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Fabrication of porous titanium scaffold with controlled porous structure and net-shape using magnesium as spacer

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ABSTRACT

This paper reports a new approach to fabricating biocompatible porous titanium with controlled pore structure and net-shape. The method is based on using sacrificial Mg particles as space holders to produce compacts that are mechanically stable and machinable. Using magnesium granules and Ti powder, Ti/Mg compacts with transverse rupture strength (~85 MPa) sufficient for machining were fabricated by warm compaction, and a complex-shape Ti scaffold was eventually produced by removal of Mg granules from the net-shape compact. The pores with the average size of 132–262 μm were well distributed and interconnected. Due to anisotropy and alignment of the pores the compressive strength varied with the direction of compression. In the case of pores aligned with the direction of compression, the compressive strength values (59–280 MPa) high enough for applications in load bearing implants were achieved. To verify the possibility of controlled net-shape, conventional machining process was performed on Ti/Mg compact. Compact with screw shape and porous Ti scaffold with hemispherical cup shape were fabricated by the results. Finally, it was demonstrated by cell tests using MC3T3-E1 cell line that the porous Ti scaffolds fabricated by this technique are biocompatible.

1. Introduction

Titanium is a widely used material for bone implant applications owing to its excellent mechanical properties, chemical stability, and biocompatibility [1]. Although Ti has many advantages as an implant material, a mismatch of stiffness between bone and Ti implant, referred to as 'stress shielding', may cause bone resorption and loosening of implant [2]. One promising solution to this problem is fabrication of porous Ti with suitable porosity characteristics, including size, distribution, and interconnectivity of the pores [3]. Ti with porous structure generally shows stiffness levels which can reduce the stress shielding effect, and when the structure has well interconnected pores in the size range of 100–500 μm, fixation of implant can be enhanced by bone ingrowth through the pores [4,5].

For these reasons, various methods to fabricate porous Ti were reported, including rapid prototyping [6], replication of polymeric sponge [7], and freeze casting [8]. Most of the reports on porous Ti just focused on control of porous structure, such as pore size, shape, and interconnectivity. Control of porous structure is one of the most important issues for research on porous materials. However, for real applications, notably in commercial implants with complex shape, control of net-shape needs to be addressed as well, as it is extremely difficult to form or machine metals with open pores due to their ductile behavior. During forming or machining, pores are easily closed by smearing or get contaminated by the debris. Controlling the processing conditions (processing speed, cutting depth, and the choice of the cutting tool) is one approach to overcome this limitation, but it cannot resolve the problem completely. The amount of smearing and contamination can be reduced but cannot be eliminated entirely [9]. In this study, a method to fabricate net-shape porous Ti scaffold with controlled pore structure is proposed. To satisfy this combination of requirements, we used the space holder method, which has the advantage of ensuring controllable porosity, pore size, and pore distribution, while providing the ability to machine the compact composed of Ti powder and spacer particles. A schematic diagram illustrating the individual processing steps leading to a net-shape porous Ti part is shown in Fig. 1. The essence of the method is that mechanically stable and sufficiently strong Ti/Mg compacts are obtained, which makes it possible to first machine a compact to the desired shape. Removal of Mg from the machined part by chemical reaction using an acid is then carried out as a next processing step. Finally, sintering results in a net-shape porous Ti scaffold.

From among various possible spacers including sodium chloride [10], carbamide [11], and poly (methyl methacrylate) [12], magnesium was chosen as a most suitable candidate. In the past, some authors recommended to use Mg granules [13,14] as space holders. However, we applied our own criteria that led us to choosing Mg granules as spacers in fabricating porous net-shape Ti scaffolds with controlled porous structure. We were guided by the following considerations. First,

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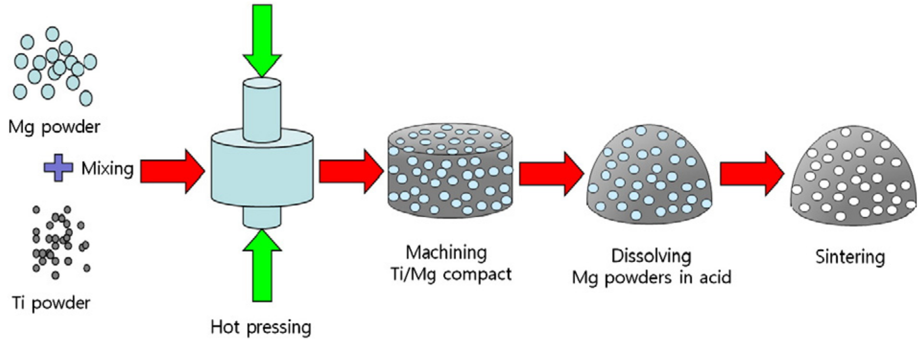

Fig. 1. Schematic diagram illustrating fabrication of porous titanium with controlled porous structure and net shape.

due to its high reactivity Mg can easily be removed from a Ti/Mg compact by an acid once the net shape of the scaffold is obtained by forming or machining. Second, being reasonably ductile, Mg can be deformed during powder compaction, e.g. by uniaxial pressing. The deformation of Mg particles in this process will affect the mechanical properties of the resulting porous scaffolds because, as will be demonstrated below, upon their removal the shape and arrangement of deformed Mg particles will give rise to anisotropic and aligned pores. Third, Mg has relatively high strength and a large elastic modulus (45 GPa) compared to polymeric spacers and salts, and it has a relatively high melting temperature (650 °C). We shall demonstrate that by using this concept it was possible to fabricate strong, high-density Ti/Mg compacts with high transverse rupture strength (~85 MPa), which is higher than the critical strength (27.3 MPa) required for machinability [15].

The porous Ti scaffolds are used for the bio-medical applications, e.g. bone substitutes. Thus, their biocompatibility should be examined. In this study, it was examined by in vitro cell test using MC3T3-E1 cell which is a pre-osteoblast cell. By comparing with commercial Ti plate, it was demonstrated that the porous Ti scaffolds are biocompatible.

This means that biocompatible porous Ti scaffolds with net-shape can be produced by conventional machining of the Ti/Mg compacts to desired shape with subsequent, a posteriori, chemical removal of Mg space-holder particles.

2. Experimental procedure

Commercially available Ti powder (−325 mesh, Alfa Aesar, Ward Hill, MA, USA) and Mg granules (20–100 mesh, Alfa Aesar, Ward Hill, MA, USA) were used as the starting materials. Mixtures of Mg granules (50, 60, and 70 vol.%) with Ti powders were held in 0.5 wt.% of ethanol for 30 min. Ethanol acted as a binder to cover Mg granules with Ti powders for homogeneous mixture. The mixtures were compacted in cylindrical dies at 400 °C and 600 MPa using uniaxial pressing to obtain Ti/Mg compacts. The pressing temperature and pressure were chosen empirically. The compacts obtained were not strong enough

Fig. 2. Typical optical images of the porous Ti scaffolds produced with various initial Mg contents (50, 60 and 70 vol.%, left to right).

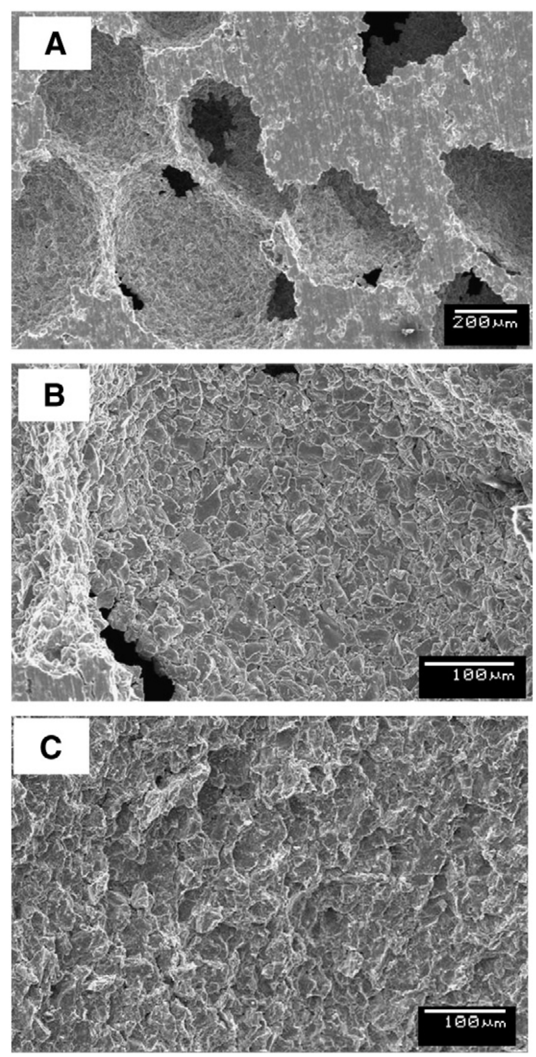

Fig. 3. Typical SEM images of (A, B) porous green body produced with initial Mg content of 60 vol.%, and (C) cross-section of compacts packed only with Ti powder under same condition.