Evaluation of Mechanical Properties of Highly Porous Titanium Considering its Application as a Biomaterial

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Abstract

Porous titanium implants can be produced by powder metallurgy in combination with suitable space holder materials. Various mechanical experiments were done to characterize this material regarding the influence of the processing parameters on microstructure and mechanical properties taking into account the properties of the human bone. In this paper, the anistropic behaviour of uniaxially compacted samples was analysed in compression tests and compared to the behaviour of isostatically pressed samples. The failure of the struts of the porous titanium and the crack- initiation and –growth was examined by in-situ SEM analysis.

Keywords : titanium foam, porous titanium, biomedical application, mechanical properties, anisotropy

1. Introduction

Open porous titanium foams are known as an attractive implant material in biomedical applications. The open porosity contributes to the forming of a structural and functional bond between bone and implant. In addition, titanium ensures good biocompatibility with the surrounding tissue providing long term stability [1]. Recently, a manufacturing route was developed for the production of net shape parts retaining the open porosity. Main feature of the route was the shaping in the unsintered state by green machining of pressed compacts using conventional methods like milling or turning [2]. The first application as an implant material is an interbody fusion device for the human lumbar spine (Fig. 1). The promising bone ingrowth behaviour of these implants has been confirmed by in-vitro [3] and in-vivo studies [4].

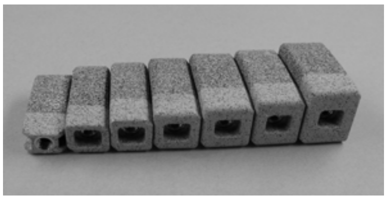

Fig. 1. PlivioPoreTM implant system for interbody fusion of lumbar spine (courtesy of Synthes AG , Switzerland).

In the present investigation, the mechanical properties of a titanium foams with a porosity of approximately 60 Vol.% and pore sizes in the range of 355-500 µm were investigated. In case of uniaxially pressed samples, the influence of the compaction direction on the compression strength was analysed. Discussion of the results was done in relationship to isostatically pressed samples and to the mechanical properties of cancellous and cortical bone. To understand the failure mechanisms of titanium foams, crack-initiation and –growth in the struts were examined by in-situ SEM analysis.

2. Experimental and Results

Titanium-powder with a particle size smaller than 45 µm, produced by the HDH-process (supplier GfE, Nuremberg) and a space holder material with particle sizes of 125-250 µm and 355-500 µm were mixed in a ratio of 30:70 (Vol.%). The space holder was ammonium bicarbonate (supplier Merck, Darmstadt). The mixture was uniaxially pressed to cylinders with a diameter of 60 mm. After this the cylinders were thermally treated at moderate temperature to remove the space holder, which decomposes to water, carbondioxide and ammonia. The porous samples were sintered at 1300 °C for 3 hours in argon-atmosphere. A detailed description of the manufacturing route is given elsewhere [2]. For the characterization of the mechanical properties, cylinders with a diameter of 6 mm and a height of 9 mm were cut by electro discharge machining. The mechanical tests were done on a Zwick 1387.The samples for the SEM examinations were prepared by grinding and polishing of the surface. Investigations were performed with a SEM (LEO 440). In Figure 2, the stress-strain curves of uniaxially pressed porous titanium samples are compared to related measurements on cancellous and cortical bone taken from literature [5]. The analysed foams are found to be anisotropic due to the re-arrangement of irregular space holder particles during the compaction resulting in an anistropic microstructure (Fig. 3a). At lower strains, an enhanced strength of the titanium foams was found if the load was applied perpendicular to the compaction direction. The curve is characterized by a small slope in the plastic regime which is well known for metal foams. If the load was exerted parallel to the compaction direction, the monotonic increase of the stress-strain curve is quite unusual for a highly porous metal. A detailed microstructural study during compression shows that even at low deformations fracture of the titanium struts occurs due to the notch effect resulting from the angular pore shape. At higher deformations the fragments are arranged in a layerwise structure (Fig. 3b). The homogeneous shift of the fragments results in a ongoing closure of the pores, which seems to be the main reason for monotonic increase of the stress-strain curves in case of parallel loading. A similar behavior was found in case of isostatically pressed samples. The stress-strain curve of a sample with a porosity of 59,8% (not shown here) fits the curve of the sample loaded parallel quite well.

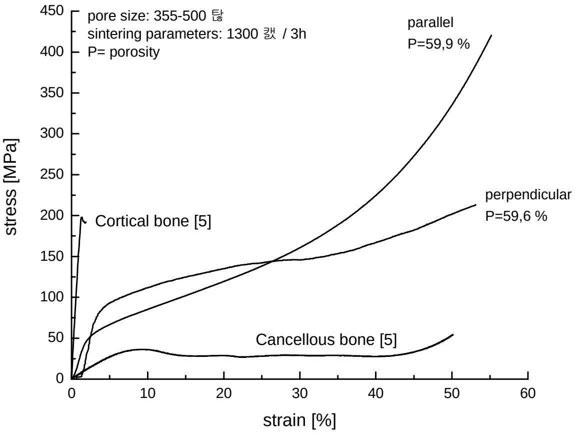

Fig. 2. Stress-strain behaviour of axially pressed porous titanium samples depending on the compaction direction in comparison to the human bone.

In the elastic regime, the Young´s modulus is calculated from the slope of the curve. A small displacement of the curve at strains below 2 % is attributed to a settling of the experimental set-up and is neglected in the calculation. Young´s moduli of 4.4 GPa (perpendicular) and 3.0 GPa (parallel) were found. Compared to these results, the different microstructures of human bone exhibit a clearly enhanced anisotropy. The mechanical behaviour of the cortical bone is chracterized by its brittleness combined with a relatively high Young´s modulus of nearly 20 GPa. The cancellous bone shows a high elongation at fracture, while the Young´s modulus remains rather low (< 1 GPa). Depending on the desired application, the mechanical properties of the titanium foam can be adapted to cortical or cancellous bone by adjusting the porosity by the content of the space holder. This process is well understood [6].

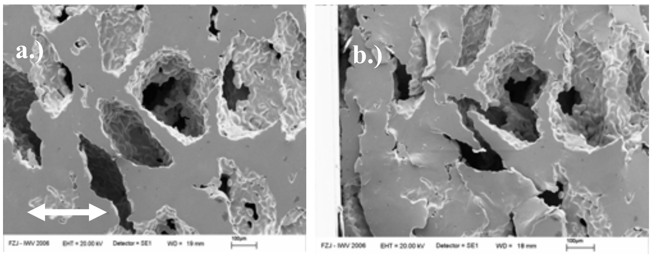

Fig. 3. Structure of porous titanium. a.) anisotropic pore shape before testing. The compaction direction is shown by an arrow b.) after testing at a deformation of 25 %. The load was brought up parallel to the compaction direction.

3. Summary

Titanium foams produced by the space holder method show anisotropic properties if the compaction is done uniaxially. The irregular space holder particles re-arrange during the compaction of the powder mixture leading to an anisotropic alignment of the pores. At low strains, the strength of the foams is higher perpendicular to the compaction direction and lower along the compaction axis. In either case, the Young´s modulus and the strength of titanium foam with 60% porosity lie inbetween the related properties of the human bone types reducing the risk of stress-shielding compared to dense titanium implants.

4. References

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Acknowledgements

The authors would like to thank Egebert Wessel for microstructural investigations by SEM.