Hydroxyapatite based ceramic materials

Anna Maria Janus

1. HYDROXYAPATITE

Hydroxyapatite is the major mineral component of human bones. From the point of view of its chemistry, it is calcium orthophosphate which has in its structure hydroxyl groups and in its stoichiometric is described with formula – $Ca_{10}(PO_4)_6(OH)_2$. Biological properties of hydroxyapatite are very favorable; it is not only biocompatible (which means that after implantation it causes no side effects) but also bioactive (this means that implants made with this material bond with the surrounding bone tissue through formation of a chemical bond) [Hench 1993]. These properties made hydroxyapatite an excellent material for production of ceramic materials intended for use as implants in dentistry and treatment of orthopedic injuries.

Hydroxyapatite which is used to treat bone defects can originate from a wide variety of sources. The gold standard is obtained during preparation of the so called autografts, which are small parts of patient's own bone tissue harvested from a donor site and then transplanted to the damaged region. Unfortunately, autologous bone can be harvested in limited amount only and may be accompanied by a damage to the donor site. A solution to this problems based on preparation of allografts (i.e. extraction of bone tissue from cadavers of another patient) has also a number of drawbacks, as the use of allografts may be accompanied by disease transmission and requires application of immunosuppressant drugs. Moreover, additional ethical and religious concerns appear [Baino, 2011]. As hydroxyapatite derived via various synthesis routes or prepared through transformation of animal bones is readily available, such materials are almost exclusively used in the therapy of damaged bone tissues.

A number of synthesis routes to produce hydroxyapatite has been developed in recent years and they can be classified into precipitation [Jarcho, 1976], hydrolysis [Yoshimura, 1994], solid state [Yeong, 2001] and combined [Luo, 1995] methods. Synthetic hydroxyapatite most often is a nano-powder of specific surface area of a few dozen m^2/g and high thermal stability. It can be synthesized either in stoichiometric or non-stoichiometric Mg, Si, F, CO_3^{2-} doped form.

Methods utilizing thermal treatment of bones [Murugan, 2003], supercritical fluids [Barakat, 2008] and leaching of organic matter with lye [Haberko, 2003] are used to extract hydroxyapatite from bones (i.a. bovine and porcine). Fig. 1 shows cortical parts of porcine bones obtained after leaching out of organic matter with sodium hydroxide solution, this material will be ground to obtain hydroxyapatite powder at a later preparation stage.

Fig. 1. Cortical part of porcine bones after leaching of organic matter with sodium hydroxide solution.

Biological hydroxyapatites always contain in their structure carbonate groups and various other cationic and ionic substitutions in the crystallographic network and hence exhibit deviations from the stoichiometry. Numerous research indicates that biocompatibility of biological hydroxyapatites and synthetic non-stoichiometric hydroxyapatites is better than that of stoichiometric hydroxyapatite [Janus, 2008; Landi, 2008; Komlev, 2009].

An interesting combination of synthetic and biological routes is visible in preparation of hydroxyapatite from corals – in this method calcium carbonate skeleton produced by a living organism is transformed to hydroxyapatite with the use of ammonia hydrogen phosphate [Roy, 1975].

2. HYDROXYAPATITE CERAMICS

Hydroxyapatite powders on their own find use in medicine as bone cements. Nevertheless, most often they are processed to ceramic materials. Depending on the type of application dense, microporous or macroporous ceramics are produced. Dense ceramics have total porosity of less than 5 vol. % while porosity of microporous and macroporous ceramics exceeds 5 vol. %. The difference between microporous and macroporous materials rests with the pore size, which in microporous materials is in the range of tenth of to several micrometers and in macroporous ceramics is several tens to several hundreds of micrometers. Hydroxyapatite powders are also used to produce coatings on metallic implants.

2.1. Dense and microporous ceramics

Dense and microporous ceramics are most often prepared by sintering of green tablets at desired temperature and in desired atmosphere. Green tablets are obtained by means of pressing. Most commonly two step process, in which initial axial pressing with pressure of approximately 15 MPa in forms is followed by isostatic pressing with pressure of at least 200 MPa, is used. Sintering temperature can range from 600 to approximately 1450°C and the sintering atmospheres include air, mixtures of air and water vapor and carbon dioxide. The minimum temperature allowing for preparation of dense ceramics is approximately 1200°C. Sintering at lower temperatures almost always yields microporous materials. Fig. 2 shows ceramics prepared from porcine origin hydroxyapatite and sintered at 1200°C. In Fig. 3 micrograph showing morphology of ceramics presented in Fig. 2 is given.

Dense and macroporous hydroxyapatite ceramics should not only be biocompatible but also they should exhibit sufficient mechanical strength, hardness, good crack resistance and stability under *iv vivo* conditions.

Fig. 2. Dense ceramics prepared from porcine origin hydroxyapatite and sintered at 1200°C [Janus, 2010].
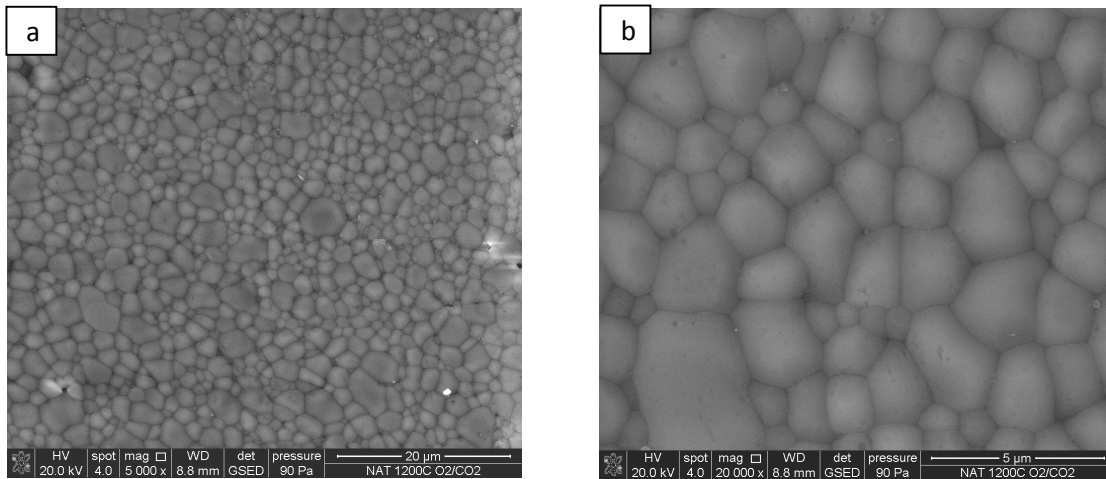
Fig. 3. Micrographs of morphology of ceramics shown in Fig. 2 at various magnifications
a) 5 000x and b) 20 000x [Janus, 2010].

Dense and microporous hydroxyapatite ceramics find application in repair of bony defects in dental and orthopedic applications, immediate tooth root replacement, maxillo-facial reconstruction, augmentation of alveolar ridge, middle ear reconstruction, percutaneous devices, adjuvant to the placement of metal implants and as bioreactors [Hench, 1993].

2.2. Macroporous ceramics

A number of methods has been developed to produce macroporous hydroxyapatite ceramics. These include application of solid porogens, gel casting of foams and replication methods [Janus, 2007]. The best results are usually obtained by application of the so call polymer sponge method. In this method polymer foam of desired structure and shape is impregnated with aqueous slurry of hydroxyapatite. Excess of the slurry is removed be means of pressing and dried foam with hydroxyapatite deposited within its structure is burned out at elevated temperature. While the foam degrades to yield volatile compounds the powder is sintered and macroporous material is obtained. Fig. 4 shows a photograph of macroporous ceramics obtained by use of polymer sponge method from porcine origin hydroxyapatite and phosphate glass [Janus, 2010].

Macroporous hydroxyapatite ceramics should primarily exhibit a structure of large number of interconnected macropores. The average macropore size should be close to several hundred micrometers while the minimum size of macropore interconnections should be close to 50 micrometers. In Fig. 5 desired internal structure of macroporous hydroxyapatite based ceramics is shown [Janus, 2010]. Such ceramics have also to be of sufficient mechanical strength.

The most important applications of macroporous hydroxyapatite ceramics are repair of bone defects in orthopedics and scaffolds for tissue engineering.

Fig. 4. macroporous ceramics obtained by use of polymer sponge method from porcine origin hydroxyapatite and phosphate glass [Janus, 2010].
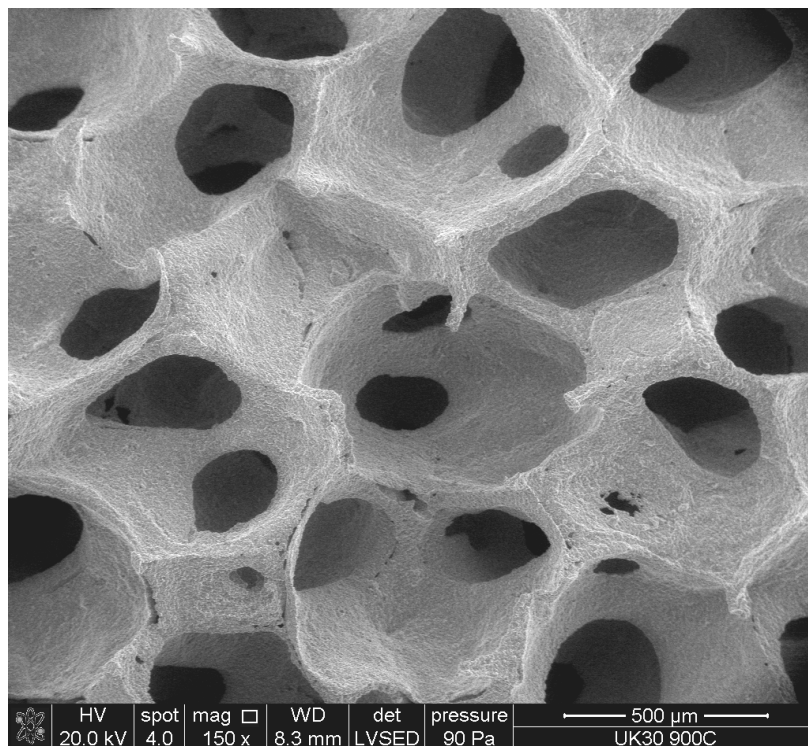

Fig. 5. Micrograph of macroporous hydroxyapatite based ceramics prepared by means of polymer sponge method [Janus, 2010].

2.3. Coatings on metallic implants

Bioactivity and osteoconductivity of hydroxyapatite is often use to improve *in vivo* performance of metallic implants. Hydroxyapatite coating can be applied onto a metal surface by use of such methods as dip coating, electrophoretic deposition, hot isostatic pressing, ion-beam sputtering, ion beam dynamic mixing, plasma spraying, conventional flame spraying and high-velocity oxy-fuel (HVOF) combustion spraying [Tsui, 1998]. The technique most commonly used for preparation of hydroxyapatite coatings on metallic

implants is plasma spraying. In this technique hydroxyapatite powder is introduced into the plasma jet, emanating from plasma gun. The material is melted and propelled to the substrate. Once the molten material reaches the substrate it solidifies rapidly and forms a deposit (a coating).

Characteristics of most importance for hydroxyapatite coatings are good adhesion to the substrate, long-term durability of the adhesion between the coating and the substrate, strong cohesive strength, high degree of crystallinity, chemical purity and phase stability.

Hydroxyapatite coatings are commonly used in titanium implants for hip replacement surgery (Fig. 6).
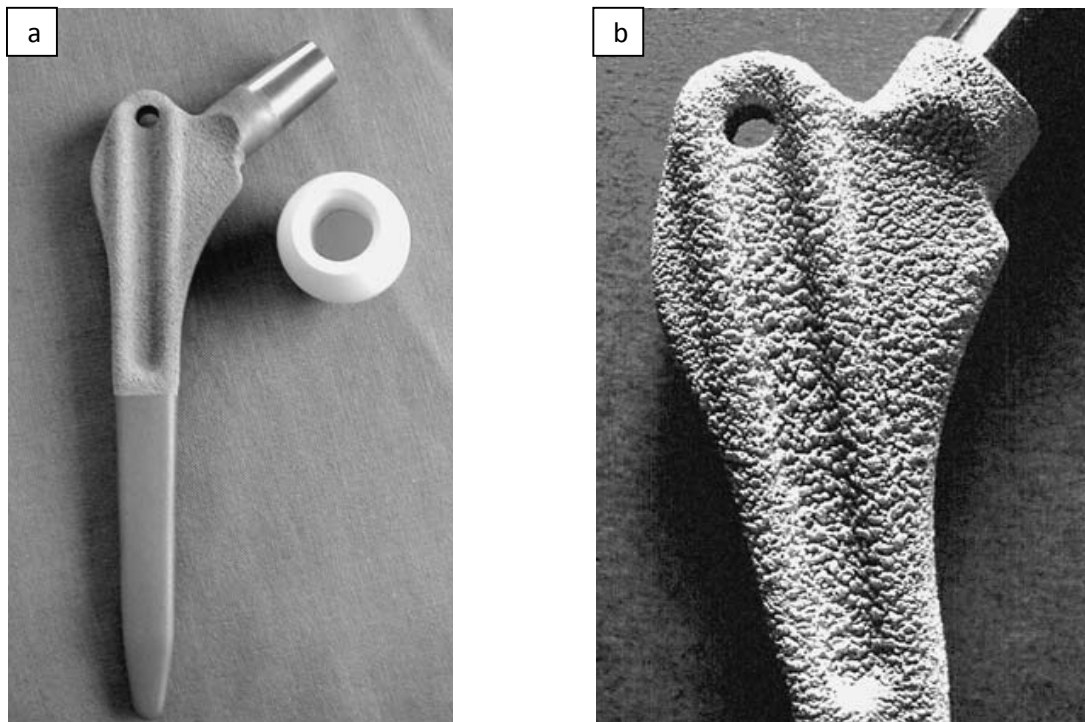

Fig. 6. a) femoral stem with titanium alloy/hydroxyapatite coating, b) Magnified view of the hydroxyapatite coating [Landor, 2007].

3. REFERENCES

[Baino, 2011] Baino F., Vitale-Brovarone C., Three-dimensional glass-derived scaffolds for bone tissue engineering: Current trends and forecasts for the future, Journal Of Biomedical Materials Research A, 97A (2011) 514-535.

[Barakat, 2008] Barakat N.A.M., Khalil K.A., Sheikh F.A., Omran A.M., Gaihre B., Khil S.M., Kim H.Y., Physiochemical characterizations of hydroxyapatite extracted from bovine bones by three different methods: Extraction of biologically desirable HAp, Materials Science and Engineering C, 28 (2008) 1381-1387.

[Haberko, 2003] Haberko K., Bućko M., Haberko M., Mozgawa W., Pyda A., Zarębski J., Natural hydroxyapatite – preparation and properties, Engineering of Biomaterials, 6 (2003) 32-37.

[Hench, 1993] Hench L.L., Wilson J., An Introduction to Bioceramics, World Scientific, Singapore, New Jersey, London, Hong Kong (1993) 139-199.

[Janus, 2007] Janus A.M., Faryna M., Verné E., Vitale Brovarone C., Preparation of phosphate glass reinforced hydroxyapatite scaffolds for tissue engineering, Inżynieria Materiałowa, XXVIII (2007) 265-269.

[Janus, 2008] Janus A.M., Faryna M., Haberko K., Rakowska A., Panz T., Chemical and microstructural characterization of natural hydroxyapatite derived from pig bones, Microchimica Acta, 161 (2008) 349-353.

[Janus, 2010] Janus A.M. PhD Thesis, Morphology of natural hydroxyapatite designated for biological applications, Institute of Metallurgy and Materials Science of Polish Academy of Sciences, Krakow, 2010.

[Jarcho, 1976] Jarcho M., Bolen C.H., Thoomas M.B., Bobick J., Kay J.F., Doremus R.H., Hydroxylapatite synthesis and characterization in dense polycrystalline form, Journal of Materials Science, 11 (1976) 2027-2035.

[Komlev, 2009] Komlev V.S. Fadeeva I.V., Gurin A.N., Kovaleva E.S., Smirnov V.V., Gurin N.A., Barinov S.M., Effect of the Concentration of Carbonate Groups in a Carbonate Hydroxyapatite Ceramic on Its In Vivo Behavior, Inorganic Materials, 45 (2009) 329–334.

[Landi, 2008] Landi E., Logroscino G., Proietti L., Tampieri A., Sandri M., Sprio S., Biomimetic Mg-substituted hydroxyapatite: from synthesis to in vivo behaviour, Journal of Materials Science: Materials in Medicine, 19 (2008) 239-247.

[Landor, 2007] Landor I., Vavrik P., Sosna A., Jahoda D., Hahn H., Daniel M., Hydroxyapatite porous coating and the osteointegration of the total hip replacement, Arch Orthop Trauma Surg, 127 (2007) 81-89.

[Luo, 1995] Luo P., Nieh T.G., Synthesis of ultrafine hydroxyapatite particles by a spray dry method, Materials Science and Engineering C, 3 (1995) 75-78.

[Murugan, 2003] Murugan R., Rao K.P., Kumar T.S.S., Heat-deproteinated xenogeneic bone from slaughterhouse waste: physico-chemical properties, Bulletin of Materials Science, 26 (2003) 523–528.

[Roy, 1975] Roy D.M., Porous biomaterials and method of making same; US Patent No. 3,929,971, December 30, 1975.

[Tsui, 1998] Tsui Y.C., Doyle C., Clyne T.W., Plasma sprayed hydroxyapatite coatings on titanium substrates Part 1: Mechanical properties and residual stress levels, Biomaterials, 19 (1998) 2015-2029.

[Yeong, 2001] Yeong K.C.B., Wang J., Ng S.C., Mechanochemical synthesis of nanocrystalline hydroxyapatite from CaO and CaHPO$_4$, Biomaterials, 22 (2001) 2705-2712.

[Yoshimura, 1994] Yoshimura M., Suda H., Okamoto K., Ioku K., Hydrothermal synthesis of biocompatible whiskers, Journal of Materials Science, 29 (1994) 3399-3402.