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Numerical simulation of the fatigue behavior of additive manufactured titanium porous lattice structures

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ABSTRACT

In this paper, the effects of cell geometry and relative density on the high-cycle fatigue behavior of Titanium scaffolds produced by selective laser melting and electron beam melting techniques were numerically investigated by finite element analysis. The regular titanium lattice samples with three different unit cell geometries, namely, diamond, rhombic dodecahedron and truncated cuboctahedron, and the relative density range of 0.1–0.3 were analyzed under uniaxial cyclic compressive loading. A failure event based algorithm was employed to simulate fatigue failure in the cellular material. Stress-life approach was used to model fatigue failure of both bulk (struts) and cellular material. The predicted fatigue life and the damage pattern of all three structures were found to be in good agreement with the experimental fatigue investigations published in the literature. The results also showed that the relationship between fatigue strength and cycles to failure obeyed the power law. The coefficient of power function was shown to depend on relative density, geometry and fatigue properties of the bulk material while the exponent was only dependent on the fatigue behavior of the bulk material. The results also indicated the failure surface at an angle of 45° to the loading direction.

1. Introduction

Porous metals and scaffolds are considered one of the best candidates used as bone replacement materials due to flow permeability as well as matching stiffness to bone. Scaffolds are a member of the family of cellular solid materials with open cells. In contrast to closed cell foams, fluid can pass through the media in open-cell foams. Matching stiffness of the scaffolds reduces the risk of stress shielding which bone tissue absorbs due to unloading. Flow permeability allows tissue regeneration within the scaffold and the replacement of scaffolds with the living tissue.

Materials with cellular structure have been the subject of intensive research in recent decades. Gibson [1] provided a comprehensive review on the mechanical properties of some natural cellular solids. Meyers et al. [2] properly reviewed the structure and properties of biological cellular materials. Scaffolds can be produced using the conventional methods for manufacturing metal foams such as space holder or replication process [3,4]. Furthermore, in recent years, the new developments in additive manufacturing techniques have allowed their application for the production of biomedical implants [5–9]. Additive manufacturing techniques have several advantages over other conventional production methods. They provide control on the geometry of cells and struts. They also let us control relative density within implants as needed. The microstructure of implants can also be customized based on each patient's needs and conditions. The major drawback of additive manufacturing techniques is their high cost compared with other production methods such as space holder technique. However, the cost is expected to be reduced by future developments.

Mechanical properties of cellular solids are affected mainly by four factors: relative density, cell topology, strut shape (solid distribution in the struts) and finally mechanical properties of the bulk material. The manufacturing process would affect strut shape and mechanical properties of struts, as relative density and cell topology is determined beforehand. Aluminum foams such as “Duocel” have struts with smooth shape while in metal lattice structures made by additive manufacturing process; the cross section of struts randomly varies along the strut length. In addition, the mechanical property of bulk material in lattice structure would be different from testing specimen made by conventional methods due to strut grain structure and other factors.

Bone replacement implants experience cyclic loading during daily activities. Therefore, implant fatigue failure as one of their possible modes of failure should be studied. The fatigue failure of closed cell and open cell aluminum and other metal foams has been investigated by several researchers [10–17]. The accumulated strain versus the number of cycles is usually recorded in the uniaxial fatigue test of metal foams and used to evaluate their fatigue behavior. In spite of different

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topologies of closed cell and open cell foams, their fatigue failure has three distinct stages. In stage I, which is in the order of tens to hundreds of cycles, accumulated strain is increased. During stage II which is in the order of 10^4 to 10^6, accumulated strain remains almost constant. At stage III, which lasts for few cycles, accumulated strain is increased rapidly, leading to specimen failure. Fatigue tests of most cellular materials are performed under compressive–compressive loading and the stress ratio of 0.1. In open cell aluminum foams, the applied macro scale cyclic compressive stresses result in cyclic bending moment applied to the constituent struts. The mechanism of failure in the struts is crack initiation and propagation and the final fracture under tension–tension loading as a result of fluctuating bending moment.

Titanium alloys are appropriate choices for orthopedic implant due to their biocompatibility, high strength and other attractive mechanical properties. Fatigue behavior of titanium lattice structure has been investigated in recent years by many researchers [8,18–20]. Titanium scaffolds show a behavior similar to aluminum foams under cyclic loading. The fatigue strength of Ti6Al4v scaffolds has been reported to be in the range of 0.1–0.25 yield strength of scaffolds, which is lower than the normalized endurance limit of solid titanium (i.e. 0.4 yield strength) [18]. Rough surface of struts, notch sensitivity of titanium alloy, the presence of void and porosity in struts, microstructure and residual stress are believed to be the cause of this difference. Leuders et al. [21] found that heat treatment and HIP process could significantly increase the endurance limit of additive manufactured Ti6Al4V materials.

Fatigue testing of scaffold structures is a costly and time consuming process. On the other hand, there are many factors that affect the fatigue behavior of cellular materials such as relative density, cell topology, and struts' geometry. Consequently, it is preferable to study the effect of these factors before manufacturing. Numerical simulation is used in many researches to study the effect of such factors on the quasi-static elastic properties of titanium scaffold structures. In current research, we employed numerical simulation to study the effect of relative density and cell topology on the fatigue behavior of additively manufactured scaffolds. The results of numerical simulation were compared with experimental results including material response under cyclic loading and fracture surface. Mechanism of fatigue failure has also been discussed in details.

2. Numerical simulation

2.1. Geometry and finite element model

Commercial FEM package ANSYS was used to simulate the fatigue failure. Finite element model of three different regular open-cell structures of diamond (D), rhombic dodecahedron (RD), and truncated cuboctahedron (TC) were generated. The geometry of these structures is shown in Fig. 1.

Each strut is modeled as a beam and discretized with 6 to 9 three-node Timoshenko beam elements. In many researches, two important issues have been neglected in modeling cellular materials using beam elements. The first one is the effect of the overlapping material in the vertex of connected struts and the second one is the effect of joint stiffness and material distribution on the mechanical behavior of material, which has been shown to have a significant effect on the mechanical properties of scaffolds [22]. Dependence of relative density on the strut geometry is usually expressed as:

$$\frac{\rho^*}{\rho_s} = C\left(\frac{r}{l}\right)^2 \tag{1}$$

where r and l are radius and length and C is a geometrical constant which depends on the geometry of cell. Gibson [23] has suggested that vertex corrected relative density should have the form of:

$$\frac{\rho^*}{\rho_s} = C_1\left(\frac{r}{l}\right)^2 - C_2\left(\frac{r}{l}\right)^3. \tag{2}$$

Again, C_1 and C_2 depend on the cell geometry as presented in the Table 1 for three different cell geometries. In deriving constants, it is assumed that each vertex has a volume equal to that of the sphere with strut radius. It is also assumed that each joint is extended to the radius of $0.7R_m$ away from the vertex center, where R_m is the strut mean radius.

The second issue is the effect of joint stiffness on the overall stiffness of the structure. The cross section area of struts is larger at vertices, resulting in higher stiffness in joints and the shorter length of struts with uniform cross section. For this reason, the area of elements around the vertices is increased by a factor of two.

There are geometrical irregularities in scaffolds manufactured by electron beam melting or similar techniques such as selective laser melting. The first one is that the thickness of struts is not uniform along the strut length, showing relatively high deviation from the mean value. This type of irregularity is modeled by assigning a random cross section to each element of strut along its length as depicted in Fig. 3. Random radius had Gaussian distribution normalized standard deviation of 0.15 and the maximum variation was limited to 0.3 radius of strut. These values were similar to those reported in the literature [24]. There could be slight waviness in struts, implying that they might not be in a straight line. In this way, even axial force could result in bending moments in struts and reduction in the strength of struts. For modeling this type of irregularity in finite element model, section of each element was moved randomly by the standard deviation of 0.1R, where R was the radius of the element cross section. Length of all struts was 1000 μm in all models. Strut sizes of all structures at different relative densities are listed in Table 2.

Represented volume element (RVE) consisted of 8 cells in the loading direction (z axis) and 5 cells in two other directions perpendicular to the loading direction. The ratio of height to width was at least 1.6, close to the value of 1.5–2 in the experimental samples. The size of RVE was

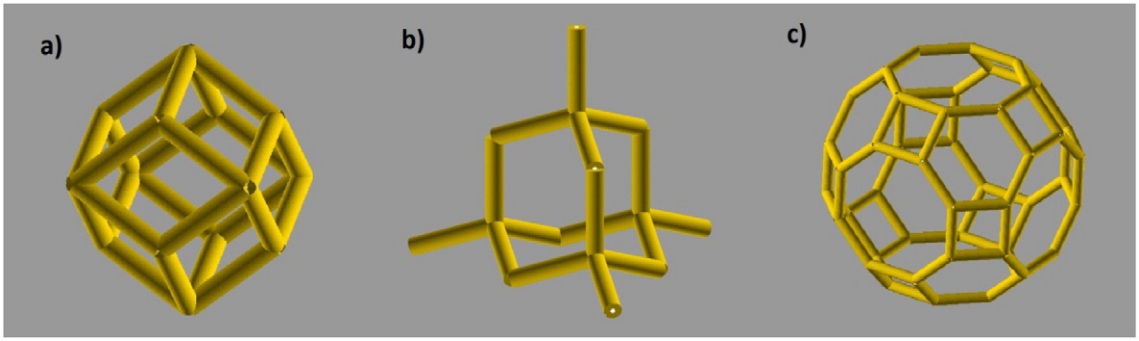

Fig. 1. Geometry of a) rhombic dodecahedron, b) diamond and c) truncated cuboctahedron structures.