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Design and Simulation of Porous Ti-6Al-4V alloy structures for Additive Manufacturing of Bioimplants

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Abstract

This paper presents the efforts made in design and finite element simulation of porous Ti-6Al-4V alloy structures to determine the elastic modulus of porous parts produced with the additive manufacturing technology for biomedical applications. The major problem concerning with the typically used metallic bioimplants is the mismatch of elastic modulus between the implant and the human bone, which resulted in degradation of surrounding bone structure and disassociation of the implant. The present work focused on design the porous Ti-6Al-4V alloy structures and also study the influence of porosity on elastic modulus of implants made of Ti-6Al-4V alloy material. The three-dimensional strut-based cellular structure employed to build the porous structures ranging from 10% to 50% porosity volume. This work established the appropriate porosity to minimize the mismatch of elastic modulus between the implant and the bone by adding the porosity to the implant structure, and it demonstrates the proof of tailoring the elastic modulus of bioimplants.

***Keywords*:** Additive Manufacturing, Elastic modulus, Porosity, Ti-6Al-4V alloy

1. Introduction

Additive Manufacturing (AM) is a process that produces the parts by adding the material together, typically layer-by-layer method, based on the three dimensional (3D) computer aided design (CAD) data. The AM technology allows complex designs and also impact on the manufacturing procedures in various fields including automobile, aerospace, and biomedical engineering. Due to the improvement in additive manufacturing technology and the availability of various materials, the AM technology is using to produce orthopaedic implant structures and scaffolds. In general, the implants are used as structural reinforcements inside the human body for load bearing applications. The temporary implants include screws and plates, whereas the permanent implants include hip and knee joints and require more toughness, sufficient strength, and resistance to wear between the joints. The various AM technologies are available for metals including selective laser melting, direct metal laser sintering and electron beam melting, which are capable of manufacturing functional metallic parts for orthopaedic applications in a single step. However, the major issue with bio-metallic implants is the mismatch of modulus between the bone and implant which results in disassociation of the implant[1]. Moreover, the bone formation and in-growth is less for the dense implant. These problems can be minimized by using the porous implant structures. This paper presents the proof of tailoring the elastic modulus of Ti-6Al-4V material.

Additive manufacturing technology have the potential to build the intricate geometries, multi material parts, functionally graded materials, porous lattice structures, conformal cooling channels, based on the requirement of structures used in the aerospace, automotive, tooling, medical applications etc. A lattice structure is a periodic arrangement of unit cells with two or three-dimensional structures, and are linked to cellular solids. The structures of cellular solids can be categories into two types such as stochastic structures and non-stochastic structures based on the spatial arrangement of their unit cells[2]. The materials having stochastic structures are characterized by a random distribution of their unit cells whereas the materials with non-stochastic structures are characterized by an ordered distribution of their unit cells. Figure 1 presents the broad classification of cellular solid structures. Figure 2 (a – f) presents the cellular structures of open cell foam, closed cell foam, 2D honeycomb structure, 3D strut-based cellular structure, 3D triply periodic minimal surface (TPMS) based gyroid and diamond cellular structure. The lattice structures possesses superior properties, which results in promising solution for various applications such as light weight structures, heat exchangers, energy absorbers, acoustic insulators to reduce the noise and vibrations, and orthopaedic implants. Due to the unique capabilities of additive manufacturing technology, make it possible to manufacture the parts with desired porosity. This work covers the design and FEA simulation of porous structures to predict the elastic modulus of implant structures produced by using the additive manufacturing technologies. Moreover, this work presents the proof of tailoring the elastic modulus of bio-implants manufactured by using additive manufacturing techniques.

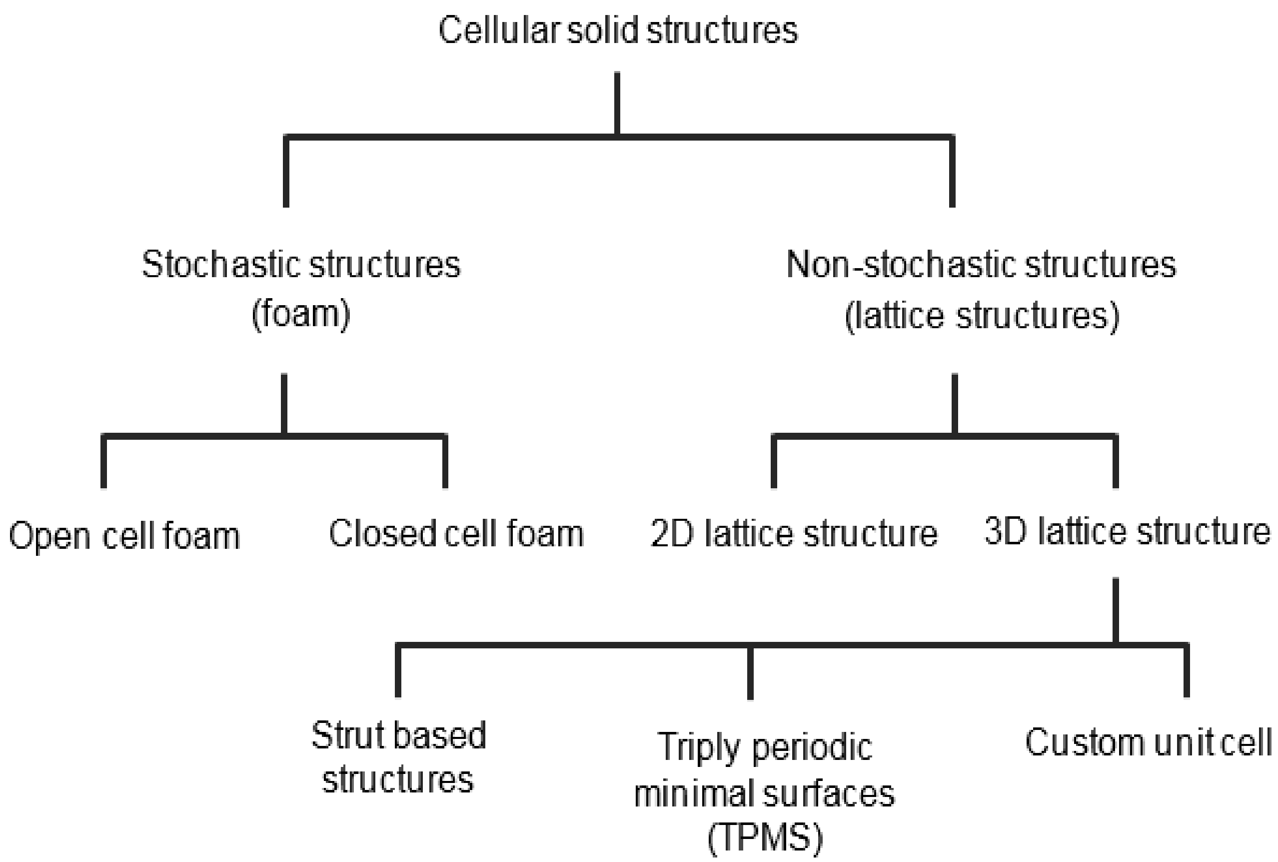

Figure 1. Classification of cellular solid structures

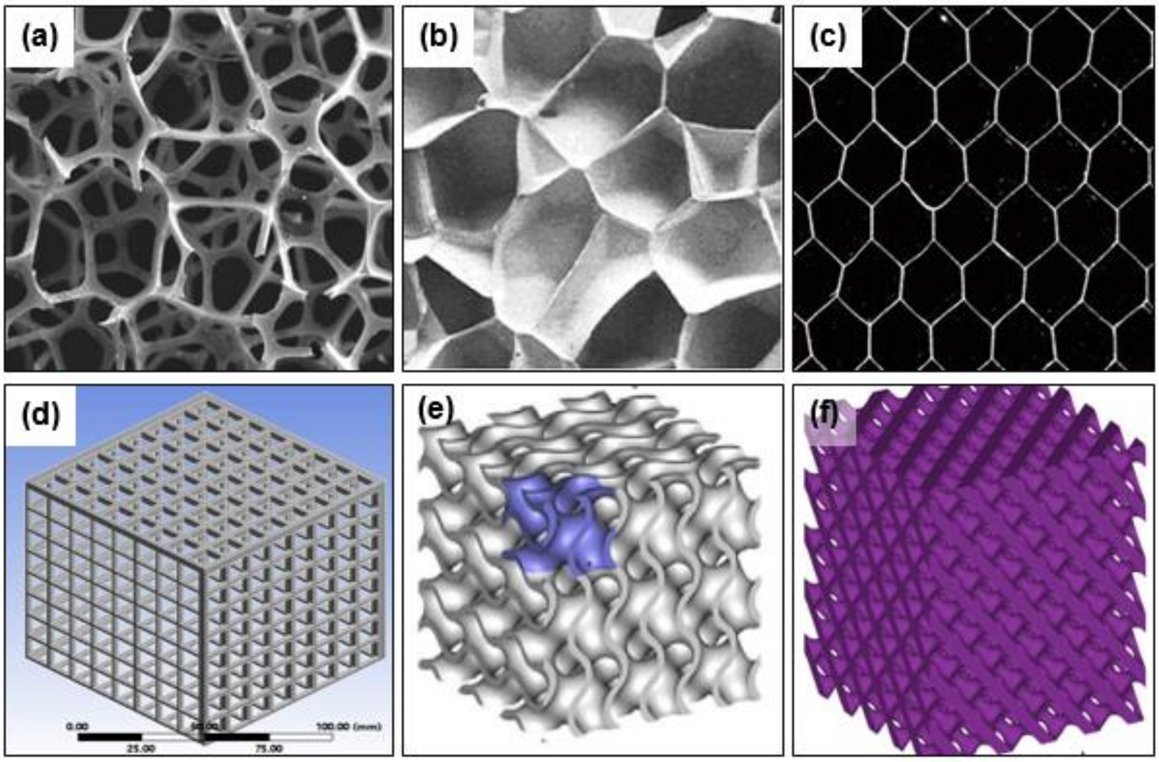

Figure 2. (a) Stochastic open cell foam, (b) Stochastic closed cell foam, (c) 2D honeycomb structure, (d) 3D strut-based cellular structure, (e) 3D triply periodic minimal surface (TPMS) based gyroid cellular structure[3] and (f) 3D TPMS based diamond cellular structure.

2. Methodology

2.1 Design of porous Ti-6Al-4V alloy structures

The important factor for structural design of various porous structures is the relationship between the porosity volume and the elastic modulus. The simple cube is developed with different porosities ranging from 10% to 50% using square pore holes. Figure 3 (a-c) presents the porous cube structures with 10% porosity, 30% porosity and 50% porosity. The porous structure is constrained at one face and the force applied at the opposite face, showed in Figure 4 (a).

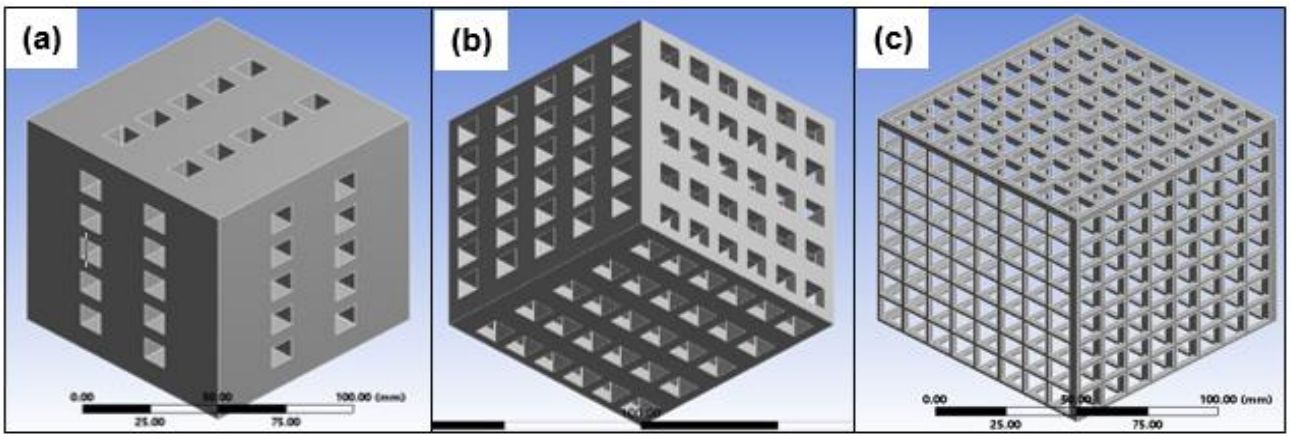

Figure 3. Design of simple cube structures with (a) 10% porosity, (b) 30% porosity, and (c) 50% porosity.

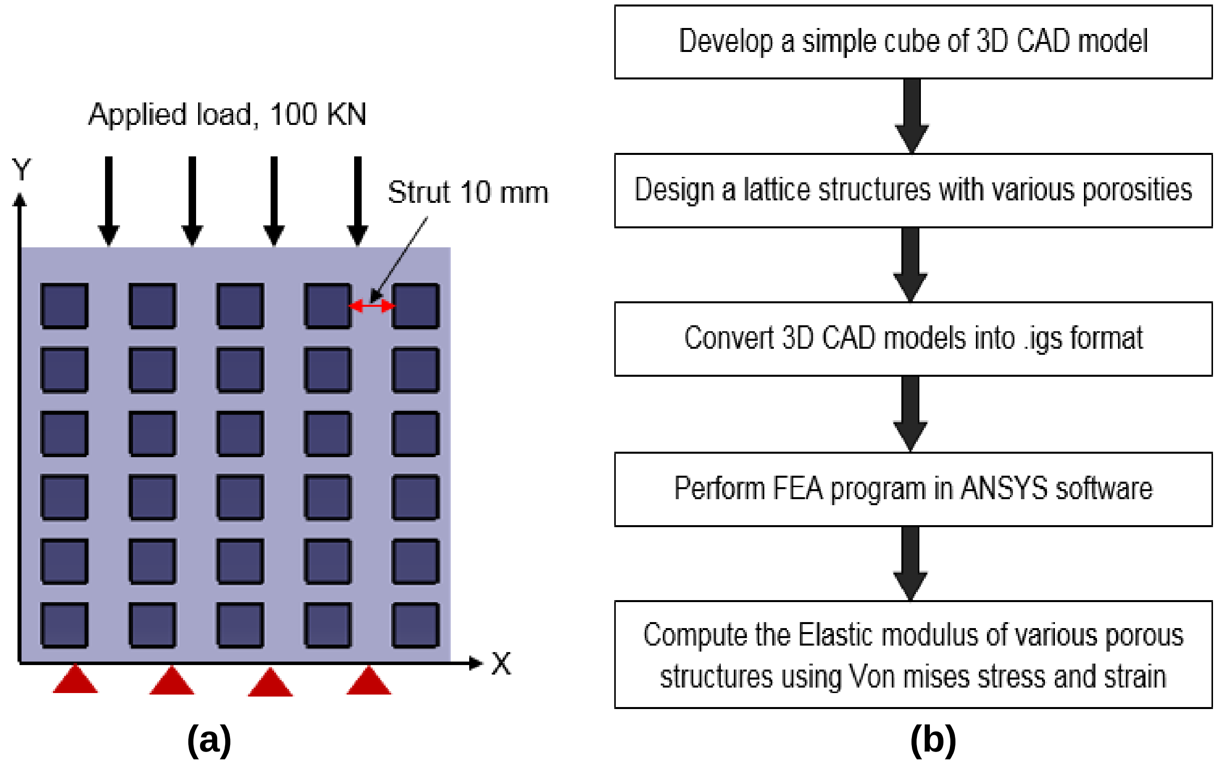

Figure 4. (a) Porous cube structure with boundary conditions and (b) sequence of steps in design and FEA simulation for estimating the elastic modulus of porous structures.

The finite element analysis (FEA) program ANSYS was performed to estimate the elastic modulus of porous structures using Von mises stress and the strain. The key steps involved in design and simulation for predicting the elastic modulus of porous structures is presented in the Figure 4(b). The elastic modulus was estimated by using the relationship between the Von mises stress and the strain obtained from the FEA simulation.

3. Results and discussion

The simple cube structures with porosities ranging from 10% to 50% were designed using the 3D CAD model. From the FEA simulation, it was found that the Von mises stress decreased with increasing the porosity volume upto 40%, and beyond that, the stress was increased. The FEA contour plots for stress distribution in porous structures are presented in Figure 5(a-c).

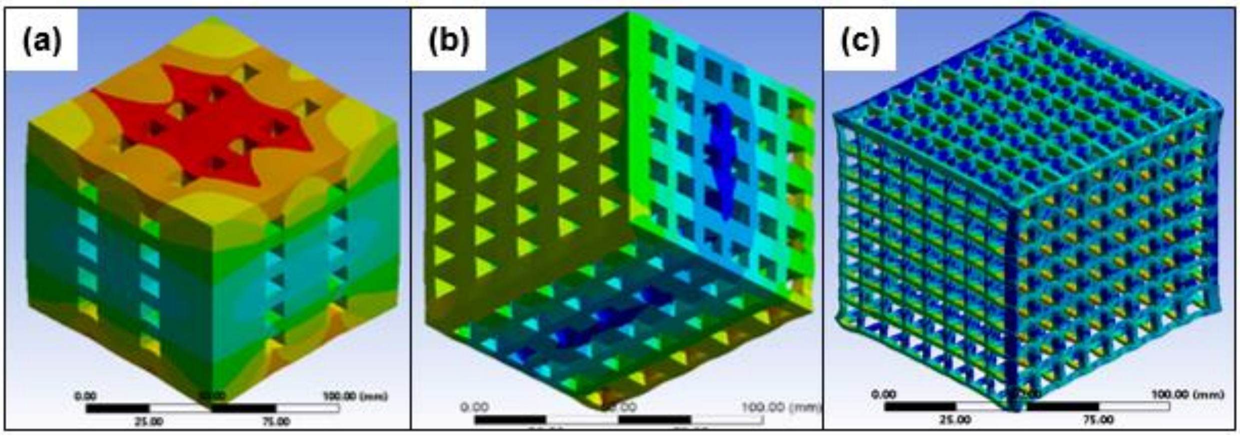

Figure 5. FEA contour plots for stress distribution in porous structures with (a) 10% porosity, (b) 30% porosity, and (c) 50% porosity.

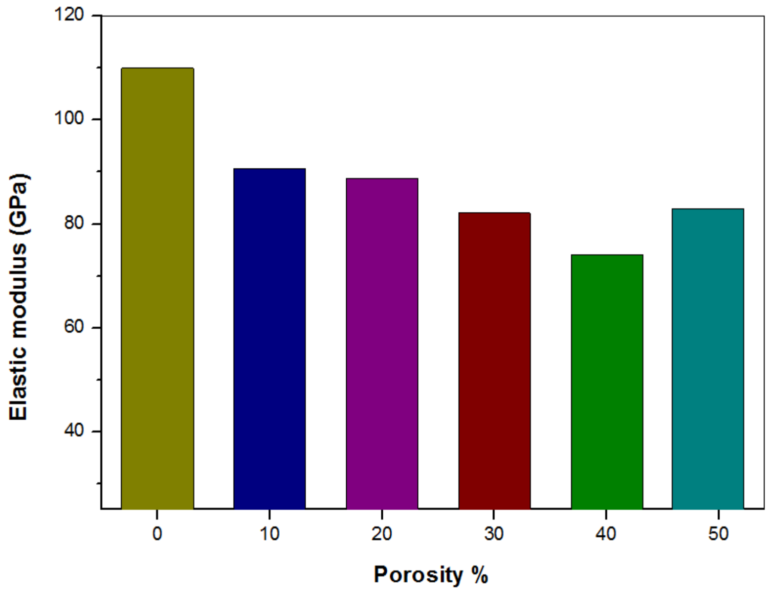

Figure 6. Effect of porosity on elastic modulus

The effect of porosity volume on the elastic modulus was presented in the Figure 6. From the results presented in Figure 6, it is clear that the elastic modulus of Ti alloy without porosity possesses 110 GPa and gradually deceased from 90 GPa to 74 GPa while increasing the porosity volume from 10% to 40%, respectively. However, the elastic modulus of porous structure increased from 74 GPa to 83 GPa with increasing the porosity from 40% to 50%. This can be attributed to the densification phenomena of the porous structure and it behave like a solid structure due to increasing the self-contacting surfaces[2].

4. Conclusions

This work demonstrate the proof of tailoring of elastic modulus of metallic bioimplants using appropriate porosity volume. The FEA program in ANSYS simulated to determine the elastic modulus of the porous Ti-6Al-4V structures. From the results, it is found that the Ti-6Al-4V structure with the porosity of 40 vol.% possess the elastic modulus about 74 GPa. From this work, it is clear that the elastic modulus of the bioimplants can be tailored by using the additive manufacturing technology. Future work includes the experimental validation of elastic modulus of the porous Ti-6Al-4V alloy structures with the present results.

References

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