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Research paper

Development and mechanical characterization of porous titanium bone substitutes

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ABSTRACT

Commercially Pure Porous Titanium (CPPTi) can be used for surgical implants to avoid the stress shielding effect due to the mismatch between the mechanical properties of titanium and bone. Most researchers in this area deal with randomly distributed pores or simple architectures in titanium alloys. The control of porosity, pore size and distribution is necessary to obtain implants with mechanical properties close to those of bone and to ensure their osseointegration. The aim of the present work was therefore to develop and characterize such a specific porous structure. First of all, the properties of titanium made by Selective Laser Melting (SLM) were characterized through experimental testing on bulk specimens. An elementary pattern of the porous structure was then designed to mimic the orthotropic properties of the human bone following several mechanical and geometrical criteria. Finite Element Analysis (FEA) was used to optimize the pattern. A porosity of 53% and pore sizes in the range of 860 to 1500 μm were finally adopted. Tensile tests on porous samples were then carried out to validate the properties obtained numerically and identify the failure modes of the samples. Finally, FE elastoplastic analyses were performed on the porous samples in order to propose a failure criterion for the design of porous substitutes.

1. Introduction

In most cases, clinical failure of prosthetic solutions is due to the stress-shielding generated by the mismatch of mechanical properties between bone and implant (Karachalios et al., 2004). The mechanical properties of bone depend on many factors such as anatomical part, sex and age. The global elastic properties of cortical bone are usually described by the orthotropic tensor of elastic moduli defined by nine constants. Its longitudinal compressive strength was estimated to be 200 MPa by Reilly and Burstein (1975) and Reilly et al. (1974). In long bones, the cortical tissue represents approximately 25% of the whole bone volume. Consequently, as a first order approximation an apparent compressive strength of 50 MPa is considered in this study.

The intrinsic properties of bulk titanium are significantly higher than those of cortical bone. To minimize the negative impact of this stiffness incompatibility, substitutes with a controlled porosity can be introduced. Oh et al. (2003) obtained the Young's modulus of porous titanium close to that of bone by changing the voids volume fraction f_V. They

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reduced this property from 110 GPa (bulk titanium) to 10 GPa for $f_V = 0.35$.

Moreover, as demonstrated by many authors (Otsuki et al., 2006; Heinl et al., 2008; Xue et al., 2007; Hollander et al., 2006), the existence of porosity is also propitious for the substitute osseointegration, the essential factor of the long-term reliability of the implant. The question arises: do the size, shape, topology and volume fraction of voids have any influence on the substitute colonization? Only a few studies have addressed this crucial problem. There is no consensus in the literature about the optimal pore size to enhance bone ingrowth. In their pioneering work, Otsuki et al. (2006) showed that the pores of the structure have to be interconnected in order to ensure the bone ingrowth. These authors also compared the type of tissue formed as a function of time and implant internal architecture. They tested two levels of porosity (50% and 70%) combined with two ranges of pore sizes (between 250 and 500 μm and between 500 and 1500 μm) and concluded that the size of pores should range from 500 to 1500 μm for both levels of porosity to get a tissue of good quality. Xue et al. (2007) demonstrated that the bone colonization is impossible for a pore size under 100 μm. Chen et al. (2009) tested the osteogenesis on structures with pores ranging from 100 to 400 μm but did not speak out against higher pore dimensions. Hollander et al. (2006) tested porous structure with pore dimensions of 500, 700 and 1000 μm and concluded that the growth of human osteoblast is possible for all these types of porosities. Those authors did not indicate a maximal pore size either. Generally speaking, no clearly identified rule exists to allow the optimal design of implants or bone substitutes in commercially pure porous titanium (CPPTi).

Several manufacturing processes of porous titanium are known among which freeze casting (Yook et al., 2009), space holder technique (Niu et al., 2009), rapid prototyping (Li et al., 2006) or laser processing (Parthasarathy et al., 2010; Heinl et al., 2008; Krishna et al., 2007). Freeze casting and space holder processes mostly lead to randomly distributed pores whereas rapid prototyping and laser processing are adopted when a controlled architecture is required.

The freeze casting technique enables a porous material with a compressive strength close to that of bone to be obtained, but its main drawback underlined by Yook et al. (2009) is the pore size that does not exceed 300 μm for a long manufacturing time of 7 days. Higher pore sizes can be reached with the space holder technique but the mechanical properties obtained are lower than those of human bone (Niu et al., 2009). In both cases, the control of the elastic properties anisotropy seems to be difficult.

In the literature, rapid prototyping and laser processing are often reported to generate bulk titanium or porous titanium with simple pore architecture (Parthasarathy et al., 2010; Heinl et al., 2008; Krishna et al., 2007; Li et al., 2006). These techniques are generally used in the case of titanium alloys.

In this paper, the Selective Laser Melting (SLM) process was chosen to produce porous titanium with a particular periodic internal architecture. In a first part, the properties of titanium samples processed by SLM are studied and compared to the ISO Standard Specifications. Crystallographic texture and residual stress measurements are also examined to estimate the anisotropy of samples obtained by this technology.

In a second part, an elementary pattern is designed to approach the mechanical properties of human bone and to enable the optimal implant osteointegration. The final section is dedicated to the question of elastoplastic global properties and simple failure assessment for such porous implants.

2. Materials and methods

2.1. Criteria for elementary pattern definition

To design and optimize an elementary pattern for bone substitutes, several criteria had to be simultaneously taken into account. With biocompatibility, the criteria adopted in this study are as follows:

- Elastic (global) properties as close as possible to those of cortical bone (including the anisotropy).
- A maximal allowed apparent stress not exceeding 50 MPa.
- A maximal stress exerted at any point of the pattern smaller than $\sigma_{ad} = \sigma_Y/k$, where σ_Y is the yield point of the CP Ti and $k = 1.5$ corresponds to a safety coefficient.
- Interconnected pores (Otsuki et al., 2006).
- A pore size greater than 100 μm to facilitate bone colonization (Shiomi et al., 2004; Xue et al., 2007; Chen et al., 2009).
- A porosity in the range of 50% to 70% as defined by Otsuki et al. (2006).
- A pattern shape enabling the perfect periodic paving of 3D space.

To perform such an optimization, the mechanical properties of commercially pure titanium processed by SLM have to be identified first. A classical experimental procedure is adopted to characterize the elastoplastic properties of CP Ti.

2.2. Characterization of CP Ti processed by SLM

Elastoplastic properties of CP Ti processed by SLM

To characterize the intrinsic properties of CP Titanium processed by SLM, three types of standard tensile test specimens (NF EN ISO 6892-1) have been manufactured with a SLM machine prototype. The direction of powder layer deposit varied for each type of specimen and was either longitudinal (L), transverse (W) or through specimen thickness (T). According to the standard, the dimensions of the gauge part of the samples have been fixed to 7 mm (L) × 3 mm (W) × 0.5 mm (T). The actual raw gauge sections of the specimens were measured after fabrication with an optical 3D measurement device (InfiniteFocus, Alicona, Austria).

The elastoplastic properties of the material have been determined using an Instron 5866 tension/compression testing machine equipped with a load-cell allowing a precise force measurement with an error less than 0.4% in the range of 0.1–10 kN. The Bluehill 2 software package was used to control the nominal stress rate during tests. A video tension device developed by Apollor® enabled the strain measurement. All the tests have been carried out at room temperature and quasi-static strain rate (10^{-3} s^{-1}).