

The importance of metallic materials as biomaterials

Abstract

Metallic materials can be considered the most important engineering materials; they are used as biomaterials due to their excellent thermal conductivity and mechanical properties. The main property required of a metal as biomaterial is that it does not illicit an adverse reaction when placed into services, that means to be a biocompatible material. The present mini review is aimed to show principles of technological importance of metals used as biomaterials. In general, metallic biomaterials are used for load bearing applications and must have sufficient fatigue strength to endure the rigors of daily activity. Currently, the metallic materials used for biomedical applications are 316L stainless steel, cobalt chromium alloys (CoCrMo), titanium-based alloys (Ti-6Al-4V) and miscellaneous others (including tantalum, gold, dental amalgams and other "specialty" metals). Metals are technologically interesting because their properties can be altered in function of the manufacturing processes used, in a more ample and versatile way compared to the polymeric materials and the ceramics.

Keywords: metallic materials, biomaterials, mechanical properties, biocompatible material, manufacturing processes

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Givanildo Alves dos Santos

Federal Institute of São Paulo, Brazil

Correspondence: Givanildo Alves dos Santos, Federal Institute of São Paulo, IFSP, São Paulo, SP, Brazil,
Email givanildo@ifsp.edu.br

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Mini review

Metals can be considered the most important engineering materials.¹ Metallic materials are pure metals (titanium, for example) and alloys, which are composed of two or more elements, with at least one being a metallic element. They have large numbers of nonlocalized electrons; that is, these electrons are not bound to particular atoms. Many properties of metals are directly attributable to these electrons. Metals are extremely good conductors of electricity and heat and are not transparent to visible light; a polished metal surface has a lustrous appearance. Furthermore, metals are quite strong, yet deformable, which accounts for their extensive use in structural applications.² These materials are technologically interesting because they can be ductile (aluminum) or brittle (cast iron) and their properties can be altered depending on the chemical composition and / or manufacturing processes used.

Metals and alloys can be divided into two basic groups: ferrous and nonferrous. Ferrous metals are based on iron; the group includes steel and cast iron. Nonferrous metals include the other metallic elements and their alloys. In almost all cases, the alloys are more important commercially than the pure metals.³ The nonferrous metals include the pure metals and alloys of aluminum, copper, nickel, silver, titanium, zinc, cobalt and other metals. The present mini review is aimed to show principles of technological importance of metals used as biomaterials.

Metals are used as biomaterials due to their excellent thermal conductivity and mechanical properties. Biomaterials are artificial or natural materials, used to in the making of structures or implants, to replace the lost or diseased biological structure to restore form and function. Thus biomaterial helps in improving the quality of life and longevity of human beings and the field of biomaterials has shown rapid growth to keep with the demands of an aging population. Biomaterials are used in different parts of the human body as artificial valves in the heart, stents in blood vessels, replacement implants in shoulders, knees, hips, elbows, ears and orthodontal structures.⁴⁻⁶

In general, metallic biomaterials are used for load bearing applications and must have sufficient fatigue strength to endure the rigors of daily activity. At the time, the metallic materials used for biomedical applications are 316L stainless steel, cobalt chromium alloys (CoCrMo), titanium-based alloys (Ti-6Al-4V) and miscellaneous others (including tantalum, gold, dental amalgams and other "specialty" metals). Titanium is becoming one of the most promising engineering materials and the interest in the application of titanium alloys to mechanical and tribological components is growing rapidly in the biomedical field,⁷ due to their excellent properties. Table 1 lists the various metallic materials that are used in total hip joint replacement.^{8,9}

The main property required of a metal as biomaterial is that it does not illicit an adverse reaction when placed into services, that means to be a biocompatible material. As well, good mechanical properties, osseointegration, high corrosion resistance and excellent wear resistance are required. That is, the material used as implants are expected to be highly non toxic and should not cause any inflammatory or allergic reactions in the human body.⁷

The mechanical properties that help to decide the type of metallic material are hardness, tensile strength, Young's modulus and elongation. An implant fracture due to a mechanical failure is related to a biomechanical incompatibility. For this reason, it is expected that the material employed to replace the bone has similar mechanical properties to that of bone. The bone Young's modulus varies in a range of 4 to 30 GPa depending on the type of the bone and the direction of measurement.^{10,11} Osseointegration is the capacity for joining with bone and other tissue; it is another important aspect of the use of metallic alloys in bone applications. Porous coatings are useful for a good integration of implant with the bone.

Metals are susceptible to degradation by corrosion, a process that can release by-products that may cause adverse biological responses. The corrosion resistance of a surgically implanted alloy is an essential characteristic since the metal alloys are in contact with a very

aggressive media such as the body fluid due to the presence of chloride ions and proteins. In the corrosion process, the metallic components of the alloy are oxidized to their ionic forms and dissolved oxygen is reduced to hydroxide ions. The corrosion characteristics of an alloy are greatly influenced by the passive film formed on the surface of the alloy and the presence of the alloying elements.

Wear always occurs in the articulation of artificial joints as a result of the mixed lubrication regime. The movement of an artificial hip joint produces billions of microscopic particles that are rubbed off cutting motions. These particles are trapped inside the tissues of the joint capsule and may lead to unwanted foreign body reactions. Histocytes and giant cells phagocytose and “digest” the released particles and form granulomas or granuloma-like tissues. At the boundary layer between the implant and bone, these interfere with the transformation process of the bone leading to osteolysis. Hence, the materials used to make the femoral head and cup play a significant role in the device performance. Since the advent of endoprosthetics, attempts have been made to reduce wear by using a variety of different combinations of materials and surface treatments.⁷

Steels are still the main metallic materials in engineering applications. Stainless steel 316L is an example of the application of these alloys as biomaterial. It can be used in the manufacture of elements such as femoral stems and heads, combining good mechanical strength and corrosion resistance. However, the main advantage of steels in relation to other metallic materials is the cost-benefit ratio. In general, steels are versatile in terms of properties. There is a linear relationship between manufacturing process, structure and properties. For example, forging is a bulk deformation process in metal working commonly employed in the manufacture of stainless steel prostheses. Depending on the compressive loads applied to the material, structures (grain sizes) are formed which increase its mechanical strength.

However, when it is intended to improve properties for application as biomaterial, other metallic materials stand out, among them titanium alloys and cobalt alloys. These nonferrous metal materials, despite having higher processing costs than steels, provide these materials with gains in mechanical strength and corrosion resistance, providing a longer useful life of the prostheses made with such materials.

Cobalt-based alloys is one of the only alloys with its good corrosion resistance and good mechanical strength in chloride environments, which is due to alloying additions and the formation of the chromium oxide Cr_2O_3 passive layer. They are now frequently used for the metal-on-metal hip resurfacing joints due to their better corrosion resistance and wear performance.¹²

Titanium alloys are fast emerging as the first choice for majority of applications due to the combination of their outstanding characteristics such as high strength, low density, high immunity to corrosion, complete inertness to body environment, enhanced compatibility, low Young's modulus and high capacity to join with bone or other tissues. Their lower Young's modulus, superior biocompatibility and better corrosion resistance in comparison with conventional stainless steels and cobalt-based alloys, make them an ideal choice for bio-applications.¹³ Because of the mentioned desirable properties, titanium and titanium alloys are widely used as hard tissue replacements in artificial bones, joints and dental implants. Concerning the medical applications of these materials, the use of commercially pure Titanium is more limited to the dental implants because of its limited mechanical properties. In cases where good mechanical characteristics are required as in hip implants, knee implants, bone screws, and plates, Ti-6Al-

4V alloy is being used.^{14,15} One of the most common applications of titanium alloys is artificial hip joints that consist of an articulating bearing (femoral head and cup) as shown in Table 1.

Table 1 Metallic materials used in total hip joint replacement

Material	Applications
Metals	Titanium-based Ti (commercially pure)
	Ti-6Al-4V
	Ti-5Al-2.5Fe
	Ti-Al-Nb
	Stainless steel 316L
	Cobalt-based alloys
	Cast Co-Cr-Mo
	Wrought Co-Ni-Cr-Mo
	Wrought Co-Cr-W-Ni

Tantalum-coated implants combine strength, corrosion resistance. The titanium can be coated with a porous metal (tantalum) by vapor deposition techniques. The coating enables bone cells to attach themselves to the implant. The coating highly porous with sponge like configuration is conducive to bone formation, enabling rapid and extensive tissue infiltration and strong attachment.

In relation to the manufacturing, the metallic materials are more advantageous in comparison to the polymer materials and the ceramics. Ferrous and non-ferrous metals can be manufactured through a wider range of manufacturing process possibilities, while polymeric materials are restricted to the shaping processes for plastics and ceramics to particulate processing. In the case of metals, these possibilities of manufacturing processes include shaping processes, property-enhancing processes and surface processing.

Shaping processes are operations that apply heat, mechanical force or a combination of these to effect a change in shape of the work material. These operations include casting (solidification process), powder metallurgy, bulk deformation, sheet metalworking, metal machining, abrasive processes, welding, and other processes. They are designed procedures that results in physical changes to a work material with the intention to achieve the desired properties. That is, the necessary properties (mechanical strength, for example) for the application of the material. Forging is an important industrial process used to make a variety of high-strength components for bioengineering. The high precision micromachining of titanium, stainless steel and other special metallic alloys applicable to health is an example of importance of modern manufacturing in bioengineering.

Property-enhancing processes are performed to improve mechanical or physical properties of the work material. They include heat treatments (annealing or quenching in steel, for example) and sintering of powdered metals.

Surface processing is performed to prepare and/or change properties of material surface. These operations include cleaning, surface treatments, and coating and thin film deposition processes. Physical vapor deposition (PVD) and chemical vapor deposition

(CVD) are thin films processes used to form extremely thin coatings in implants, for example.

In addition to the aforementioned manufacturing processes, a computer aided design (CAD) program takes an image of the part of the prosthesis and the additive manufacturing technology can create the part of the appropriate dimensions made of metal powders or another materials.

In short, medical devices and implants benefit from new developments in a wide range of metallic materials and manufacturing processes. Ferrous and nonferrous metal materials continue to be crucial in these applications because they present technological viability in terms of optimization of manufacturing processes, materials and desired properties.

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Conflict of interest

The author declares no conflict of interest.

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