

Effects of Sintering Conditions on Hydroxyapatite for Use in Medical Applications: A Powder Diffraction Study

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Commercially available hydroxyapatite (HA) has been subjected to different temperatures and sintering-time schedules, to examine the effects of these two variables on crystal structure. Small but significant decreases in unit-cell volume and hydroxy-ion channel size are seen on sintering for 1 h at temperatures in excess of 1000 °C. This has been ascribed to the loss of small amounts of carbonate from the channels within the structure. The stability of the HA phase was seen up to a sintering temperature of 1400 °C, with decomposition only seen in the 1450 °C sinter. Extended sintering times at 1300 °C failed to cause decomposition; however, small increases in c-axis length and unit-cell volume were observed.

Bone consists of two major phases;¹ an organic, mainly collagenous, phase and an inorganic phase based on calcium phosphates, made up primarily of hydroxyapatite (HA), $\text{Ca}_5(\text{PO}_4)_3\text{OH}$. This combination of organic and inorganic phases represents a unique composite material, with HA as the principal reinforcing component.

Synthetic HA is finding considerable success in clinical applications,² particularly in the orthopaedic field, owing to its bioactivity, which promotes bone growth directly onto its surface. New devices and procedures have been developed which utilise this property, such as coating a femoral prosthesis with HA to give direct biological fixation of the prosthesis into the bone rather than using conventional bone cements. The ceramic may also be used in solid form for space filling after bone tumour removal, to help restore the cosmetic appearance and avoid associated long-term problems.

In order to prepare this ceramic material either as a coating or in solid form, a heat-treatment process must be undertaken. This heat treatment can significantly affect the structure of HA and may influence the long-term properties of the material. An investigation of these effects on presintered commercially available material forms the basis of the present work. This material is identical to that currently used in the production of femoral prostheses coatings.

The crystal structure of apatite $\text{Ca}_5(\text{PO}_4)_3\text{F}_2$ was first determined over 60 years ago^{3,4} and since then various related apatites including hydroxy- and chloro- derivatives have been investigated thoroughly.^{5–7} The structure of HA is hexagonal, space group $P6_3/m$, and is built up from a three-dimensional framework of calcium oxide and phosphate polyhedra. Two calcium sites are present in the structure: Ca(1) is located in an octahedral site, while Ca(2) is seven-coordinate. The Ca(2) atoms are arranged such that they form channels which run parallel to the *c* axis (Fig. 1). The hydroxy ions are located within these channels but show disorder along the *c* axis being shifted away from the 2a site (0,0,0.25) normally occupied in the fluoroapatites, to half occupy the 4e site (0,0,0.19). The phosphate tetrahedra in HA are nearly regular.

Experimental

Sample Processing

Commercially available HA powder (Plasma Biotol, UK, batch P120) was obtained and dried for 24 h at 70 °C. Samples were then vibratory sieved to less than 74 µm to produce a

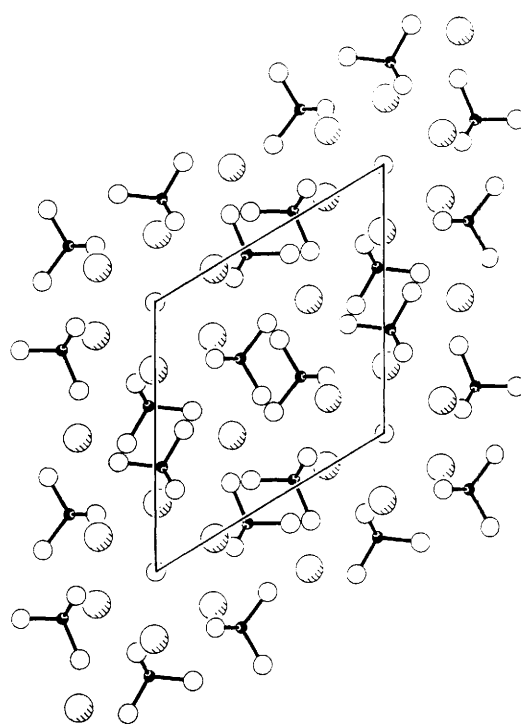


Fig. 1 Projection down *c* axis of hydroxyapatite showing P (black circles) O (open circles) and Ca (shaded circles)

free-running powder for pressing. The powder was pressed into 30 mm diameter pellets (*ca.* 4 g of powder), using a uniaxial pressure of 288 MN m⁻². Pellets were dried in an oven at 70 °C for a minimum of 24 h prior to firing. The dried pellets were heated on an alumina tile at 4 °C min⁻¹ up to the sintering temperature (1000–1450 °C). The pellets were left at the sintering temperature for 1 h before slow cooling to room temperature in the furnace. A second set of samples were produced with extended sintering times at 1300 °C using the same method. Sintering times of 6, 12 and 48 h were used.

X-Ray Diffraction

X-Ray powder diffraction data were collected for each sample (Fig. 2) on a Siemens D5000 diffractometer in flat-plate geometry using graphite monochromated Cu-K α radiation

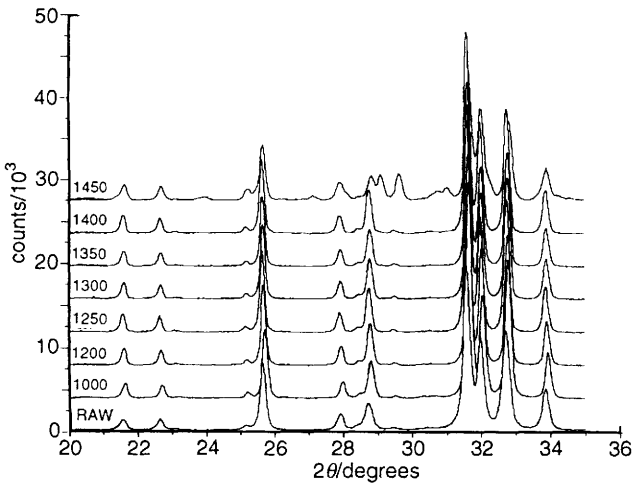


Fig. 2 Variation of hydroxyapatite X-ray diffraction pattern with sintering temperature

($\lambda=1.5418\text{ \AA}$). Data were acquired from 5 to $110^\circ\ 2\theta$, at intervals of 0.02° with a count time of 12 s per step. Calibration was with an external Si standard. The crystal structure of HA was refined for each sample by the Rietveld method, using the program GSAS.⁸ The starting model used in refinement was based on the single-crystal structure determination.⁹ Peak shapes were modelled on a pseudo-Voigt distribution and an asymmetry parameter was refined. Scattering factors for neutral atoms were assumed. In each case, five background parameters, a scale factor, four peak-shape variables, cell parameters and a zero-point correction were refined before variation of the structural parameters. Isotropic thermal parameters were refined for all atoms and a site occupancy parameter refined for the hydroxy oxygen. The hydrogen atom was not located. The final refined parameters for the 1200°C sintered sample are presented in Table 1 with the corresponding fitted profile in Fig. 3. Complete tables of

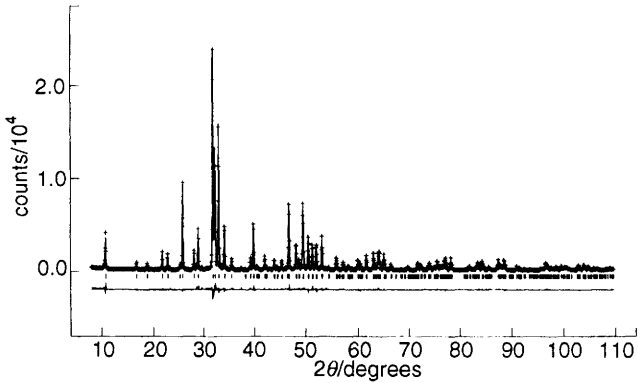


Fig. 3 Fitted X-ray powder profile for 1200°C sintered hydroxyapatite showing observed (plus signs) calculated (line) and difference (lower) plots. Reflection positions are indicated by markers.

refined parameters and bond lengths and angles for all samples are included as supplementary data.[†]

Results and Discussion

Selected data collated from the refined parameters for the samples corresponding to the various sintering temperatures are presented in Table 2. It is clear from these data that little variation is observed in the average bond lengths within the Ca or P polyhedra. The main changes occur in the hydroxy oxygen occupancy and Ca(2)–O(H) bond length. There is a shortening of the Ca(2)–O(H) bond length between 1000 and 1200°C , which is accompanied by a reduction in the site occupancy from $0.554(6)$ to $0.487(5)$. The latter is much closer to the theoretical value of 0.5 (within 3 esds). This change is also reflected in the Ca(2)–Ca(2) distance

[†] Supplementary Data available from the Cambridge Crystallographic Centre, see Information for Authors, *J. Mater. Chem.*, 1994, Issue 1.

Table 1 Final refined parameters for hydroxyapatite sintered at 1200°C for 1 h

$a=9.4155(1)\text{ \AA}$, $c=6.8867(1)\text{ \AA}$, $V=528.72(2)\text{ \AA}^3$						
atom	wyc.	x/a	y/b	z/c	$U_{\text{iso}}/\text{\AA}^2$	occ.
Ca(1)	4f	0.3333(–)	0.6667(–)	0.0020(3)	1.10(5)	1.0(–)
Ca(2)	6h	0.2458(2)	0.9919(2)	0.25(–)	1.09(4)	1.0(–)
O(1)	6h	0.3268(5)	0.4847(5)	0.25(–)	0.6(1)	1.0(–)
O(2)	6h	0.5840(5)	0.4631(5)	0.25(–)	1.4(2)	1.0(–)
O(3)	12i	0.3415(4)	0.2573(4)	0.0699(4)	1.9(1)	1.0(–)
O(H)	4e	0.0(–)	0.0(–)	0.1908(15)	2.2(5)	0.487(5)
P	6h	0.3974(2)	0.3679(3)	0.25(–)	1.19(6)	1.0(–)

$R_{\text{wp}}=10.84\%$; $R_{\text{ex}}=4.10$; $\chi^2=6.99$; for 35 variables, 5098 observations, corresponding to 502 reflections.

Table 2 Variation in structural parameters for hydroxyapatite with sintering temperature

firing temperature/ $^\circ\text{C}$	$O_{\text{occ.}}$	average Ca(1)–O/ \AA	average Ca(2)–O/ \AA	average P–O/ \AA	Ca(2)–OH/ \AA	Ca(2)–Ca(2)/ \AA
pre-sintered powder	0.579(6)	2.42	2.45	1.54	2.398(2)	4.098(3)
1000	0.554(6)	2.42	2.46	1.55	2.407(2)	4.093(3)
1200	0.487(5)	2.43	2.44	1.53	2.389(2)	4.077(3)
1250	0.480(6)	2.43	2.45	1.53	2.388(2)	4.076(3)
1300	0.483(6)	2.43	2.45	1.53	2.386(2)	4.072(3)
1350	0.483(6)	2.43	2.45	1.54	2.387(2)	4.071(3)
1400	0.483(7)	2.43	2.45	1.54	2.391(3)	4.069(3)

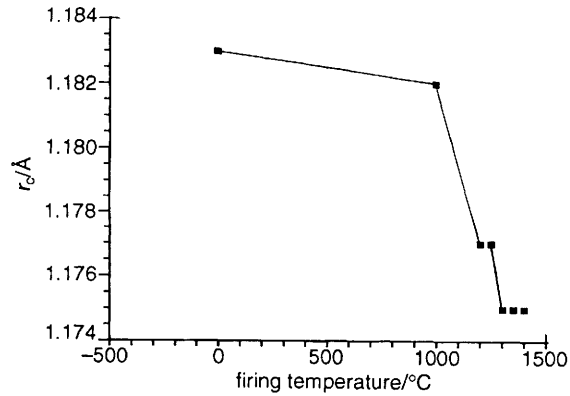


Fig. 4 Variation in hydroxy channel radius r_c with sintering temperature in HA

$\{d[\text{Ca}(2)-\text{Ca}(2)]\}$ across the hydroxy channel. This distance can be used to calculate the hydroxy channel radius r_c as follows:

$$r_c = \frac{d[\text{Ca}(2)-\text{Ca}(2)]}{2} \tan \frac{\pi}{6}$$

The variation in r_c with sintering temperature is shown in Fig. 4. These results clearly show that there are significant changes associated with the hydroxy oxygen after sintering above 1000 °C. The larger channels and higher O(H) site occupancy of the presintered material are consistent with presence of small amounts of carbonate within the channels. Indeed the values for $d[\text{Ca}(2)-\text{Ca}(2)]$ and r_c are identical to those derived from naturally occurring carbonated hydroxyapatite.² The loss of carbonate above 1000 °C therefore leads to contraction of these channels resulting in an overall decrease in the a -axis length and unit-cell volume (Fig. 5). The loss of CO₂ from the lattice is likely to result in the formation of oxide ions¹⁰ which would effectively lower the site occupancy with respect to the theoretical value for HA as fewer sites would need to be occupied in order to preserve electroneutrality. However, as the observed value in the sintered materials is close to the theoretical, it is likely that oxide ions formed in this way react with atmospheric water after cooling to yield the stoichiometric hydroxyapatite.

Very high sintering temperatures can lead to decomposition of HA to $\alpha\text{-Ca}_3(\text{PO}_4)_2$ and or $\beta\text{-Ca}_3(\text{PO}_4)_2$. In the present work samples sintered at 1450 °C for 1 h showed a mixture of all three phases. Samples sintered at 1400 °C, however, remained as pure HA. This temperature is considerably higher than has previously been reported.¹¹

The effects of extended sintering times at 1300 °C were investigated; the results are summarised in Table 3 and Fig. 6. No decomposition to α - or $\beta\text{-Ca}_3\text{PO}_4$ was seen with sintering times up to 48 h. Despite a decrease in the a -axis length with extended sintering between 1 and 6 h, the unit-cell volume increases slightly due to the significant increase in c -axis length. Above 6 h sintering little significant change occurs.

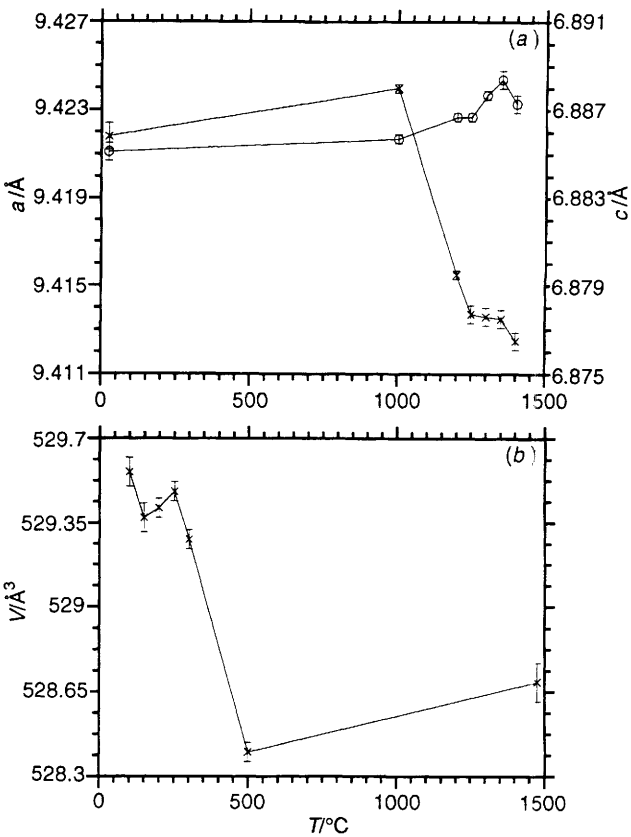
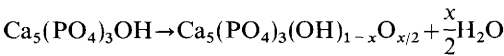


Fig. 5 Variation in (a) HA unit-cell parameters [(\times) a ; (\circ) b] and (b) HA unit-cell volume, with sintering temperature. Error bars correspond to ± 2 esd

The hydroxy channels appear to become larger as indicated by increases in $d[\text{Ca}(2)-\text{Ca}(2)]$ and r_c values, resulting in an increase in the Ca(2)–O(H) bond length. Whereas in the presintered material these factors suggested low levels of carbonation, at such high temperatures significant carbonation is unlikely, indeed the hydroxy oxygen occupancy remains close to the theoretical value. This change may be associated with the formation of small numbers of oxide ions:



This is accompanied by a c -axis expansion and a relaxation of the structure. This relaxation can be observed in the variation of distortion of the PO₄ moiety, a measure of which is the tetrahedral distortion index (Table 4). This parameter reduces significantly after 6 h sintering indicating a much more regular tetrahedral environment for P. A value of *ca.* 3.53 is found in single-crystal studies.² The distortion index for the 12 h sample, however, appears anomalous in this respect.

Clearly variation of sintering conditions has small but significant effects on the structure of HA. Temperatures above

Table 3 Variation in structural parameters for hydroxyapatite with sintering time

firing time/h	O _{occ.}	average Ca(1)–O/Å	average Ca(2)–O/Å	average P–O/Å	Ca(2)–OH/Å	Ca(2)–Ca(2)/Å
presintered powder	0.579(6)	2.42	2.45	1.54	2.398(2)	4.098(3)
1	0.483(6)	2.43	2.45	1.53	2.386(2)	4.072(3)
6	0.481(5)	2.42	2.45	1.54	2.401(2)	4.100(3)
12	0.471(6)	2.43	2.45	1.53	2.396(2)	4.091(2)
48	0.474(6)	2.42	2.45	1.54	2.413(3)	4.110(3)

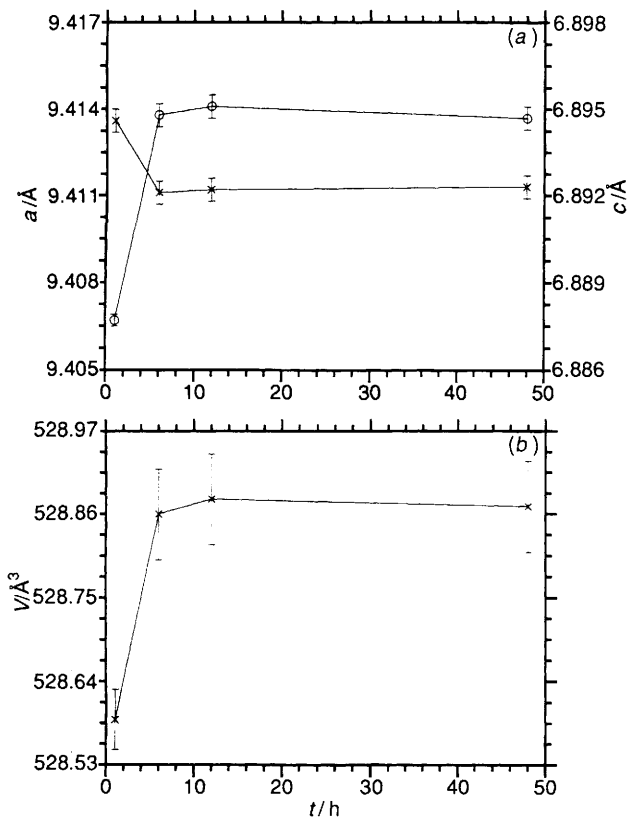


Fig. 6 Variation in (a) HA unit-cell parameters [(\times) a ; (\circ) b] and (b) HA unit-cell volume, with sintering time at 1300 °C. Error bars correspond to ± 2 esd

1000 °C but below 1450 °C are required in order to drive off carbonate, but extended sintering at these temperatures could result in the formation of oxide ions *via* water loss. These small variations may help in understanding long-term proper-

Table 4 Effect of time on distortion index^a

firing time/h	D_{ind}
0	6.270
1	2.642
6	1.061
12	5.625
48	1.347

$$^a D_{\text{ind}} = \frac{\sum_{i=1}^6 (\theta_i - 109.17)^2}{6} \quad (\theta = \text{angle O-P-O}).$$

ties and allow for optimisation of sintering conditions for HA used in bone grafting and other medical applications.

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