Finite Element Analysis and Manufacture of Porous Structure Based on SLM Technique

Yaling Wang, Xianshuai Chen, Yuanxin Luo, Chunyu Zhang, Peng Zhang, and Wei Feng

***Abstract*—Selective laser melting (SLM) technique has been widely used in stomatology in recent years because of the advantages of its digitization and efficient. However, information about it is limited. What is more, studies have shown that porous structural dental implants based on SLM technique is beneficial to combination of implant and bone tissue. In this study, designing and manufacturing new types of porous implants based on SLM technique and performing simulation from the perspective of biomechanics are the main content. The results show that hollow structure has higher stress and strain in stress-concentration areas compared with solid structure. However, these differences would not form great influence. There are not obvious defects for the samples based on SLM technique on surface.**

***Index Terms*—Porous, FEA, manufacture, SLM.**

I. Introduction

The ability of SLM technique to produce components with very complex designs is one of the unique advantages of the technique that can be applied in biomedical applications. SLM technique melts metal powder to form the metal parts with complex structure based on the principle of superposition of layered manufacturing. Compared with other conventional manufacturing technology in this aspect, SLM technique has the irreplaceable advantages and become a hot research topic, as the academic dissertation [1]. Therefore, the technique is widely applied to many branches of stomatology, including oral and maxillofacial surgery, dental prosthesis, dental implantation and orthodontics, as said in the journal paper [2]. Nevertheless, the SLM study is still in its infancy, the mechanical properties, biocompatibility and materials are subject to further discussion. An understanding of the effect of implant design on its mechanical performance is required for any further improvement. Some studies have been performed to investigate the influence of a dental implant design on its mechanical properties, as described in the journal [3]. Study reveals that the different design is an important parameter needs to be considered and porous structure could enhance bone ingrowth. Therefore we investigate the effect of two different structures on mechanical properties based on SLM technique, which allows the separate control of pore structure, to determine the optimal porous structure for metal implants manufactured by this process. What's more, recent studies have shown that appropriate inner-porous structure promote the osseointegration of implant and bone tissue. Designing surface or entire porous structure dental implant can get better biomechanical performance. Due to the introduction of pore, which has become the research focus, the elastic modulus of porous titanium has effectively reduced the phenomenon of "stress shielding" has been avoided, and its unique porous structure is beneficial to the bone ingrowth. In this study, two different structure are simulated to determine if the porous structures could meet the clinical demands in mechanical properties when the ability of osseointegration is promoted.

II. Materials and Methods

The first step of the numerical analysis is to draw three-dimensional geometric models of the jaw bone and the corresponding implant. In this study, two different structural implants are modeled, with the same dimensions of 4.8-mm diameter, 7.6-mm length, 1.2-mm pitch and 0.4-mm thread depth in implant body. The implant system is modeled as an integrated structure. In this study, a straight abutment is designed with the maximum diameter of 4.6mm and the length of 5.6mm. Cortical and cancellous bones are also modeled representing the cross-section of the posterior human mandible. Two-millimeter thickness of cortical bone was modeled around the cancellous bone and implant neck, a journal paper [4]. In order to understand the effect of porous structure on the distribution of stress and strain, a solid structure is modeled with 0.6-mm pore in the surface of the implant. The other hollow structure is not only with 0.6-mm pore in the surface but also has a hollow structure inside the implant body, as is shown in Fig. 1.

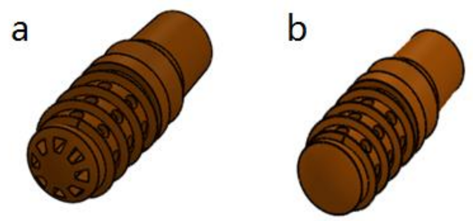

Fig. 1. Models of porous structure.

TABLE I: Mechanical Properties of Materials

Materials	Elastic modulus [GPa]	Poisson's ratio
TA2	108	0.33
Ceramic	68.9	0.28
Cortical bone	13.7	0.3
Cancellous bone	1.37	0.3

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A large number of studies have demonstrated when doing small deformation and static analysis, materials used in study were assumed to be continuous, homogeneous and isotropic. All of the materials applied to the implant systems are listed in tableI, just as journal paper [5]-[8]. The 100N of the buccal oblique force is applied with 30° to the long axis of the implant on the buccal cusp. The mesial and distal surfaces of alveolar bone were constrained in x, y and z directions (displacements=0) as the boundary condition. For the simulation of osseointegration after implant placement, a bonded condition was set at the implant-bone interface and the simplified crowns were bonded with abutment.

The samples based on SLM technique are different from those based on CNC technique. Mechanical properties of TA2 have been greatly promoted, such as elongation,from the average of 17% to 27% . At the same time, porosity would cause influence on the mechanical properties of formed parts. Some works has been performed to determine the relationship between the elastic modulus of porous parts and their relative porosity according to the (1):

$$E^{*}=E \times (1-\Phi)^{2} \qquad (1)$$

where E and E^* are the elastic of materials and relative elastic of porous structure, Φ is the porosity. In this study, relative elastic of hollow structure with porosity of 19.6% could be calculated as 69.8GPa according to Table I and (1).

III. Results

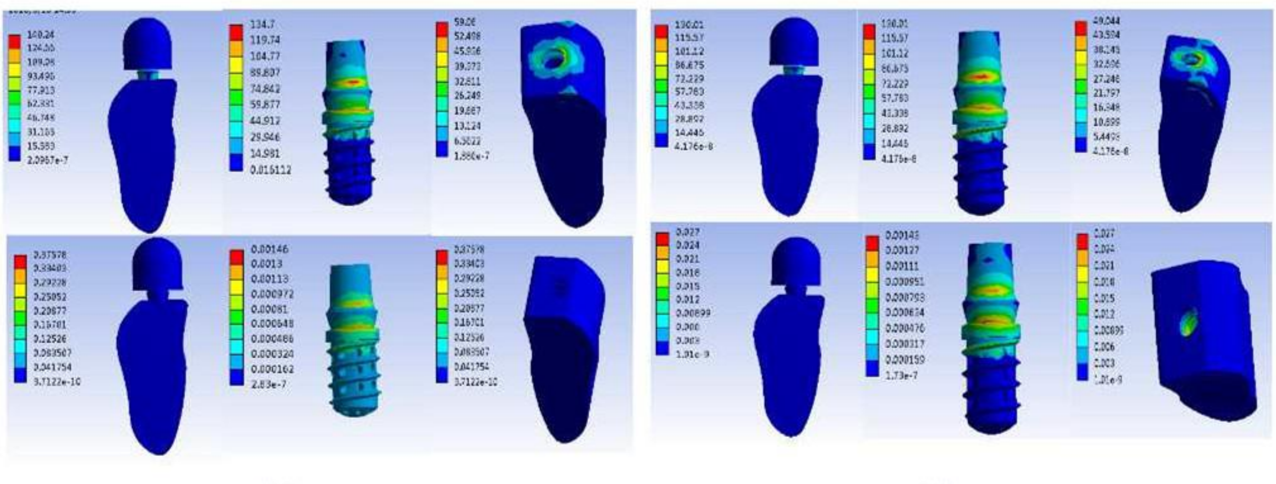
The 3D models established in solidworks 14.5 surface could be immediately generated in ANSYS Workbench Interface without translating into other intermediate format by seamless link between the two softwares. The distribution of stress and strain in the two models is mainly used to evaluate their mechanical properties.

Pure titanium parts manufactured by SLM technique are equipped with good mechanical property and biocompatibility, Tensile strength and yield strength are corresponding to 383GPa and 475MPa as journal paper [9].

The developed finite element models provide the magnitudes and distributions of the stress and strain throughout implant system. Fig. 2(a), (b) shows the stress distribution for the implant system of different structures. Stress distribution is almost the same for two different structures but the highest stress occurred for hollow structure, of around 140 MPa at the crown-implant contact region. As for the implant, the maximum stress is located in the neck of implant, with the values of 134MPa in hollow structure and 130MPa in solid structure, 28.2% and 27.4% of yield strength of pure titanium parts based on SLM technique. The porous structures are the areas with high stress around the first lap of screw. Lower-middle parts of implants are not subjected to force basically. In the alveolar bone, the maximum stress is observed in crestal region around the socket in cortical bone, which corresponded with the clinical finding of maxillary crestal bone loss, as said in journal paper [10], with the values of 59MPa and 49MPa. The stress of cancellous bone is so small that we can ignore its influence on implant system.

The distribution of strain in the implant system is consistent with that of stress. As can be seen from the pictures, the maximum strain in two structural implant system is 0.37mm and 0.027mm respectively. In the implant, the areas of largest stress are the parts of largest strain, with the values of 0.00146mm and 0.00143mm. With regard to the alveolar, maximum strain is located at the bottom of cavity in cancellous bone, with the values of 0.37mm and 0.027mm.

In comparison with solid structural implant system, hollow structural implant system is subjected to larger stress and strain, the maximum stress of implant in hollow structure is 0.8% and the strain is 0.00003mm more than solid structure .In conclusion, as for implant, the differences in strain and stress are too small to cause obvious influence in mechanical properties. The results of FEA show that the stress and strain are both keep in small values and don't reach the yield strength of samples based on SLM technique.



(a) (b)

Fig. 2. The distribution of stress and strain (a), hollow implant system (b) solid implant system.

From the Fig. 3 (a), (b), the dental implant is still in a safe state after 5 million times cyclic loading and fatigue fracture phenomenon doesn't happen with the minimum safety factor of 7.0. The distribution of implant fatigue safety coefficient is in line with stress distribution basically. The areas with larger stress have lower level in safety factor such as the implant-abutment surface, abutment-crown surface and porous structure at the first lap of thread which are in higher stress, with the values between 7.0 and 13.0 in hollow implant and 7.9 and 13 in solid implant. It is believed that fatigue damage happens on the three areas with higher stress firstly.

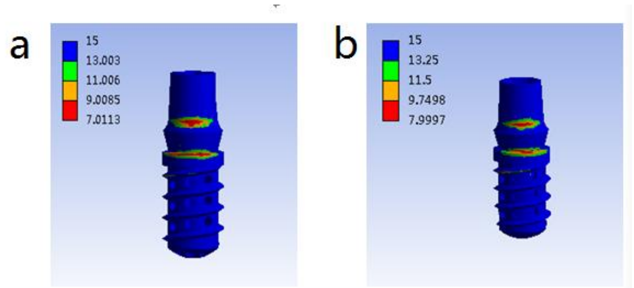


Fig. 3. Fatigue safety factor of dental implant. (a) hollow implant (b) solid implant.

IV. Manufacture of Samples

Pure titanium is widely used to manufacture dental implant in SLM technique due to the good biocompatibility and high corrosion and mechanical resistance. What is more, the elastic modulus is high relative to bone tissue. With this advantage, it can accelerate the ingrowth of tissue. In this study, TA2 is used for formed materials. SLM technique build parts layer by layer, from the bottom up, by scanning a focused laser or electron beam that melts a powdered raw material and promotes its consolidation. A powder is uniformly distributed over each layer prior to the subsequent layer scanning. The geometry and internal architecture of the parts are controlled by selectively applying the laser or electron beam power to the desired areas of consolidation.

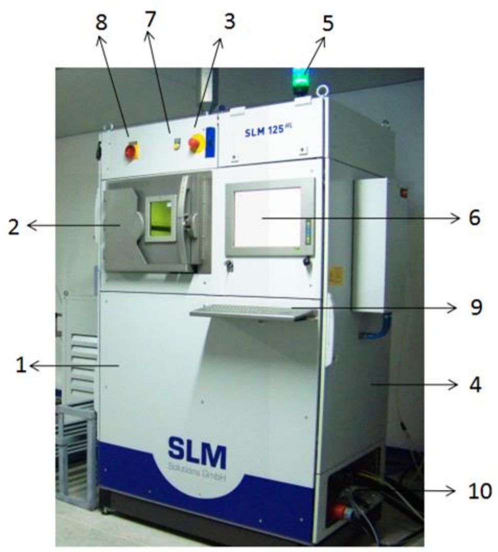


Fig. 4. The fabrication setup in SLM125HL YLR-100-WC; 1.process cabinet 2.process chamber 3.emergency STOP button 4.control cabinet 5.signal lamp 6.screen 7.[RESET] button 8.main switch with emergency STOP function 9.keyboard 10.connctions.

SLM125HL YLR-100-WC of SLM Solution company is used to study SLM technology in this paper, as is shown in Fig. 4. The size of machinable parts is 125 mm × 125 mm × 75 mm, and the scanning speed is 15cm3/h, layer thickness can be controlled from 20μm to 75μm, the scanning spot size is 70μm to 130μm, the minimum processing thickness is 140μm to 160μm. The dimensional accuracy, porosity, level of oxygen and nitrogen and the mechanical properties for a given relative density were influenced by the energy input as journal paper [11]. Based on the experiment results, the optimum technical parameters are shown in Table II.

TABLE II: Processing Parameter of SLM Technique

process parameters	laser powder	scannin g interval	scanning speed	layer thicknes s	Scanning spot
value	100w	0.13mm	255mm/s	70 μ m	87 μ m

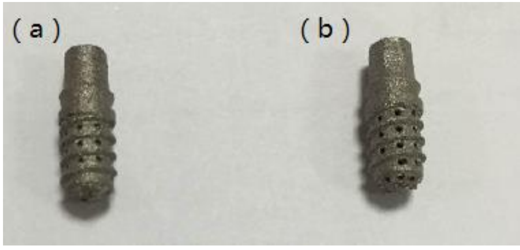


Fig. 5. The samples based on SLM (a), solid structure (b), hollow structure.

Two samples are manufactured according to the above parameters based on SLM technique, as shown in Fig. 4(a), (b). SLM technique can produce the whole parts without macroscopic defects. However, both the processing parameters resulted in small spherical particles visible on the surface. As for interior structure, some balling phenomenon is caused by temperature gradient and scanning interval. Therefore, the energy density of SLM machine has different degrees influence on the quality of samples with different materials, porosity and structure. It is the main direction for us to study the parameters of SLM technique in different structures.

V. Conclusion

In this study, relevant conclusions are listed in follows according to FEA and manufacture in porous structures:

1) Hollow implants basically satisfy the mechanical properties to bear occlusal force and save materials compared with solid structure based on SLM technique. All of the models are in safe states has been shown that proper hollow structure would not reduce the strength of the implant and result in loss of the fatigue fracture in this case. The stress concentration area may be broken according to fatigue and static analysis. However, some unreasonable hollow structure would lead to inadequate strength.
2) The samples based on SLM technique don’t have obvious defects. But there is much balling phenomenon in their inner structure and around the pores. Therefore, appropriate structure should be chosen carefully in implant design. Effect of different designs based on SLM technique on the stress and strain distribution still need to be investigated. What is more, setting parameters according to different structure in SLM machine is the main problem to study new processes.

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