

Formation of Nano CoFe₂O₄ Crystallites in Hydroxyapatite

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ABSTRACT

Embedding nano size CoFe₂O₄ ferrite particles in a hydroxyapatite (HAP) host would make them to better candidates for hyperthermia treatment of cancer. The formation of nano crystallites of CoFe₂O₄ ferrites in the hydroxyapatite Ca_{10-3x}Fe_{2x}Co_x(PO₄)₆(OH)₂ where x= 0-0.5 %mole mixtures heated to temperatures between 500 and 1250°C for 2 hrs were monitored by several techniques. The DSC/TGA scan shows that the crystallization occurs at 731°C. The developments of peaks in the XRD patterns and of new vibration modes in the FT-IR spectrums of the Fe³⁺/Co²⁺ doped hydroxyapatite (HAP) compounds heated above 750°C indicate the formation of CoFe₂O₄ nano crystallites inside the HAP lattice. ESR measurements show the Co²⁺ ions substituting into the Ca(1) sites in HAP lattice when the HAP is heated above 750°C. SEM show that crystallites of irregular shapes coalesced into larger aggregates of cubic symmetrical structure characteristic of CoFe₂O₄ spinel as the annealing temperature is increased.

Keywords: Hydroxyapatite, Nano CoFe₂O₄ Particles, Biocompatible ceramics, Material Characterization.

1 INTRODUCTION

Mild hyperthermia, done at 41-46°C, is one of the promising new methods of cancer therapy. One of the new modalities is based on micro-or nano scale mediators in the form of injectable colloidal dispersion of magnetic particles directly into tumor [1-3]. Another method to perform hyperthermia is to utilize hydroxyapatite (HAP) as the medium for implanting the magnetic particles close to the cancer. This would be especially useful for treating bone cancer. The main constituent in hydroxyapatite (HAP) is calcium phosphate which has an excellent biocompatibility with bones. In the present work, we are interested in the formation of nano size CoFe₂O₄ ferrite particles within the HAP lattice. To obtain nano size particles, we have used microwave irradiation technique to produce the Fe³⁺/Co²⁺ doped calcium phosphate powders.

2 EXPERIMENTAL

The starting chemical used for the preparation of Ca_{10-3x}Fe_{2x}Co_x(PO₄)₆(OH)₂ (where x= 0-0.5 %mole) were reagent grade Ca(NO₃)₂·4H₂O, [NH₄]₂HPO₄, Fe(NO₃)₃·9H₂O, Co(NO₃)₂·6H₂O and [NH₄]OH. We have fixed the concentrations of the reactions to have a content ratio of (Ca+Fe+Co)/P equal to 1.67, with a Fe³⁺ to Co²⁺ ratio of 2:1. To achieve an intimate mixing, each of the substates was dissolved in 50 ml of de-ionized water. 25 ml of the Ca(NO₃)₂·4H₂O solutions were mixed with 25 ml of the Fe(NO₃)₃·9H₂O solution and of the Co(NO₃)₂·6H₂O solution in breaker. The pH of a 50 ml solution of [NH₄]₂HPO₄ was adjusted to 9.0 with [NH₄]OH. The mixture containing the Ca, Fe and Co was then added to the pH adjusted [NH₄]₂HPO₄ solution. The pH of the resulting mixture was again adjusted to 9.0 by adding [NH₄]OH under a constant stirring. After stirring for several minutes, the clear aqueous solutions of a given pH value were put into a household type microwave oven operating in the frequency bands centered at 915 MHz. The reaction was initiated by irradiating the solution for 120 seconds under ambient atmospheric conditions. After cooling to room temperature, the precipitates were extracted by freeze drying the various solutions. The changes in the nature of the crystal structure, the chemical compounds being formed and the size of CoFe₂O₄ ferrites were monitored by DSC/TGA (differential scanning calorimeter and thermal gravimetric analysis, XRD (x-ray diffraction), FT-IR (Fourier transform infrared) and ESR (electron spin resonance). SEM (scanning electron microscope) micrograms showed that crystallites of irregular shapes would coalesce into larger aggregates of cubic symmetrical structure characteristic of CoFe₂O₄ spinel ferrites as the doped HAP powders were heated to higher temperatures.

3 RESULTS

3.1 DSC/TGA results

In Figures 1 and 2, we see the TGA curves (done at a heating rate 10°C/min under a nitrogen atmosphere) for the Fe³⁺/Co²⁺-doped HAP, Ca_{10-2x}Fe_{2x}Co_x(PO₄)₆(OH)₂ (x = 0.1-0.5). The weight losses in the temperature range 100°C - 450°C for an undoped HAP and for the five doped HAP are 7.76, 4.73, 19.38, 25.53, 20.39 and 24.85%, respectively. It appears that the relative amount of weight loss increases

when the level of $\text{Fe}^{3+}/\text{Co}^{2+}$ substitution is increased (with the exception of the $x=0.3$ sample). The endothermic peaks at about 100°C correspond to the loss of absorbed water. The weight losses in the temperature range 200°C - 450°C are due to the loss of water in the precursor [$\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$]. The gradual decrease in the weight from 600°C to 1200°C are due to the slow elimination of the carbonate groups linked to HAP structure. Looking at the weight loss curve for $x=0.1$ doped HAP (Figure 1), we see that there is change in the weight loss in the temperature range between 700 - 800°C . A careful examination of the TGA curve for the other doped HAP (Figure 2) indicates that similar changes occur in the other doped samples in the same temperature regions. The changes in weight in this region are due to the loss of the water generated during the transformation of HAP to β -TCP at these temperatures. The existence of the transformation of HAP to β -TCP (tricalcium phosphate, β - $\text{Ca}(\text{PO}_4)_2$) is seen in the XRD patterns shown in Figure 3. The lack of any weight loss above 800°C can be viewed as a sign that the doped HAP's have become chemically stable after they are heated to 800°C .

The DSC curve for the $x = 0.1$ HAP shown in Figure 1 also provides information about the crystallization of the HAP. The upper curve in Figure 1, which is the DSC scan, has a very weak endothermic peak with an onset at 731°C . We take this peak to indicate the formation of a new crystalline phase in the HAP powder. Our interpretation that a phase transition has occurred at 731°C is supported by our XRD studies and ESR studies.

3.2 XRD results

In Figure 3 shows the XRD patterns for the undoped HAP and the five $\text{Fe}^{3+}/\text{Co}^{2+}$ doped HAP's, i.e., $\text{Ca}_{10-2x}\text{Fe}_x\text{Co}_x(\text{PO}_4)_6(\text{OH})_2$ (with $x = 0.1-0.5$) XRD. The four sets of patterns are for the following heat treatment; no heat treatment, heating at 500°C , at 750°C and at 1200°C for 2 hrs. When the powders are not heated, the XRD patterns of all samples look the same, i.e., they show the peaks generated by the HAP lattice. No new peaks are observed in the six samples (different x values) when the powders are heated to 500°C for 2 hrs. Heating the powders to 750°C , which is above the crystallization temperature, leads to the appearance of new peaks in the XRD patterns of the higher doped HAP's. When the powders are heated to 1250°C , additional peaks appear in the XRD patterns of all the doped powders. The new peaks appear even in the XRD pattern of the undoped powder which means that the peaks do not arise from the formation of any new compounds formed by the impurities. The new peaks belong to β -TCP whose formation was used to explain the change in the weight loss observed in the TGA curves between 700 and 800°C (see Figures 1 and 2). Increasing the annealing temperature from 750°C leads to the appearance of a small peak at $2\theta \sim 31.8^\circ$. This peak belongs to the CoFe_2O_4 spinel ferrites. The line width of this peak is such that when used

in Scherer's formula, indicates that the size of the particle is very small (in range of nm).

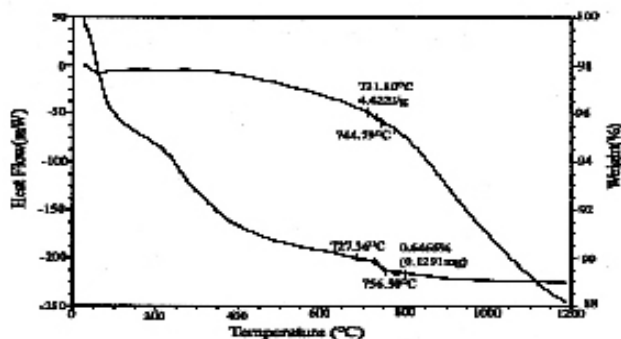


Figure 1: The DSC/TGA curves for the As-prepared $\text{Fe}^{3+}/\text{Co}^{2+}$ (2:1) $x=0.1\%$ mol substituted in hydroxyapatite powder for scanning rate $10^0\text{C}/\text{min}$.

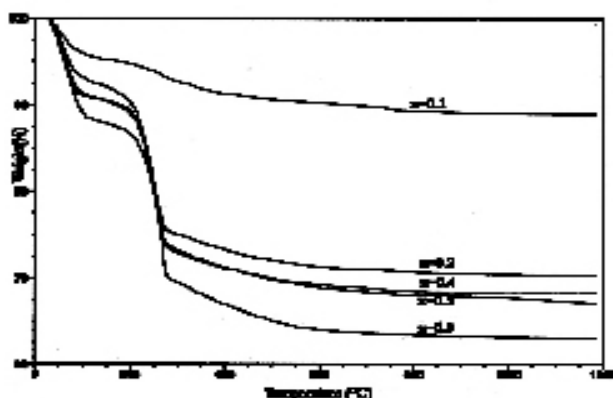


Figure 2: The TGA curves for the As-prepared $\text{Fe}^{3+}/\text{Co}^{2+}$ (2:1) $x=0.1-0.5\%$ mol substituted in hydroxyapatite powder for scanning rate $10^0\text{C}/\text{min}$.

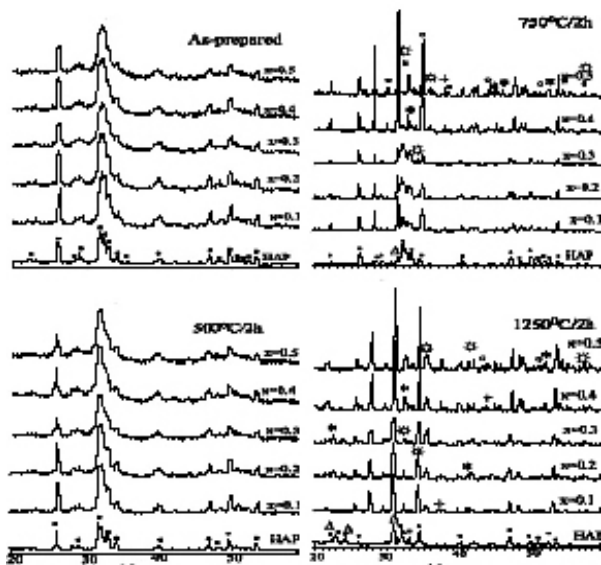


Figure 3: The XRD patterns of $\text{Fe}^{3+}/\text{Co}^{2+}$ substituted hydroxyapatite synthesized as function of heat treatment and ions composition (HAP structure (●), β -TCP(Δ), CoO (+), CaO (▪), Fe_2O_3 (*) and the nano CoFe_2O_4 ferrite (°)).

3.3 FT-IR results

The FT-IR spectrums for an as-prepared HAP and for iron/cobalt doped HAP annealed at 750°C for 2 hrs are shown in Figure 4. The FT-IR spectrum of the as-prepared sample contains two absorption peaks at 3575 and 627 cm⁻¹. These correspond to the stretching and vibrating modes of the hydroxyl group, respectively [4]. Looking at the peak for the stretching mode of hydroxyl (OH)⁻¹, we see that it becomes more intense as the level of the iron/cobalt substitution is increased to x=0.2 and then decrease as x is increased to 0.3. The peak disappears as the Fe³⁺/Co²⁺ concentration as x is increased to 0.4 and then to 0.5. As the amount of Fe³⁺/Co²⁺ substitution is increased past x=0.2, a broad band which is attributed to adsorbed water on surfaces appears at 3416 cm⁻¹. The bands in the FT-IR spectrums appearing at 798 and 885 cm⁻¹ are due to the vibrations (stretching) of the Fe³⁺-Co²⁺ bonds when the Fe³⁺ ions are in the tetrahedral and octahedral shaped crystals of CoFe₂O₄ ferrite, respectively.

In addition to the absorption by the hydroxyl group, there are absorption peaks due to the (PO₄)⁻³ groups in the HAP. The intense bands in the as-prepared HAP spectra at 1088, 1035 and 961 cm⁻¹ are due to the stretching mode in (PO₄)⁻³ while the doublets at 602 and 562 cm⁻¹ are due to the bending mode in (PO₄)⁻³. The band appearing at 962 cm⁻¹ is due to the presence of the β-TCP (β-tricalcium phosphate) phase crystallized during the thermal treatment.

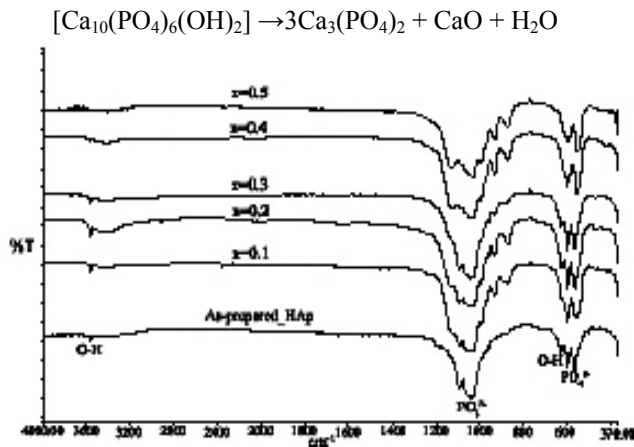


Figure 4: FT-IR spectra of Fe³⁺/Co²⁺ substituted in Hydroxyapatite synthesized for difference concentrations at 750°C/2h.

3.4 SEM results

The changes in the microstructure of the Fe³⁺/Co²⁺ doped HAP were monitored by the SEM. Figure 5 shows the SEM micrograms of the x=0.1 and 0.5 doped HAP's heated to the different temperatures. In Figures 5a, 5b and 5c, we see the grains formed when the two levels of doping powders are heated to 500°C (5a and 5b) and 1250°C (5c and 5d). Grains having sizes between 0.5-2.5 μm in length

are observed. They are rod shaped and become larger as the heating temperature is raised. The formation of nano crystals in the HAP matrix was studied by compressing as-prepared powders (with x=0.1 and 0.5 at pressure of 10 tons) and then heating the compressed powders to 750°C and 1250°C. This causes a large number of small and fine granules to form (see Figures 5e, 5f and 5g). This formation can be seen as changes in XRD patterns when the heating temperature is increased from 750°C and 1250°C. In Figure 5e, which is the SEM microgram for x=0.5 doped specimen heated at 750°C for 2 hrs., many of the grains formed consist of both tetrahedral and octahedral shaped crystals. Raising the heating temperature, the fine granules begin to coalesce into aggregates of crystallites of different shapes (See, Figures 5f and 5g). At 1250°C, we see the crystallites begin to form into large aggregates of cubic crystals characteristic of the spinel ferrites.

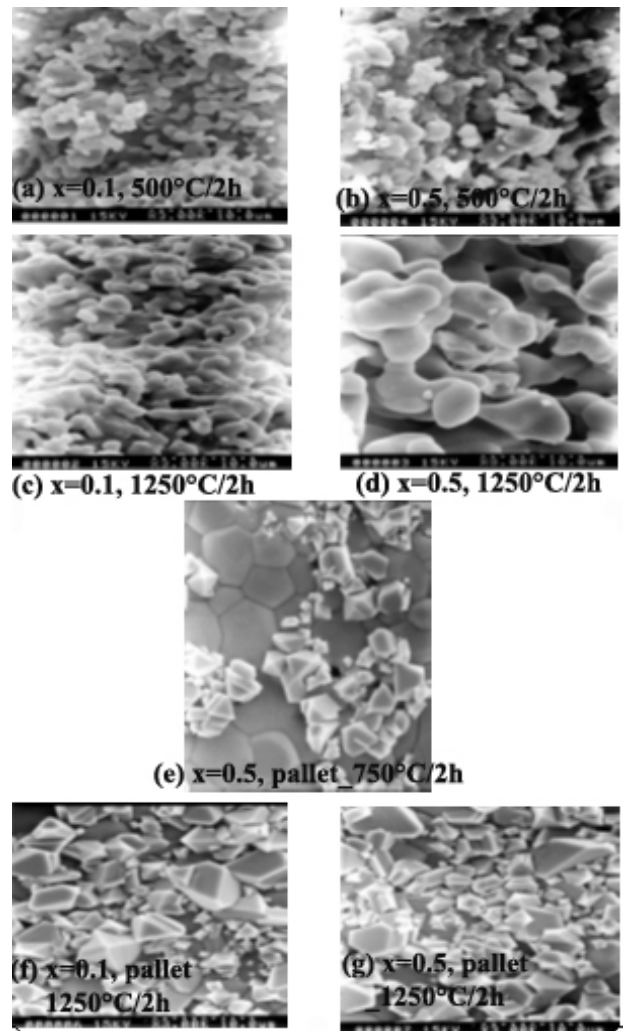


Figure 5: SEM showing the changes morphology as function of temperature of Ca_{10-3x}Fe_{2x}Co_x(PO₄)₆(OH)₂ (x=0.1 and 0.5%mol) mixture heat treatment at 500°C/2h, 1250°C/2h and pallet heat treatment at 750°C for 2h and at 1250°C/2h.

3.5 ESR results

The ESR spectrum of the $\text{Fe}^{3+}/\text{Co}^{2+}$ doped hydroxyapatite powders subjected to three heat treatments (no heat treatment, heated to 500°C for 2 hrs, and heated to 750°C for 2 hrs.) are shown in Figure 6. Each figure (6a, 6b and 6c) shows the ESR spectra of the five doping levels. Figures 6a and 6b exhibit the resonance dispersion curves for iron have g factors of 2.01 and 4.23. The ions having the g-factor of 4.23 are the Fe^{3+} whose magnetic moments are perpendicular to the direction of the applied field. The ESR spectra in Figure 6c contain an extra peak, one corresponding to an ion having a g-factor of 8.93 Fe^{3+} . This peak is due to Fe^{3+} ions whose moments are parallel to the field. The peak is not observed in the spectra shown in Figures 6a and 6b.

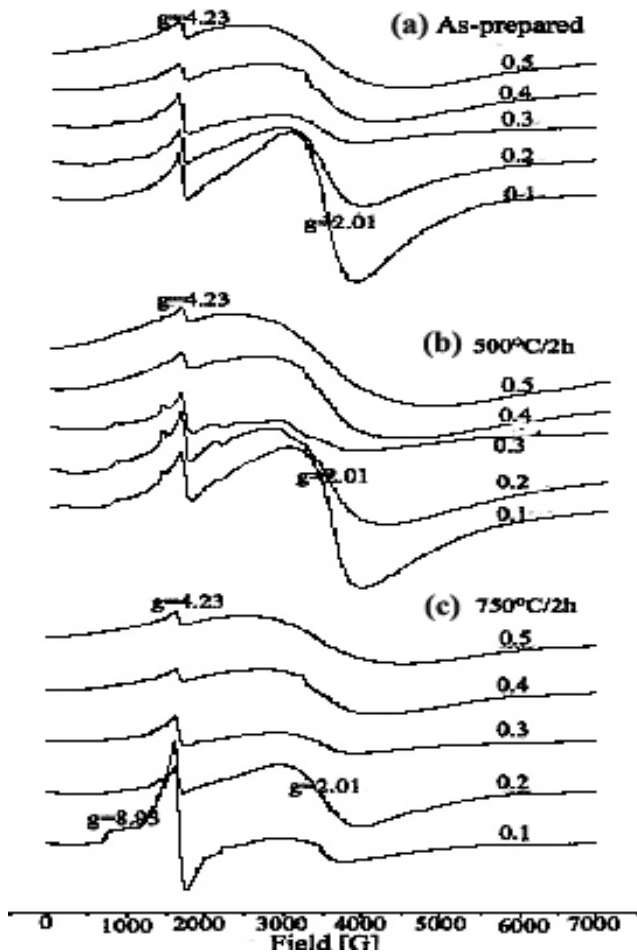


Figure 6: X band ESR spectra of $\text{Fe}^{3+}/\text{Co}^{2+}$ substituted in hydroxyapatite as function of temperature.

Finally, we have analysis the ESR signal in the samples annealed at 1250°C through a simulation of an observed spectrum with the spin-Hamilton [5]. Our simulation of the spectrum yields the following values: $g_x = g_y = 3.41$, $g_z = 2.01$, $A = 30\text{G}$, $D = 30\text{-}40\text{G}$ and $E = 0\text{G}$ with an isotopic line width of 55G . The value we obtained ($E/D = 0$)

corresponds to the simulation where the local environment of the paramagnetic ion Co^{2+} is purely axial symmetric. Since the $\text{Fe}^{3+}/\text{Co}^{2+}$ are replacing the calcium ions in $\text{Ca}_{10-2x}\text{Fe}_{2x}\text{Co}_x(\text{PO}_4)_6(\text{OH})_2$ and the local environment of the Co^{2+} ion must have axial symmetry, the Co^{2+} ions must be substituting into the Ca(1) site in the HAP lattice.

4 CONCLUSIONS

Our results indicate that nano crystallites of CoFe_2O_4 are being formed in the doped hydroxyapatite $\text{Ca}_{10-2x}\text{Fe}_{2x}\text{Co}_x(\text{PO}_4)_6(\text{OH})_2$ (where $x = 0\text{-}0.5$ %mole) compounds when the compounds are annealed above 750°C . The DSC/TGA results indicate that a structural phase transition occurs at 731°C . The appearance of diffraction lines due to the spinal ferrite CoFe_2O_4 in the XRD patterns of the doped hydroxyapatite compounds annealed at temperatures 750°C indicate that the new phase consists of CoFe_2O_4 being incorporated into the HAP structure. The measurements point to the Co^{2+} ions replacing some of the Ca^{2+} ions located at the Ca(1) sites in the interface between the regions containing the hydroxyapatite. Our FT-IR spectrums for doped samples annealed at temperatures below 750°C show features which are not seen in the samples annealed above this temperature and vice versa. The results of the FT-IR measurements on samples annealed below 750°C are characteristic of the hydroxyapatite while the results of the measurements of samples annealed above 750°C are characteristic of CoFe_2O_4 .

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