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Research Progress of Additive Manufacturing Technology in Energetic Material Field at Home and Abroad

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Abstract

As a subversive manufacturing technology, additive manufacturing technology has many technical advantages such as high freedom of design and not limited by complex structure of parts. The application of additive manufacturing technology to the charge molding of energetic materials will subvert the traditional manufacturing concept of energetic materials, realize the advanced charge design concept, shorten the research and development time of weapons and equipment, and improve the comprehensive performance of weapons and equipment, which is of great significance for the rapid development of high-tech weapons and equipment. This paper analyzes the research progress of additive manufacturing technology in the field of energetic materials at home and abroad and puts forward some suggestions for future research of this technology.

Keywords

Additive Manufacturing Technology, Energetic Material, Research Progress

1. Introduction

In recent years, additive manufacturing has developed very rapidly, and the governments of the United States, the United Kingdom, Germany, France, Russia, Australia, Singapore, Japan, South Korea, and other countries have raised it to a strategic level to give policy support [1]. The emergence of additive manufacturing can be traced back to the emergence of the first commercial 3D printer in 1986. Since its advent, additive manufacturing has become the focus of the scientific and technological community and has been called the "third industrial revolution" new technology by the majority of scholars and institutions [2].

Over the past few years, aerospace parts manufacturing and medical applications have been the fastest-growing application areas. In 1999, the United States Defense Advanced Research Projects Agency began to study the additive manufacturing technology of energetic materials, and 3D printing technology has been applied to explosive materials, in 2020, the Netherlands National Academy of Applied Sciences (TNO) proved for the first time in the world that 3D printing propellant can be used to ignite 30mm caliber artillery shells.

As a subversive manufacturing technology, the main technical advantages of additive manufacturing technology include: high freedom of design, not limited by the complex structure of parts; Manufacturing without mold, small batch production economy is good; High utilization rate of raw materials, high level of net forming; Good production predictability, manufacturing time can be accurately predicted according to the actual plan; Fewer assembly steps, can achieve multi-part combination molding; Short product development cycle, high R&D efficiency; Manufacturing on demand, "what you see is what you get." Therefore, the application of additive manufacturing technology to the charge molding of energetic materials will subvert the traditional manufacturing concept of energetic materials, realize the advanced charge design concept, shorten the research and development time of weapons and equipment, and improve the comprehensive performance of weapons and equipment, which is of great significance for the long-term development of high-tech weapons and equipment [3].

Additive manufacturing technology combines computer-aided design, material processing, and molding technology, based on digital model files, through software and numerical control systems, professional materials are piled up layer by layer according to extrusion, melting, light curing, spray or sintering, and finally create physical objects. Three forming technologies are often used in explosive additive manufacturing, including melt deposition forming technology (FDM), stereoscopic light curing technology (SLA), and stereoscopic light curing technology—digital projection forming technology (DLP) [4] [5]. Fused deposition molding (FDM) is a relatively economical printing method at present, but most of the commonly used formulas of explosives are not suitable for using high-temperature heating and melting, and the energetic materials that can be fused and printed are mainly TNT and TNT based fusible cast explosives. Stereoscopic light curing technology (SLA) is a safe and reliable printing method, and the mechanical properties of the product are comparable to those of conventional gunpowder. DLP technology is still immature.

2. Foreign Research Status of Additive Manufacturing Technology in the Field of Energetic Materials

In 2013, the Netherlands National Academy of Applied Sciences (TNO) conducted the first fusion deposition test with TNT, successfully printing about 300 layers of three-dimensional shape TNT, which is the basis for further research on energetic additive manufacturing. In 2017, UV-curable 3D printing technology was used to prepare the hexogen + acrylic propellant, a small number of porous propellant granules with longitudinal and radial perforations, and a new type of high-packing density propellant [5]. In 2020, TNO proved for the first time in the world that it can use 3D printed propellant ignition in 30 mm caliber shells, but with a lower muzzle speed of 260 m/s -370 m/s.

Purdue University in the United States has verified the feasibility of using melt extrusion additive manufacturing technology to prepare fluoropolymer-based energetic multifunctional active materials. The fluoropolymer energetic compounds prepared by 3D printing have good consistency and are suitable for use as multi-functional active structural materials. Purdue University has developed a new vibrational 3D printing method for high-energy materials with high viscosity. *In situ*, UV curing used in conjunction with vibration-assisted printing can be used to create fully dense aluminum-containing propellants that retain their shape and structure. The additive manufacturing of composite solid propellants with complex geometric shapes is also studied. Active metal wires are made by additive manufacturing, which are printed into simple cylindrical or bifurcated geometric shapes, the drug strips are detected by X-ray, and the interior of the combustion surface is observed. By embedding the printed active material (or "active wire") in this new way, the AP/HTPB-based propellant burning surface curve can be adjusted. Trevor J. Fleck *et al.* at Purdue University prepared aluminum/polyvinylidene fluoride (Al/PVDF) fused filament composite by additive manufacturing method and evaluated its properties [6].

The US Army Research Laboratory used 3D printing technology to manufacture shaped asymptotically fired propellant. Researchers used this process to manufacture conventional 7-hole propellant and shaped porous propellant and proved the optimization of the P-T curve of shaped propellant and the feasibility of 3D printing to manufacture shaped structures through performance comparison tests [7].

The United States Naval Surface Warfare Center uses single nozzle extrusion printing technology to successfully print a variety of formulations of explosives and prepare PBX explosives with an energy density gradient. The purpose is to control the explosive energy output law through the charge structure.

In 2018, the Indian Institute of Science used a single-nozzle inkjet printer to prepare three-dimensional network AP/HTPB/Al composite solid propellants, obtain propellant charge columns with different packing densities, different burning rates, and pressure indices, and prepare propellant charge columns with graded energy densities. The Franco-German Institute (ISL) in St. Louis, France, focuses on the additive manufacturing of propellants, and the 3D-printed solid propellant formula studied contains 54% nitrocellulose (NC) and other energetic components (plasticizers and stabilizers) [8]. In 2019, a research project managed by the UK's Defence Science and Technology Laboratory (DSTL) developed a new technology that could deliver 3D-printed explosives on demand on the front lines of warfare, and the high-energy material recipe for 3D printing was manufactured in a LabRAM resonant acoustic mixer, which uses sound energy rather than physical agitation to mix the material to ensure more safe and more effective use. Many research institutions are currently working on various stages of 3D printing, but DSTL is the only one in the UK working on an end-to-end manufacturing process for high explosives.

German ICT research additive manufacturing GAP-ETPE, DNAN (C4N) based formula through FDM method, the next step will use RDX or HMX components. In 2019, the European Defense Agency launched a joint study of seven countries to create 3D printing gunpowder with new geometric configurations. Russia Nikita V. Muravyev *et al.* use modern "energetic matter + chip" to maintain the performance of energetic devices and improve their safety while reducing their size and cost. The use of additive manufacturing technology will lead to further developments in this field, especially in the design of micron/nano-electromechanical systems (MEMS/NEMS) and drug columns with improved properties. According to the US Army Technology report on March 12, 2018, the Australian Defense Science and Technology Organization (DST) has partnered with industry and universities to conduct research on the development of additive manufacturing technology for energetic materials. Energetic materials include explosives, propellants, propellants, and pyrotechnic agents. Simone Garino and others from Politecnico di Turin in Italy have proposed a propellant additive manufacturing process based on ultraviolet curing and have applied for a patent. The technology can produce charges with complex geometries, paving the way for future production targets for new propellant charges. Light curing 3D printing technology is an efficient tool used in the field of explosive molding that can be accurately regulated and precision and rapid prototyping, which is subverting the traditional manufacturing concept of the explosive and ammunition industry. At present, the feasibility and unique advantages of explosive light curing 3D printing technology have been verified. **Table 1** introduces the advantages and disadvantages of 3D printing technology.

3. Domestic Research Status of Additive Manufacturing Technology in the Field of Energetic Materials

Almost synchronized with foreign research, the relevant domestic universities and research institutes have also set up a team specializing in 3D printing research of energetic materials, at present, the advanced manufacturing technology represented by additive manufacturing is developing rapidly, and has become a new direction for more and more enterprises to achieve industrial upgrading and technological transformation. China also attaches great importance to the development of additive manufacturing technology and industry, "Made in China 2025", "13th Five-Year National Science and Technology Innovation Plan" and "Intelligent Manufacturing Engineering Implementation Guide (2016-2020)" and other development plans have listed additive manufacturing equipment and industry as one of the important development directions, hoping

Table 1. Analysis of advantages and disadvantages of 3D printing technology.

Technical classification	Advantages and applications	Drawback
Fused Deposition Modeling (FDM)	Advantages: The manufacturing system is safe and non-toxic; The process is simple, easy to operate, environmentally friendly, and does not produce garbage; Easy transportation and replacement of raw materials, and low cost; A wide variety of materials are available Application: Printing TNT fused cast explosive	Poor accuracy; Slower speed
Sterolithography Apparatus (SLA)	Advantages: The manufacture of particularly complex shapes and particularly fine parts, high precision, and better surface quality. Application: Propellant (50% RDX and 50% inert binder)	Using laser scanning molding, SLA process printers are more expensive, and can only form monochrome resin at a time.
Sterolithography Apparatus—Digital projection molding technology (DLP)	Advantages: High precision Application: TNO has been studied for a propellant formulation containing 50% RDX, 25% acrylic binder, and 25% energetic plasticizer	The technology is still immature

to promote the sustained and rapid development of the field. In China, Nanjing University of Science and Technology, Xi'an Jiaotong University, Hubei Institute of Aerospace Chemical Technology, Xi'an Aerospace Chemical Power Co., Ltd., Xi'an Institute of Modern Chemistry, Beijing Institute of Technology, China Academy of Engineering Physics and many other units are carrying out research on additive manufacturing.

Nanjing University of Science and Technology adopted the self-developed 3D printing molding principle prototype of fusion-cast explosive, successfully printed the fusion-cast explosive column containing nano octogen and trinitrotoluene by screening the formula of the fusion-cast explosive and optimizing the process parameters. The microstructure, density and uniformity, compressive strength, and detonation velocity were compared between the printed and the traditional cast cylinders. The results showed that the structure of the 3D printed drug column was dense, and the density was 1.65 g/cm^3, which was increased by 2.0%. The compressive strength is 55.6 kg/cm^2, an increase of 273%; the Detonation speed is 7184 m/s, an increase of 2.1%; The comprehensive performance is better than that of the traditional casting molding column [9] [10].

Xi'an Institute of Modern Chemistry has preliminarily prepared an RDX-based emitter composed of RDX and a photosensitive resin binder system using photocuring technology, carried out the photopolymerization curing molding of the emitter, and prepared a new LOVA emitter with a solid content of 70% by using the photopolymerization curing technology, and completed the related performance research. Nanjing University of Science and Technology successfully developed an extrusion deposition additive manufacturing prototype suitable for propellant printing and molding and successfully printed a propellant sample with a compression strength of up to 2300 kg/cm^2 [11].

Liaoning Qingyang Special Chemical Co., Ltd. designed a multi-row annular cavity tubular structure integrated propellant suitable for 3D printing technology; According to the principle that 3D printing technology can manufacture special-shaped objects and the burning law of the parallel layer of the propellant, the whole propellant with high burning surface with multiple rows of annular hollow groove tubular structure is designed. The changes in the combustion surface of the propellant, the amount of gas generated, and the rate of gas generated with combustion were analyzed. The calculation method of the relative burning surface of the propellant and the relative gas generation with combustion is established.

The School of Mechanical Engineering of Xi'an Jiaotong University proposed a new 3D printing jet molding method to solve problems such as long time-consuming, complicated processes, many control factors, and difficult molding of special-shaped products in the traditional molding of PBX explosives. The method is based on the 3D printing jet theory, and the material to be formed is sprayed onto the substrate through a high-precision jet mechanism, and then deposited point by point to form 3D. The results provide theoretical and methodological support for the new integrated processing and molding of PBX explosives.

Institute of Chemical Materials, China Academy of Engineering Physics, used high energy CL-20 and insensitive TATB as the main explosive, GAP and N-100 as binder, and prepared three kinds of CL-20/TATB composite charge structural charge columns with axial multilayer structure, radial multilayer structure and axial/radial composite multilayer structure by 3D printing technology [12].

Although foreign research on additive manufacturing technology started earlier in the time dimension and is more extensive in the spatial dimension, the overall gap between new manufacturing processes at home and abroad in the field of energetic materials is not significant. It can be seen from the above introduction that the Netherlands and the United States developed earlier in the field of explosive additive manufacturing, and the research is more in-depth. In the past 10 years, China has also struggled to catch up with the international advanced level in the field of explosive additive manufacturing, and the gap between the international advanced level is not large. Nanjing University of Science and Technology adopts the self-developed fusing casting explosive 3D printing prototyping principle. Xi'an Institute of Modern Chemistry has preliminarily prepared RDX-based propellant using photocuring technology, and Xi'an Jiaotong University has proposed a new 3D printing jet molding method.

However, compared with foreign countries, China's explosive light-curing 3D printing technology is still in the early stage of research, can only prepare low solid content explosive products, and many commercial light-curing adhesives still need to be imported, resulting in China's existing printing materials difficult to meet the explosive formula of high solid content, high viscosity material characteristics requirements, and rapid printing molding requirements.

4. Conclusion and Prospect

In summary, additive manufacturing is a promising manufacturing technology, the future development trend of precision control and precision strike of weapons and equipment will inevitably promote the development of propulsion and damage units in the direction of diverse, shaped and exquisite, and missile engines and warheads need to crack the problems of multi-layer material charge, complex shape charge, high-precision charge and so on. Based on the characteristics and advantages of additive manufacturing technology and the successful experience of national defense, the basic research of additive manufacturing technology in the field of explosives has been carried out, and it can be applied to the production of explosives in the future. With the development of AI technology and big data technology, the future 3D printing technology will develop in the direction of intelligence and simplicity, which can provide a better use experience.

Although the feasibility and unique advantages of the additive manufacturing technology of energetic materials have been verified, the large-scale preparation of energetic materials such as explosives, propellants, and solid propellants, especially large-scale energetic materials, has not been realized. In the future, it is still necessary to carry out in-depth research on the formulation and process parameter optimization of energetic materials and scale enlargement. With the technological innovation of additive manufacturing technology process, materials, and equipment research and development, coupled with the practical needs of the explosive industry in product quality, process automation, and safety, the future explosive additive manufacturing technology will develop in depth. Explore the research of additive manufacturing technology in the precision manufacturing of warhead, flexible manufacturing and precision charging of engine propellant charge, integrated manufacturing of warhead and engine, integrated molding of projectile body charge and coating layer, integrated manufacturing of multi-layer composite charge, 3D printing manufacturing of detonating and detonating charge, 3D printing manufacturing of micro special equipment, etc. It will be the key field of explosive additive manufacturing technology development in the next few years. Once the additive manufacturing technology of energetic materials is applied, it will subvert the development mode of explosive manufacturing and realize the precise, efficient, and safe preparation of energetic materials. At this stage, the additive manufacturing technology of energetic materials is still in the preliminary research stage, the degree of research and the insufficiency of cross-disciplinary research, but the prospect of additive manufacturing technology has been confirmed, and I believe that it will play a huge potential in the field of energetic manufacturing in the future.

Given the current development of additive manufacturing technology, the following suggestions are put forward:

1) In the 3D printing of large-size explosive charges, it is still necessary to solve a series of problems such as 3D printing equipment amplification, the matching of explosive formula and nozzle, the adaptability of the charging process, the safety of the charging process, quality, and efficiency, which restrict the application of 3D printing technology in the field of explosives.

2) Additive manufacturing is used to prepare highly specialized materials with unique dimensions and material properties that vary according to the gradient of demand. For energetic material applications, lattice structures, porous structures, and tilted solid shapes can be created to concentrate or disperse energy. However, there are significant challenges to overcome, in particular obtaining very high particle content (>80 vol%), and further research in this area is recommended.

3) At this stage, although the feasibility and advantages of additive manufacturing composite solid propellants have been verified, it is still necessary to vigorously develop the formulation and optimization of solid propellants suitable for additive manufacturing, further optimize the manufacturing process and process parameters, expand the process scale to gram and kilogram levels, develop multi-nozzle printing technology, and improve the printing efficiency of solid propellants. Achieve high precision and large volume preparation.

4) Requirements and additive manufacturing corresponding issued standards more perfect, in the context of the expanding market size, to make 3D printing can be standardized, industrial development, must strengthen the top-level design, improve the industry standards, software, and hardware intelligence higher, the development of supporting materials has become an important content of the next step of innovation and development.

5) At present, the whole industrial chain of additive manufacturing in China has failed to achieve effective collaborative development, although some cooperation mechanisms have been established between universities, research institutes, and enterprises, the overall cohesion is not strong. Analysts of the National New Materials Industry Development Strategy Advisory Committee suggest that the entire additive manufacturing industry needs to develop together, integrate superior resources, jointly explore the market, avoid going it alone, and need an institutionalized platform to serve members and also the leadership of industry organizations.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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