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Effect of Porosity on the Properties of Open Cell Titanium Foams Intended for Orthopedic Applications

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Abstract. Porous metals have been used in various orthopedic applications as coating to promote implant fixation or as scaffolds for bone reconstruction. Since these materials were up to recently only used as thin coating (i.e. sintered beads or mesh) and not available into shapes adequate for detailed characterization, the effect of the structure on the static and dynamic properties of these materials has not been widely reported in the literature. This paper presents the effect of the porosity (49.3-66.7%) on the static and dynamic properties of titanium foams produced with a powder metallurgy process. All materials exhibited compression curves with three stages, typical of ductile porous materials. When the porosity level increases, the materials become more brittle. The compression yield strength increases while the modulus is more or less unaffected when the porosity increases from 49.3 to 66.7% and does not follow the power law model accepted for porous medium. The shear strength/adhesion with dense substrates increases with density and is proportional to the compression yield strength. The fatigue limit is not directly link with the porosity. The discrepancies observed are attributed to differences in the structure as the porosity increases.

Keywords: Titanium foam, porosity, mechanical properties, fatigue, orthopedic implant

PACS: 81.05.Rm, 87.85.J-, 81.05.Zx, 81.20.Ev, 81.20.Hy, 81.40.Lm, 81.40.Np, 81.70.Bt, 81.70.Jb

INTRODUCTION

Metallic foams have been developed and used in various orthopaedic treatments such as coating for implant fixation or self standing porous components for bone reconstruction, augmentation and fusion. These materials are much more porous than the traditional porous coatings (sintered beads and mesh, thermal spray coating). The increased porosity provides good friction with bone, elastic modulus much closer to those of bones, more space for bone ingrowth and interlocking as well as more surfaces for bone-implant contact. It is well established that the mechanical properties of porous mediums are affected by the porosity. Gibson and Ashby developed scaling laws linking Young's modulus and compressive yield stress to the porosity of open-cell foams [1]:

$$E_c = \alpha \cdot E_c^o \left(\frac{\rho}{\rho_o} \right)^2 \quad (1)$$

$$\sigma_{y,c} = \beta \cdot \sigma_{y,c}^o \left(\frac{\rho}{\rho_o} \right)^{3/2} \quad (2)$$

where α and β are scaling law coefficients and E_c^o and $\sigma_{y,c}^o$ are respectively the Young's modulus and compressive yield stress of the dense material. Equ. 1 and 2 are valid as long as the structure and chemical composition remain unchanged with porosity as the scaling law coefficient depends on the porous structure, the material composition and microstructure.

Since the use of metallic foams is relatively recent in orthopedic applications, the impact of their structure on their properties has not been widely reported in the literature. For example, little publications have presented the effect of the porosity on the fatigue or shear properties of these materials.

Since porous materials behave very differently depending on their structure and characteristics, and no standard exists for the evaluation of the mechanical properties of foams for orthopedic applications, it is important to report the curves and specify the way the different properties are measured.

This paper describes the effect of porosity on the properties of titanium foams produced with a powder metallurgy process. All foams had similar chemical composition but different porosities (pore size and pore fraction). The foams were tested in compression under static and cyclic loading. The effect of porosity on the shear/adhesion of the foam with dense titanium (i.e. CpTi) was also investigated.

EXPERIMENTAL PROCEDURE

Titanium foams were produced using a process described in [2]. Briefly, spherical pure titanium powder was admixed with a binder and a chemical foaming agent. The resulting powder mixture was poured into a mold and heated up to foam, debinded and sinter the material. Specimens with different porosity levels were produced by modifying the formulation.

The specimens for the monotonic compression and fatigue tests were small cylinders (11 mm OD and 14.5 mm long). The specimens for the shear/adhesion tests were produced by coating dense CpTi titanium rods (21.74 mm long and 12.65 mm OD) with a ring of titanium foam (20.56 mm OD and 10 mm thick).

The porosity of the specimens was evaluated using the weight and physical dimensions of the cylinders. Polished sections of the specimens were observed with an optical microscope. Oxygen content was evaluated using an inert gas fusion technique with a LECO TCH-600 analyzer. Carbon content was evaluated using the combustion method with a LECO CS-600 analyzer.

The mechanical tests were done at room temperature in air using MTS machines. Monotonic compression was performed at a crosshead speed of 2.5 mm/min. Unloading were done during the compression tests to monitor the variation of the elastic recovery with deformation. Shear/adhesion tests were done by pressing the dense titanium rod through the foam while supporting the foam. The diameter of the cavity in the support member was 15 mm to allow the free displacement of the titanium rod.

Cyclic tests were done in compression/compression using a load ratio ($R = \sigma_{\min}/\sigma_{\max}$) of 0.1 and sinusoidal 10 Hz cycling. The tests were ended either at a user defined deformation of 22.5% or at 5×10^6 cycles (defined as no rupture). Cumulative deformation and deformation amplitude were measured with a platen-mounted LVDT position sensor (Intertechology, Don Mills, Canada, model 0243-000).

The apparent compression yield strength was determined by the intersection of the lines parallel to the elasto-plastic loading (i.e. stage 1) and the plastic deformation plateau (i.e. stage 2) as defined in Figure 1. The compression modulus was evaluated by plotting the slope of the elastic recovery as a function of the deformation. The values extrapolated at zero deformation were used to determine the compression modulus. The shear strength was defined as the maximum stress recorded during the shear testing. The fatigue limit was defined as the maximum stress observed where no rupture was observed at 5 million cycles.

FIGURE 1. Compression curve presenting 3 deformation stages: the elasto-plastic loading, the plastic deformation plateau and the consolidation b) zoom on the initial portion of the curve presenting the method used to measure the yield strength and the elastic recovery used to evaluate the compression modulus.

RESULTS

Table 1 and Figure 2 describe the porosity, pore size and chemical composition of the foams characterized in this study. The porosity level ranges from 49.3 to 66.7%. As opposed to sintered beads, the porosity of the material comes mainly by the large pores created during the foaming and not only by the space between the titanium particles. It results a much larger porosity than with sintered beads.

Figure 2 presents the pore size distribution measured by image analysis on 2D sections on the 49.3% and 66.7% porosity foams. Foam E has the highest porosity and the pores range mostly from 500 μm to 1.5 mm. Larger pores usually come from the coalescence of smaller pores that are difficult to differentiate during the image analysis segmentation procedure. Foam A has much smaller pore size, ranging typically from 50 to 700 μm .

TABLE 1. Characteristics of the titanium foams investigated in this study.

Foam	Porosity (%)	Av. Pore size (μm)	%O (wt%)	%C (wt%)
A	49.3	375	0.37	0.14
B	54.0	475	0.39	0.13
C	58.4	625	0.36	0.17
D	62.0	775	0.33	0.16
E	66.7	925	0.36	0.16

Figure 3 presents typical compression curves obtained with the foams having different levels of porosity as well as the specimens after the compression tests. The curves are smooth and exhibits three deformation stages, as usually observed on ductile foams: stage 1: elasto-plastic loading; stage 2: plastic deformation plateau and stage 3: consolidation. During the elasto-plastic loading, the load is not uniformly distributed in the material. Indeed, some zone are plastically deformed while some others remain in the elastic domain. Local irregularities in the porous structure and microstructure of the material can lead to stress concentrations which may exceed the yield strength of the base material and, therefore, lead to local plastic deformation. Once an area is plastically deformed, the local stress may drop due to the redefinition of new load paths within the porous structure. As a result, the slope of the initial loading is affected by these simultaneous elastic and plastic deformations and is lower than the compression elastic modulus of the material. This behavior also means that when the material is loaded up to the apparent yield strength, determined with the method described above, a permanent plastic deformation has already occurred.

FIGURE 2. Pore size distributions and structures of two foams investigated in this study a) Foam A (49.3%) and b) Foam E (66.7%).

During the second stage (i.e. plastic deformation plateau), the material is deformed mostly plastically. For all materials tested in this study, the stress steadily increases during this stage, indicating that consolidation take place and the porosity is reduced (or densities is increased). During the last stage (stage 3: consolidation), the density of the structure dramatically increases and the stress increases accordingly. Although orthopedic implants should not be subjected to important plastic deformations in service, the complete compression curves give indication of the material's ability to deform plastically and information about their relative ductility.

While all curves are smooth and exhibit the three stages typical of ductile porous medium, differences of relative ductility can be observed on the compacted specimens after the tests (Figure 3). When the porosity is low, the materials deform plastically into a pancake. When the porosity level increases, the apparent ductility is reduced and apparent cracks are formed during the tests. This difference is associated to modifications of the material structure when the

porosity varies. In fact, since the ductility of the titanium base metal is mostly affected by its chemical composition and the foams used in this study have more or less the same chemistry (Table 1), the difference observed mostly come from structural effects.

FIGURE 3. Typical compression curves obtained with foams of different densities.

Figure 4 presents the evolution of the elastic recovery as a function of deformation for Foam B. The behavior observed is more or less the same for all the foams characterized in this study. The variation of the slope of the elastic recovery with deformation is different from observations reported on other metallic foams [3,4]. It is recognized that deformation changes the structure of the foams by bending, buckling, stretching, and cracking of the cells walls and affect the elastic moduli of the materials [5]. In the present case, the modification of the structure causes a consolidation of the material.

FIGURE 4. Evolution of the elastic recovery as a function of deformation (Foam D). The value extrapolated at zero deformation was taken as the compression modulus.

Figure 5a presents the evolution of the compression modulus, evaluated with the method described previously, with porosity. The compression modulus remains more or less constant within the porosity range investigated in the present study. Variations are important and due to difficulties associated with the measurement technique. According to Gibson-Ashby model (Eq. 1), the relation between the modulus and the porosity should be quadratic, which is not the case in the present study. This should be attributed to modifications in the structure of the material as the porosity increases.

The apparent compression yield strength increases from 72 MPa to 159 MPa when the porosity decreases from 66.7 to 49.3 MPa. The increase of the yield strength with density is consistent with observations reported in the literature on porous materials [1,6] and fit the Gibson-Ashby equation (Eq.2) with $\beta = 0.89$.

FIGURE 5. a) Compression modulus and b) yield strength measured on foams having different level of porosity.

Figure 6 presents a curve obtained during a shear/adhesion test for Foam A. The curve shows that some plastic deformation took place before the rupture

of the material. Indeed, a reduction of the foam ring thickness has been observed after the test indicating that the load contributes to the compaction of the foam in contact with the support member. The fracture surface observations showed that the rupture took place not only at the interface but also in the foam. This shows that the load is efficiently transferred to the foam through a strong interface. This is indicative of a good adhesion between the foam and the dense core rod. The shear strength, defined as the maximum load divided by the sheared surface, plotted against porosity is presented in Figure 6. The results show that the shear strength/adhesion increases as the porosity decreases. The shear strength relative to the yield strength of the foam is, however, more or less constant and is between 25 and 30% of the yield strength of the materials.

FIGURE 6. a) Typical shear/adhesion curve obtained with the dense titanium rod coated with Foam A and b) maximum shear strength as a function of porosity. Absolute values as well as the values relative to the compression yield strength are reported.

Figure 7 presents the S-N curves for foams with different porosities (49.3 and 66.7%). There is no direct link between the absolute fatigue limit and the porosity. In fact, the fatigue limit at 5 millions cycles

is more or less the same (~75 MPa) for the 49.3 and 56 % porous foams (Figure 7a). On the other hand, the fatigue limit of the 66.7% porous foam is significantly lower, probably due to its lower ductility and strength. When the fatigue limit is reported relative to the compression yield strength, the observations are different. The relative fatigue limit of the 56 and 66% porous foams are similar while the relative fatigue limit of the denser foam (i.e. 49.3% porous) is much lower. These findings were unexpected since the fatigue limit is generally dependent on the yield strength and ductility of titanium [7]. Since the compression strength and ductility of the material decrease with porosity, a reduction of the fatigue limit was expected with the increase of porosity. These discrepancies could be associated with the modification of the structure when the porosity increases. A possible explanation could be the increase of the cells wall thickness and the reduction of the cell wall density with porosity that may affect crack propagation and the fatigue properties of the materials. Other tests should, however, be conducted to confirm this hypothesis and describe the effect of the structure of the material on the fatigue properties of these materials.

CONCLUSION

Foams having different porosities were produced with a powder metallurgy process. Porosity significantly affects the yield strength and the adhesion/shear strength of the material. However, the modulus vs relative density do not follow a power law function as predicted by the Gibson-Ashby model. This is probably associated to difficulties in measuring with precision the compression modulus but also to modifications of the structure of the material when porosity increases. Besides, no clear relation was observed between the fatigue limit and the porosity of the material. This shows that the fatigue limit is not only affected by the yield strength and ductility as they are for dense materials but also by other structural parameters such as the strut or cell wall structure, thickness and density. Other tests should be conducted to elucidate the structural parameters and properties that affect the fatigue performance of these materials.

FIGURE 8. Fatigue behavior of foams having different porosities a) S-N curves and b) normalized S-N curves.

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