Synthesis and Characterization of Hydroxyapatite Nanopowders by Emulsion Technique

Susmita Bose* and Susanta Kumar Saha

School of Mechanical and Materials Engineering, Washington State University, Pullman, Washington 99164-2920

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Nanocrystalline HAp powder was synthesized using surfactant template systems. Composition of the microemulsion and synthesis parameters had significant effect on the formation of HAp nanopowder and their surface area and morphology. Powders were prepared with a surface area of 130 m^2/g and particle size between 30 and 50 nm with needle shape and spherical morphology. Nanocrystalline hydroxyapatite (HAp) powder was synthesized using the reverse micelle-processing route. Cyclohexane was used as the oil phase, mixed poly(oxyethylene)$_5$ nonylphenol ether (NP-5) and poly(oxyethylene)$_{12}$ nonylphenol ether (NP-12) as the surfactant phase, and a solution of $Ca(NO_3)_2$ and H_3PO_4 was used as the aqueous phase. The powders were characterized by BET surface area analyzer, powder X-ray diffraction, and transmission electron microscopy. It was found that experimental conditions such as aqueous/organic phase volume ratio, pH, aging time, aging temperature, and metal ion concentration in the aqueous phase affected the crystalline phase, surface area, particle size, and morphology of HAp nanopowders. With the use of this technique, nanopowders were prepared with different morphology depending on the reaction parameters.

Introduction

In recent years significant research effort has been devoted to developing inorganic nanocrystals because of their potential applications in biology, electronics, optics, transport, and information technology. Although several approaches investigated ways of making these nanocrystals, controlling the size, shape, and crystallinity and various parameters affecting the size and shape of these materials still need to be found. Recently, surfactant-based template systems are being explored to synthesize nanosize materials and they are assumed to be very efficient templates for controlling particle size and shape.[1] In this study we are reporting synthesis of calcium phosphate-based nanopowder using a reverse micelle template system. Calcium phosphate-based materials, especially bioactive hydroxyapatite (HAp, $Ca_{10}(PO_4)_6(OH)_2$), are used as bone substitute material[2,3] due to their similarity, chemically and structurally, to the mineral portion of bone. The major phase in bone is HAp with a calcium-to-phosphorus ratio of 1.67. Other important calcium phosphate phases, such as, α and β tricalcium phosphates with a calcium-to-phosphorus ratio of 1.5, are also used in bioresorbable applications. Although these materials are highly biocompatible, their use is limited to non-load-bearing applications because of their poor mechanical strength[4] due to poor sinterability. Successful application of Ca−P-based ceramics in a load-bearing bone graft application will require high strength and toughness. Sintering and densification of any ceramic depends on the powder properties such as particle size, distribution, and morphology.[5,6] The processing of fine-grained HAp ceramics by pressureless sintering demands control over the powders since many strength-limiting microstructural heterogeneities stem from the powder itself. It is believed that nanostructured calcium phosphate ceramics can improve the sintering kinetics due to a higher surface area and subsequently improve mechanical properties significantly.

Various synthesis methods have been used for HAp powders including solid-state reaction,[7] precipitation and hydrolysis of calcium phosphates,[8,9] and sol−gel.[10−14] All of these methods produce HAp powder where agglomeration cannot be controlled during syn-

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* Corresponding author. E-mail: sbose@wsu.edu.

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thesis or drying or at the processing step. Agglomeration can cause lower sintered density as well as crack-like voids during densification. High aspect ratio morphology in the starting powder can also cause poor packing, which results in exaggerated grain growth during sintering. This microstructural heterogeneity can seriously affect mechanical properties of sintered HAp parts. Thus, to produce sintered monolithic HAp part with desired mechanical properties, one needs to use agglomerate-free low aspect ratio fine HAp powder with high surface area.

Microemulsion has been shown to be one of the few techniques which are able to deliver a particle size in the range of nanometers with minimum agglomeration.[1] A microemulsion is a thermodynamically stable transparent solution of two immiscible liquids such as water and oil stabilized by an ampiphilic surface-active agent or surfactant. Generally, the water phase, having a high dielectric constant, is dispersed under agitation in an oil phase (water-immiscible organic solvent) having low dielectric constant. Addition of a surfactant between the two immiscible phases is necessary to control interfacial tension. In the case of a water-in-oil microemulsion, reverse micelles are formed when the aqueous phase is dispersed as microdroplets surrounded by a monolayer of surfactant molecules in the continuous hydrocarbon phase. These microdroplets of water that are stabilized in a nonaqueous phase by a surfactant act as a microreactor or nanoreactors in which reactions are conducted. These spatially and geometrically restricted, self-assembling media of reverse micelles can be used in the synthesis of nanophase materials without much agglomeration with high surface area.

The emulsion technique provides an alternative to other nonconventional synthesis methods for ceramic materials. Few studies have been reported on the development of fine HAp powders with spherical morphology. However, limited reports are available on the effect of powders properties like particle size, distribution, density, and morphology on the densification behavior and mechanical and microstructural characteristics of those powder compacts.[15−21] Ahn et al. have reported nanostructure processing of hydroxyapatite-based bioceramic in the presence of yttria-stabilized zirconia, prepared by chemical precipitation and pressure-assisted sintering of these powders.[15] Sonoda and co-workers have reported hydroxyapatite synthesis with smaller size and aspect ratio using pentaethyleneglycol dodecyl ether emulsion compared to a nonemulsion technique.[22] Lim et al. have reported the synthesis of HAp powders with a specific surface area between 42 and 80 m^2/g and an average particle size between 0.53 and 1.15 μm with agglomerated morphology. They have also reported the formation of nanocrystalline HAp in nonionic surfactant emulsion where the specific surface area of the system varied from 7 to 75 m^2/g depending on petroleum ether concentration.[23] Layrolle and co-workers have synthesized HAp powders with an average surface area of 26 m^2/g and an average particle size of 200 nm with a strongly agglomerated morphology with an average agglomerate size of 45 μm.[10] In the present study, we are discussing the synthesis of the HAp nanopowder with a surface area as high as 130 m^2/g using reverse micelle as a template system and particle size in the range of 30−50 nm with different morphology depending on the reaction parameters and the related powder characterization.

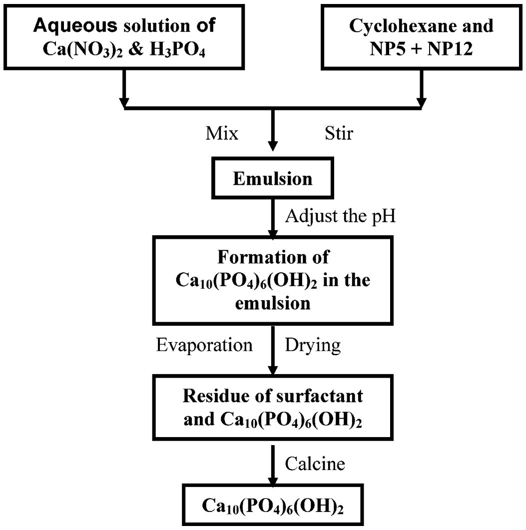

Figure 1. Flowchart for the synthesis of HAp by the emulsion technique.

Our effort is focused toward the development of synthetic routes to produce HAp nanopowder using an emulsion technique. The organic phase was prepared by mixing surfactants (poly(oxyethylene)$_5$ nonylphenol ether (NP-5) and poly(oxyethylene)$_{12}$ nonylphenol ether (NP-12) in cyclohexane. A homogeneous emulsion was formed by mixing the aqueous solution into the organic phase. The pH of the emulsion was adjusted to 7 to obtain phase pure hydroxyapatite. Powders were characterized using X-ray diffraction (XRD) and transmission electron microscopy (TEM) for their morphology and BET surface area analysis. Physical and microstructural development of the powder during heating was also investigated.

Experimental Section

The starting materials used in the present work are calcium nitrate (Alfa Aeser) and phosphoric acid (Fisher) for the calcium and phosphorus precursors, respectively, cyclohexane (Fisher) as the organic phase, poly(oxyethylene)$_5$ nonylphenol ether (NP-5) and poly(oxyethylene)$_{12}$ nonylphenol ether (NP-12) (both from Aldrich) as the surfactants. These reagents were used as received without any further purification. The flowchart for the preparation of HAp is illustrated in Figure 1. Aqueous solutions of calcium nitrate and phosphoric acid were made by dissolving them in deionized water. The initial

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strength of calcium ion in the aqueous solution was varied from 5.0 to 3.0 or 1.0 M in three different studies. The calcium to phosphorus atom ratio in the precursor was maintained at 1.67 to 1 in all of the cases. 10 vol % of surfactant (1:1 mixture of NP5 + NP12 by volume) was added to cyclohexane to make the organic phase. Aqueous solution and organic phase were mixed according to the volume ratios of 1:5, 1:10, and 1:15 to obtain the reverse micelle systems. The emulsion was converted into a transparent gel during mixing and stirring. The pH of the emulsion was adjusted to 7 by adding concentrated ammonium hydroxide with continuous stirring. The emulsion was aged at room temperature for 12 h. The experiment was also performed at aging temperatures of 0 and 80 °C at different aging times. Then, the emulsion was evaporated on the hotplate at ~ 150 °C. The evaporated mass was dried on the hotplate at ~400 °C for several hours to obtain HAp precursor powders. The precursor powders were heat-treated at different temperatures from 450 to 650 °C for 1 h in a Muffle furnace to obtain crystalline HAp powders.

Phase analysis of the calcined powders was performed by powder XRD studies using a Philips fully automated diffractometer with Co Kα radiation and Ni filter. The XRD data were collected at room temperature over the 2θ range of 20−70° at a step size of 0.02° (2θ) and a count time of 0.5 s/step. Samples were investigated for their microstructural and morphological features using JEOL, JEM 120 TEM. Specific surface area measurements were done by using a Tristar Micromeritics five-point BET surface area analyzer. The samples were first outgassed at 350 °C and then allowed to cool at room temperature with a continuing flow of nitrogen gas.

Results and Discussion

Several experimental parameters were found to have an effect on the surface area, crystalline phase purity, particle size, and morphology of the HAp nanopowders. Experiments were conducted varying synthesis parameters such as pH, aqueous/organic phase volume ratio in the reverse micelle, aging temperature, aging time, and metal ion concentation in the aqueous phase. The pH of the reverse microemulsion was found to have a significant influence on the formation of hydroxyapatite. The emulsions using an aqueous/organic phase volume ratio 1:10, obtained after mixing the aqueous and organic phases, had a pH of 2. The resulting powder from this solution, after calcining at 450 °C, showed a BET surface area of 15 m^2/g. X-ray diffraction analysis indicated that HAp phase was not formed in the powders obtained from this emulsion at pH 2, and the starting aqueous/organic phase volume ratio did not play any significant role in the phase formation. Ammonium hydroxide solution was added dropwise to the reverse micelle with continuous stirring to adjust the pH at 7. Once the pH of the microemulsion was adjusted to 7, HAp phase was formed, which is consistent with the finding that HAp is formed in alkaline or neutral pH.[8−11] Figure 1 shows the process flowchart for the synthesis of nanocrystalline HAp powder using the surfactant template system.

To obtain phase pure crystalline HAp powders using pH of the microemulsion at 7, concentrations of Ca^{2+} ions were varied between 5.0 and 1.0 M, keeping the aging time at 12 h and temperature at 25 °C. Using 10 vol % of surfactant (NP-5 + NP-12) in cyclohexane, the aqueous to organic volume ratio was varied between 1:5 and 1:15. After aging the reaction mixture for a different period of time, the emulsion was evaporated on the hotplate first at ~150 °C and then dried on the hotplate at ~400 °C for 2−3 h. Once dried, the powder was calcined between 450 and 650 °C for 1 h. These powders were analyzed for phase purity by XRD. The diffraction patterns of some selected samples are shown in Figure 2. At pH 7, the monophasic crystalline HAp is formed irrespective of other experimental parameter variations such as aging time, aging temperature, Ca^{2+} ion concentration, and aqueous−organic ratio. The XRD patterns of the powder calcined at 450 °C exhibited the broad peaks due to their nanocrystalline nature, and three nearby major peaks merge to one broad peak. After the powders were calcined at 650 °C, the crystallinity of the powders increased, and the three major peaks could also be distinguished.

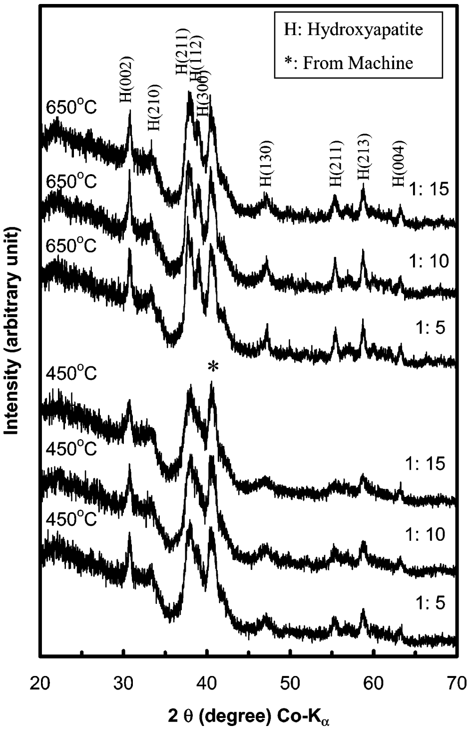


Figure 2. XRD diffraction patterns of calcined HAp powders obtained from emulsion having 1:5, 1:10, and 1:15 aqueous/organic phase volume ratios at 450 and 650 °C.

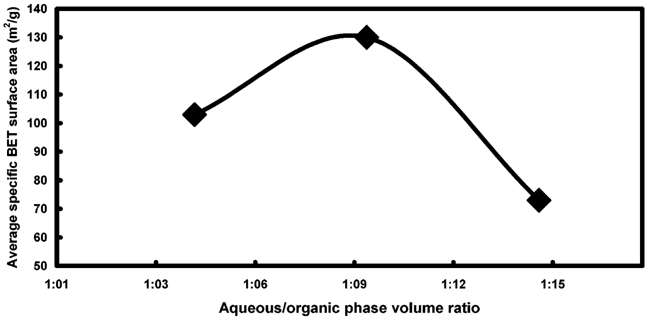
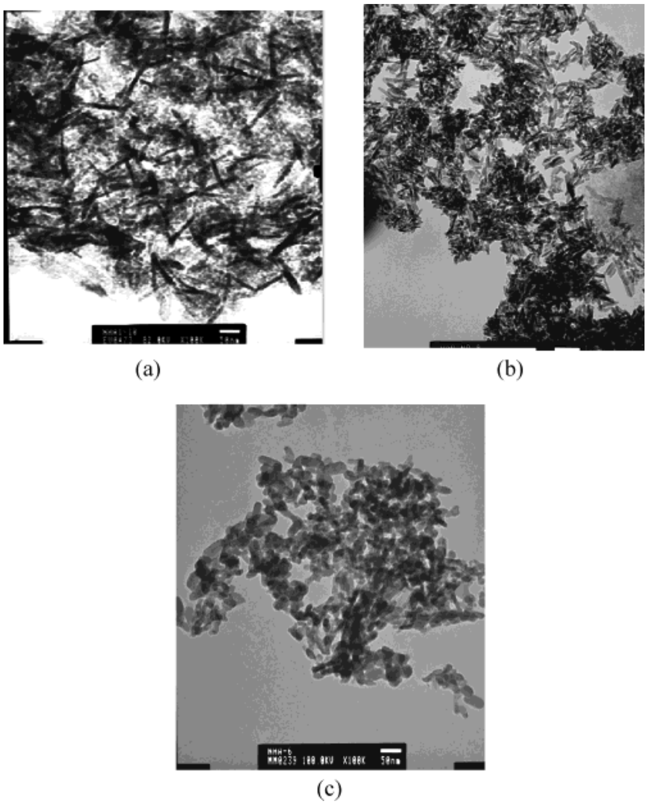


Figure 3. Change in BET surface area of HAp powders as the aqueous organic phase volume ratio changes, synthesized by using NP5 + NP12 as surfactant: [Ca^{2+}] = 5.0 M, aging time = 12 h, and aging temperature = 25 °C.

The composition of the reverse microemulsion governs the shape and size of the reverse miceller domains, as well as the particle morphology and size. This was reflected by the average specific BET surface area and morphology of the powders shown in Figure 3 and Figure 4. The surface area of the calcined powders


(a) (b)

(c)

Figure 4. Change in morphology of HAp powders as the aqueous organic phase volume ratio changes, synthesized by using NP5 + NP12 as surfactant: [Ca^{2+}] = 5.0 M, aging time = 12 h, and aging temperature = 25 °C. (a) The aqueous organic phase volume ratio is 1:5 (BET surface area = 103 m^2/g), (b) 1:10 (BET surface area = 130 m^2/g), and (c) 1:15 (BET surface area = 73 m^2/g).

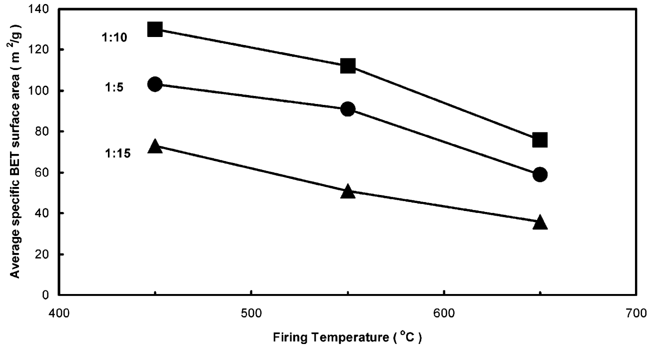


Figure 5. Change in BET surface area of HAp powders as the firing temperature changes, synthesized by using NP5 + NP12 as surfactant: [Ca^{2+}] = 5.0 M, aging time = 12 h, and aging temperature = 25 °C.

obtained at pH 7 exhibited significant improvements in phase purity and BET surface area compared to the powder obtained at other pH. It was as high as 130 m^2/g, when the aqueous/organic phase volume ratio in the emulsion was maintained at 1:10. Variation of BET surface area with different aqueous/organic phase volume ratios is shown in Figure 3. As the aqueous/organic ratio increases, the size of the polar core of the reverse micelle increases, leading to bigger particle size and decrease in surface area. Needle shape particles with high aspect ratio were formed when aqueous/organic phase volume ratio was 1:5 in the reverse emulsion, as shown in Figure 4. The average widths of the particles were in the range of 5−10 nm and the length between 50 and 100 nm for powders calcined at 450 °C. The aspect ratio of the particles decreased with increasing the aqueous/organic phase volume to 1:10. Platelet shape particles were formed in that condition. The particles had an average width below 10 nm and length in the range of 30−50 nm. When the aqueous/organic phase volume ratio was further increased to 1:15, the aspect ratio of the particles decreased even more with a decrease in surface area. It was also observed that the powders obtained from emulsions having an aqueous/organic phase volume ratio of 1:15 were more agglomerated with respect to the powders made with 1:5 and 1:10 aqueous/organic ratios. The high surface area of the latter powders with respect to the former one also supports this observation. Surfactants dissolved in organic solvents form spherical aggregates called reverse micelles. If the medium is completely free of water, the aggregates are very small and polydisperse. The presence of water is necessary to form relatively large surfactant aggregates, which can be used for micro- or nanoreactors for chemical reactions. The shape of the polar core depends on the amount of water, organic solvent, and surfactant and on their ratio, which can make it elongated or spherical. The formation of acicular or spherical particles at different organic/aqueous phase volume ratios can be explained due to the formation of different shapes of the polar cores in the emulsion. The control of the shape of the nanocrystal is a real challenge and more research is needed to confirm the exact mechanism that determines nanocrystal morphology.[1a] Simmons et al. hypothesized that the morphology of cadmium sulfide nanocrystals were directly related to the shape of the reversed micelle systems in which they were synthesized.[24]

Our preliminary densification studies showed that the powder morphology had a more significant effect on densification compared to the effect of surface area. We were able to achieve over 98.5% theoretical densification using the powders having a lower aspect ratio but less than 100 m^2/g BET surface area.

With an increase in calcination temperatures, the surface area decreased for all of the calcined powders, as shown in Figure 5. After calcination at 650 °C, powders obtained from emulsion having the aqueous/organic phase volume ratio 1:10 exhibited an average specific surface area of 75 m^2/g only. The decrease in the surface area at a higher calcination temperature was due to sintering effect within the powder particles. For various aqueous-to-organic ratios, room temperature was found to give HAp nanopowders with higher surface area. With diminishing or enhancing of the aging temperatures, the surface area of the calcined powders decreased as shown in Figure 6. The aging time had some effect on the particle morphology. HAp powders were synthesized from 1.0 M Ca ion solution after aging for 1, 6, and 12 h. There was no significant difference in the BET surface area as a function of aging time between 1 and 12 h as shown in Figure 7. Although the powders obtained after 6 h of aging exhibited slightly lower surface area compared to the other two conditions, after 12 h of aging the powders showed more

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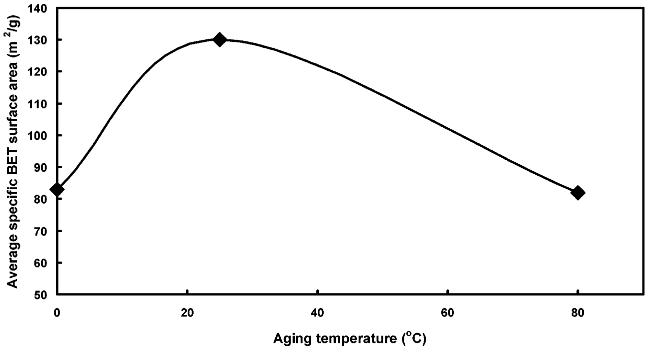

Figure 6. Change in BET surface area of HAp powders as the aging temperature changes, synthesized by using NP5 + NP12 as surfactant: aqueous/organic phase volume ratio = 1: 10, and [Ca^{2+}] = 5.0 M.

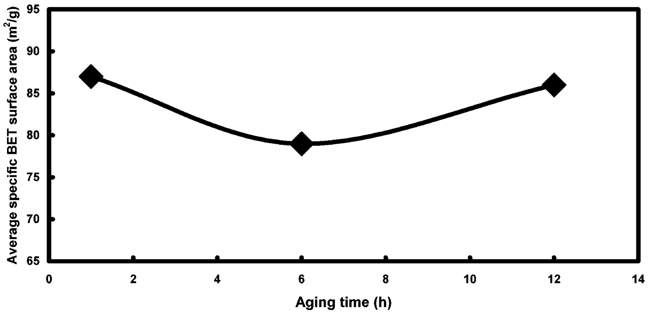

Figure 7. BET surface area of HAp powders as the aging time changes, synthesized by using NP5 + NP12 as surfactant: aqueous/organic phase volume ratio = 1:10, [Ca^{2+}] = 1.0 M, and aging temperature = 25 °C.

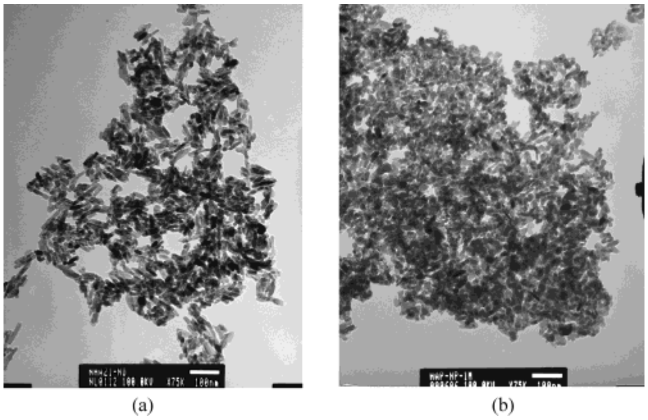
(a) (b)

Figure 8. Morphology of HAp powders as the aging time changes, synthesized by using NP5 + NP12 as surfactant: Aqueous/organic phase volume ratio = 1:10, [Ca^{2+}] = 1.0 M, and aging temperature = 25 °C. (a) Aging time, 1 h (BET surface area = 87 m^2/g) and (b) 12 h (BET surface area = 86 m^2/g).

spherical morphology compared to the powders aged at different conditions. TEM micrographs of powders as shown in Figure 8 show that the powders obtained after 1 h of aging had rectangular platelet morphology. However, powders obtained after 12 h of aging were nearly spherical with lower aspect ratio. With increasing aging time of the emulsion to 72 h, the BET surface area of the powders calcined at 450 °C decreased significantly, which may be due to crystal growth within the emulsion for the extended period of time.

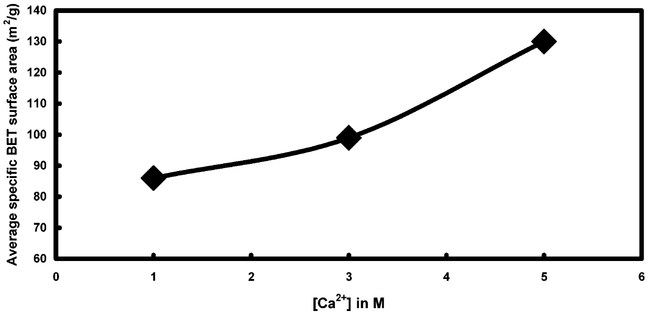

Figure 9. BET surface area of HAp powders as the metal ion concentration changes, synthesized by using NP5 + NP12 as surfactant: aqueous/organic phase volume ratio = 1:10, aging time = 12 h, and aging temperature = 25 °C.

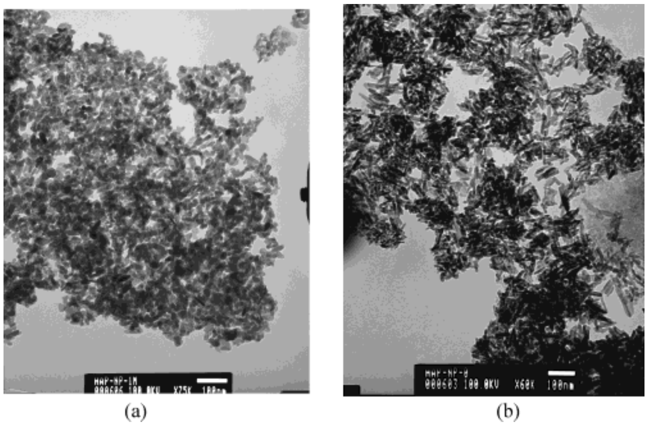
(a) (b)

Figure 10. Morphology of HAp powders as the metal ion concentration changes, synthesized by using NP5 + NP12 as surfactant: Aqueous/organic phase volume ratio = 1:10, aging time = 12 h, and aging temperature = 25 °C. (a) Ca^{2+} ion concentration is 1 M (BET surface area = 86 m^2/g) and (b) 5 M (BET surface area = 130 m^2/g).

Metal nitrate concentration in aqueous phase also affected the surface area of the synthesized nanopowders. HAp powders were prepared by using 1.0, 3.0, and 5.0 M Ca^{2+} ion solution and an aqueous/organic phase volume ratio of 1:10. With increasing metal ion concentration from 1.0 to 5.0 M, the BET surface area of the powders calcined at 450 °C increased from 86 to 130 m^2/g, which is shown in Figure 9. The morphology of the HAp particles was found to depend on the initial concentration of the Ca^{2+} ion in solution. The nearly spherical particles were produced from 1.0 M Ca^{2+} ion solution, which is shown in Figure 10. These particles had a narrow size distribution from 30 to 50 nm. Contrary to that, needle-shaped particles were formed with 5.0 M Ca ion solution. All results of different BET surface areas of HAp nanopowders are summarized in Table 1. Our results showed that the surface area as well as the morphology of HAp nanopowders could be tailored by varying different synthesis parameters, such as aqueous–organic ratio, metal ion concentration, and aging time.

Conclusion

Nanocrystalline HAp powders have been synthesized using a microemulsion technique. Composition of the microemulsion system, pH, aging time and temperature, and metal ion concentration were found to have significant effect on the formation of HAp nanopowder as well as on their surface area and morphology. High surface area HAp crystalline phase can be synthesized at 450

°C using aqueous solutions of Ca and P ions and NP-5 + NP-12 surfactant in cyclohexane organic solutions. The surface area, morphology, and particle size depend on the experimental conditions. The morphology changes from needle shape to nearly spherical when the aqueous/organic phase volume ratio in the emulsion changes from 1:5 to 1:15. It was also observed that the characteristics of the powders change with the variation of pH, aging time, aging temperature, and strength of the aqueous phase of the emulsion. With use of this technique, powders characteristics can be tailored according to the requirements. Powders were prepared with surface area as high as 130 m^2/g and particle size in the range of 30−50 nm with needle shape, platelet, and nearly spherical morphology.

Table 1. Experimental Details of the HAp Synthesis Using (NP5 + NP12) as Surfactant[a]

strength of $[Ca^{2+}]$ ion in aqueous phase	aqueous/organic phase volume ratio	aging temp (°C)	aging time (h)	average BET surface area (m^2/g)
5.0	1:5	25	12	103
5.0	1:10	25	12	130
5.0	1:15	25	12	73
5.0	1:10	0	12	83
5.0	1:10	80	12	82
3.0	1:10	25	12	99
1.0	1:10	25	12	86
1.0	1:10	25	1	87
1.0	1:10	25	6	79

[a] Contents in the aqueous phase: $Ca(NO_3)_2 = 0.01$ mol, $H_3PO_4 = 0.006$ mol. Organic phase = 10 vol % of (1:1) (NP5 + NP12) in cyclohexane. pH of the emulsion was adjusted = 7.

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