Materials Science and Engineering C 29 (2009) 2003–2010

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Development of bioresorbable Mg-substituted tricalcium phosphate scaffolds for bone tissue engineering

Xing Zhang, Tsukasa Takahashi, Kenneth S. Vecchio *

Department of NanoEngineering, UC San Diego, La Jolla, California, USA

ARTICLE INFO

Article history:
Received 22 January 2009
Accepted 13 March 2009
Available online 24 March 2009

Keywords:
Beta-tricalcium phosphate
Mg-substituted
Bioresorbable
Scaffolds

ABSTRACT

Mg-substituted tricalcium phosphate (β-TCMP) samples were prepared either by the solid-state reaction of $CaHPO_4$ (DCPA), $CaCO_3$ and MgO powder at 1000 °C, or by a two-step process: wet precipitation of a precursor and further calcination of the precursor. The transition temperature from β-Tricalcium Phosphate (TCP) to α-TCP increases with the increase of Mg^{2+} content in β-TCMP samples. A β-TCMP sample with 3 mol% Mg^{2+} has a β-TCP to α-TCP transition temperature above 1300 °C, which was then used to fabricate various β-TCMP scaffolds in this study. Interconnected porous β-TCMP ceramics, with pore size >100 μm and relative density of ~81% to 84%, were developed by a replication method using polyurethane foam as a template; micropores were also found in the scaffold struts. β-TCMP ceramics with a porous structure in the center and a dense shell-like structure outside, mimicking human bone, were fabricated by a molding method. Dense β-TCMP ceramic rings were also produced with an average compressive strength of 129 MPa.

1. Introduction

Bioresorbable materials have been considered as ideal temporary scaffolds in bone tissue engineering, which would facilitate the initial formation of new bone tissue and finally be replaced by the new bone. Among them, β-tricalcium phosphate [$Ca_3(PO_4)_2$, β-TCP] ceramics have been widely used due to their good biocompatibility and osteointegration properties [1–7]. However, the poor mechanical properties of β-TCP ceramics, due to the brittleness and insufficient compaction by sintering below the β-TCP to α-TCP transformation temperature ~1125 °C, limit their use to non-load-bearing applications, such as filling of cancellous bone defects. Magnesium-substituted tricalcium phosphate [$(Ca,Mg)_3(PO_4)_2$, β-TCMP] has been recently found with higher phase transformation temperatures [8–11], which have better compaction during sintering [12] at temperature above 1125 °C, compared with pure β-TCP. Therefore, β-TCMP could be an ideal material for fabrication of bioresorbable bone scaffolds in high-temperature sintering process.

On the other hand, the structure, morphology and mechanical strength of the temporary scaffold are also very important. Scaffolds should have open pores and fully interconnected geometry, which would allow the in-growth of cells and tissues, and facilitate vascularization [13–17]. A pore size of 100 μm is generally considered as a minimum requirement for the in-growth of new bone tissue [18]. Interconnection sizes of >100, >40, and >5 μm were required for the in-growth of mineralized tissue, osteoid, and fibrous tissue, respectively [13,19]. Both micro- (<10 μm) and macro- (>50 μm) porosity have been demonstrated to influence long-term bone adaptation [20–22]. In addition, mechanical strength of scaffolds should be considered for the application in load-bearing cases, as well as for practical handling of the scaffolds during surgery. Moore et al. [23] present an excellent review of the critical aspects of synthetic bone graft substitutes, their mechanical properties and clinical applications.

In this investigation, porous β-TCMP ceramics, with interconnection pore size above 100 μm and micropores in the struts, were developed by a replication method using polyurethane foam as a template. However, these macroporous β-TCMP ceramics are very brittle, which could only be used in non-load-bearing cases. To increase the mechanical strength, β-TCMP scaffolds with a porous structure in the center and a dense shell-like structure outside, mimicking human bone, were fabricated by a molding method. Dense β-TCMP ceramic rings with high strength were also produced in this study, which would be used as scaffolds in load-bearing cases as well as constructs combined with other porous ceramics or polymers.

2. Materials and methods

2.1. Synthesis of β-TCP with/without Mg^{2+} substitution

Solid-state reaction was used to synthesize β-TCP or β-TCMP powder [8,9]. The starting materials are dicalcium phosphate anhydrous ($CaHPO_4$, DCPA, Reagent grade, Fisher Scientific, USA), calcium carbonate chemical ($CaCO_3$, ACS reagent, EM Science, USA), and magnesium oxide (MgO, ACS reagent, Fisher Scientific, USA).

* Corresponding author.
E-mail address: kvecchio@ucsd.edu (K.S. Vecchio).

0928-4931/$ – see front matter
doi:10.1016/j.msec.2009.03.012

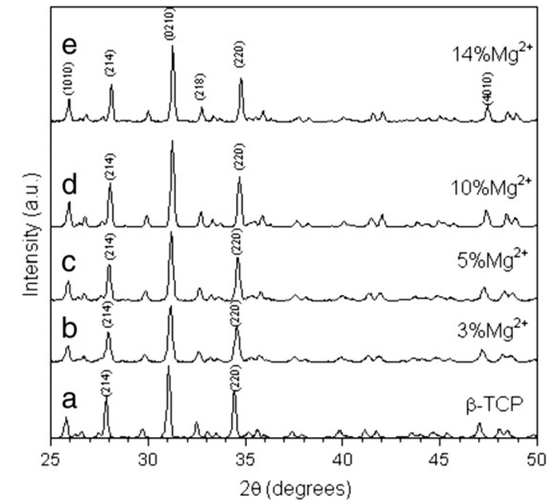

Fig. 1. XRD pattern of β-TCMP samples with different Mg^{2+} content produced at 1000 °C for 6 h: pure β-TCP, (b) 3 mol% Mg^{2+}, (c) 5 mol% Mg^{2+}, (d) 10 mol% Mg^{2+} and (e) 14 mol% Mg^{2+}.

Pure β-TCP was prepared by mixing DCPA and $CaCO_3$ powder with the Ca/P molar ratio of 1.5 in a mortar and heating the mixture in a furnace in air at 1000 °C for 6 h. β-TCMP powder was prepared by adding specific amounts of MgO into the mixture of DCPA and $CaCO_3$, with a (Ca + Mg)/P molar ratio of 1.5.

β-TCP and β-TCMP powders were also prepared by a two-step process: wet precipitation of a precursor and further calcination of the precursor at 800 °C. This method and characterization of the powders as-prepared were reported in our previous study [12] which also described the creation of dense ceramics from these powders.

Hereafter, β-TCMP samples with 1 mol%, 3 mol%, 5 mol%, 10 mol% Mg^{2+} prepared by the solid-state reaction in this paper are designated as β-TCMP-1-SS, β-TCMP-3-SS, β-TCMP-5-SS and β-TCMP-10-SS, respectively. β-TCMP powder with 3 mol% Mg^{2+} prepared through the two-step process is designated as β-TCMP-3. β-TCMP-3-SS and β-TCMP-3 were used to create porous structures and dense structures, respectively.

2.2. Fabrication of β-TCMP scaffolds

Interconnected macroporous β-TCMP ceramics were produced by a replication method with the polyurethane foam. β-TCMP slurry samples were prepared by mixing β-TCMP-3-SS powder and 5 wt.% polyvinyl alcohol (PVA) solution in a weight ratio of 1:1. The slurry samples with different amount of β-TCMP-3-SS (~1.2 g to 1.5 g) were infiltrated into the polyurethane (PU) foam pieces (~15 mm × 15 mm × 12 mm), which were heated to 600 °C with a heating rate of 4 °C/min for pyrolysis of the PU foam, and further heated from 600 °C to 1250 °C at a rate of 2 °C/min, and sintered at 1250 °C for a dwell time of 2 h to create porous ceramics.

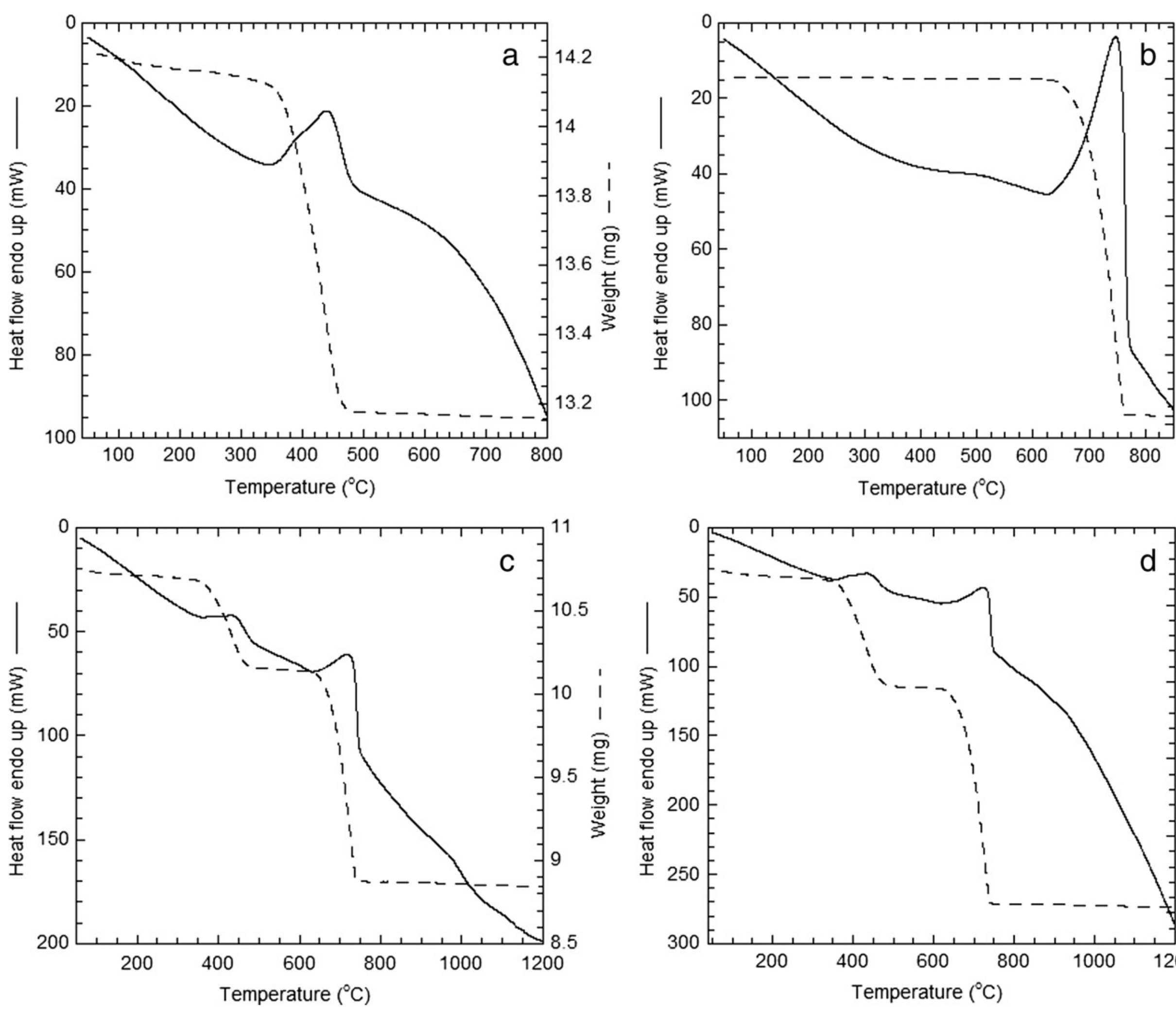

Fig. 2. TG/DTA results of different powders: (a) DCPA, (b) $CaCO_3$, (c) mixture of DCPA and $CaCO_3$ for synthesis of pure β-TCP, and (d) mixture of DCPA, $CaCO_3$ and MgO for synthesis of β-TCMP-5-SS, heated in air at 10 °C/min.