Research on the Performance of Honeycomb Support Structure Based on SLM

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Abstract. Selective laser melting (SLM) can break through the constraints of traditional manufacturing methods and enable the fabrication of lightweight and complex parts. However, in the SLM manufacturing process, the overhang structure requires a support structure to be successfully manufactured. At present, the typical support structure is the lattice structure, which has poor manufacturability, and the manufacturing defects of some of the bars cause the structure to yield in advance, and the reliability is not high. In this paper, we design honeycomb structures with different parameters. A set of structural parameters with excellent performance were obtained. The compression test was carried out using the WDW-100 universal material testing machine, which shows that the honeycomb structure of this set of parameters has high strength and meets the requirements of manufacturing. Finally, taking the sensor mount as the object, this set of parameter honeycomb structure is used for lightweight reconstruction, which can obtain better weight reduction effect under the premise of satisfying the strength of the parts, which provides technical support for the lightweight design of parts.

1. Introduction

3D printing technology has been rapidly developed in recent years and has been widely used in aerospace, automotive, construction, medical, weaponry and other fields, especially in the field of personalized customization and rapid production. 3D printing technology use layer-by-layer accumulation manufacturing method to create complex structures that are difficult or even impossible to manufacture in conventional manufacturing methods.

Selective laser melting (SLM) is one of the most commonly used technologies for metal 3D printing. Its powerful processing capability significantly shortens the part production cycle. In order to obtain lightweight parts, people often hollow out the parts and form a large number of overhang structures. The characteristics of SLM technology layer-by-layer powder scanning process make the quality of the overhang structure poor, which will cause defects such as warping deformation or collapse, high surface roughness, and even part manufacturing failure. The support structure [1] is designed for the overhang structure to withstand the overhang structure powder and prevent collapse deformation. It can also effectively restrain the shrinkage stress after the molten pool cooling, keep the stress balance and prevent...
the parts from warping. Connect the formed and unformed parts to prevent parts from moving and increase stability.

At present, researchers at home and abroad have conducted a lot of research on 3D printing support structures. Wang [2] et al. proposed the supporting structure of "skin-frame", and used the designed frame structure to fill the printed parts instead of the internal redundant materials. This supporting structure made the weight redundant effect of the printing parts up to 70%. SK. Moon [3] compared the performance of Kagome, pyramid and hexagonal structures, and redesigned the unmanned wing with Kagome structure, providing a method for lightweight manufacturing of UAV. Chen Y [4] proposed a design method based on the internal support structure of the truss, and filled the three-dimensional micro structure as the support structure into the internal design space of the part, thus realizing the internal optimization of the structure, and finally established the internal support structure database. Designers can select the appropriate support structure from the database according to different design requirements. J. Vanek [5] et al. proposed a tree-like support structure design method based on model geometry features and minimization of support materials. By determining the printing direction of minimization support structure, they captured and detected the point features that need to be supported and generated a light-weight tree support structure. Zhang [6] et al., taking hexagon as the dominant frame on the boundary surface of the structure, designed an internal frame support structure of the central axis tree, which can withstand loads from different directions and disperse loads to resist deformation. D Yamanaka [7] proposed a design method of truss support structure with controllable density. The method first optimizes the model density distribution to meet the quality characteristics of a given condition. Secondly, constructing the truss structure in the shell structure represents the density distribution, and the object density and the truss density are determined by iterative optimization of the number and position of the truss nodes to minimize the error between the two. Finally, the lightweight object with controllable center of mass is printed.

At present, the commonly used support structure is the two-dimensional or three-dimensional lattice structure. The structure composed of slender rods can be made with poor manufacturability, which is easy to cause manufacturing defects, and some of the members of the structure are yielded in advance, which is easy to cause warpage and local buckling and other defects. Meanwhile, there is almost no theory for the design of support structure. The design process is largely realized according to the designer's personal experience, and has certain subjectivity and uncertainty. In order to ensure the manufacturing process is successful, the support structure is often over-engineered, resulting in unnecessary waste [8]. This paper studies the performance of honeycomb support structure, explores a set of supporting structure parameters suitable for SLM technology, and provides technical support for 3D printing lightweight design.

2. Analysis of Honeycomb Supported Structure

2.1. Analysis of Honeycomb Structure Parameters

Due to the limitations of conventional manufacturing methods, two sides of the honeycomb structure are often made to have a double wall thickness, which can't give full play to the lightweight effect of honeycomb structure. The honeycomb structure is designed for SLM as shown in Fig.1. SLM technology has the characteristics of free molding. It can change the parameters of honeycomb structure arbitrarily, and the structure can be designed flexibly according to actual needs. Honeycomb structure is a discontinuous structure. There is no so-called density concept, and the relative density can only be calculated by equivalent processing. The relative density is the most important characteristic parameter of the honeycomb structure, which refers to the ratio of the density of the honeycomb structure to the density of the honeycomb material. Taking the unit body in the dotted line in Fig.1, the relative density is obtained as in the equation (1).
Figure 1. SLM manufacturing honeycomb structure

\[
\bar{\rho} = 1 - \frac{3}{(\sqrt{3} + \frac{t}{L})^2}
\]  

(1)

It can be seen from equation (1) that the relative density of the honeycomb structure is only related to the side length and the wall thickness of the hole, regardless of the height. The relative density variation is less affected by the side length and is more sensitive to changes in the wall thickness of the honeycomb structure. The relative density of the honeycomb structure can be quickly changed by adjusting the wall thickness of the honeycomb structure.

2.2. Heat Transfer Analysis of Support Structure

The heat source of SLM technology is a high-energy laser. The metal powder melts, solidifies and cools rapidly under the action of the laser beam. In this process, the manufactured parts will generate thermal stress. Titanium alloy (Ti6Al4V) has a high melting point and poor thermal conductivity, which will generate large thermal stress during processing. The generation of residual stress is mainly affected by two factors: temperature gradient and cooling rate.

In terms of the temperature gradient, the laser instantaneously inputs a large amount of energy, and the temperature of the powder near the laser irradiation point rises rapidly, forming a tiny molten pool, and the molten pool forms a large temperature gradient with the surrounding tissue. According to the principle of thermal expansion and cold contraction, the metal in the molten pool is heated to expand and compressive stress is generated on the surrounding structure. During the rapid solidification and cooling of the molten pool, the metal at the solidification point contracts, and the surrounding tissue generates tensile stress on the solidification point [9] as shown in Fig.2.

Figure 2. SLM thermal analysis model

In terms of cooling rate, according to Fourier's law of thermal conduction:

\[
Q = -\lambda A \frac{dT}{dx}
\]  

(2)
Q refers to the heat transferred per unit time, \( \lambda \) represents the thermal conductivity of the material, \( A \) represents the area of the heat transfer cross section, \( T \) is the temperature, and \( x \) represents the coordinates in the direction of heat conduction. The heat transfer rate is proportional to the thermal conductivity, the cross-sectional area, and the rate of temperature change perpendicular to the cross-section. The thermal conductivity of titanium alloy is equal to 15.24 W/ (m·K), the thermal conductivity of metal powder is about 1/100 of the same material entity, and the thermal conductivity of shielding gas argon is equal to 0.0173 W/ (m·K).

As shown in Fig. 3, in the manufacturing of overhang structure, the underside of the molten pool are unmelted powders, and the heat conduction mainly depends on the metal powder below, and the heat conduction efficiency is low. The large amount of heat is accumulated so that the temperature of the molten pool is higher than when the solid structure is manufactured. More powder is adsorbed into melting pool and the surface quality becomes worse. When support structure is added to overhang structure, the heat transfer medium changes and the cooling rate increases. Excess heat can be transmitted through the support structure. The change of the structure causes the change of the cooling rate to cause uneven shrinkage deformation of the manufactured part, and when the shrinkage deformation is excessively large and plastic deformation occurs, residual stress will be generated. At the same time, when the strength of the support structure is too small to resist the thermal stress, warping deformation is easily caused. Therefore, the support structure density is an important factor affecting the manufacturing quality and lightweight effect of the manufactured part.

### 3. Experiment Process

For experimental measurement convenience, each sample contains 8 honeycomb holes. The commercial metal 3D printer has a maximum printing support interval of 5 mm, so the designed honeycomb side lengths are 2.0 mm to 3.0 mm. In order to explore the influence of honeycomb structure side length and wall thickness parameters on the performance of overhang structure, 6 samples were designed, and the structural parameters are shown in Table 1. For comparison, four lattice structures were designed with diameters of 0.75, 1.0, 1.25, and 1.5 mm, respectively.

| Sample | Side length (mm) | Wall thickness (mm) | Relative Density (%) |
|--------|-----------------|---------------------|----------------------|
| 1      | 2               | 0.5                 | 23.64                |
| 2      | 2.25            | 0.5                 | 21.45                |
| 3      | 2.5             | 0.3                 | 12.54                |
| 4      | 2.5             | 0.5                 | 19.63                |
| 5      | 2.5             | 0.75                | 27.35                |
| 6      | 2.5             | 1.0                 | 34.00                |
| 7      | 2.75            | 0.5                 | 18.10                |
| 8      | 3.0             | 0.5                 | 16.79                |
In this experiment, Ti6Al4V titanium alloy powder was used as raw material, and its chemical composition was: Al (5.5–6.75%), V(3.5–4.5%), Fe ≤ 0.3%, C ≤ 0.08%, N ≤ 0.05%, H ≤ 0.015%, O ≤ 0.2%, and the particle diameter is 15 to 45 µm. The sample was fabricated by FS271M metal 3D printer from Farsoon High-Technology Co., Ltd. Process parameters in the manufacturing process have an important impact on mechanical property, so all samples were manufactured in the same cylinder and processed in one time, which made the SLM process parameters strictly consistent, excluding materials, machine equipment status and environmental change on the influence of samples. The molding chamber is filled with argon gas as protecting gas, and the oxygen content is controlled below 1000 ppm to prevent oxidation during processing. The processing parameters used are shown in Table 2. All samples were well manufactured and produced without manufacturing defects such as warpage and collapse which are shown in Fig 4.

**Table 2. Process Parameters for SLM Processing**

| Laser power | Layer thickness | Scanning speed | Spot diameter | Platform temperature |
|-------------|----------------|----------------|---------------|----------------------|
| 225W        | 30µm           | 1100m/s        | 70–200µm      | 150°C                |

**Figure 4. Samples made by SLM technology**

We perform mechanical performance tests on the support structure to verify that the structural strength meets the requirements. The equipment used in this mechanical performance experiment is WDW-100 universal material testing machine. The load range is 0.3–100kN, and the load measurement accuracy is ±0.5%. The samples are small-sized parts, and the deformation is small after being stressed. To ensure the accuracy of the experiment, an extensometer was used to measure the small displacement generated by the sample, as shown in Fig. 5. The load was continuously applied at a loading speed of 0.5 mm/min, and the sensor collected the load-displacement data of the sample and records it through a computer. The whole test was carried out at room temperature of 25°C.

**Figure 5. Test of mechanical properties**

The design of the support structure should consider the lightweight effect, mechanical properties, etc. The honeycomb support structure with side length of 2.5mm and wall thickness of 0.5mm has better
comprehensive performance and its strength is 305.1 MPa, which can meet the requirements of support structure. Fig. 6 shows the stress-strain curve of the lattice structure.

The strength of the lattice structure with a diameter of 0.75 mm is only 254.9 MPa. The strength increases slightly with the increase of the diameter, and the strength is 362.1 MPa when the diameter reaches 1.5 mm. It can be seen from the stress-strain curve that when the partial rod of the lattice structure is first yielded, the bearing capacity of the structure is instantaneously reduced, and the overall structure is also yielded. When the honeycomb structure partially yields, the structure can still withstand the huge load. Therefore, the honeycomb structure has higher stability than the lattice structure.

![Figure 6. The stress-strain curve of lattice structure](image)

4. Reconstruction of the Sensor Mount

In the field of mechanical manufacturing, especially in the aerospace industry, lightweight design of parts is a topic of constant concern. The lightweight design of the parts helps to reduce aircraft weight, save fuel consumption, increase load capacity and increase payload. Commonly used lightweight design methods include: the use of lightweight high-strength materials, topological optimization of the structure and lightweight sandwich structure. In this paper, the sensor mount of aircraft was used as the object, which is reconstructed using honeycomb structure. Fig.7. shows the actual size and working environment of the sensor mount. Its bottom is fixed and withstands 10 times the gravitational acceleration load when launched.

![Figure 7. Working environment of the sensor mount](image)

Firstly, the model is imported into ANSYS Workbench 15.0 for finite element simulation to analyze the stress during the launching process of the mount. The stress distribution of the base is shown in
Fig. 8. The maximum stress is generated near the fixed surface of the bottom, the maximum stress is $1.06 \times 10^4$ Pa, far less than the strength of the material, and the material is not fully utilized.

Figure 8. The stress distribution of the sensor mount

Secondly, according to the previous study, when the thickness of the skin is 2mm, the structure can achieve higher strength and rigidity, and at the same time ensure the lightweight design of the structure [10]. Set the thickness of the shell of the sensor mount to 2mm, and fill the inner overhang area with the honeycomb support structure with a side length of 2.5mm and a wall thickness of 0.5mm. The honeycomb structure can support the overhanging area while achieving lightweight design of the parts, as shown in Fig. 9. The sensor mount is made of titanium alloy, and the average density of titanium alloy is 4.5g/cm³. After calculation, the weight before reconstitution is 112.87g, the weight after reconstitution is 66.25g, and the weight loss effect is 41.3%.

Figure 9. The internal structure of the sensor mount after reconstruction
Perform simulation analysis on the reconstructed sensor mount again to verify whether the strength of the sensor mount meets the strength requirements, as shown in Fig.10. The maximum stress still appears near the fixed surface of the bottom surface, and the shell is still at a low stress level, which can maintain a certain rigidity without deformation. The maximum stress on the mount is $1.75 \times 10^4$ Pa, which is much lower than the yield strength of Ti6Al4V material (1000MPa).

5. Conclusion
This paper researches the honeycomb structure based on SLM technology that provides support for the manufacture of overhang structure, which overcomes the shortcomings of common lattice support structures that are prone to instability. The influence of structural parameters on the performance of overhang structure was studied. This method reduces the possibility of warping deformation in SLM manufacturing from the source, which provides a new idea for the design of support structure. This set of parameters of the honeycomb structure can withstand a maximum load of 61.8kN, its strength reaches 305.1MPa, fully meet strength requirements, to ensure the success of manufacturing process. The honeycomb structure of the optimal parameters obtained by the experiment was used to carry out lightweight reconstruction of the sensor mount, and the weight of the sensor mount was reduced by 41.3%. The strength of reconstructed sensor mount meets the requirement of use, and the design method provides technical support for lightweight design of parts.

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