Original Research Article

The simulation of additive and subtractive composite manufacturing process of tricalcium phosphate bioceramics

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Abstract: This paper studies the additive and subtractive composite manufacturing process of tricalcium phosphate (TCP) bioceramics, focusing on the simulation of its processing process. By optimizing the process parameters, the mechanical properties of bioceramics materials are improved, and their quality in biomedical applications is improved. A method combining additive manufacturing (AM) with subtractive manufacturing (SM) technology is proposed to overcome the limitations of traditional bioceramics manufacturing methods. This paper provides new ideas for improving bioceramics manufacturing technology through process simulation, performance evaluation and experimental verification.

Keywords: Tricalcium phosphate; Bioceramics; Additive; Subtractive composite manufacturing; Process simulation

1. Introduction

Tricalcium phosphate (TCP), a critical bioceramic material, is widely used in orthopedic repair and regenerative medicine. Its excellent biocompatibility, biodegradability and similarity to human bone tissue make it one of the ideal bone repair materials[1]. With the development of medical technology, especially the increasing demand for application in bone tissue engineering and regenerative medicine, how to improve the processing quality, performance and precision of TCP materials has become a hot topic in current research. Although traditional TCP bioceramics preparation methods, such as sintering and pressing, can produce relatively stable ceramic materials, they are challenging to meet the needs of modern medicine for personalized customization and high precision due to their complex processing, low precision, and considerable shape restrictions[2].

In recent years, additive manufacturing (AM) and subtractive manufacturing (SM) technology have been widely used in industrial manufacturing, and their potential in biomaterial processing has gradually emerged. Additive manufacturing technology, especially 3D printing technology, can build three-dimensional structures with complex shapes by adding materials layer by layer, with high design flexibility and material utilization. Subtractive manufacturing technology usually finely processes the target material by removing excess material, which can provide high-precision surface quality and dimensional control[3]. Additive and Subtractive Composite Manufacturing is a kind of new manufacturing mode which combines additive and subtractive manufacturing. The key advantage of this method is that it cannot only make use of the advantages of AM in form complexity and material utilization, but also make use of the advantages of subtractive manufacturing in dimension precision and surface quality[4]. This composite manufacturing method has significant advantages when processing bioceramic materials, especially when processing fragile materials such as tricalcium phosphate.

This thesis aims to optimize the technological parameters of tricalcium phosphate bioceramics by means of process simulation. By establishing a simulation model, the effects of different processing paths and parameter settings on the final product's performance are simulated, the manufacturing effects under different conditions are analyzed, and then a suitable process optimization scheme is proposed.

2. Characteristics and applications of tricalcium phosphate bioceramics

2.1. Chemical properties and structural characteristics of tricalcium phosphate

Tricalcium phosphate contains calcium and phosphate ions, and its chemical formula is $Ca_3(PO_4)_2$. Its molecular structure comprises a network structure composed of calcium and phosphate ions, which gives tricalcium phosphate good biocompatibility and adaptability. TCP has low solubility in water, but it can interact with bone tissue in the body to form hydroxyapatite (HA), which plays an essential role in bone healing and repair.

Tricalcium phosphate has a relatively complex crystal structure, of which there are two common crystal forms: α-TCP and β-TCP. α-TCP is formed at high temperatures and has low thermal stability, but its solubility is high, which is conducive to accelerating the bone repair process; β-TCP is stable at room temperature, has high thermal stability and low solubility, and is suitable for long-term application in bone repair. The stability of β-TCP makes it difficult to degrade in the body for a long time and can provide long-term support for bone tissue, so it is widely used in clinical practice.

2.2. Biocompatibility and biodegradability of tricalcium phosphate

An essential characteristic of tricalcium phosphate material is its biocompatibility, which means that the material can be in harmless contact with biological tissue in the body without causing immune rejection. The degradation process of TCP in the body is relatively slow, and it can be gradually replaced by new bone tissue through interaction with bone tissue, thereby completing bone repair. This feature makes it an ideal choice for bone repair materials, especially in treating significant bone defects and the need for bone regeneration.

Biodegradability is another critical characteristic of biomaterials, which means that the material can gradually decompose in the body and be absorbed by the organism. The body's degradation rate of tricalcium phosphate can be regulated by changing its microstructure or compounding with other biomaterials. Studies have shown that the degradation rate of TCP material is closely related to its crystal form. The degradation rate of β-TCP is slower, while α-TCP is faster. In addition, as new bone tissue is generated, the degradation products of TCP (such as calcium and phosphorus) will also be absorbed by the body, which positively affects bone tissue regeneration.

2.3. Orthopedic application of tricalcium phosphate

Due to its excellent biocompatibility and adjustable mechanical properties, tricalcium phosphate has many applications in bone repair and regenerative medicine, especially in bone defect repair, bone transplantation and bone tissue engineering. In clinical applications, tricalcium phosphate is often used to treat fractures, bone defects and some intractable bone diseases. TCP material can be used as a filling material for bone defects, promote the regeneration of bone tissue, and fuse with surrounding bone tissue. Studies have found that tricalcium phosphate can promote the proliferation and differentiation of osteoblasts and improve bone healing, especially in repairing bone defects in essential parts such as the hip and spine.

3. Application of Additive and Subtractive Manufacturing Technology in Bioceramics

Additive and Subtractive Manufacturing (ASM) is an innovative manufacturing model combining additive and subtractive manufacturing technologies. This composite technology aims to overcome the shortcomings of a single manufacturing method by leveraging both advantages, thereby achieving higher manufacturing accuracy, efficiency and flexibility. Additive and subtractive manufacturing techniques combine additive and subtractive manufacturing to create a new manufacturing model that can take advantage of both. Additive manufacturing is responsible for rapid prototyping and constructing complex structures, while subtractive manufacturing performs high-precision post-processing through fine cutting, grinding, etc., thereby improving parts' surface quality and dimensional accuracy. In bioceramics, additive and subtractive manufacturing technology has great potential, especially in the manufacturing process of tricalcium phosphate bioceramics. Tricalcium phosphate materials are highly brittle, and traditional manufacturing methods may cause cracks or uneven stress distribution, affecting the final performance of the material. Therefore, additive and subtractive manufacturing technology can improve the material's surface quality and structural integrity through acceptable post-processing, ensuring its performance in biomedical applications.

Specifically, additive and subtractive composite manufacturing technology has the following advantages in the application of bioceramics:

Manufacturing of complex structures: Additive manufacturing technology can produce complex three-dimensional structures, such as bone scaffolds, bone defect repair materials, etc. These structures require highly personalized design and high-precision production. Additive manufacturing can design and manufacture bone repair materials that conform to the physiological structure of patients according to their differences.

Optimization of surface quality: Tricalcium phosphate materials may have problems with rough or uneven surfaces during the additive manufacturing process, and subtractive manufacturing technology can eliminate these irregular shapes through precision cutting, improve the surface smoothness of the material, and thus enhance the mechanical properties of bioceramics.

Improvement of material properties: Through fine subtractive manufacturing, defects that may occur in the additive process (such as pores, microcracks, etc.) can be removed, and the density and mechanical properties of the material can be improved, thereby improving its stability and durability in practical applications.

4. Experimental verification and result analysis of additive and subtractive composite manufacturing process of tricalcium phosphate bioceramics

4.1. Experimental design and implementation

4.1.1. Additive manufacturing experiment

Laser sintering technology was used to 3D print tricalcium phosphate bioceramics, and different parameters such as laser power, scanning speed and layer thickness were set for comparison. The surface microstructure of the printed samples was observed by scanning electron microscopy (SEM), and the phase change was analyzed by X-ray diffraction (XRD) (Table 1).

Table 1. Additive manufacturing parameters.

Laser power (W)	Scanning speed (mm/s)	Layer thickness (mm)	Surface roughness (µm)	Porosity (%)
100	500	0.2	2.3	8.5
150	500	0.2	2.8	10.2
200	500	0.2	3.2	12.1

4.1.2. Subtractive manufacturing experiment

The samples were cut using CNC machine tools, with different cutting speeds, feed rates and cutting depths set, and carbide tools were selected for the experiment. The effects under different processing conditions were analyzed by measuring indicators such as surface roughness and porosity.

4.2. Experimental results and analysis

4.2.1. Temperature field and thermal stress analysis

During the additive manufacturing process, the higher the laser power, the higher the temperature of the molten pool, resulting in more significant thermal stress in the material. The experimental data and simulation results show that when the laser power is 200W, the thermal stress distribution is more concentrated, affecting the shape and surface quality of the printed object.

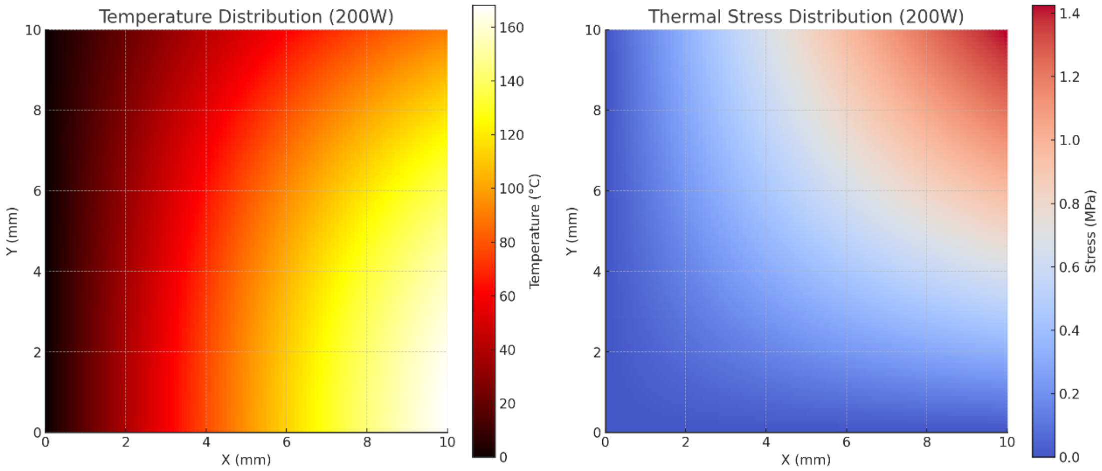

Figure 1. Temperature field and thermal stress distribution during additive manufacturing.

Figure 1 illustrates the temperature field and the heat stress distribution in the process of adding TP bioceramics at different laser power levels. When the laser power is between 100 W and 200 W, the variation of temperature and stress on the surface and interior of the material is simulated. With the increase of the laser power, the temperature of the molten pool will increase gradually, and the heat stress will be concentrated at the edge of the material.

4.2.2. Surface quality and dimensional accuracy

In the additive manufacturing process, when the laser power is low (100W), the surface roughness is low, and the porosity is minor, which is suitable for producing high-quality bioceramics. A higher cutting speed (100 m/min) and smaller feed rate (0.1 mm/rev) can obtain better surface quality and dimensional accuracy in subtractive manufacturing.

4.2.3. Mechanical properties analysis

The experimental results show that when the laser power is low in the additive manufacturing process, the material has better density and relatively better mechanical properties. In the subtractive manufacturing process, under the condition of higher cutting speed, the surface density of the material increases and the mechanical properties are improved.

5. Conclusion

In this paper, the effect of different technological parameters on material performance is discussed by simulation and experiment. It is found that in additive manufacturing, the higher laser power (100 W) and the medium scanning speed (500 mm/s) can achieve better surface quality and mechanical performance, whereas the higher laser power (200 W) can lead to too much heat stress and influence the quality of the final product. Higher cutting speeds (100 m/min) and a lower feed rate (0.1 mm/rev) assist in improving the surface roughness and dimension precision in subtractive manufacturing. The simulation results are in good agreement with the experiment data, which proves the validity of the optimization scheme. Through reasonable selection of technological parameters, the production quality and performance of tricalcium phosphate bioceramics can be improved effectively.

Funding

(1) Shandong Provincial Natural Science Foundation (ZR2021QE253)
(2) Hebei Natural Science Foundation (E2022203136)

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