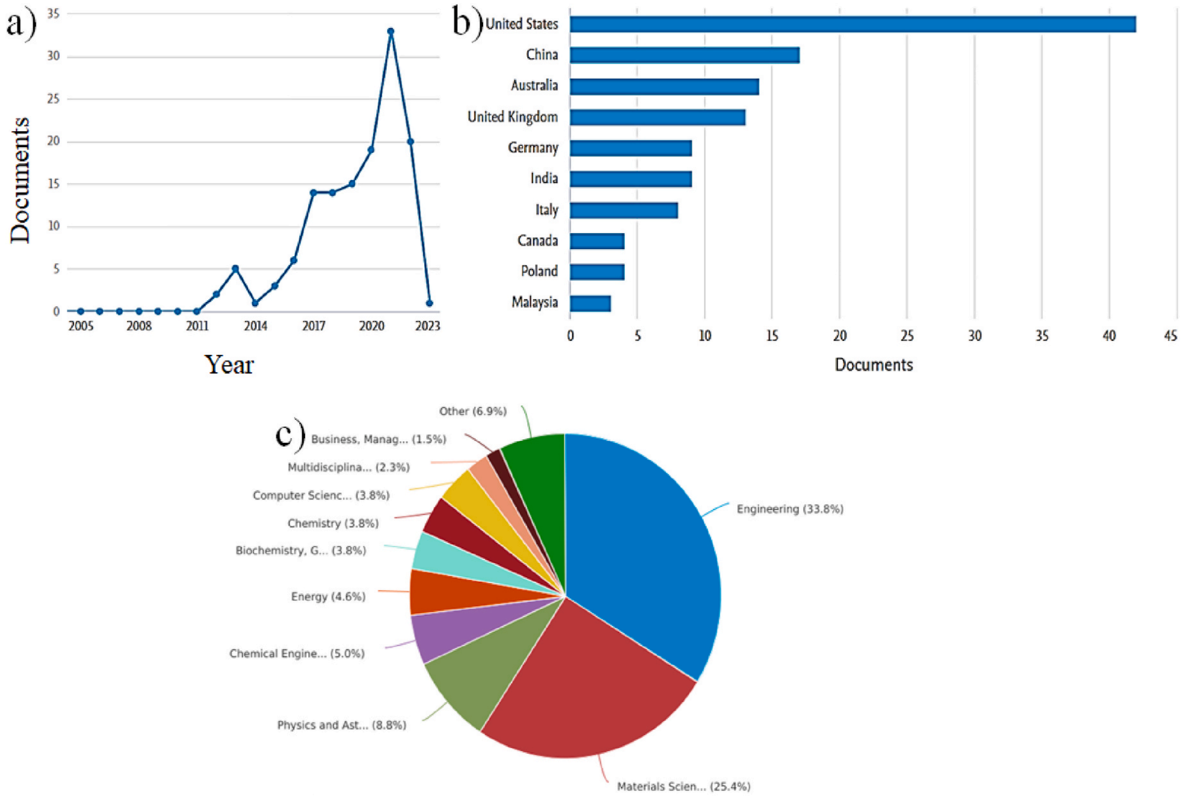

Fig. 3. Scopus statistics regarding the search algorithms from Table 1.

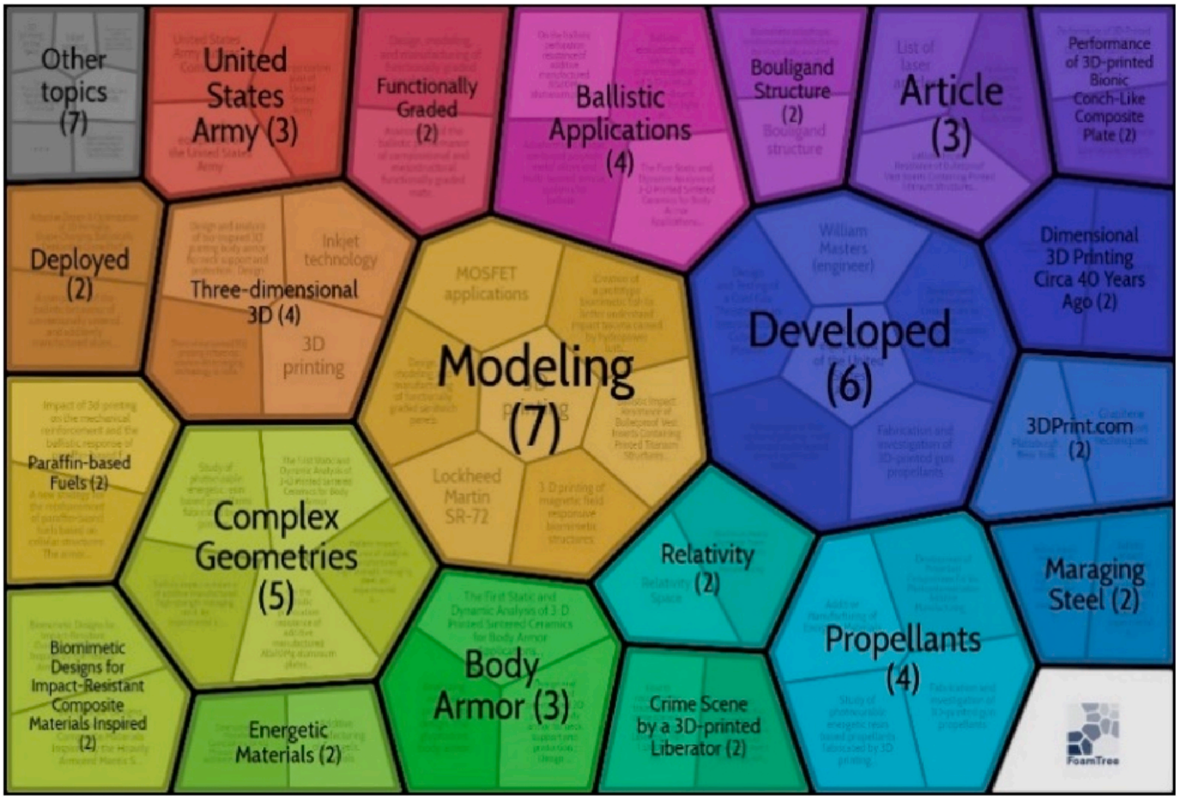

Fig. 4. Clustering with more specific topics [98].

et al. [34] investigated the importance of high strain rates in protecting infrastructure and personnel during dynamic impact scenarios. Previous research emphasized design features that improve integrity under dynamic loading, and AM methods showed the potential to optimize 3D geometry and improve structural performance.

In addition, research has focused on the development of multi-material AM techniques to create hybrid shielding systems. By combining different materials into a single component, researchers aim to optimize features such as ballistic resistance, thermal protection, and electromagnetic shielding. Porter et al. [101] studied the fabrication of 3D-printed structures inspired by fish dermal armor, with the goal of replicating their mechanical functionalities and informing the design of articulated and multi-material structures. Furthermore, Pelz et al. [102] explored the use of AM techniques, specifically direct ink writing (DIW), to produce advanced ceramic specimens with enhanced damage tolerance for applications in armor, engine components, and harsh environments. The enhancement of thermal conductivity in thermoplastic polyurethane (TPU) composites using 3D printing and hexagonal boron nitride (hBN) platelets has also been investigated by Lui et al. [103], achieving successful alignment of hBN platelets to improve performance. Finally, a novel method utilizing electric field-driven (EFD) microscale 3D printing has been developed by Li et al. [104], to fabricate high-performance flexible transparent electromagnetic interference (EMI) shielding films with a silver mesh, offering a cost-effective and scalable solution.

These advancements have the potential to revolutionize the design and manufacturing of modular armor systems that can adapt to varying combat scenarios. AM has also shown promise in improving the customization and rapid prototyping capabilities of armor and military equipment. The ability to rapidly iterate designs and produce prototypes on demand allows for faster evaluation and refinement of armor systems.

9. Materials and processes

Armor applications involve many diverse materials as mentioned before, although the type of materials is specific for the type of applications demanding sometimes extreme dynamics. In the military, there are a lot of parts made of metals and alloys, as expected for the type of loading and mechanical behavior required in guns and other devices. In general, metals have greater mechanical, thermal strength and similar toughness than polymeric materials. Furthermore, metals are more durable and easier to clean. Also, metals are more ductile than ceramics. These characteristics made them ideal for multiple armor applications, from personal guns to large vessels. Table 3 summarizes the technologies, materials, and some parameters and applications for investigation that clearly report these data.

9.1. Metals

Among these materials are stainless steel AISI 316L [105], Tungsten alloys [109], Ti–6Al–4V [112], AlSi10Mg [117], and M300 Maraging Steel [120]. These materials have in common that have either corrosion resistance or very good mechanical, toughness, or other functional properties. Therefore, applications run from structural, bio, and extreme conditions, such as corrosive environments, impact, or high-temperature exposure. Among the most common fabrication technologies found were laser powder bed fusion (LPBF) [112], selective laser melting (SLM) [114], and Laser AM (LAM) [115]. Besides, there are multiple articles involving AM of metals and alloys. The parameters are difficult to compare in many cases due to a lack of data from specifically the same material, mostly due to the immense possibilities in terms of materials, printing technologies, and applications. This only shows the current high opportunities for research and development in the metals AM.

Table 3
Main AM Technologies found in the search algorithm presented before.

Technology	Materials	Parameters	Applications	Ref.
Laser powder bed fusion (LPBF)	AISI 316L	Laser power: 300 W, scanning speed: 2000 mm/s, and layer thickness: 30 μm	helicoidal structure. energy absorption	[105]
FDM	PLA	nozzle width: 0.4 mm, printing temperature: 200 °C, bed temperature: 60 °C, layer height: 0.2 mm, infill: 100 %, and printing speed: 50 mm/s	Forensic stab injuries	[106]
PolyJet multimaterial (material jetting)	Photoresins: VeroWhite *and tangoblackplus*	16 μm, print head at 68–71 °C, printing space 18–25 °C	Potential armor and impact	[107]
Simulation	Hybrid resins	Liquid Injection molding Simulation (LIMS) with FEA	Composites with continuous fibers	[108]
Laser powder bed fusion and direct laser metal deposition	Ti–6Al–4V	Raw Ti–6Al–4V powder (25–45 μm) to produce layer thickness of 30 μm and 60 μm; argon flow, oxygen level <0.1 %, and chamber temperature 200 °C	Ballistic performance and armor materials	[109]
FDM	Polyamides (PA), ABS, and high impact polystyrene (HIPS), with basalt fibers	The printing layer was set to 0.125 mm, and the printing temperature of the thermoplastic matrix layer and the fiber lay were 273 °C and 232 °C	Armor protection	[110]
FDM	PC, ABS, PLA, TPLA, PA and TPU	Nozzle diameter 4 mm; layer thickness 0.2 mm; nozzle temperature: 275, 240, 205, 215, 245, and 225 °C	Impact and armor	[111]
Laser Powder bed fusion (LPBF)	Tungsten	Laser power: 350–400 W; beam spot size: 68–70 μm; layer thickness 40 μm	Impact, fusion power plant, armor	[112]
Direct energy deposition (DED)	Ti–6Al–4V and CP-Ti	low-voltage (<20 kV) gas-discharge gun for heating and melting of the substrate and wire	Ballistic, projectile impact	[113]
Selective laser melting (SLM)	Maraging steel	Laser power: 180 W, Later thickness: 30 μm, laser velocity: 600 mm/s	Ballistic impact	[114]
Laser additive manufacturing (LAM)	Tungsten alloys	W powder of 7 μm, Laser spot diameter of 3 mm based on a 3-kW fiber laser.	Rod armor-piercing projectiles	[115]
SLA	Photoresin energetic resin (APNIMMO)	UV laser of 405 nm. No information of printing parameters was included.	Propellants as energy source in barrel weapons and solid rocket motors	[116]
SLM	AlSi10Mg	ABAQUS/Explicit, FEM Simulation of Split-Hopkinson pressure bar (SHPB) and ballistic impact target plate	Ballistic	[117]
SLM	AlSi10Mg	Equipped with a YLR-500 ytterbium fiber laser, scanning speed 2200 mm/s, laser power 400 W, hatch spacing 50 μm, and layer thickness 30 μm. FEA with Ansys simulation	Potential in aerospace, protective armor, and automotive industries	[118]
Continuous Filament Fabrication (CFF)	Nylon with aramid fibers	Samples of 3 mm thickness and 50 mm diameter. No information on printing parameters was included.	Armor and ballistic protection	[119]
SLM	M300 Maraging Steel	400 W laser source, exposure velocity: 720 mm/s, Hatching distance: 0.12 mm, Layer thickness: 0.05 mm	Ballistic	[120]
Direct Ink Writing (DIW)	Multimaterial: B4C, SiC, and additives for rheology	Nozzle diameter: 1.2 mm; slicing parameters: 1.2 mm layer height, 1.2 mm trace width, and print speed of 5 mm/s	bioinspired structures such as a bouligand arrangement	[102]
FDM	Nylon	Printing nozzle diameter: 0.4 mm, nozzle temperature 250 °C, printing speed 150 mm/s	Bioinspired structures	[121]
FDM	PLA	Not specified.	Ballistic test 140–250 m/s and FEA simulation	[122]
SLA	Several acrylates	UV laser of 405 nm	Gun propellants	[123]
SLM	AlSi10Mg	200 W Yb:YAG fiber laser, Argon atmosphere,	Ballistic perforation resistance	[124]

*Powder bed fusion (PBF) or SLM.

9.2. Polymers

In terms of processing, polymers can be divided into thermoplastics and resins, by FDM and photopolymerization AM technologies. With FDM used PLA [106]; Polyamides (PA), ABS, and high impact polystyrene (HIPS) [110]; PC, ABS, PLA, TPLA, PA, and TPU [111]; and Nylon [119]. Process parameters such as printing temperature and bed temperature are well-known for these materials, while others depend at large on the application. All these polymer materials are relatively inexpensive and ductile when compared with other engineering materials. Thus, in Table 1 the applications run from dynamic to bioinspired. Photo-resins were found to be used in high-performance applications, from aerospace to high impact [107,116,123].

9.3. Ceramics

Ceramic materials were very little related to armor and had a high impact on the systematic search conducted in this investigation. A multimaterial [102] composed of B4C, SiC, and additives was made aiming at bioinspired structures, using the DIW technology.

Table 4 summarizes the structures and the mechanical tests, for those papers that clearly reported this data. Most of the structures are bioinspired. The materials and printing technologies found are quite like those reported in Table 1. However, the papers are different, which confirms the opportunities for research and development in the areas of armor and high-impact applications. The composite materials were mostly particles reinforced polymers by SLA.

10. Advanced materials and structures for protection and impact resistance

In recent times, there is an increasing demand for lightweight materials and structures in many areas such as construction and transportation, but also including armor and impact resistance [1]. These materials and structures are expected not only to be lightweight but also to possess crucial attributes such as high specific strength and exceptional energy absorption capabilities [3]. Key factors, including contact surface area, percentage of porosity, pore size, pore shape, pore nature, and pore morphology, play a pivotal role in the design of novel lightweight materials and structures or in enhancing existing ones [4].

Table 4
Main structures found in the search algorithm presented before.

Structures	AM technology	Material	Mechanical Test	Ref
Hierarchical	FDM	PLA	Compression	[125]
Conch shell, beetle exoskeleton, and nacre	PolyJet	Photoresins: VeroWhite *and tangoblackplus*	Drop tower	[107]
Nacre	SLA	Photocurable Resin and Boron Nitride	Fracture toughness	[126]
Tungsten lattice	LPBF	Tungsten	Compression and thermal shock	[112]
Honeycomb	FDM	Nylon and nanocomposites	Drop weight impact and simulation	[127]
Porcupine quill	SLA	Photoresin Accura ClearVue	Armor	[128]
Lamellar microstructure (for both α and β phases)	LPBF	Ti6Al4V	Ballistic, Split-Hopkinson pressure bar	[34]
Cell artery	SLA	Photoresin flexible Formlabs Form3 and ballistic gelatine.	–	[129]
Lattice structures	–	AISI 316L	Projectile impact	[130]
Carbon dots	FDM	ABS/paraffin	Ballistic and combustion tests	[131]
Cellular structure	SLM	Ti6Al4V/Twaron CT 75para-aramid fabric	Projectile test	[29]
Curved shells	Colorjet 3D printing (CJP)	Binder and Cyanoacrylate as reinforcement	–	[132]
Chamaeleon tongue	FDM	Nylon	FEA with Abacus, and rapid ejection (tongue)	[121]
Gyroid cell	FDM	Paraffin wax blends	High-performing green paraffin-based fuels	[133]
Auxetic	SLM	NiTi and auxetics	Compression and impact of projectile-plate	[134]
Chiton scales	Multimaterial SLA	Photocurable Resin and	Nanoindentation and mechanical tests	[135]

*Powder bed fusion (PBF) or SLM.

Nature has effectively harnessed topological principles to enhance the microscale mechanical properties of metals. This strategy can be applied at the macroscale, where variations in grain size, orientation, and distribution can impede stress transfer and while lead to improvements in specific mechanical properties [1,5–7]. As a prime example, biomimetic apatite hierarchically structured in parallel-fixed hollow microtubules has been synthesized and characterized, offering a biomorphic scaffold with a biomimetic nanostructure surface for innovative applications in bone engineering [8].

Over millions of years of natural selection and evolution, numerous organisms have developed resilient protective structures to enhance their survival in their respective environments [9]. These biological protective structures range from the robust shells of mollusks to the osteoderms of crocodilians [10] and are crucial for providing effective mechanical defense against predator threats. Inspired by these natural defense mechanisms, researchers and engineers have developed bio-inspired materials and structures known for their exceptional impact resistance and energy absorption qualities [11,12]. This natural inspiration has led to pioneering structures, such as bio-inspired scaled flexible armor [13], bio-inspired modular constructions [14], bionic stab-resistant body armor [15], and bio-inspired sandwich structures [16–18].

An examination of the structural and material solutions incorporated into current ballistic inserts used in bulletproof vests reveals the prevalence of layered material systems [19,20]. These systems encompass a variety of materials, including ceramics [21], ceramic composites [22], and polyethylene [23,24], each contributing to the vest's ability to protect against small-caliber ammunition commonly fired from handguns. These vests are meticulously engineered to shield the vital internal organs of the human body, covering an area of approximately 0.5 square meters [25].

Continuous advancements in material engineering [26] and production technologies have paved the way for the development of increasingly efficient bulletproof vests. Ongoing research initiatives in the realm of personal protection [27] are primarily focused on expanding the area of protection while simultaneously reducing the areal density of these vests.

Remarkable adaptations observed in certain animals, particularly chameleons [28] and chitons [13], have not only served as a source of inspiration but also have provided valuable directions for engineering solutions. Through extensive simulations and meticulous nanocaracterization tests, researchers and engineers have gained insights into the intricate mechanisms and structural features that contribute to the development of new structures. This knowledge, in turn, has facilitated the development of innovative engineering solutions based on the extraordinary attributes observed in nature. These bio-inspired approaches have the potential to revolutionize various fields of technology and design, from materials science to biomimetic engineering, by offering a deeper understanding of how nature's principles can be harnessed for practical applications.

Curved structures, gyroid patterns, and notably, auxetic cells, have become focal points of extensive research and experimentation, especially in the context of dynamic testing. Researchers are keen on exploring their behavior and properties under various dynamic conditions.

Investigations into curved structures aim to uncover their unique dynamic characteristics, shedding light on how they respond to forces and vibrations [29]. Gyroid patterns, with their intricate and self-replicating design, are the subject of extensive studies to understand their dynamic performance and their potential in applications where energy absorption and dissipation are crucial [30].

Auxetic cells, with their counterintuitive property of expanding when subjected to tension or vice versa, have captured the imagination of scientists and engineers alike [31]. These cells are subjected to a range of dynamic tests to comprehensively assess their behavior under changing and often challenging conditions. Researchers are particularly interested in how auxetic structures can enhance energy absorption, impact resistance, and other dynamic attributes in a variety of applications.

By exploring the dynamic behavior of these diverse structures, researchers aim to unlock new possibilities for innovative engineering solutions in fields as varied as materials science, aerospace, and protective technologies. The extensive research and experimentation being conducted on these structures underscore their potential to revolutionize various dynamic applications.

11. Metamaterials and advanced material architectures

In the realm of advanced materials, a revolutionary technology stands at the forefront — 3D printed Mechanical Metamaterials (MmMs). This disruptive innovation holds immense promise for applications in armor and the military domain. These materials exhibit exceptional mechanical properties, offering transformative features that include substantial weight reduction, extensive customization possibilities, and multifunctional attributes.

11.1. Mechanical metamaterials (MmMs)

Mechanical metamaterials (MmMs) constitute a class of engineered materials that are distinguished by their remarkable structural design and properties derived primarily from their structural arrangement rather than their intrinsic material composition [136,137]. In contrast to traditional materials, where properties are dictated by the inherent behavior of their building blocks, MmMs attain outstanding mechanical attributes through purposeful design and organization of their internal architecture, operating at micro or macroscale. The fundamental design principles of MmMs involve the generation of intricate and often repetitive patterns, lattices, or structures that manifest unconventional mechanical responses. Hence, additive manufacturing (AM) stands as the ideal technique for crafting components of MmMs, offering precise control over the geometry, topology, and spatial arrangement of constituent elements. Consequently, MmMs can exhibit remarkable properties crucial for applications in armor and the military, including negative Poisson's ratio, negative stiffness [138], extreme light weight, high strength, energy absorption, impact resistance, and enhanced mechanical functionalities.

11.2. Auxetic networks

Within the realm of mechanical metamaterials (MmMs), a distinct subset known as auxetic networks are recognized by their negative Poisson's ratio, implying that they expand perpendicularly when subjected to stretching or compression [139,140]. This auxetic behavior arises from the structural topology of these networks rather than from the inherent properties of the materials used in their construction [141]. The distinctive arrangement of auxetic metamaterials endows them with superior capabilities to efficiently absorb and dissipate energy compared to materials exhibiting a positive Poisson's ratio [142,143]. This remarkable attribute makes auxetic materials very promising in applications where efficient energy absorption and dissipation are of paramount importance. For example, auxetic metamaterials often exhibit higher fracture toughness, allowing them to absorb more energy before failure [144]. When subjected to impacts, these materials expand perpendicularly, deftly distributing and dissipating the applied force. This responsive behavior effectively reduces localized stress concentrations and serves to prevent catastrophic failure, making auxetic networks particularly suitable for applications requiring high impact resistance, such as shielding systems.

11.3. Low-density advantage

Another advantage of metamaterial architecture is their impressively low density, often only a fraction of that of the bulk material from which they are derived. In particular, properties such as stiffness do not deteriorate with density reduction [145,146]. This translates into the possibility of significantly reducing the weight of military and armored equipment produced by additive manufacturing, without compromising structural or protective capabilities. By employing precisely engineered geometric patterns and architectures, MmMs can distribute and redirect forces to maximize strength and minimize weight [145]. This weight reduction contributes to increased mobility for soldiers, allowing them to operate with less physical exertion and greater agility in the field.

11.4. Multifunctional material systems

Furthermore, MmMs provide the opportunity to integrate multiple functionalities into a single material system. Beyond their protective capabilities, these materials can be engineered to incorporate supplementary features, including enhanced thermal insulation [147,148], electromagnetic shielding [149], and self-healing properties. When combined with their inherent mechanical advantages, MmMs fabricated through additive manufacturing emerge as versatile candidates for delivering comprehensive protection and elevated survivability across diverse military environments.

12. Current regulations

The introduction of Additive Manufacturing (AM) technologies in the military sector has ushered in significant advancements and innovative solutions. This section provides an overview of the strides made possible by AM in military applications while also highlighting the challenges posed by the lack of specific regulations tailored to this field.

The emergence of digital technologies presents a multitude of challenges for regulators, encompassing various dimensions. These challenges include adaptability, variability, variety, novelty, and accessibility from a product perspective, as well as new market entrants, evolving roles of key stakeholders, and innovative delivery models from an industry structural perspective [150].

The current regulatory landscape indicates clear difficulties in fulfilling the obligation to grant market access exclusively to products that meet the criteria of being safe and effective. Multiple contributing factors have led to this issue, including the existence of regulatory loopholes, deliberate exemptions from regulatory scrutiny, a reduction in standards, and a lack of comprehensive technical assessment methods for certain novel technologies.

New manufacturing techniques bring challenges associated with their technological uncertainty, requiring the development of procedures to understand and control the process. This can be critical to broadening commercial viability and adoption. Each approach incentivizes a different level of innovation and addresses technological uncertainty differently, but regardless of the approach taken to regulate them, the emergence of new and uncertain technologies, such as additive manufacturing technology applications, has led to an increasing demand for adaptive regulation that is periodically reviewed to ensure that it updates its content and incorporates the latest available knowledge [151].

12.1. Addressing the regulatory gap

The adoption of AM technologies in the military sector has brought significant advances and innovative solutions. However, the rapid expansion of AM capabilities has also highlighted a pressing concern: the absence of comprehensive regulations specific to its use in military applications.

Despite the growing popularity of AM in the military industry, our literature review yielded no direct allusions to the application of enforceable regulations explicitly tailored to AM in this context. Unlike other established industries, the AM field is still relatively young and evolving, leading to a lack of standardized guidelines tailored to the unique requirements of military manufacturing. As a result, the integration of AM into military armor systems and other defense critical components lacks a cohesive framework to ensure uniformity and consistency in production. The absence of well-defined regulations poses considerable challenges in terms of safety, quality, and performance. Without clear guidelines, it is difficult to assess the mechanical and electrical strength-based self-detection properties of 3D printed structures, leading to uncertainty in terms of their reliability for military applications [152].

While some general standards exist from organizations such as ASTM International [153], they may not sufficiently address the specific complexities of AM in military contexts. This regulatory gap hinders the widespread adoption of AM technologies, as military organizations must navigate uncertainty and ambiguity when incorporating these cutting-edge manufacturing methods.

To address this critical issue, concerted efforts are needed to develop and implement rigorous regulations that are explicitly tailored to AM applications in the military sector. Collaborative partnerships between industry stakeholders, government agencies, and research institutions are crucial to establish comprehensive guidelines that uphold safety, performance, and reliability standards. By working together, these areas can ensure that the transformative potential of AM in military applications is harnessed safely and effectively.

13. Perspectives, challenges, and recommendations

12.1. Perspectives

The integration of Additive Manufacturing (AM) technology in military applications opens a realm of promising possibilities. The capacity to swiftly fabricate intricate, tailor-made components on demand offers the potential to significantly boost operational readiness, diminish logistical burdens, and enhance the overall efficiency of military systems [93]. The integration of continuous carbon fibers within 3D-printed thermoplastic structures, as demonstrated in the study by Luan et al. [92] which showcases the integration of continuous carbon fibers into 3D-printed thermoplastic structures, illustrates AM's potential for structural reinforcement and self-monitoring in essential components such as armor.

Moreover, the development of 3D printable biomimetic artificial muscles, as proposed by Coltelli et al. [93], introduces an inventive approach to fortify military exoskeletons and facilitate stealthy underwater propulsion systems. These advancements hold the promise of enhancing the capabilities of military personnel and equipment, unveiling new horizons for defense strategies [93].

13.2. Challenges

Despite the tantalizing prospects, several challenges obstruct the widespread adoption of AM in the military sector. The absence of comprehensive regulations tailored to the unique military applications of AM stands out as a significant impediment. Current regulations predominantly address general AM standards, but the lack of specific directives for military contexts results in ambiguity and curbs the broad utilization of this technology.

Furthermore, as highlighted by Mahmood et al. [154], limitations in dimensional control and surface finish of 3D printed parts need to be addressed to ensure uniform and reliable performance in military applications. The quality and consistency of components produced by AM are crucial for their integration into critical defense systems.

13.3. Recommendations

To fully unlock the potential of AM in military applications, several recommendations are put forth.

13.3.1. Regulatory framework

There exists an urgent imperative to establish comprehensive and tailor-made regulations for AM in the military sector. Collaborative initiatives between government agencies, research institutions, and industry stakeholders are essential to formulate standardized guidelines that specifically address safety, performance, and quality standards pertinent to military manufacturing.

13.3.2. Research and development

Sustained investment in research and development is indispensable to surmount the existing limitations in dimensional control and surface finish. In-depth research on material properties, process parameters, and post-processing techniques can yield substantial enhancements in the reliability and consistency of 3D-printed components [154].

13.3.3. Testing and validation

Rigorous testing and validation procedures must be strictly applied to ensure the integrity of parts manufactured by AM in military applications. Comprehensive assessments of mechanical properties, self-monitoring capabilities, and long-term durability are essential to instill confidence in military decision-makers [92].

13.3.4. Collaborative initiatives

Participation in collaborative initiatives involving military organizations, research institutions, and industrial partners can stimulate knowledge exchange and expedite advancements in AM technologies. These partnerships can also effectively address specific requirements and challenges encountered in the military sector.

14. Conclusions

The integration of 3D printing technology into the military sector represents a revolutionary transformation. It offers diverse and transformative applications, ranging from weapons prototyping and spare parts manufacturing to the creation of UAV components, body armor and communications equipment. While traditional manufacturing methods have played a historic role in the development of military equipment, additive manufacturing (AM) is increasingly being explored as a promising alternative in these applications, highlighting the evolution and challenges of this transition.

AM has the potential to reshape traditional supply chains, reducing lead times and enabling on-demand production of complex military components. It showcases advances in materials science, exemplified by the integration of continuous carbon fibers into 3D printed thermoplastics, resulting in lightweight and robust armor materials. The emergence of biomimetic artificial muscles, created through a combination of microfluidics and 3D printing, may improve the mobility and efficiency of military personnel. The role of standardization efforts by organizations such as ASTM and ISO is critical to ensure the reliability and interoperability of AM technologies in military applications.

A comprehensive literature search, using the Scopus database, was conducted to gather information related to AM and 3D printing in military and armor applications. This search, which focused on topics such as ballistic applications, shock loading and impact testing, identified numerous articles. Subsequent analysis helped to classify materials, structures, AM technologies, applications, and opportunities within this sector.

Recent research in AM for armor and military applications has demonstrated significant advances, focusing on optimizing the mechanical properties of military components produced using AM. This includes exploration of materials, designs, and performance improvements.

In the field of materials and processes for shielding applications, a wide range of materials are used, such as metals, polymers, and ceramics. These materials present numerous opportunities for research and development in the field of shielding and high impact applications.

Innovative structures and biomimetic designs are actively explored, encompassing hierarchical structures, exoskeletons, mother-of-pearl, shells, metal lattices, honeycombs, cellular structures, and animal-inspired designs such as chameleons and chitons. In addition, mechanical metamaterials (MmM), characterized by unique structural designs that offer exceptional mechanical properties through their architecture, are gaining attention.

The authors see the integration of 3D printing technology in the military sector as a revolutionary transformation that offers a wide range of applications. Furthermore, they perceive additive manufacturing (AM) as a promising and viable replacement for traditional manufacturing methods in the context of military and armor applications. This transition is seen as a response to the changing demands of modern warfare, marked by the need for advanced, tailored, and lightweight armor solutions.

Furthermore, the authors are optimistic about the potential of AM to revolutionize military applications, particularly in terms of customization and operational effectiveness. However, they acknowledge the existence of challenges. These challenges include the need for comprehensive standards, the resolution of issues related to dimensional control and surface quality, and the establishment of rigorous testing and validation procedures to ensure the reliability of 3D printed components intended for military use.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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