PROCESS CHARACTERIZATION OF IDEAL POROUS STRUCTURE MANUFACTURE BASED ON SELECTIVE LASER MELTING (SLM)

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ABSTRACT: In order to analyze the process characterization and the design rules of porous structures, several types of porous structures were designed and produced by selective laser melting (SLM). For purpose of manufacturing a porous structure accurately, design rules based on SLM, such as the critical inclined angle of the strut, the minimum building feature and the mutual constraint among the unit cell geometrical parameters need to be considered in early stage. Other problems of the porous structure, such as powder adhesion or surface micro-pores, were analyzed. The paper also discussed another innovative design method for porous structure based on SLM technology. The obtained results provide the basis for the design of porous structure and the pre-judgment of manufacturing quality.

1. INTRODUCTION

At present, the research of manufacturing porous material has evoked many scholars' interests. Compared with the general metallic material, the structure controlling of porous material is more complicated. The SLM technique has been widely used in medical and aerospace fields. The new manufacturing process of porous structure is a good research and development subject.

The principles of manufacturing the porous structure by SLM are as follow: A regular porous structure was pre-designed in the CAD model beforehand. The laser beam was controlled to skip pore area and only scanned the powder outside the pore area. After the fabrication was finished, the residual powders inside the pore are removed to form porous structure. For this kind of method, the pore's shape, size, and distribution are pre-set in CAD modeling stage. However, whether the regular porous structure could be obtained is controlled by laser spot diameter, powder particle size, particle morphology, the heat affected zone around the micro tracks.

Researchers had done certain exploration researches on the porous structure manufacture through additive manufacturing. Those researches included basic process optimization, materials, applications exploration and so on. Yadroitsev *et al.* (2009) used the SLM device equipped with fiber laser (spot diameter 70 μm) to manufacture stainless steel filter with micron-sized pores through SLM process. Warnke *et al.* (2009) and Stamp *et al.* (2009) had also manufactured porous titanium alloy based on SLM process.

By judging from the published research results, we could find that the design rules and key points for laser addictive manufacturing of porous structure were mentioned rarely. Su *et al.* (2013) had discussed the processability and fabricating process of porous fabrication by SLM, but their discussion focused less on the design and process restrictions. This paper will present technological characteristics and some design rules of porous structure, the analysis on the difficulty of forming porous structure and the certain theoretical basis provided for designer at the early stage.

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2. EXPERIMENTAL METHODOLOGY

2.1 experimental equipment and material

The apparatus used was self-developed Dimetal-100, which was a pre-commercial SLM workstation with a maximum laser power 200 W continuous wavelength of 1090 nm Ytterbium fiber laser. The building envelop was 100 × 100 × 100mm. The focusing optics could produce 70µm spot diameter. The chamber was protected with Argon or Nitrogen atmosphere with no more than 0.15% O_2. The optimum thickness of the powder layer spread by scraper was 20-50 µm.

Material 1: Gas atomized 316L stainless steel powder was used in this experiment, the mean diameter was 17.11µm, and apparent density was 4.04g/cm^3.

Material 2: The pure Ti powder that had irregular shape was also used, and the mean diameter of powder size was 50 µm.

2.2 experimental process

Several types of interconnecting porous structures were designed, sliced, and then imported the data into the Dimetal-100 equipment for manufacture. Next the forming characters of porous structures were observed and analyzed. At last, designing rules and some suggestions for precise production of porous structures based on SLM were put forward.

3. RESULTS & DISCUSSIONS

3.1 porous structures production

As Table 1 shows, type a, b, c had defects such as plugging of pores and adhering slag, which resulted in the poor manufacturing results of the side. Seen from the side view of type d, some inclined struts had fractured due to insufficient strength. Combined with experimental analysis before, referred to experimental results of other researchers, the authors believed there are several factors affecting the production of porous structures by SLM: (1) The optimized process to get 100% dense metal part; (2) The improved design of the porous structure based on SLM process; (3) The customized scanning strategy for small entity (strand diameter<200µm), for example, outline scanning after raster scanning can improve the quality.

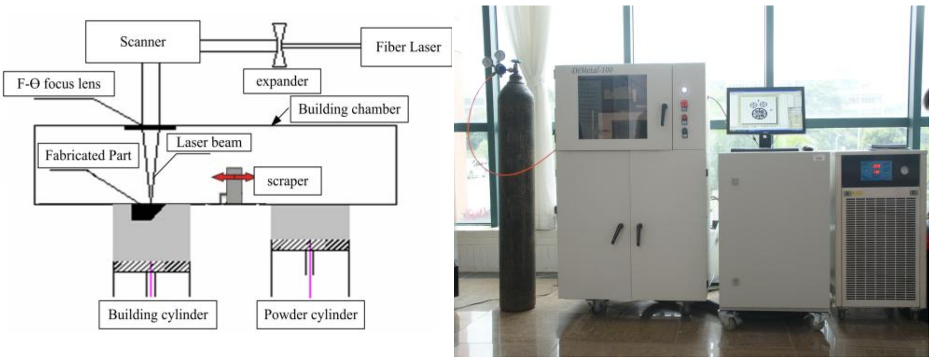


Figure 1. SLM manufacturing principle and equipment

3.2 theoretical analysis of porous structure processibility

3.2.1 forming experiment of inclined struts

Ten 200μm-diameter struts with various inclined angles were produced as shown in Figure 2. The process parameters as follows: layer thickness 40 μm, laser power 150 watts, scanning spacing 80 μm, scanning speed 600 mm/s. Struts of inclined angles 15° and 20° deformed, And struts of inclined angles 25° and 30° had adhering slag. This is an important result as it indicates that fabricated strut has the critical inclined angle, which was useful for porous structure design.

3.2.2 design rules for typical porous structure

According to the above summarized experimental results, the design of porous structure should consider the following three conditions: the critical inclined angle of the strut, the minimum building feature and the mutual constraint among the unit cell geometrical parameters.

The design rules for the porous structure that fit for SLM process were summed up as follow.

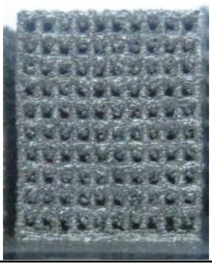
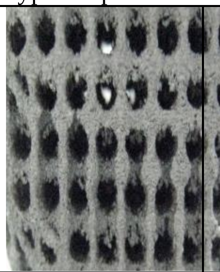
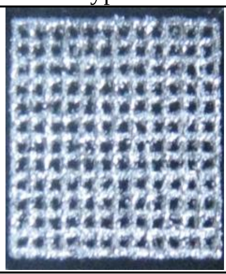
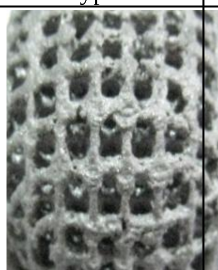
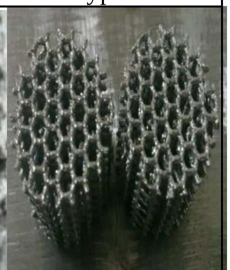
Critical inclined angle° $\le \theta < 90°$ (1)

$d \ge$ minimum building feature(related to the device parameters) (2)

$1/2 \times L \times \sin 2\theta > d$ (3)

Based on above-mentioned design rules, the porous structures as shown in figure 4 were produced.

Table 1. Manufacturing results of several types of porous structures

Side view				
	Type a	Type b	Type c	Type d
Top view				
	Type a (pure Ti)	Type b (pure Ti)	Type c (pure Ti)	Type d (316L ss)

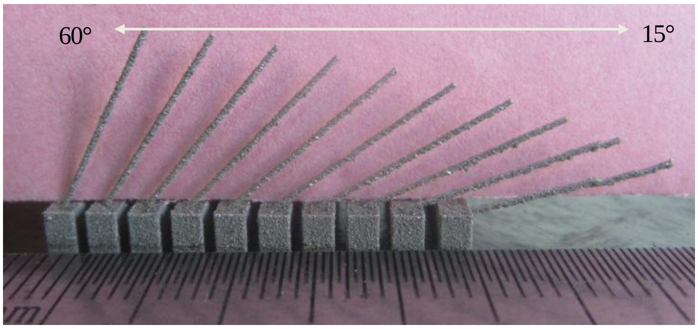
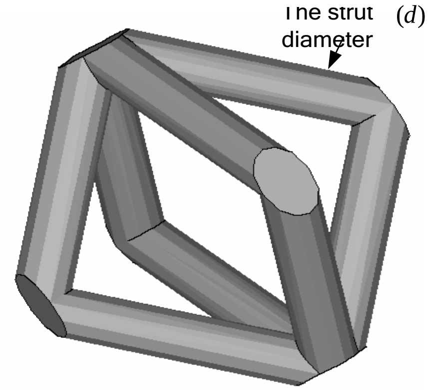


Figure 2. Inclined struts forming experiment(inclined angle: 15°~60°)

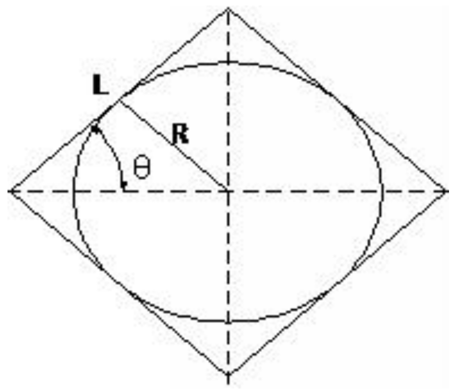
3.3 discussions

In order to produce ideal porous structure, optimized process is basis, only when dense stainless steel part is obtained, it can ensure the strength of porous structure. The study on critical inclined angle provided geometrical limitations for the design of porous structure, that is, the inclined angle of the unit cell's strut should be bigger than the critical angle when manufacturing metal parts by SLM, otherwise the inside of the porous structure would be jammed by the powder.

The SLM manufacture of porous structure still has other problems, such as powder adhesion and exists of micro-pores on surface as shown in figure 4(b). From the view of manufacturing, micro-pores on the surface of the strut belong to the processing defect due to the instability of molten pool in the melting and solidification process. However, the micro-pores may be good for bone in-grown from the analysis of medical applications.

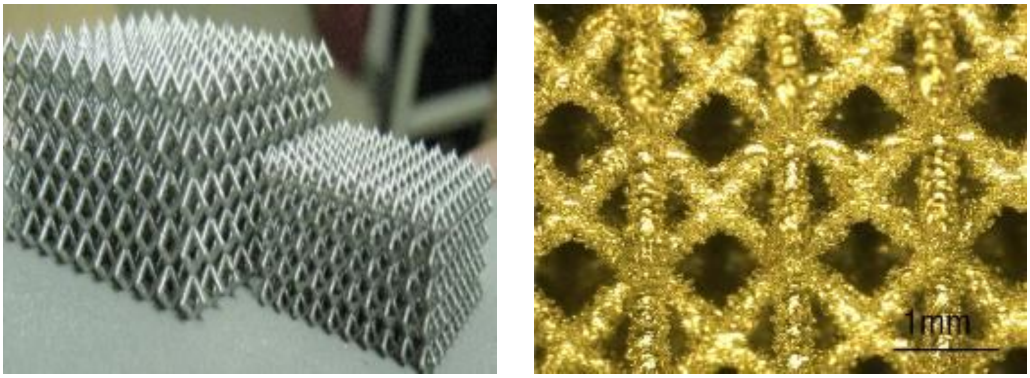


(a) unit cell



(b) plane model of unit cell

Figure 3. The unit cell with octahedral structure



(a) optimized porous structures (b) enlarged view of porous structure

Figure 4. the result of SLM manufacturing porous structures

Based on the designing restrictions/rules discussed above, there should be other innovative designing methods suitable for the SLM production of porous structure. Parthasarathy et al. (2011) and Patrick et al. (2009) had introduced different designing ways of porous structures. Implicit surfaces are collections of certain conditions in the space, which can be expressed as function $F(x,y,z)=c$, when $c=0$, all conditions that meet $\{(x,y,z)\in R^3 \mid F(x,y,z)=0\}$ would define a surface. The porous structure surface obtained from the implicit surface has the following advantages: (1) smooth surface has no obvious stress concentration effect, and stress tended to be evenly distributed throughout the structure. (2) By changing the parameters of mathematical functions, the porous structure parameters such as unit cell size, porosity and specific surface area can be changed easily.

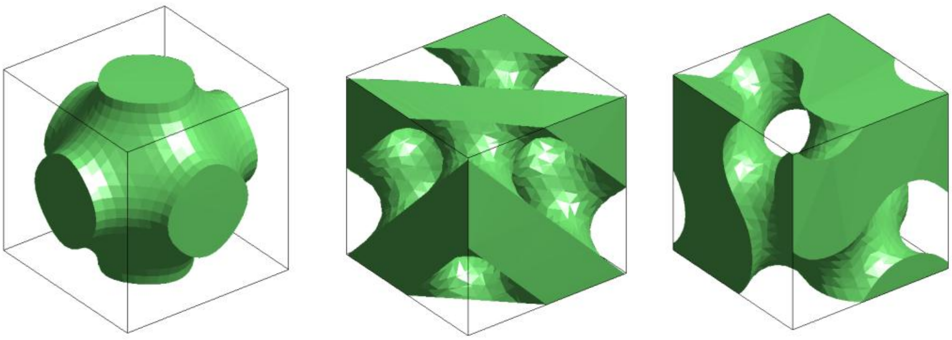


Figure 5. Three kinds of typical porous structure surface based on implicit surface method

Figure 6. The result of SLM manufacturing porous cranial graft based on implicit surface method

4. CONCLUSIONS

This paper discusses the technological characteristics of ideal porous structure manufacture based on selective laser melting. Based on the experimental results, conclusions as follows:

(1) Different design of porous structures could result in large difference in production effect.
(2) In order to manufacture the porous structure accurately, designers need to consider design rule in early stage. The design rules includes the critical inclined angle of the strut, the minimum building feature and the mutual constraint among the unit cell geometrical parameters.
(3) The processibility and other quality problems of the ideal porous structure, such as powder adhesion or micro-pores on surface, were discussed and analyzed. The paper also discussed other innovative design method for porous structure based on SLM technology.

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