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Research Paper

Porous titanium manufactured by a novel powder tapping method using spherical salt bead space holders: Characterisation and mechanical properties

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ABSTRACT

Porous Ti with open porosity in the range of 70–80% has been made using Ti powder and a particulate leaching technique using porous, spherical, NaCl beads. By incorporating the Ti powder into a pre-existing network of salt beads, by tapping followed by compaction, salt dissolution and "sintering", porous structures with uniform density, pore and strut sizes and a predictable level of connectivity have been produced, showing a significant improvement on the structures made by conventional powder mixing processes. Parts made using beads with sizes in the range of 0.5–1.0 mm show excellent promise as porous metals for medical devices, showing structures and porosities similar to those of commercial porous metals used in this sector, with inter-pore connections that are similar to trabecular bone. The elastic modulus (0.86 GPa) is lower than those for commercial porous metals and more closely matches that of trabecular bone and good compressive yield strength is retained (21 MPa). The ability to further tailor the structure, in terms of the density and the size of the pores and interconnections has also been demonstrated by immersion of the porous components in acid.

1. Introduction

Permanent, porous biomaterial structures have the ability to provide a transitional space between bone and a biomaterial substrate (which provides the main structural support) and an appropriate level and geometry of porosity will allow the in-growth of new bone tissue and vascularisation, so that good integration with the host bone tissue can be obtained (Lewis, 2013; Li et al., 2014). Porous titanium continues to attract attention as a biomaterial for medical applications, owing to its excellent specific mechanical properties, chemical stability and biocompatibility (Lewis, 2013; Li et al., 2014; Geetha et al., 2009) and numerous processes have been developed to manufacture porous Ti, comprehensively reviewed in Li et al. (2014) and Ryan et al. (2006).

Porous metal fabrication using sacrificial space-holders offers the ability to control the pore size and shape, with the potential to achieve good pore uniformity and

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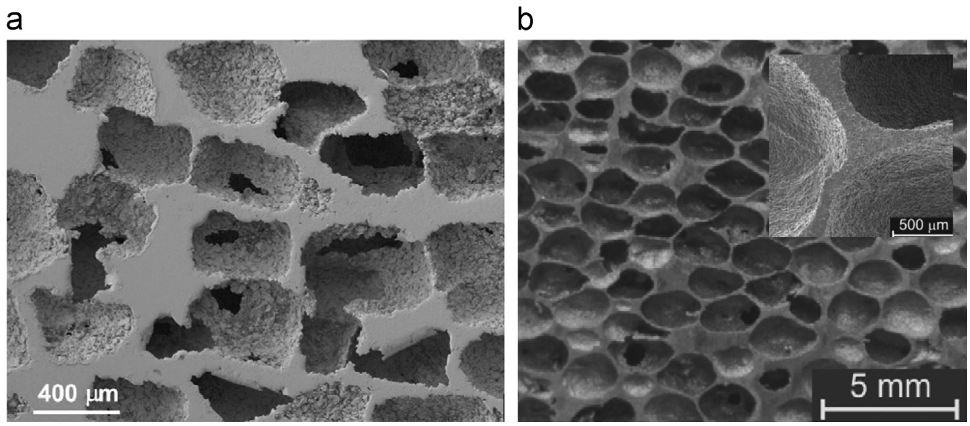

Fig. 1 – Porous Ti made using a space holder route showing (a) irregular pore structures (Ye and Dunand, 2010) and (b) poor inter-pore connectivity (Smorygo et al., 2012).

interconnectivity (Esen and Bor, 2007; Kim et al., 2013; Ye and Dunand, 2010; Mansourighasri et al., 2012; Sharma et al., 2011; Smorygo et al., 2012). There are problems with this method, however, originating from unpredictable and inhomogeneous mixing of the space holder and metal powder, exacerbated by irregularly-shaped space holders and powders with large differences in sizes. For these common cases, the homogeneity of space holder – metal powder blend is difficult to control, both within a part and from part-to-part. This is clearly unacceptable for a high quality product such as a medical device, which demands a robust and reproducible manufacturing route. Fig. 1 shows examples of porous Ti structures made using space holders (Ye and Dunand, 2010; Smorygo et al., 2012), exemplifying some of the problems, for example; irregular pore structures and struts of variable thickness, due to the use of irregularly-shaped space holders, and poor macro scale connectivity between pores, due to lack of space holder–space holder contact during the mixing process.

This study aims to demonstrate a new approach to interspersing Ti powder with a spherical salt bead space holder, in an effort to enhance the reproducibility of mixing and hence of the porosity and interconnectivity in the resulting porous part. Porous Ti structures made by this route have been characterised and their structures and compressive mechanical properties are presented and compared with those for commercial porous metals used in medical devices.

2. Experimental

2.1. Materials

Commercial purity titanium powder with an irregular shape was used, as shown in Fig. 2, with a nominal size $<45\ \mu m$ (with a D_{50} of 39 µm with D_{10} and D_{90} values of 17 and 71 µm respectively). Near-spherical NaCl beads were produced according to a method described in Jinnapat (2011) and were sieved into four different size ranges: 0.5–1.0 mm, 1.0–1.4 mm, 1.4–2.0 mm and 2.0–2.5 mm. The morphology of the smallest and largest NaCl beads in this range is shown in Fig. 3.

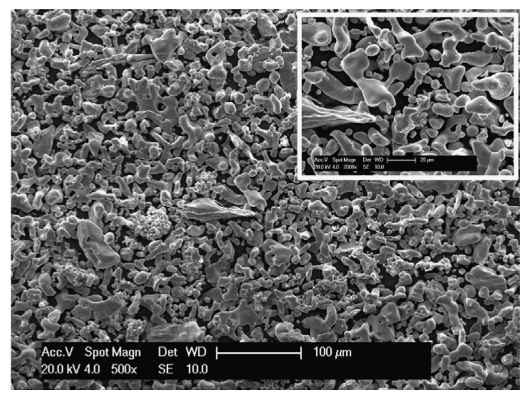

Fig. 2 – SEM images of the titanium powder.

The packing behaviour for the two components was studied using a Quantachrome Autotap™ machine by tapping a known mass of powder in a graduated measuring cylinder. The apparent and tap densities were 0.90 and 0.97 $g\,cm^{-1}$ for the salt beads (corresponding to packing fractions of 0.55 and 0.59 respectively for the porous NaCl beads, which have a density of $1.65 \pm 0.05\ g\,cm^{-1}$ (Jinnapat, 2011)) and 1.47 and 1.98 $g\,cm^{-1}$ for the Ti powder (corresponding to packing fractions of 0.33 and 0.44 respectively).

2.2. Preparation of green parts

Ti powder and NaCl beads were combined using a tapping-based method similar to that reported in Jinnapat and Kennedy (2010). In this process, 4.3 g of salt beads were poured into the cavity of a 22 mm diameter die (with the bottom punch in place) and packing was enhanced by brief tapping using the same Autotap™ machine described earlier, which employs a simple lifting and dropping action, tapping at roughly 4 Hz. Ti powder, in varying masses (typically in the range of 2–4 g) was then placed on top of the bed, where after the top punch was inserted. The whole assembly was then tapped, using the same machine, stopping after a predetermined number of cycles. An image of the tooling and a schematic of the layered structure and the tapping direction (marked with an arrow) are given in Fig. 4.