Finite Element Analysis of Porous Ti-6Al-4V Alloy Structures for Biomedical Applications

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Abstract. In this article, design and finite element simulation of porous Ti-6Al-4V alloy structures was presented. Typically, titanium and titanium alloy implants can be manufactured with required pore size and porosity volume by using powder bed fusion techniques due to advancement in additive manufacturing technologies. However, the mismatch of elastic modulus between human cortical bone and the dense Ti-6Al-4V alloy implant resulted in stress shielding which accelerate the implant failure. The porous implant structures help in reduce the mismatch of elastic modulus between the cortical bone and implant structure and also improve the bone ingrowth. Hence, the present work focuses on design of Ti-6Al-4V alloy porous structures with various porosities ranging from 10% to 70% and simulated to determine the elastic modulus suitable for human cortical bone. The sample with 45% porosity is found to be best suited for replacement of cortical bone with elastic modulus of 74Gpa, preventing stress shielding effect and enhanced chances of bone ingrowth.

Keywords: Additive manufacturing, porosity, elastic modulus, Ti-6Al-4V alloy.

1. Introduction

The field of Additive manufacturing has brought a drastic change in part design and manufacturing due to its ability to manufacture complex geometries with required features in various fields such as automotive, aerospace and biomedical industry. Additive manufacturing (AM) also referred as rapid prototyping or layer by layer manufacturing or 3D Printing. The AM can be defined as the process that uses 3D CAD data for building of three dimensional objects usually layer by layer deposition of material. Additive manufacturing has the ability to produce metallic components by using metallic powder as input. The various AM techniques used for metals include direct metal laser sintering, selective laser melting, electron beam melting. Due to the development of AM technology, typically it is used for producing orthopedic implants and scaffolds [1] to [3]. However the implant should possess certain mechanical properties for long-term load bearing applications in the human body. These implants are categorized into permanent and temporary on the basis of application, and the implants should possess good biocompatibility, high ratio of strength to weight. The major problems associated with the metallic implants include bone ingrowth, mismatch of elastic modulus and weight of the implant. In order to overcome these adverse situations, porous structures are employed for metallic implants. This paper provides detailed information about design of porous structures for Ti-6Al-4V alloy. The porous structures improve bone ingrowth and minimize the stress shielding effect which does not allow the bone to dislocate.
2. Materials and methods

The Ti-6Al-4V alloy is used for orthopedic implants because of its good biocompatibility, low density, high corrosion resistance, non toxic nature, and low elastic modulus compare to Co-Cr alloy and 316L stainless steel. Hence, the Ti-6Al-4V alloy was chosen to design the porous structures with porosity ranging from 10% to 70% and simulated to understand the variation of elastic modulus with respect to porosity percentage of the implant material.

2.1. Design of porous structures

A short cylinder was modeled as per the ASTM standards using 3D CAD Software with different porosities ranging from 10% to 70%. Several factors affect the bone ingrowth into pore space provided, like interconnectivity of pores, pore size, pore shape, porosity percentage. The porous structure has great impact on bone ingrowth into the pore space provided. The optimum pore size is 1000 micrometers. Pores must be interconnected to maintain vascular system for establishing bone ingrowth. Figure 1 shows the cylindrical structures of various porosity percentages ranging from 10 to 70.

![Figure 1. 3D CAD models of porous structures of various porosity percentages](image)

The sequence of steps involved in design of 3D CAD models of cylindrical structures and FE analysis of Ti-6Al-4V alloy porous structures are presented in the Figure 2. Finite element simulation was carried out for the cylindrical porous specimens by applying boundary conditions. The elastic modulus of porous samples determined by Von Mises stress and strain relations in WORKBENCH 16.0 commercial software.
3. Results and discussions

The cylindrical shape structures of different porosity percentages varies in the range of 10 to 70 were designed using the 3D CAD software. By the finite element analysis, it was observed that the Von Mises stress was decreasing in nature by increasing the percentage of porosity up to 40, and after 40%, the Von Mises stress was increasing in nature. The distribution of stress in porous structures are shown in the Figure 3. The Variation in elastic modulus with respect to porosity percentage was shown in the Table 1. From the results shown in Table 1, the elastic modulus of Ti-6Al-4V alloy of zero percentage porosity has 110 GPa and it decreases from 97 GPa to 70 GPa when there is increase in the porosity percentage range of 10 to 40. However, with increase in the porosity percentage from 40 to 70 the elastic modulus of porous structure increases from 70 GPa to 95 GPa. The reason behind for above effect is densification of the porous structure and as self-contacting surfaces increases, it behave like a solid structure [4, 5].

Table 1. Variation of elastic modulus with porosity percentage

| S.No | Porosity (%) | Elastic Modulus (GPa) |
|------|--------------|-----------------------|
| 1    | 0            | 110                   |
| 2    | 10           | 97                    |
| 3    | 30           | 80                    |
| 4    | 40           | 70                    |
| 5    | 50           | 83                    |
| 6    | 60           | 85                    |
| 7    | 70           | 95                    |
4. Conclusion

From the FE analysis it was found that for biomedical implants made of porous Ti-6Al-4V alloy structures with a porosity percentage of 40 possess elastic modulus close to that of human cortical bone. The porous implant structure may also enhances the bone ingrowth through the pores provided for implant and minimizes the mismatch of elastic modulus that resulted in minimum stress shielding effect. Hence, there will be no chance for dislocation of implant from the joint.

References

[1]. Krishna, B.V., Bose, S., Bandyopadhyay, A.: Low stiffness porous Ti structures for load-bearing implants, Acta Biomater., vol. 3, no. 6, pp. 997–1006, (2007).
[2]. Tamburrino, F., Graziosi, S., Bordegoni, M.: The Design Process of Additively Manufactured Mesoscale Lattice Structures: A Review, J. Comput. Inf. Sci. Eng., vol. 18, no. 4, p. 040801, (2018).
[3]. Al-Ketan, O., Rowshan, R., Abu Al-Rub, R.K.: Topology-mechanical property relationship of 3D printed strut, skeletal, and sheet based periodic metallic cellular materials, *Addit. Manuf.*, vol. 19, pp. 167–183, (2018).

[4]. Maskery, I., Aremu, A.O., Parry, L., Wildman, R.D., Tuck, C.J., Ashcroft, I.A.: Effective design and simulation of surface-based lattice structures featuring volume fraction and cell type grading, *Mater. Des.*, vol. 155, pp. 220–232, (2018).

[5]. Jayanthi, P., Starly, B., Shiv kumar, R.: A design for the additive manufacture of functionally graded porous structures with tailored mechanical properties for biomedical applications, *Journal of Manufacturing Processes* vol. 13, pp. 160-170, (2011).