Digest Journal of Nanomaterials and Biostructures Vol. 1, No. 2, June 2006, p. 37 – 42

SOL - GEL CHEMICAL ROUTES FOR PREPARING BIOACTIVE FLUORHYDROXYAPATITE THIN FILMS AND POWDERS

G. E. Stan, J. M. F. Ferreira[a]

National Institute for Materials Physics, Magurele - Bucharest, Romania
[a]Department of Ceramic and Glass Engineering, University of Aveiro, Portugal

Bioactive apatite materials are usually used as coatings onto surface of biocompatible metals, leading to implants which take advantage of the coating's bioactivity and good mechanical properties of metals. Until recently the most prominent bioactive coating was hydroxyapatite (HA). In this work, powders and apatite type films were prepared on Ti6Al4V medical grade alloy using three sol-gel chemical routes by mixing different calcium and phosphorous precursors $Ca(NO_3)_2$, P_2O_5 and $C_6H_{15}PO_3$, and two fluoride reagents: HPF_6 and NH_4F. The resulting calcium phosphates and fluorapatite/hydroxyapatite solid solution (FHA) compounds were investigated by SEM, XRD and evaluated in vitro in SBF Kokubo solution. The best results were obtained for the $Ca(NO_3)_2$+ $C_6H_{15}PO_3$+ NH_4F chemical route which produced monophasic powders with a high crystallinity degree.

1. Introduction

Sol-gel is a flexible method for preparing biocompatible films with complex structures [1]. It has been known for almost half a century that ceramics made of calcium phosphate salts can be used successfully for replacing and augmenting bone tissue [2]. The most widely used calcium phosphate based bioceramics are hydroxyapatite [HA - $Ca_{10}(PO_4)_6(OH)_2$)] and β-tricalcium phosphate or β-whitlockite [β-TCP, $Ca_3(PO_4)_2$], and recently it is fast developing the flour included hydroxyapatites: fluorapatite [FA, $Ca_{10}(PO_4)_6F_2$] and fluoridated hydroxyapatite or fluor-hydroxyapatite [FHA, $Ca_{10}(PO_4)_6(OH)_xF_{1-x}$] available in pastes, putties, solid matrices, granules and thin films. For osseointegration purposes, fluorapatite could be a material of interest because of its similarity to bony apatite and lower solubility in aqueous solutions like body fluid in comparison to HA and β-TCP respectively. On the other part, metallic based implants have high strength and fracture toughness, but their bonding ability to bone tissue is very low. In this paper we have studied different chemical routes, varying the process parameters for preparing thin bioactive flour-hydroxyapatite (FHA) films onto metallic substrates and pure and fine monophasic powders. Thus FA/HA films would facilitate joining between the prosthesis and the osseous tissue, and increase the long-term stability and integrity of the implant due to its chemical similarity to the calcium phosphate minerals in biological hard tissue, and its ability to form a strong chemical bond with bone [3]. The morphology and the composition of the thin films and powders can be relatively easy to be controlled by sol-gel processing parameters such as starting pH of the sol, annealing for crystallization temperature [4] and addition of auxiliary chemical reagents [5]. The roughness of the metallic surface, in order to improve the adherence between the substrate and the ceramic coating, can be obtained by promoting the formation of a TiO_2 layer after a cleaning/pasivating chemical treatment [6,7]. This study aimed at the preparation of bioactive FHA films on Ti6Al4V substrates through three different chemical routes using various Ca/P precursors and F promoting reagents. The resulting powders and thin layers were qualitatively and quantitatively evaluated by SEM and XRD. Their bioactive potential was tested by using in vitro Kokubo test.

2. Materials and methods

The powders and the thin films were prepared by three chemical routes, with different combinations of calcium and phosphorous precursors and fluorine reagents. The dip-coating velocities were also varied (between 0.3 and 3 mm/s). The films and powders were annealed in air at 500, 600 and 950°C. A biphasic Ti6Al4V alloy was used as substrate. Structural and morphological characterization (XRD, Rigaku D/Max RA) with a scan speed of 1°(2θ)/min and a step of 0.02° and SEM, Hitachi S-4100 with Rontec Energy dispersive spectroscopy) were performed, and the bioactive potential was estimated by Kokubo test. The chemical sol-gel routes were as follows: (i) mixing a refluxed phosphoric pentoxide ethanol solution with a calcium nitrate tetrahydrate ethanol solution and using hexafluorophosphoric acid as F precursor reagent; (ii) mixing a phosphoric pentoxide in a water-ethanol solution and using ammonium fluoride as precursor for F; (iii) dissolving calcium nitrate tetrahydrate and triethyl phosphite in a water-ethanol solution and adding gradually ammonium fluoride as precursor for F. The films were submerged in Kokubo solution for characterizing the fluorine incorporation influence upon bioactivity.

3. Results and discussion

Calculated amounts of phosphoric pentoxide (P_2O_5, Riedel-deHaen) and calcium nitrate tetrahydrate ($Ca(NO_3)_2{\cdot}4H_2O$, Riedel-deHaen) were dissolved in absolute ethanol (C_2H_6O, Merck) to form 2 M solutions. These two solutions were mixed in Ca/P molar ratio of 1.67. Hexafluorophosphoric acid (HPF_6, Aldrich, AR) prepared in 6.78 M aqueous solution was choose as the fluorine containing reagent. Controlled amounts of HPF_6 were gradually added to the Ca-P solution, and finally refluxed for 24 hours.

After refluxing, the resulting sol became foggy and latter white opaque. The dipping sols could remain stable for 24 hours before precipitation occurred. When the dipping sol derived from the initial mixed precursor solution with HPF_6 was used for the preparation of films, all of the resulting films showed a small amount of apatite and two calcium phosphates phases in their XRD patterns.

Calcium species have a strong tendency to react with HF to form CaF_2 [8]. The HF produced in the reaction is rapidly consumed by the calcium species forming fine CaF_2 particles even in case of refluxing the mixture. The formation of solid CaF_2 causes the foggy aspect of the refluxed mixture. The XRD patterns of the gel state demonstrated that the solid product formed is CaF_2.

By the condensation reaction, the potential FHA sol was transformed in a light yellow gel, which displayed CaF_2 lines in X-ray diffraction investigation. The gel was transformed into powders by applying different heat treatments in order to observe and to obtain different phases and degrees of crystallinity. Three different heat-treatments in air were used: 600°C for 1 hour (the powder obtained was dark grey), 600 °C for 15 minutes (the powder was black) and 950°C for 1 hour (the powder was light grey). At 600°C and 950°C for 1 hour from XRD patterns were distinguished two calcium phosphates with low crystallinity peaks: the orthorhombic calcium pyrophosphate $Ca_2P_2O_7$ and the monoclinic dicalcium phosphite $Ca_2(PO_3)_2$. After a shorter heat treatment in air at 600°C for 15 minutes, besides the calcium phosphates mentioned previously, low intensity peaks of hydroxyapatite could be also identified. We supposed that the initial high sol acidity (pH~0.96) led to a multiphase low crystalline coatings less suitable for medical applications.

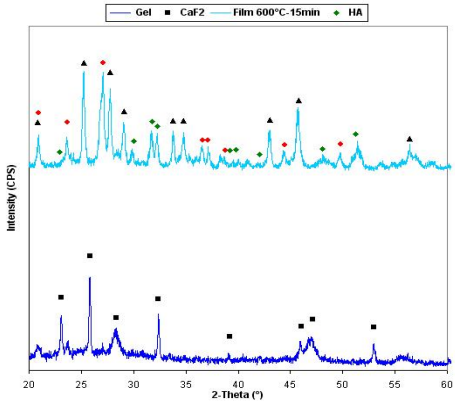

Fig. 1. XRD patterns of the first chemical route: gel and HA/FA film heat-treated at 600 °C for 15 minutes.

A scanning electron microscopy analysis has been performed on dip-coated samples of titanium alloy. This has provided supplementary information regarding the chemical composition and the morphological structure of the deposits. The investigated coated samples have been prepared by immersion in the FHA dipping sol with various speeds between 0.5 and 3 mm/s, and then dried and heat-treated.

The structure presented multiple cracks, due to the high acidity (pH~0.96) of the dipping sol and to the vibrations existing during the immersion of the samples, and certain domains with crystallized particles. The surface morphology was rough and comprised agglomerates of nano-particles. The heat-treatment that offered better results was the one applied to the samples at 600 °C for 15 minutes in air, the withdrawal speed from the dipping sol being 0.5 mm/s. The surface morphology of these samples had a more smooth appearance, and contained zones without cracks.

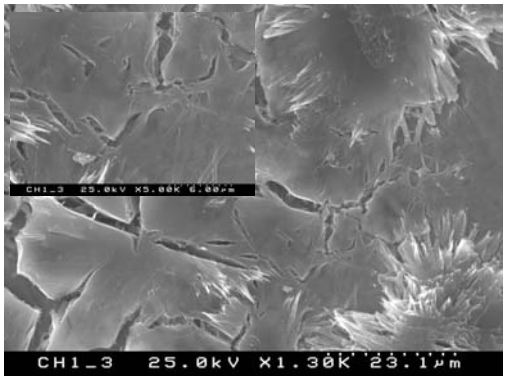

Fig. 2. Scanning electron microscopy photos of FHA 1 layers on Ti6Al4V annealed at 600 °C for 15 minutes in air, withdrawal speed of 0.5 mm/s.

Fig. 3 shows SEM photos taken to coated titanium based alloy sample maintained for 21 days in SBF solution. The morphology of the immersed sample demonstrates that even the small amounts of the apatite type compounds present in the coating induced the creation of new bonds and the growth of calcium phosphates onto the sample surface, due to its bioactivity. Energy dispersive spectrometry (EDS) analysis allowed us to distinguish the presence of calcium and phosphorous on the substrate coated with sol, proving once more that the surface ingrowths consist of calcium phosphates.

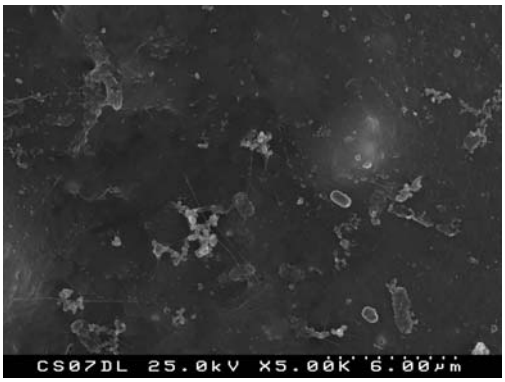

Fig. 3. Scanning electron microscopy photos of a 21 days immersed Ti6Al4V coated sample in simulated body fluid.

For the second route the sol was prepared mixing a 0.6 M phosphoric pentoxide (P_2O_5, Riedel-deHaen) in ethanol – water solution, 2M calcium nitrate tetrahydrate ($Ca(NO_3)_2 \cdot 4H_2O$, Riedel-deHaen) ethanol solution and 0.4 M ammonium fluoride (NH_4F, Riedel-deHaen,)

After aging at 38°C the sol became strongly precipitated, being separated in two distinct parts: a trasparent supernatant liquid and a gelatinious white precipitate due to the strong tendency of the calcium species to form CaF_2 molecules. The reaction developed more slowly in comparison with the first case, when the HPF_6 was used as fluorine reagent. The first signs of precipitations occurred aproximately after 36 hours. In order to perform the dip-coating of the titanium alloy samples, the sol was stirred and heated at 75°C for 3 hours. Thus a stable, white-transparent dipping sol was obtained, wihout any sign of precipitation along 6 weeks. The gel state was obtained by maintaing a small amonut of liquid dipping sol in an oven at a constant temperature of 80°C for 48 hours. The gel and the fluor-hydroxyapatite coatings on Ti6Al4V substrates prepared by the sol-gel method using the organo-metallic precursors and the fluorine reagent mentioned above were characterized by X-ray diffraction and scanning electron microscopy.

The XRD patterns of the coatings and the calcinated powder obtained at 500°C in air (Figure 4) presented besides the majoritary apatitic phase other bioactive calcium phosphates phase as whitlockite [$Ca_3(PO_4)_2$] [9]. The main problem is the high solubility of $Ca_3(PO_4)_2$ and its fast resolvable properties, making the coating less suitable for anchoring the new formed bone at the surface of the substrate.

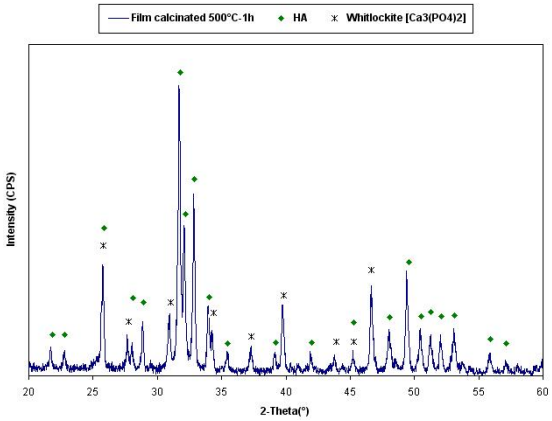

Fig. 1. XRD patterns of the second route fluor-hydroxyapatite thin layers onto Ti6Al4V.

The SEM morphology (Fig. 5) reveals an inhomogeneous surface with agglomerated nanoparticles, with a good potential for preparing efficient implant coatings in order to promote bone ingrowths.

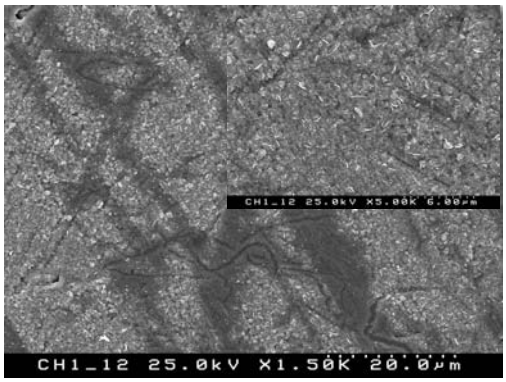

Fig. 2. Scanning electron microscopy images of a Ti6Al4V dip coated sample at a withdrawal a speed of 1.2 mm/s.

In the third chemical route the dipping sol was prepared by mixing calcium nitrate tetrahydrate ($Ca(NO_3)_2 \cdot 4H_2O$, Riedel-deHaen) + triethyl phosphite ($C_6H_{15}PO_3$, Aldrich) + ammonium fluoride (NH_4F, Riedel-deHaen).

The obtained sol was maintained in a controlled pH range of 8 – 10, in order to have a preferred formation of the fluor-hydroxyapatite, and keep a high stability of the reaction. The dipping sol was subsequently fed into an oven, where it was held at a constant temperature of 80°C for 2 days which represented suitable conditions for the condensation process to take place, leading to the formation of the fluor-hydroxyapatite gel.

The basic pH values provided a large number of OH^- ions to the solution. The OH^- surely acted as capturing the released H^-, rendering the solution less acidic and more importantly accelerating the reaction in forward direction.

The XRD investigations (Fig 6) confirmed the presence of apatite signals in the gel structure.

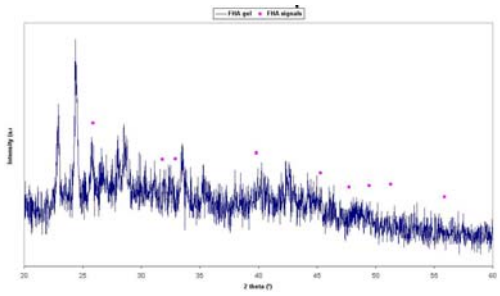

Fig. 6. XRD patterns of the third route fluor-hydroxyapatite gel.

Thus, after a series of different heat-treatments the gel has been transformed in powders with different colors and grain size depending of the applied temperature. The resulting powders were characterized by X-rays diffraction (XRD).

The best results have been obtained after the calcination at 950°C in ambient air. The obtained powders were white and presented a fine appearance.

The XRD analysis (Figure 7) showed a high crystalline, monophasic apatite compound, with no impurity or other residual calcium phosphates phase's or traces of CaO or CaF_2 present. This structure should have a good influence on the acceptance by the body of the implant was deposited on, due to a low dissolution rate.

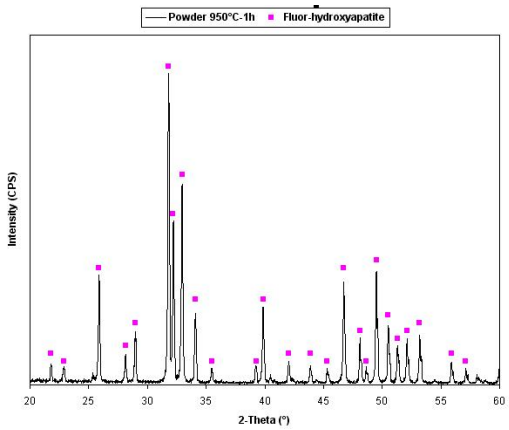

Fig. 3. XRD patterns of third route fluor-hydroxyapatite powder calcinated in air at 950°C.

The lattice parameters were calculated in order to establish if the compound obtained is fluorapatite/hydroxyapatite solid solution. The calculated "a" parameter with an average value of 9.367 demonstrated that the powders obtained in this work were indeed fluor-hydroxyapatite type. The valuable results obtained within the third chemical route will constitute the objective of a further future study upon the bioactivity properties.

4. Conclusions

FHA monophasic structures were successfully prepared by sol-gel route. We show that it is essentially to choose carefully the chemical route, and to maintain a perfect control over the sol pH, dip coating velocity and annealing for obtaining pure structures.

Acknowledgments

I would like to thank Prof. Jose Maria da Fonte Ferreira from the Department of Ceramic and Glass Engineering, University of Aveiro for the support, advises and cooperation given during my research studies in his laboratories.

References

[1] L. L. Hench, J. K. West, Chem. Rev. **90,** 33 (1990).
[2] L. D. Piveteau, B. Gasser, L. Schlapbach, Biomaterials **21,** 2193 (2000).
[3] W. Weng , S. Zhang , K. Cheng , H. Qu , P. Du , G. Shen , J. Yuan ,Gaorong Han, Surface and Coatings Technology **167**, 292 (2003).
[4] W. Weng, J. L. Baptista, Biomaterials **19**, 125 (1998).
[5] C. You, S. Oh, S. Kim, J. Sol–Gel Sci. Tech. **21**, 49 (2001).
[6] D. Liu, Q. Yang, T. Troczynski, Biomaterials **23**, 691 (2002).
[7] S. N. Bhaskar, D. E. Cutright, M. J. Knapp, J. D. Beasley, B. Perez, T. D. Driskell, Oral Surg Oral Med Oral Path 1971;31:282.
[8] K. Cheng, G. Han, W. Weng, H. Qu, P. Du, G. Shen, J. Yang, J.M.F. Ferreira, Materials Research Bulletin **38**, 89 (2003) -97.
[9] C. C. Berndt, G. N. Haddadt, A. J. D. Farmer, K. A. Gross, Materials Forum **14**, 161 (1990).