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Short communication

Hydroxyapatite–tricalcium phosphate–bioactive glass ternary composites

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Abstract

In this work hydroxyapatite, β-tricalcium phosphate and a new bioactive glass have been used to produce ternary composites for orthopedic applications. Thanks to the particular properties of the glass, whose formulation delays the devitrification processes at high temperature, sintering the composites at a relatively low temperature (800 °C) has been possible. In this way, two basic aims have been reached, since the glass preserved its amorphous nature and the reactions between the constituent phases were substantially reduced. Moreover, the ternary composites had a dense and uniform microstructure, which resulted in good mechanical properties (Vickers micro-hardness: 280 ± 22HV; elastic modulus: 28.7 ± 3.6 GPa). In vitro tests confirmed the apatite-forming ability of the composites soaked in a Simulated Body Fluid (SBF). Basing on the obtained results, the new ternary composites represent an intriguing alternative to conventional biomedical materials whenever a controlled bone-bonding rate is required.

Keywords: A. Sintering; B. (Ternary) composites; C. Mechanical properties; E. Biomedical applications

1. Introduction

The use of synthetic materials, especially calcium phosphates such as hydroxyapatite (HA) or β-tricalcium phosphate (β-TCP), represents an important approach to realize bone graft substitutes in order to face skeletal defects [1,2]. Another possibility is provided by bioactive glasses. If their composition is appropriate, bioactive glasses exposed to a physiological environment are able to promote the growth of an apatite layer on their surface, which supports the development of a strong bond with the host bone tissue [3]. Despite their increasing success, bioactive glasses are not suitable for load-bearing applications, due to their brittle behavior and relatively poor mechanical properties. In order to overcome this limitation and to achieve a closely controlled bone-bonding rate, bioactive glass–HA and bioactive glass–TCP binary composites are target of an intensive scientific research [4]. Nevertheless, unwanted phase changes and/or reactions may occur during the fabrication process. Besides, bioactive glasses commonly experience a devitrification if they are thermally treated to obtain sintered bodies, and this is expected to retard the bioactivity reactions [5].

The present letter describes the production of completely new ternary composites, composed by bioactive glass, HA and TCP. Very little has been published on ternary composites so far, and the few papers on the subject usually deal with different systems, since they propose binary composites (mainly glass/HA composites) and the third phase (most of all, TCP) derives from a thermal decomposition or reaction, sometimes leading to the complete disappearance of the original glassy phase [6,7].

On the contrary, in the present contribution the TCP is introduced from the beginning as an independent phase, on account of its desirable bio-resorbability. An additional innovation is represented by the bioactive glass, i.e. the new BG_Ca/Mix, whose formulation (in mol%: 2.3 Na_2O, 2.3 K_2O, 45.6 CaO, 2.6 P_2O_5, and 47.3 SiO_2) has been recently proposed to limit any potential devitrification process at high temperature [8]. The glass is applied here for the first time to produce ternary composites, aiming to facilitate the sintering process, thus maintaining the integrity of the three original constituent phases.

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2. Materials and Methods

The BG_Ca/Mix powder (grain size < 45 μm) was produced by conventional melting, as previously described [8]. In brief, the raw materials in powder form (Na_2CO_3, K_2CO_3, $CaCO_3$, $Ca_3(PO_4)_2$, SiO_2, analytical grade, by Carlo Erba Reagenti, Rodano-Milano, Italy), were weighted, mixed and melted in a platinum crucible at 1450 °C for 30 min (with a decarbonation step at 1050 °C for 1 h). The glass was fritted in room-temperature water and milled to the desired grain size. A ternary composite including 60 wt% BG_Ca/Mix, 20 wt% HA (CAPTAL® Hydroxylapatite, Plasma Biotal Ltd., UK; Particle size: d(0.1) = 20.498 μm, d(0.5) = 40.791 μm, d(0.9) = 72.435 μm, values determined by means of a laser granulometer, Mastersizer 2000 Ver. 5.22, Malvern Instruments Ltd., Malvern UK; BET Surface Area = 0.7773 m^2/g, determined with Micromeritics Instrument Corp. Gemini V2.00) and 20 wt % β-TCP (Sigma-Aldrich Chemie Gmbh, Munich, Germany; Particle size: d(0.1) = 2.027 μm, d(0.5) = 4.170 μm, d(0.9) = 8.647 μm; BET Surface Area = 1.5309 m^2/g) was then prepared by mixing the starting powders. The composition of the ternary composite was defined according to preliminary tests, proving lower glass fractions did not induce a satisfactory densification, whereas higher glass fractions reduced the mechanical properties. According to the available literature, the HA-to-TCP ratio was designed to balance the reaction rate of the ceramic components in a physiological fluid [1,2]. The mixed powders were uniaxially pressed at 45 MPa for 10 s to obtain green bodies.

In order to preserve the glassy phase during sintering and, at the same time, to produce samples with adequate densification, the thermal behavior of the mixed powders was accurately investigated. In fact, Differential Thermal Analysis, DTA, (NETZSCH DSC 404; NETZSCH-Gerätebau GmbH, Selb, Germany; mass of the powder required to perform the test: 30 mg) and Optical Dilatometry, OD, (Misura 3.32; Expert System Solutions, Modena, Italy) were employed to investigate the sintering kinetics and to detect possible devitrification processes. Both tests were performed from room temperature to 1200 °C at 10°/min (in air). According to the results of the DTA and of the OD, as described in detail in the following section, the samples were heat-treated at the selected temperature T_{HT}=800 °C with a dwell time of 3 h (heating rate: 5 °C/min from room temperature to 500 °C; 10 °C/min up to the maximum temperature). At the end of the thermal treatment, the samples were extracted from the kiln and left to cool in air naturally. In order to asses the consequence of the glass devitrification, a second group of samples was fired at the crystallization temperature T_c=874 °C (3 h dwell time, same heating/cooling conditions as before).

The samples were characterized by X-ray diffraction (X'Pert PRO, Panalytical, Almelo, The Netherlands) in the 10°–70° 2θ range (0.02° s^{-1} scanning rate, steps of 0.017°), while their microhardness was assessed by means of Vickers indentation (MicroVickers Hardness Tester, Mod. 402MVD, Wolpert Wilson Instruments, Aachen, Germany) using a 100 g_f load (loading time: 10 s; 15 indentations on each sample) and their Young's modulus was measured by means of a resonance-based technique (EMOD, Lemmens Grindosonic Electronika® MK5, LTD.; this technique is based on the correlation existing between the natural frequency of resonance of an elastic material and its elastic properties [9]). The bioactivity of the samples treated at T_{HT} was studied in vitro according to the procedure described by Kokubo et al. [10,11]. To this aim, the samples were soaked in 25 ml of simulated body fluid (SBF) and then kept at 37 °C. The soaked samples were 5 × 5 × 10 mm^3 prisms, with a proportion between the (apparent) surface area of the specimen (250 mm^2) and the volume of SBF (25 ml) which is equal to 10, as suggested by Kokubo et al. [11]. The SBF has been replaced twice a week. After given times of 1, 3, 7 and 14 days the samples were extracted from the SBF, rinsed using deionized water and then left to dry at room temperature. SEM analysis (ESEM Quanta 2000, FEI Co., Eindhoven, The Netherland) equipped with energy dispersive X-ray spectroscopy (EDS) (Inca, Oxford Instruments, UK) was used to investigate the microstructure of the composites before and after soaking in SBF.

3. Results and discussion

The results of the OD and DTA carried on the composites are represented in Fig. 1(a). The thermodilatometric curve shows that the sintering process starts at about 780 °C. A strong shrinkage is then reported in the temperature interval 830 °C–860 °C, while the maximum contraction rate is at the (theoretical) sintering temperature T_s ~ 853 °C. At higher

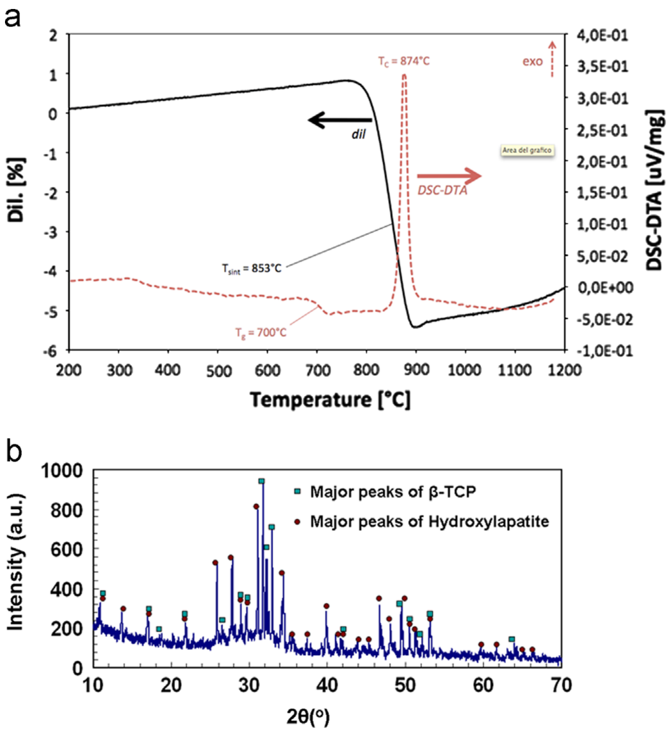

Fig. 1. Characterization of the thermal behavior: DTA and OD curves (a) and XRD spectrum (b) of the sample treated at T_{HT} = 800 °C. For the sake of clarity, only the principal peaks of HA and β-TCP were marked in the diffractogram.

temperatures the process stagnates because the system viscosity increases because of the devitrification process, as proven by the DTA curve, where the strong exothermic peak at $T_c = 874$ °C can be ascribed to the partial crystallization of the BG_Ca/Mix. According to the DTA, the onset crystallization temperature is around 850 °C. Since it is reported that the newly formed crystalline phases can be scarcely bioactive in comparison with the starting glass [5], the ternary composites were heat-treated at a temperature $T_{HT} = 800$ °C which is lower than the theoretical sintering temperature $T_s \sim 853$ °C, in order to avoid the onset crystallization (850 °C). However the heat-treatment at T_{HT} was prolonged for three hours, in order to exploit a long isothermal step to induce an adequate densification while preserving the amorphous nature of the glass matrix. In this way, it was possible to densify the samples at a relatively low temperature, whereas conventional HA/glass composites usually require much higher temperatures (1200–1300 °C) [6]. For example, the sintering process of composites based on the widely used 45S5 Bioglass® is precociously affected by the crystallization of the glass at about 600 °C [5]. This fact is even more crucial for ternary composites, where high temperatures may induce reactions between the glass and the calcium phosphate phases and/or their decomposition.

The diffractogram of the sample treated at T_{HT} (Fig. 1(b)) presents the peaks ascribable to HA (JCPDS-ICDD: 00-009-0432) and β-TCP (JCPDS-ICDD: 00-009-0169). The attribution of the single peaks was not straightforward, since various peaks of the two calcium phosphates overlap. However all the peaks in the spectrum belong to HA and/or β-TCP, thus confirming that the glassy phase did not crystallize and no reaction occurred between the starting phases during the heat-treatment at 800 °C. On the contrary, as shown in Fig. 2, the XRD spectrum of the sample treated at $T_c = 874$ °C reveals the devitrification of the glass with the formation of wollastonite (JCPDS-ICDD: 00-027-0088).

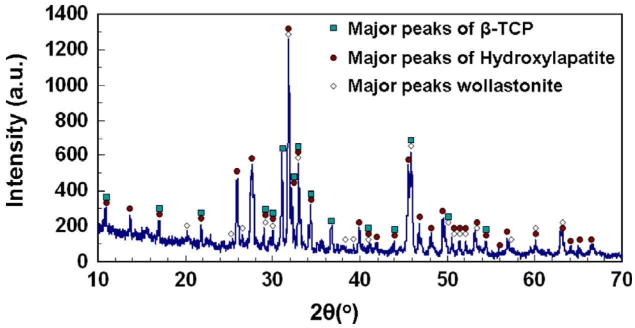

Fig. 2. XRD spectrum of the sample treated at $T_c = 874$ °C.

Fig. 3 shows the surface of the samples treated at T_{HT} and T_c. Although both samples are adequately consolidated, the samples treated at T_c are characterized by a residual porosity and by a defective microstructure, since in this case the sintering process was delayed by the concomitant crystallization, which hinders the viscous flow [12]. This fact is further confirmed by the microhardness values (280 ± 22HV and 186 ± 27HV for samples treated at T_{HT} and T_c, respectively), whereas it is less apparent looking at the elastic modulus, i.e. 28.7 ± 3.6 GPa (samples treated at T_{HT}) and 34.8 ± 1.8 GPa (samples treated at T_c). A comparison between these values and those reported in the literature is difficult, since very little has been published on ternary composites and, moreover, the hardness values are affected by several parameters, in particular by the sintering temperature. Anyway, these values are quite satisfactory if compared to bioactive glass/HA composites with a similar percentage of glass [13,14].

The assessment of the in vitro bioactivity was focused on the samples treated at T_{HT}. According to Kokubo et al. [10,11], in vitro assays involve the exposure of the samples, for a given period of time, to a fluid (SBF) which acts as a simplified human plasma, with the aim of investigate the apatite-forming ability of the material. Recently some criticisms have been addressed to these trials, which may lead to false positive (or negative) results [15], however in vitro tests represent a cheap and relatively easy tool to explore the bio-reactivity of a new material. The surface of the samples looks rather changed just after 3 days in SBF, while after 7 days (Fig. 4(a)) it is completely covered by globular-like precipitates with the typical HA morphology. Indeed the deposits are mainly composed by calcium phosphate (X-EDS spectrum in Fig. 4

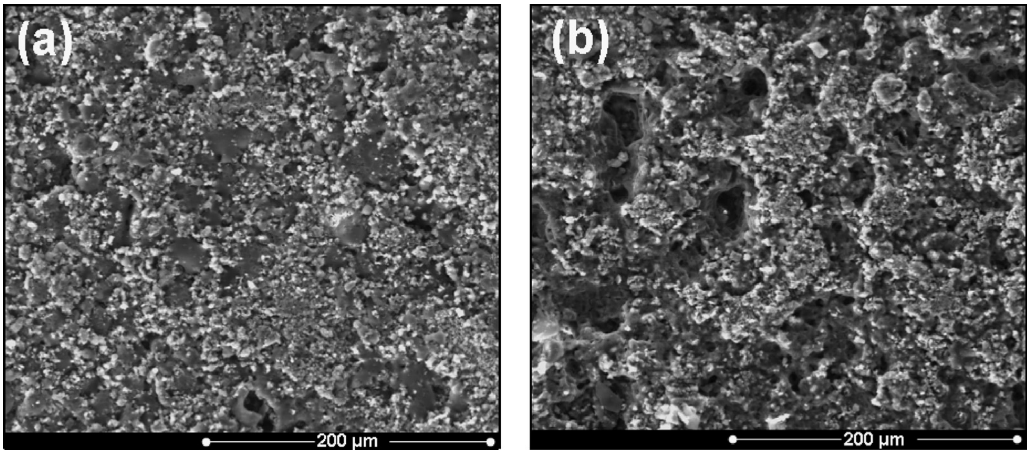

Fig. 3. Surface of the ternary composites treated at T_{HT} (a) and T_c (b).

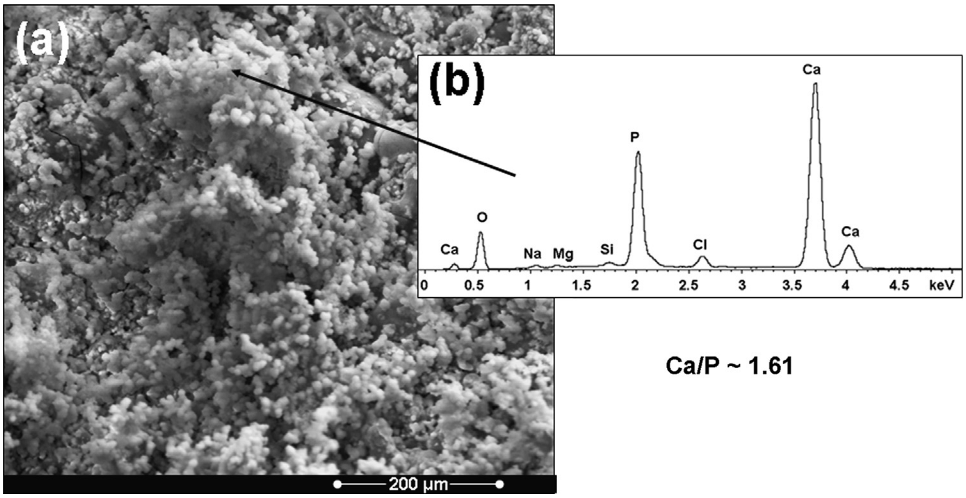

Fig. 4. Surface of the ternary composites treated at T_{HT} after soaking in SBF for 7 days (a) and (b) EDS spectrum performed on the spot reported in (a).

(b)) with a Ca/P ratio ~1.61. This value is indicative, since the analysis is mainly qualitative, however it is comparable to that of stoichiometric apatite (1.67 [16]). These results confirm the apatite-forming ability of the ternary composites in contact with SBF.

4. Conclusions

In the present contribution, the recently developed BG_Ca/Mix glass was employed to produce highly bioactive ternary composites including HA and TCP. Thanks to the glass peculiarities (relatively high crystallization temperature), it was possible to densify the samples at a relatively low temperature (800 °C), thus maintaining the integrity of the constituent phases and, in particular, avoiding the devitrification of the glass. According to the results of the microstructural, mechanical and in vitro characterization, the novel composites may constitute an attractive alternative to conventional biomaterials whenever a controlled bone-bonding rate is required. Further work will be addressed to investigate the biological performance of the ternary composites, in particular compared to conventional biphasic composites.

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