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Research on the Application of Discrete Minimal Surfaces in 3D Printing

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Abstract: As a new disruptive technology in the manufacturing industry, 3D printing can meet personalized customization through the application of discrete minimal surfaces, providing a smooth channel for connecting with a large number of users, which has important practical value. Based on the design foundation of discrete minimal surfaces structure, 3D printing technology was used to produce porous TC4 titanium alloy with discrete minimal surfaces. The microstructure changes and compressive properties of the samples were compared and observed in different states of deposited microstructure and after heat treatment. After research, it was found that using Rhino modeling software and the Grasshopper plugin, a discrete minimal surface model was generated. Further processing was carried out using 3-matic topology optimization software, which then processed the multi porosity of the discrete minimal surface. The compressive strength of the porous TC4 titanium alloy with discrete minimal surface increased with the increase of apparent density. The research results provide an important foundation for subsequent research.
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1. Introduction

As an additive manufacturing technology, 3D printing usually uses computer hardware and software to control the electron beam, build solid parts by driving three-dimensional CAD models, and further use the electron beam to melt metal powder and achieve accumulation manufacturing, and then produce multi-shape parts of porous materials. Compared with traditional technology, 3D printing technology has the advantages of high strength, low density, light weight and good permeability. However, if we want to make better use of this technology, we must rely on the technical support of discrete minimal surfaces. Generally speaking, the average curvature of the discrete minimal surface is zero, and the surface is smooth and the structure is stable, so it has high application value in 3D technology. The use of discrete minimal surfaces and porous structure matching technology can not only increase the surface strength of materials, but also be applied to human tissue engineering, presenting better adsorption and wide permeability, thereby providing technical support for the development of 3D printing technology. In view of this, this article selects a spatial geometric mathematical model of discrete minimal surfaces, generates a 3D printing model through multiple software parameters, and prepares samples through electron beam additive manufacturing. It is expected that this experiment will provide important data support for the preparation and application of engineering process products.

2. Fundamentals of Discrete Minimal Surface Structural Design

Since the introduction of discrete minimum surfaces into the field of computer-aided geometric design (CAGD), the problem of modeling structures for discrete minimum surfaces has attracted the attention of many scholars. In this case, the specific method of integrating discrete minimal surfaces with 3D technology has gained enormous production value in practical activities. In general, CAGD is designed and manufactured with the help of computers to obtain the structure of the geometry. The methods of CAGD applied to discrete minimal surfaces are divided into two main categories, namely, approximation solution and exact representation.

The model construction of discrete minimal surfaces is generally achieved using the Rhinoceros+Grasshopper platform. In terms of advantages, this platform is an important digital model generation platform in the current field of parametric design due to its advantages in programming, logicality, visualization, and compatibility with multifunctional plugins. In terms of function, the platform has an excellent programming software foundation, which can provide important support for the parameterization of discrete minimal surfaces through powerful processing plugins. Specifically, the Rhinoceros+Grasshopper platform can use graphics to deduce the hand-copied design thinking mode, assist in digital modeling of discrete minimal surfaces, and creatively involve mathematical logic structures directly in the visualization process of 3D printing, allowing upstream and downstream technical personnel to participate in this open design based on open and collaborative thinking. In this way, the cycle time can be significantly reduced, which drives optimization of the final result.

Due to the strong continuity of the surface, significant curvature changes, and numerous hollow structures, the discrete minimum surface model has not yet been able to handle some complex shapes with skin hollows. Applying discrete minimal surface models to 3D printing technology can effectively accomplish the practical task. Firstly, improving the application level of discrete minimal surfaces in 3D printing can achieve the melting of metal powders by electron beams, manufacture porous materials with diverse shapes, and thus form 3D manufacturing materials with excellent strength, thermal insulation, and volume area. Second, improving the application level of discrete minimal surfaces in 3D printing can make better use of the advantages of low average curvature, improve the composite degree of porous structures and minimal surfaces, create smooth surface materials, and ensure the stability of 3D printing structures.

3. Experimental design

3.1 Design of discrete minimal surface porous structure

This experiment uses Gyroid surface structure as the 3D printing model for specific design, and the specific expression is:

$$f(x,y,z) = sin(x)cos(y) + sin(y)cos(z) + sin(z)cos(x) = 0 \qquad (1)$$

Consider that hidden functions cannot be drawn by industrial Solid 3D drawing software (including Solid Works, CATIA), but Rhino software can. Specifically, in the Windows operating environment, Rhino software can independently create, edit, and analyze tasks, thereby converting the operating environment into NURBS curves, surfaces, and solids. This approach is not limited by model complexity, size, etc., and can support the output of multi deformation discrete minimal surface meshes. In view of this, this experiment is based on Rhino software and combined with Grasshopper plug-in to parameterize the mathematical algorithm of minimal surface. The Gyroid minimal surface model is generated by this modeling algorithm, which includes the following steps:

Step 1: Open Rhino software and set up the Grasshopper discrete minimum surface drawing plugin in advance. On this basis, the overall structural size is set to 30mm × 30mm × 30mm. Step 2: Select the function operator under “math” in the menu bar, and input the mathematical formula (1) into the function editing end to build a logical modeling instruction based on this. Step 3: Adjust the discrete minimum surface function image to control parameters and adjust the model. Step 4: Based on the above steps, export the generated model into the common “.stL “format for 3D printing, and then save it to the desktop folder.

3.2 Raw materials

In this experiment, TC4 titanium alloy powder was prepared by atomization method. According to integrated research, the density of the powder is 4.43g/cm3, and the specific chemical composition is shown in Table 1. Generally speaking, TC4 titanium alloy powder meets the manufacturing powder standard ASTM F1108 and has been applied in multiple fields.

Table 1 Chemical composition of TC4 titanium alloy powder (w/%) (part)

	A1	V	O	N	C
TC4	6.49	4.00	0.14	0.009	0.005
Astm F1108	5.55	4.23	<0.19	<0.04	<0.09

3.3 Equipment and process

In the following experiments, this article will use Sailong-S2 type 3D printing equipment to shape the porous TC4 titanium alloy with discrete minimal curved surfaces. The equipment is developed by Xi’an Sailong Metal Materials Co., Ltd. The specific parameters are: ① Maximum forming size (200mm × 200mm × 240mm); ② Maximum scanning speed (8000m/s); ③ Forming dimension accuracy (± 0.3mm); ④ Electron beam spot diameter (≤ 0.3mm). At the same time, the forming process parameters used by the equipment are as follows: ① Model cutting layer thickness (50m); ② Bottom plate preheating temperature (720 °C); ③ Preheating current (22mA); ④ Preheating electron beam scanning speed [(18) × 101mm/s]; ⑤ Melting current (15mA); ⑥ Melting electron beam scanning speed (7.2 × 103mm/s). In specific experiments, the forming process of porous TC4 titanium alloy with discrete minimum curved surfaces is mainly divided into two parts for processing: software and hardware .

3.4 Sample characteristics

After the above operation, the sample characteristics will be described next. In this section, this article measures the sample density of discrete minimum curvature porous TC4 titanium alloy after 3D printing. Further, the samples are polished, corroded, and the microstructure of the porous TC4 titanium alloy with discrete minimum surface is observed under a metallographic microscope through operational processes such as deposition and heat treatment.

4. Results and analysis

4.1 Morphology and density analysis

After research, it was found that by observing the macroscopic morphology trend, it can be seen that with the increase of apparent density, the pore size of the sample gradually decreases after 3D printing of the discrete minimum curved porous TC4 titanium alloy. Further analysis of the apparent density of the discrete minimal curved porous TC4 titanium alloy sample shows that the apparent density of the sample is lower than the theoretical apparent density, and there is a certain deviation between the two.

4.2 Microstructure

After the deposition and annealing process, the deposited microstructure of discrete minimal curved porous titanium alloy samples is mainly β columnar crystal, with obvious grain boundaries distributed along the deposition direction. Columnar β crystals are filled with small acicular martensite with vertical orthogonal or oblique orientation. In this process, the metastable fine acicular martensite decomposes at high temperature to form elongated sheet α phase and coarse sheet α phase.

4.3 Compression performance

In the deposition state and the heat treatment state respectively, all the experimental samples go through three stages, namely, the elastic stage, the yield stage and the platform stage. First of all, in the initial compression stage, the sample pressure gradually increases with the increase of strain variables. At this time, the relationship between the pressure and strain of the sample is linear. After the strain increases to 3%, the stress continues to increase. At this stage, the growth trend of the relationship between the two shows a non-linear relationship. When the strain increases to 8%, the compressive stress value will also be at its maximum state. Afterwards, with the continuous increase of stress, the stress of the specimen decreases. When the strain value exceeds 25%, the further increase of the strain value will cause the stress to remain unchanged, and the specimen will enter the platform operation stage. Further analysis reveals that as the apparent density increases, the compression curve begins to show an upward trend.

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