Finite Element Modeling of the Elastic Modulus of Ti6Al4V Scaffold Fabricated by SLM

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ABSTRACT

In recent years, porous materials have been attracted by biomedical engineers as load bearing scaffolds due to their mechanical properties which can be similar to those of body tissues. Among such materials, cellular sandwich structures are of more important because of their regular micro-structure. One can design the internal micro-structure to achieve the desired mechanical properties. The elastic modulus of a scaffold is one of the most important mechanical properties in practical applications. In this paper, a beam finite element model is developed to predict the elastic modulus of a Ti6Al4V scaffold with regular micro-structure fabricated by Selective Laser Melting (SLM). At first, the mechanical properties of annealed Ti6Al4V are attributed to the struts material. But the obtained elastic modulus is not satisfactory in comparison with experimental one. In the second model, the mechanical properties of Ti6Al4V fabricated by SLM with the same processing parameters as those applied to manufacture the scaffold are assigned to the struts material. Using this model, the predicted elastic modulus of the scaffold is in good agreement with experimental one.

Introduction

Currently, researchers are interested in lightweight metallic foams for use in high performance load bearing applications. Thanks to Rapid Prototyping Methods (RPM), it is possible to fabricate cellular sandwich structure with a predefined micro-structure. Among RPMs, Selective Laser Melting (SLM) is of more importance as a new technique which allows for the creation of metal structures with fine details. This technique has the potential to create open cellular lattice structures with a resolution of 50 micro meters (Brooks et al. 2005). SLM uses 3D CAD data as a digital information source. The process starts by slicing the 3D CAD file data into layers, usually from 20 to 100 μm thicknesses, creating a 2D image of each layer followed by fusing fine metallic powders together using a high powered laser beam to create three-dimensional metal parts.

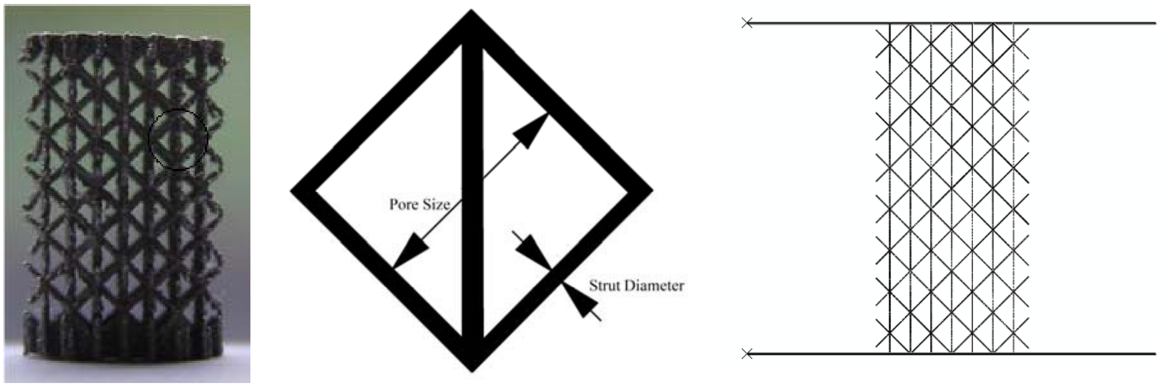
Several attempts have been reported in the literature to fabricate cellular sandwich structures using SLM (Mines et al. ; McKown et al. 2008; Garciandia 2009; Tsopanos et al. 2010; Van Bael et al. 2011). The main difficulty fabricating parts with the use of such method is to find appropriate processing parameters such as laser power, hatching space and scan velocity.

From the modeling point of view, metallic cellular materials have been investigated by several methods. Analytical methods are developed based on beam theory and can be used for highly porous materials (Gibson et al. 1999). In such methods, bending of the struts is the dominant deformation mechanism. A number of researchers have used micromechanical averaging methods to investigate the mechanical responses of porous materials (Entchev et al. 2002; Entchev et al. 2004; Nemat-Nasser et al. 2005). In such methods, the porous material is considered as a composite whose pores are inclusions with zero stiffness. Both Mori-Tanaka and the self-consistent method can be used as averaging schemes for prediction of the macroscopic response of porous materials. However, these methods can only be reliable for low porous materials. There is a different modeling approach based on assuming a periodic distribution of pores (Achenbach et al. 1990; Nemat-Nasser et al. 1999; Qidwai et al. 2001; Kwon et al. 2003; Perrot et al. 2007; De Jaeger et al. 2011). In this kind of modeling, an infinite sample reduces to a numerical problem of a unit cell with appropriate boundary conditions. In recent years, several modeling approaches have been developed using finite element method. These models can be developed using solid elements (Robertsa et al. 2002; Thelen et al. 2004; Ryu et al. 2005; Stauber et al. 2006; Shen et al. 2007; Michailidis et al. 2008; Alvarez et al. 2009; Liu et al. 2009; Liu et al. 2009; Loehnert et al. 2010; Guillen et al. 2011; Michailidis et al. 2011; Veyhl et al. 2011) as well as beam elements. Using solid elements is not computationally effective so one may prefer to use beam elements for highly porous materials. Beam finite element models can be used for random (Li et al. 2006; Borovinšek et al. 2008; Kadashevich et al. 2008; Luxner et al. 2009) as well as regular (Luxner et al. 2005; Kaoua et al. 2009; Labeas et al. 2010) micro- structures.

In this paper, a beam finite element model is developed to investigate the elastic modulus of a Ti6Al4V scaffold fabricated by SLM. Two kinds of material properties are attributed to the struts material, and the obtained elastic moduli are compared with the experimental one. The results show that the material parameters of Ti6Al4V fabricated by SLM with the same processing parameters as those used to fabricate the scaffold yields appropriate results. But, if the material properties of the raw powder are used for the bulk material, the obtained elastic modulus will be more than what was obtained in experiment.

Beam Finite Element Modeling:

Figure 1 (a) shows a Ti6Al4V scaffold fabricated by SLM (Garciandia 2009; Van Bael et al. 2011). According to Figure 1 (b), the average pore size is about 1 mm and the average strut diameter is about 0.188 mm. More details about the micro-structure can be found in (Van Bael et al. 2011).



(a) (b) (c)

Figure 1: (a) Ti6Al4V scaffold fabricated by the SLM method (Garciandia 2009; Van Bael et al. 2011) (b) illustration of the pore size and strut diameter (c) the beam finite element model of the scaffold

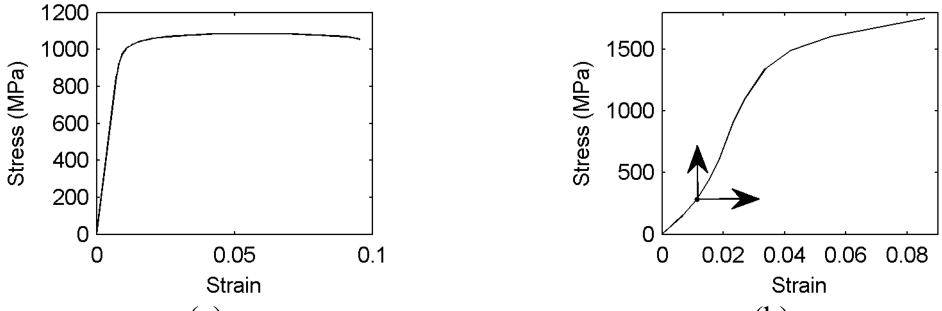
A MATLAB program is developed to simulate the micro-structure. A set of vertexes is generated which consists of the vertexes coordinate and their connections according to the real micro-structure. The generated file is then exported to the ABAQUS 6.11 as the wire frame shown in Figure 1 (c). The compression test platens are modeled as two rigid plates since their stiffness is very higher than that of the scaffold. Each strut in the micro-structure is meshed using B31 element which behaves as a Timoshenko beam. B31 elements can also be subjected to large axial strains. As the buckling of the struts is one of the most important deformation mechanisms in porous materials, the number of beam elements per each strut should be greater than 5 (V. et al. 1998; Labeas et al. 2010). In this paper, each strut is first meshed using 5 elements, and the number of elements is then increased until variation in the elastic modules is negligible. Using this convergence method, 15 beam elements per each strut should be considered. A general contact is defined in ABAQUS/EXPLICIT that allows for beam-to-beam and beam-to-rigid body contacts. All degrees of freedom of the lower platen are fixed. For the upper platen, the translational degree of freedom in the loading direction is set to -2 mm and the others are fixed. The negative sign means that the upper platen moves downward. In each 0.05 mm, the load carried by the upper platen is stored.

To calculate the elastic modulus, the axial stress-axial strain response is first plotted and the slope of the initial linear part of the curve is reported. The axial stress is calculated as the overall axial load over the loading surface. The axial strain is calculated as the axial displacement of the loaded surface over the initial height of the structure.

Bulk Material:

Since the SLM process is based on the powder of bulk material, an idea is to attribute the mechanical properties of powder to the bulk material for modeling purposes. The mechanical properties of a powder are similar to those of its annealed state

(Garciandia 2009). The stress-strain curve of annealed Ti6Al4V (Figure 2 (a)) is assigned to the bulk material.



(a) (b)

Figure 2: the stress-strain curve of (a) annealed Ti6Al4V (Vilaro et al. 2011) (b) Ti6Al4V fabricated by SLM with the same processing parameters as those used for the scaffold fabrication (Garciandia 2009)

However, the mechanical properties of powder may be affected by the fabrication process. Therefore, as the second model in this paper, the stress-strain curve of Ti6Al4V fabricated by SLM with the same processing parameters as those used for fabrication of the scaffold is attributed to the bulk material. As shown in Figure 2 (b), the stress-strain curve of the SLM part is non-linear. To simulate this stress-strain behavior as the bulk material, the convex of the curve is approximated by two linear parts. Then the origin of the coordinate system is moved to the junction of these two lines because it is believed the first linear part is due to collapse of the micro (or nano) pores and has no effects on the elastic modulus.

Results and Discussion:

Table 1 shows the obtained elastic modulus using both models 1 and 2 introduced in the previous section. As illustrated in this table, the elastic modulus obtained using model 1 is not in good agreement with that obtained by experimental measurements (Garciandia 2009; Van Bael et al. 2011). The predicted elastic modulus in this case is higher than the experimental one because the annealed parts have fewer micro (or nano) pores than those fabricated by SLM. Therefore, the stiffness of annealed part is higher than that of the SLM one.

Table 1 : Comparisson of elastic modulus between simulation and expriment

Model No.	Model 1	Model 2	Experiment (Garciandia 2009; Van Bael et al. 2011)
Scaffold elastic modulus (MPa)	357.89	215.39	225.56
Difference with experiment	58.67%	4.53%	

Using model 2, the obtained elastic modulus is in good agreement with the experimental result. In this case, the error compared with experimental elastic modulus is about 4.5 %. The predicted elastic modulus by model 2 is less than the experimental one because the tension (or compression) test samples, whose stress-strain curve is assigned to struts material, are very bigger than the scaffold struts in dimension. Therefore there are more micro (or nano) pores in them than the scaffold struts. Also the joint between the layers is weaker than the melted area so more layers cause less stiffness. As the test samples consist of more layers than the scaffold struts, stiffness of these samples is less than that corresponding to the scaffold struts. Accordingly, as the elastic modulus of SLM test samples is smaller than that of the scaffold struts, the obtained results using beam finite element simulation is smaller than experimental one too.

Conclusion:

The main purpose of this paper is to propose an approach in predicting the elastic modulus of a Ti6Al4V scaffold using finite element method. As the solid-element-base finite element models are not computationally effective, a beam finite element model is developed. The number of beam elements per strut is obtained using a convergence method according to the criterion of using more than 5 elements to able to simulate buckling of the struts. After modeling the scaffold geometry, material of the struts should be defined. Two kinds of material properties are attributed to the struts material. One using the stress-strain curve of Ti6Al4V raw powder named model 1 and another using the stress-strain curve of Ti6Al4V fabricated by SLM with the same processing parameters as those used for the scaffold named model 2. Using model 1 the elastic modulus of the scaffold is over predicted, but model 2 predicts the elastic modulus of the scaffold with a good agreement with that reported in the literature through experimental measurements.

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