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Development, Prospect and Challenge for Additive Manufacturing of Polymer Materials

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Abstract: As a manufacturing technology that fabricates three-dimensional objects by stacking materials layer by layer, additive manufacturing can be divided into laser fused deposition, electron beam fused deposition, inkjet printing and so on based on different additive manufacturing processes. In recent years, remarkable progress has been made in the additive manufacture of polymer materials. Firstly, the additive manufacturing equipment and process parameters suitable for polymer materials have been successfully developed, which realized the accurate manufacturing of complex structures. Secondly, by optimizing the formula and post-treatment of polymer materials, the performance and durability of additive products are improved. In addition, the researchers also explored the application potential of additive manufacturing of polymer materials in medical, aerospace and other fields. However, the additive manufacturing of polymer materials still faces some challenges. One of them is that the rheological properties of polymer materials have a great impact on the progress of additive manufacturing, which needs further research and improvement. Meanwhile, the heat and stress generated in additive manufacturing may lead to the deformation and degradation of polymer materials, which requires effective thermal management. Finally, compared with the traditional cutting process, the additive manufacturing cost of polymer materials is still high, so it is necessary to reduce the cost and promote production efficiency. In a word, additive manufacturing of polymer materials has broad prospects and application potential, but further research and improvement are still needed to overcome related challenges.

Key Words: Polymer Materials, Additive Manufacturing, Development, Prospect, Challenge

1. Introduction

With the development of science and technology, people have higher requirements for the function, performance and appearance of products. The traditional manufacturing method of subtractive materials fails to meet these needs, so researching and developing manufacturing technology of addictive materials has been urgent. Additive manufacturing (AM), or three-dimensional printing (3DP), is a process of creating three-dimensional objects by stacking materials layer by layer [1-3]. It is an emerging disruptive technology that is stimulating innovation in design and engineering, materials and manufacturing, which reduces costs and waste to improve efficiency. It is ready to reform manufacturing with the potential to have significant industrial, economic and social impacts. Historically, additive manufacturing technology was introduced in the 1980s and was initially limited to the manufacture or prototype design of small products [4]. Since 2009, additive manufacturing technology has developed rapidly and has drawn new dimensions in engineering applications in different industrial sectors. These are the major discoveries and milestones in additive manufacturing from the 1980s to the present. However, it is still at an initial stage and continues to develop high-quality complex components from a variety of materials and even multi-materials with high precision and high performance [5].

In recent years, with the development of computer-aided design (CAD) and computer-aided manufacturing (CAM), additive manufacturing technology has been widely used in many fields [6]. Additive manufacturing essentially aims to build three-dimensional products from CAD-generated models and provides unprecedented opportunities for digitalization of the manufacturing industry. Based on a variety of software and technology platforms, additive manufacturing technology has enhanced computing power and connectivity, which has dramatically extended its application scope for better flexibility. In addition, it also helps to improve design accuracy and reliability, and contributes to the customized manufacturing of products with almost unlimited design flexibility. Meanwhile, it also starts printing large parts and mass production, with its most extensive applications in the automotive, aerospace, consumer goods, electronics and biomedical fields. Fibrous reinforcement is introduced into 3D-printed plastic/resin products to improve their mechanical properties and enhance the expansion of additive manufacturing in polymer composites. Growing exponentially all over the world, this technology is continuously used for novel applications, efficient production, innovative 3D printing materials and competitive prices.

In this paper, the classification of the additive manufacturing process, the development of additive manufacturing of polymer materials, and the advantages and challenges of additive manufacturing of polymer materials will be discussed. Firstly, the additive manufacturing process will be classified. According to different working principles and technical characteristics, additive manufacturing can be divided into methods such as photocuring, laser sintering, electron beam fusion, etc. With their advantages and disadvantages, these methods are suitable for different materials and application scenarios. Secondly, the development of additive manufacturing of polymer materials will be emphatically introduced. Compared with traditional material subtractive manufacturing, additive manufacturing of polymer material has higher design freedom and ability to manufacture products with complex structure. High precision and high-efficiency production can be achieved by selecting suitable polymer materials and additive manufacturing processes. Then, the advantages of additive manufacturing of polymer materials will be discussed. First of all, it can realize rapid prototyping and small batch production to save time and cost. Secondly, thanks to its high design flexibility, it can manufacture products with complex structures and shapes that cannot be realized by traditional manufacturing methods. In addition, the additive manufacturing of polymer materials can also reduce the waste of materials and improve their utilization rate. In a word, as an emerging manufacturing technology, additive manufacturing of polymer materials has broad prospects and application potential. Through continuous research and development, additive manufacturing of polymer materials will play a vital role in the future manufacturing industry.

2. Classification of Additive Manufacturing Process

2.1 Material Jetting

Material jetting (MJ) is one of the fastest and most accurate 3D printing processes, in which liquid material droplets of building and supporting materials are selectively jetted onto the building platform. These droplets partially soften the previously deposited material layer, which is then cured into a whole with ultraviolet light before removing it from the platform. The MJ process is essentially similar to a two-dimensional inkjet printer. The material used in this process is usually a thermosetting photopolymer (e.g. acrylic acid) which can be in liquid form. A wide range of materials including acrylonitrile-butadiene-styrene (ABS), rubber and fully transparent materials are commercially available [7]. Multi-material printing is a key advantage of this process, which is suitable for creating realistic visual and tactile prototypes with smooth surfaces, similar to injection molded parts with uniform mechanical and thermal properties. However, MJ also has some limitations, including: (i) poor mechanical properties; (ii) photosensitivity, for which mechanical properties deteriorate over time; (iii) high material cost, which is economically unfeasible in some applications. MJ parts are mainly appropriate for non-functional prototypes.

2.2 Binder Jetting

Binder jetting (BJ) is another additive manufacturing method, in which layers of powder particles selectively deposited on the construction platform are joined by using CAD deposition liquid binder to form parts. In BJ, the printer head is designed to place adhesive droplets on powder particles placed on a platform. When one layer is formed, the platform moves down to form the next layer. The main advantages of this technique are as follows. (i) adaptability to complex designs; (ii) unconstrained support structures; (iii) higher printing speeds. BJ can contain all kinds of materials, including polymers, metals, sand and ceramics with different colors. In addition, compared with many direct 3d printing processes, BJ can manufacture large and complex parts at a relatively low cost and make high-value products from materials with strong structures. BJ technology has been mature in recent years. However, to implement this technology robustly in the industry, further research is needed to obtain the required basic data.

2.3 Vat Photopolymerization

In this method, a large barrel of liquid photocuring resin is used and a suitable laser is used to selectively harden the photosensitive liquid into layers of 3D solids, from which a solid product is constructed. In this process, the cured part can descend or rise from the photosensitive liquid resin barrel. This is a common manufacturing and prototyping technology used to rapidly produce parts with incredibly high resolution and excellent surface finish. Nevertheless, it may be more expensive and easily increase brittleness over time. It can be used to create conceptual models, rapid prototyping and complex parts with complicated geometric shapes. Z-axis layer height is usually used to define the resolution of 3D printers, which can be adjusted between 25 microns and 300 microns on modern vat photopolymerization (VPP) printers with a tradeoff between speed and quality. The development of highly sophisticated compact SLA 3D printers and innovative SLA resin formulations have a wide range of optical, mechanical and thermal properties that can be matched with standard, engineering and industrial thermoplastics. Thus, it provides opportunities to accelerate innovation and support businesses in many industries including engineering, manufacturing, dentistry, healthcare, education, entertainment, jewelry and audiology.

3. Development of Addictive Manufacturing of Polymer Materials

3.1 Material Selection and Process Development

The additive manufacturing of polymer materials mainly includes photocuring fused deposition, powder bed fusion and other technologies [1]. Besides, photocuring technology is widely used for its high speed, low cost and environmental protection. Fused deposition technology has been valued for its ability to manufacture complex structures. Selective laser fusion has been popularized for its high precision and good performance.

3.1.1 UV Curable Resin

UV curable resin is a new manufacturing technology of polymer materials and the most commonly used manufacturing method in 3D printing [2]. The resin crosslinking reaction was initiated by ultraviolet light or blue light, and three-dimensional objects were formed by stacking layer by layer. UV curable resin has been widely applied in practice for its advantages such as simple operation, low cost and environmental protection. However, it has some defects, such as low printing accuracy, poor mechanical properties and heat resistance. To improve the properties of UV curable resin, researchers have improved its mechanical properties and heat resistance by doping and compounding.

3.1.2 Fused deposition modeling

Fused deposition modeling (FDM) is a technology that heats thermoplastic polymer filaments to a molten state and extrudes fused materials by extrusion head and stacking them layer by layer to form three-dimensional objects. Thanks to its low equipment cost and convenience for usage, it is widely used [3]. However, there are still some aspects that need to be improved to further popularize its application and realize industrialization. It mainly includes the limited types of printing materials, the possible defects in the parts and the limitation of the preparation of large-volume parts. Compared with traditional processing technologies of polymer materials (such as injection molding, extrusion, pressing and casting), FDM printing technology takes a longer time, which greatly limits the possibility of mass production.

To improve the FDM performance, the printing accuracy and mechanical properties are promoted by optimizing the extrusion head structure and heating temperature. Nowadays, there are abundant researches on modifying polymer matrix by adding micro-nano fillers, so as to improve the anisotropy of FDM printed products and promote their mechanical properties and dimensional accuracy. At the same time, these researches aim to endow these materials with thermal conductivity, electrical conductivity and biomedical functions, realize the high performance and functionality of FDM printed products, and expand applications of FDM technology.

3.1.3 Selective Laser Melting

Selective laser melting (SLM) uses high-power laser beam to melt metal powder locally and stack it layer by layer to form three-dimensional objects. SLM is advantageous in high precision and high performance, but its high equipment cost and complicated maintenance limit its popularization in practical application. To solve these problems, researchers improve the printing accuracy and mechanical properties of SLM by optimizing laser parameters and process parameters.

3.2 Material Optimization and Technological Innovation

3.2.1 Optimization of Material Properties

To improve the efficiency and precision of additive manufacturing of polymer materials, researchers have optimized the properties of materials. For example, by changing the molecular weight, crosslinking degree, additives and other parameters of polymers, the mechanical properties, thermal stability and processability of materials can be improved. In addition, some new polymer materials such as biodegradable polymers, smart polymers, etc. are applied to additive manufacturing [8].

3.2.2 Innovation of Processing Equipment

To meet the needs of different application scenarios, researchers have constantly innovated the equipment and technology of additive manufacturing of polymer materials. For example, various types of lasers, scanning heads and control systems have been developed, which can realize high-precision machining of materials. In addition, some new processing methods such as multiphoton polymerization and electrochemical polymerization are in continuous improvement and development.

4. Advantages and Challenges of Additive Manufacturing of Polymer Materials

4.1 Advantages of Additive Manufacturing of Polymer Materials

4.1.1 High Efficiency

Compared with traditional technology, additive manufacturing has unique advantages. First of all, it adopts the way of stacking layer by layer, and melts and solidifies materials by energy sources such as laser beams or electron beams, so as to realize accurate cutting and manufacturing of parts. Without removing scraps, this cutting method can greatly save materials and improve the utilization rate of materials. Secondly, traditional manufacturing usually needs to use tools or dies for cutting or stamping, which will lead to numerous scraps and a waste of resources. Additive manufacturing can minimize waste by optimizing the design and process parameters, thus reducing production cost. In addition, additive manufacturing can also realize the manufacturing of complex structures, which is often difficult to realize by traditional technologies. For its flexibility and programmability, additive manufacturing is customized based on design requirements to meet the needs of different industries [9].

4.1.2 Environmentally Friendly and Green

Additive manufacturing is an advanced manufacturing method, whose greatest advantage lies that it can effectively save materials and energy. Traditional manufacturing is often by cutting and drilling to remove redundant materials to form the required parts, which not only wastes a lot of materials, but also causes serious pollution to the environment. However, additive manufacturing can add materials only where needed by stacking layer by layer, thus greatly reducing the materials used [10].

This locally additive manufacturing not only improves the utilization rate of materials, but also reduces the production cost.

In addition, additive manufacturing can save energy. For its layer-by-layer stacking, it does not carry out large-scale heat treatment or machining like traditional manufacturing in the production, thus reducing energy consumption. At the same time, because additive manufacturing can realize accurate part design, it can reduce unnecessary repeated manufacturing and further save energy.

4.1.3 Shape Control

Additive manufacturing is an advanced manufacturing method. Compared with traditional manufacturing, additive manufacturing has unique advantages, which can create almost any complex parts or products. First of all, it can decompose complex geometric shapes into a series of simple layers, and then stack them layer by layer, thus realizing the complexity of shapes. This layer-by-layer construction enables additive manufacturing to achieve high design freedom and customized production. Both the internal structure and the external contour can be precisely controlled to achieve the desired shape.

Secondly, the additive manufacturing is very flexible in the use of materials. Traditional manufacturing is often limited by the plasticity and processability of materials, while additive manufacturing can choose different materials for manufacturing according to design requirements. This enables additive manufacturing to be applied in various fields, such as aerospace, automobile manufacturing, medical and health care, etc. By selecting suitable materials, the performance of parts can be improved, such as strength, wear resistance and corrosion resistance, so as to meet the needs of different applications.

In addition, additive manufacturing has the ability to rapid prototype. Traditional manufacturing usually needs molds or tools, and carries out multiple processes to complete the manufacturing of a part. Additive manufacturing can obtain data directly from the computer model and stack materials layer by layer to make parts, which greatly shortens the manufacturing cycle and cost. This enables designers and engineers to develop and verify products faster, and improve their innovation ability and market competitiveness.

4.2 Challenges of Additive Manufacturing of Polymer Materials

There are some challenges and limitations in additive manufacturing. For example, the current cost of this technology is relatively high, and so is the cost of equipment and materials. Besides, some problems of additive manufacturing exist, such as unstable molten pools, stress concentration, etc., which require strict quality control and inspection.

4.2.1 Material Selection

There are some limitations in the printing process of additive manufacturing. Because of the different characteristics and physical properties of different materials, it is necessary to set different printing parameters for various materials, which increases the complexity and difficulty of additive manufacturing. Meanwhile, some polymer materials are prone to degradation or deformation in high temperature, high pressure and other printing environments, which leads to the decline of printed product quality. Therefore, although there are many kinds of existing polymer materials, not all polymer materials are suitable for additive manufacturing.

To overcome these limitations, researchers are developing new polymer materials to improve the efficiency and quality of additive manufacturing. For example, some new biodegradable materials have been applied in the additive manufacturing. These materials not only have good biocompatibility, but also can be decomposed and absorbed in vivo, reducing environmental pollution [11]. In addition, some materials with high strength, high toughness and high-temperature stability have been widely used in research, which is expected to promote additive manufacturing and expand its application range.

4.2.2 Printing Accuracy

At present, the printing accuracy of additive manufacturing of polymer materials is still low, which fails to meet the needs of some high-precision applications. Improving printing accuracy is one of the most critical challenges in the additive manufacturing of polymer materials. To overcome this problem, researchers are exploring new technologies and methods, such as optimizing printer hardware and printing parameters, adopting advanced data processing algorithms and so on. Moreover, through cross-cooperation with other fields, such as nanotechnology, optical imaging, etc., it is expected to bring new breakthroughs for the additive manufacturing of polymer materials [12].

4.2.3 Cost

The cost of additive manufacturing of polymer materials is relatively high, which is mainly caused by the high equipment price, large material loss in the processing, technical support and labor costs. To reduce processing costs, researchers and enterprises are trying to find innovative solutions, including adopting more advanced equipment, optimizing process flow, improving material utilization and developing new low-cost materials. In addition, the government and industry organizations are providing financial support and policy guidance to promote the development and application of additive manufacturing of polymer materials. Therefore, although there are some challenges, with the continuous technological progress and the growing market demand, the cost of addictive manufacturing of polymer additives will decrease in the future.

4.2.4 Thermal Stability

Polymer materials are prone to thermal degradation and oxidation at high temperatures, which will seriously affect their mechanical properties and thermal stability. At high temperatures, the chemical bonds of polymer chains may break, which leads to the changing molecular structure, thus affecting its original physical and chemical properties. Meanwhile, the oxidation reaction will lead to the oxidation of some elements in polymer materials to form oxides, further reducing their properties [13].

Hence, improving the thermal stability of polymer materials is vital in the additive manufacturing of polymer materials. This can not only improve the service life of polymer materials, but also improve their performance in various harsh environments. To this end, researchers are improving the thermal stability of polymer materials by changing the chemical structure of polymer materials, introducing antioxidants and developing new synthesis processes.

4.2.5 Biocompatibility

Biomedical applications require high biocompatibility of additive manufacturing

products, because these products come into direct contact with human tissues, which may affect the normal physiological functions of the human body. At present, most products made by additive manufacturing of polymer materials have some problems in the biological environment, such as inflammatory reaction, cytotoxicity and so on. These problems may have adverse effects on human health and even lead to serious health problems [14].

Thus, improving the biocompatibility of products made by additive manufacturing of polymer materials is an important research direction in the future. An in-depth study of the biocompatibility mechanism of polymer materials is required to explore new material design and preparation methods, so as to reduce or eliminate their possible negative effects in the biological environment. At the same time, new detection and evaluation methods should be developed to ensure their safety and effectiveness in practical application.

5. Conclusion

Through the research on the addictive manufacturing of polymer materials, the following conclusions can be drawn:

1. As for the classification of the additive manufacturing process, additive manufacturing is a process of manufacturing three-dimensional objects by stacking materials layer by layer. According to the energy source and material characteristics, the additive manufacturing process can be divided into fused deposition molding, photocuring molding, material extrusion molding and so on.

2. As for the development of the addictive manufacturing of polymer materials, remarkable progress has been made in recent years. By improving material formula, optimizing printing parameters and introducing new printing technology, researchers have realized high-precision, high-speed and multi-material printing of polymer materials. These advances provide new possibilities for the application of additive manufacturing of polymer materials in medical, aerospace and automobile.

3. As for the advantages of the additive manufacturing of polymer materials, first of all, it can realize the printing of complex structures and improve the freedom of design and manufacture. Secondly, the additive manufacturing process can greatly reduce the waste of materials and cut the cost. In addition, the addictive manufacturing of polymer materials can also realize personalized customization to meet the needs of different customers.

4. As for the challenges of the additive manufacturing of polymer materials, although remarkable progress has been made, there are still some challenges. First of all, the printing speed of polymer materials is relatively slow, which limits its application in large-scale production. Secondly, polymer materials may have deformation, cracking and other problems in the printing, which need further research and solution. Besides, the high cost of equipment and materials for additive manufacturing of polymer materials restricts its wide application.

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