



Advanced biomaterials in hip joint arthroplasty. A review on polymer and ceramics composites as alternative bearings



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ARTICLE INFO

Article history:

Received 11 May 2015

Received in revised form

22 June 2015

Accepted 27 July 2015

Available online 19 August 2015

Keywords:

A. Carbon–carbon composites (CCCs)

A. Ceramic–matrix composites (CMCs)

A. Polymer–matrix composites (PMCs)

B. Chemical properties

B. Microstructures

ABSTRACT

Wear of total hip prosthesis is a significant clinical problem that nowadays involves a growing number of patients. To acquire further knowledge on the tribological phenomena that involve hip prosthesis, wear tests are conducted on new biomaterials to increase materials life in orthopaedic implants. Advances in biomaterials for biomedical purposes have enhanced in the last years evolving in new improved ceramic and polymeric materials producing the *so-called* composite materials.

This paper aims to review the evolution and the current state of the art of the ceramics composites and polymers commonly used in orthopaedic field as hip joint implants. This is specified through a schematic overview by describing, in particular, the evolution of various composites materials. The authors propose commentary on the evolution and current use of biomaterials for orthopaedic application on the evolution and actually used biomaterials for orthopaedic applications.

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1. Brief history of total hip arthroplasty

Total Hip Replacement (THR) is one of the most common operations performed in the world today. An increasingly ageing population means that the number of people undergoing this operation is set to rise. The hip is a ball and socket joint formed by the head of the thigh bone (the femur) and a section of the pelvis called the “acetabulum” [1]. The stability of this structure is obtained by the bony configuration combined with a complex system of muscles and ligaments around the joint [2].

The hip can wear out at different points during a person's life. Osteoarthritis is one of the most widespread causes for joint degradation, in middle-aged people hypertrophic changes in the bone and cartilage of joints can be as prejudicial to require surgery [3]. A total hip replacement aims to provide the patient with a joint that functions as normally as possible, is resistant to dislocation, preserves as much bone as possible and which will last as long as possible [1]. Advances in surgical techniques and manufacturing technologies allow increasing success in these procedures.

2. Biomaterials used in the orthopaedic field and their improvement

A biomaterial is a material that interacts with human tissue and body fluids to treat, improve, or replace anatomical elements of the human body. Biomaterials that are used in medical devices for orthopaedics application are commonly called implants; the main characteristics of these biomaterials are summarized in Table 1. These are manufactured for a great number of orthopaedic applications. Clinical results in orthopaedics have demonstrated that a great need exists to find new and better biomaterials that would help to satisfy the minimum requirements for orthopaedic devices to perform correctly on a long-term basis [4].

3. Composites materials for hip applications

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. In contrast to metallic alloys, each component of the composite material retains its separate chemical, physical, and mechanical properties. In the usual bi-components composites, one material is present in a continuous or discontinuous form (such as filament or particles) and is called reinforcement, the other material is always present in a continuous phase and is called matrix. The latter gives the shape to the final

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Table 1
Properties of all composites biomaterials considered in this study.

Material	Density (g/cm ³)	Tensile modulus (GPa)	Poisson's ratio	Tensile strength (MPa)	Tensile elongation (%)
AISI 316L	8	193	0.3	580	50
CoCrMo	8.4	230	0.3	960	20
Ti6Al4V	4.4	115	0.33	900	10
UHMWPE	0.94	1.2	0.3	35	200–300
Alumina	3.9	350	0.22	300	<0.1
Y-TZP	6.05	205	0.3	–	–
Zirconia	6.6	200	0.23	711	16
KETRON PEEK	1.42	6.5	0.41	91	1.5
ZTA	4.40	289	0.22	414	–
Hydroxyapatite	3.05	7	0.27	48	–
PTFE	2.16	0.55	0.46	27	300
XLPE	0.47–1.26	0.005–0.69	0.4	20	340–520

element and transfers part of the mechanical loads to the reinforcement. The main advantages of composite materials are their high specific strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished part [5]. Moreover composite materials allow a flexible design so that their properties can be tailored to specific applications [6]. Table 1 shows the mechanical and chemical properties of all composites biomaterials considered in this study.

3.1. Bioceramics composites

Ceramics are non-metallic inorganic materials with a broad range of composition. Kingery [7] gave a definition of ceramics as: “the art and science of making and using solid articles which have as their essential component, and are composed in large part of, inorganic non-metallic materials”. They are usually processed by mixing particles of the material together with water and an organic binder [8]. The mixture is then moulded to obtain the desired shape, dried to evaporate the water and the binder burned out by thermal treatment. The final microstructure of the ceramic is greatly dependent on the thermal process applied, the maximal temperature reached and the duration of the thermal steps. Ceramics used in orthopaedic surgery, the so-called Bioceramics, are classified as bioactive or inert according to the tissue response when implanted in an osseous environment [9]. The bioactivity of a material can be defined as its ability to bond biologically to bone. In other words, a bioactive material have an effect on or causing a reaction in living tissue so that the inert ceramic don't stimulates a such reaction. Bioceramics must be biocompatible and functional for the required implantation time [10]. In clinical practice, inert fully-dense ceramics are used as bearings in total joint replacements because of their exceptional resistance to wear and their tribological properties [11]. In recent years ceramic materials have been recognized as being increasingly important for their chemical and physical characteristics, and have progressively attracted interest in the field of biomedicine [12,13].

Ceramic materials for total hip replacement were introduced more than 20 yrs ago; they were introduced in orthopaedics for hip implants to solve the critical problems of polyethylene wear [14,15]. The most used ceramic in the orthopaedic field are alumina and zirconia. Fig. 1 shows a picture of such ceramics used for hip implants. Alumina ceramics have been widely used for their thermo mechanical and tribologic properties: they show a very high hardness, wear resistance and chemical stability [16,17].

Zirconia ceramics have been introduced into orthopaedics as an alternative to alumina [18]. The name of the zirconium comes from the Arabic Zargon (golden in colour) which in turn comes from the two Persian words Zar (Gold) and Gun (Colour) [9]. Zirconia ceramic was introduced in the manufacture of femoral heads for

total hip replacements because of its high specific strength and toughness, which would reduce the risk of fracture. Zirconia is a well-known polymorph that occurs in three forms: monoclinic (M), cubic (C) and tetragonal (T) [19]. Pure zirconia is monoclinic at room temperature. This phase is stable up to 1170 °C. Above this temperature it transforms into tetragonal and then into cubic phase at 2370 °C. During cooling, a T–M transformation takes place in a temperature range of about 100 °C below 1070 °C. A detailed phase diagram of the material transformation is shown in Fig. 2. The phase transformation-taking place while cooling is associated with a volume expansion of approximately 3–4% [9] and a significant decrease of the mechanical properties due to the production of cracks [11,20]. Stresses generated by the expansion originate cracks in pure zirconia ceramics that, after sintering in the range 1500–1700 °C, break into pieces at room temperature. The idea to combine the tribological properties of alumina and the mechanical characteristics of yttrium-stabilized zirconia allows to obtain a new class of ceramic material with improved tribological and mechanical characteristics of cubic zirconia as the major phase, with monoclinic and tetragonal zirconia precipitates as the minor phase [9]. The process of phase transformation is in any case a crucial point during manufacturing. In 2001, in fact, the Food and Drug Administration (FDA) and the Australian Therapeutic Goods Administration (TGA) recalled a series of Ytria Tetragonal Zirconia Polycrystal (Y–TZP) hip prostheses due to a rupture risk [21]. The producer ascribed the issue to an accelerated T–M transformation, which generated severe micro-cracking.

The introduction of zirconia up to 25% wt into an alumina matrix results in a class of ceramic materials with increased toughness, known as Zirconia Toughened Alumina (ZTA) [22]. Alumina–Matrix Composites (AMC) had been developed to obtain a ceramic in which the biocompatibility and stability of alumina would be joined to enhanced toughness and mechanical properties [23,24]. In the 2000s the first ZTA material introduced in clinic was a composite known under the trade name of BIOLOX[®] delta [25]. BIOLOX[®] delta (a picture is showed in Fig. 3) is obtained by chemical–physical reactions in which at the first time is increased the hardness and the stiffness of the alumina matrix. The second reaction leads to increased hardness, strength, fracture toughness, and reliability of the ceramic, due to the formation of platelets. Finally, the third reaction leads to high fracture toughness, strength and reliability, by the formation of submicron-size Y–TZP grains finely and evenly dispersed within the alumina matrix [26]. It was shown by Deville et al. [27] that Alumina Y–TZP composites can exhibit significant ageing. Even if in his tests the ageing process was much slower than usually observed for Y–TZP ceramics, and this is attributable to the presence of the alumina as matrix component. Significant transformation level can be observed at the beginning of these ageing experiments [27]. The presence of Zirconia aggregates

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