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Journal of Magnesium and Alloys ■■ (2017) ■■–■■
www.elsevier.com/journals/journal-of-magnesium-and-alloys/2213-9567

Review

Mechanical characteristics of biodegradable magnesium matrix composites: A review

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Received 16 March 2017; revised 28 April 2017; accepted 7 May 2017

Available online

Abstract

In recent years, a new generation of biodegradable metallic materials, magnesium alloys, has been called a revolutionary material for biomedical applications (*i.e.* in orthopedics applications as a bone-implant material), thanks to the reasonable strength (similar to bone tissue, compared to available metallic alloys) and high biocompatibility of magnesium and its alloys. However, pure magnesium can corrode too quickly in the physiological pH (7.4–7.6) and high chloride environment of the physiological system and therefore lose their mechanical integrity before tissues have sufficiently. Engineering approach to this challenge (high corrosion rate of Mg) can be (*i*) alloying of element additions, (*ii*) surface treatment and (*iii*) development of metal (magnesium) matrix composites (MMCs). Magnesium-based composites, as bio-materials, can provide a combination of unique characteristics including adjustable mechanical properties (*i.e.* tensile strength, elastic modulus, ductility) and corrosion resistance. This is the main advantage of magnesium-based composites as compared with alloying and surface treatment approaches. Here, the matrix materials are biomedical magnesium alloys based on Mg–Zn, Mg–Ca and Mg–REE alloy systems (REE stands for rare earth elements including yttrium, Y, cerium, Ce, lanthanum, La). The reinforcement phases are mainly based on hydroxyapatite (HAP), calcium polyphosphate (CPP), and β-tricalcium phosphate (β-TCP) particles, and hybrid HAP + β-TCP particles. In this paper a comprehensive review is provided on different grades of biodegradable magnesium matrix composites, with focus on their mechanical properties.

Keywords: Magnesium composites; Biodegradable; Mechanical properties; Body compatibility; Nanocomposites

1. Introduction

Bone, a composite natural living tissue, is always vulnerable to fracture by means of trauma, pathology and resorption. As a composite, bone contains about 30 wt.% matrix, 60 wt.% mineral and 10 wt.% water. Metals with good body compatibility, such as stainless steel, Ti, and Pt, are traditionally employed as implants in fracture surgeries. The main challenge associated with these metallic materials is that they are not necessarily biodegradable and therefore, in most cases, a secondary operation is needed to remove these implants from patient's body after healing. This is not quite desirable due to the risks (*i.e.* infection and complications) associated with surgery and longer recovery stag along with longer hospitalization time and higher health care costs.

Materials used for implant applications in clinical surgeries can be classified, according to their degradation performance, as bio-inert material and bio-degradable materials [1]. Bio-inert materials, as their name implies, are inert implant which remains in human body as long as required (and sometime forever); they can be removed by a second surgery. A "biodegradable" product has the ability to break down, safely and relatively quickly, by biological means, into the raw materials of nature and disappear into the environment. These products can be solids biodegrading into the soil (which we also refer to as compostable), or liquids biodegrading into water. Biodegradable materials (*i.e.* metals) are those that will eventually corrode *in vivo*; these materials dissolve completely upon fulfilling the mission to assist with tissue healing with no implant residues. By this dissolution occurrence, a non-toxic oxide forms that is harmlessly excreted in the urine. Therefore, the major components of biodegradable materials are those metallic elements that can be metabolized by the human body, and demonstrate suitable degradation rates and modes in the human body [1].

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http://dx.doi.org/10.1016/j.jma.2017.05.001

Biodegradable metals can be classified as [1] biodegradable pure metals, biodegradable alloys, and biodegradable metal matrix composites. The advantage of using MMCs as biomaterials are the adjustable mechanical properties (Young's modulus, tensile strength) as well as the adjustable corrosion properties by choosing the appropriate composites [1]. The main focus of this paper will be on biodegradable metal matrix composites and, in particular, magnesium matrix composites. As the name implies, the composite contains at least two components including matrix and reinforcement. In biodegradable composites, all components within the composites must be biodegradable and non-toxic to the body.

Magnesium is the lightest metal (ranging from 1.74 to 2.0 g/cm^3) as being 33% lighter than aluminum and 77% lighter than steel. Thanks to their great strength-to-weight ratio, magnesium and its alloy are widely used in automotive and aerospace applications. Magnesium (Mg) and its alloys have been considered as potential alternatives to conventional orthopedic implant materials because of their attractive biodegradation and mechanical properties [2–4]. For instance, physical and mechanical properties of magnesium (*i.e.* elastic modulus of 41–45 GPa) is closely comparable with those of cortical and cancellous bones which would decrease the occurrence of stress shielding. Moreover, it possesses higher strength than current biodegradable polymers [5,6]. Table 1 shows the mechanical properties of pure Mg compared to other body compatible metals and to bones.

It is worth noting that the degradation rate of pure magnesium is extremely high in physiological environment restraining their applications for implant applications which is exposed to body fluid. This (*i*) deteriorates the mechanical integrity of implant before complete healing of injured bone tissue, and (*ii*) releases large amount of hydrogen gases resulting in subcutaneous bubbles and delays the healing process of damaged region. Due to these challenges in using pure Mg in bio-applications, magnesium alloys and magnesium-based composites have been developed for biodegradable implant. For bio-medical applications, a limited grade of magnesium alloys that contain non-toxic (or low-toxic) alloying elements can be used (*i.e.* Mg–Ca, Mg–Sr, Mg–Zn, Mg–Si, Mg–Sn, and Mg–Zr). Beside these Mg-based alloys, Mg matrix composites exhibit adjustable mechanical and corrosion properties as determined by the selection of the reinforcement material. Various reinforcement with different content, distribution and size can be employed (*i.e.* calcium phosphate-based ceramic [7–11], bioactive glass (BG) [12], zinc oxide [13], and calcium particles [14], calcium polyphosphate particles (CPP), hybrid HAP + β-TCP).

2. Biodegradable magnesium composites

2.1. Magnesium–hydroxyapatite matrix composites

Hydroxyapatite (HAP), a naturally occurring mineral form of calcium apatite with the formula $Ca_5(PO_4)_3(OH)$, is known to possess a low solubility in body environment [15] and possesses excellent biocompatibility and bioactivity. This is attributed to its chemical and structural similarities to bone and tooth minerals [16].

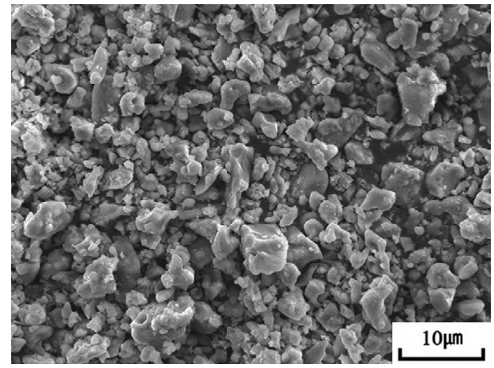

Fig. 1. SEM image of HAP powder [15].

The HAP, by itself, possesses a poor load bearing capacity which limits its application. However, HAP particle can serve as reinforcements in Mg-based MMCs as bio-materials. Different physical and mechanical properties of implants are presented in Table 1 [17]. The important properties such as compressive yield strength and fracture toughness of HAP are better than those of natural bone. The addition of small amount of HAP as a reinforcement to the biocompatible Mg matrix would be better option to achieve optimum properties.

Fig. 1 shows the SEM image of HAP powder. The powder consists of agglomeration of fine particles (1–5 μm) and the shape of the particle is mainly non-spherical and angular types.

Gu et al. [10] prepared Mg/HAP composites through powder metallurgy by pure magnesium (particle size <150 mm) and hydroxyapatite (particle size 2–3 mm) powder and studied the microstructure, mechanical property, corrosion and cytotoxicity of the composites. The manufacturing procedure they used consists of mixing 10 wt.%, 20 wt.% and 30 wt.% HAP powder with balanced Mg particles. Then the powder mixture was cold pressed into cylindrical compact at 400 MPa pressure level. Green compact was then hot pressed for 20 min at 330°C with 350 MPa pressure and extruded into rods with 10 mm diameter.

Fig. 2 shows the SEM images of Mg/HAP composites along the extrusion direction. A relatively uniform distribution of the HAP particulates is observed in the microstructure with no distinct micrometer-size porosity. Some agglomeration or clustering of the HAP particulates is observed at random intervals over the Mg/20HAP composite, whereas severe agglomeration can be seen for the Mg/30HAP composite (Fig. 2c). The average grain size of the as-extruded bulk pure Mg and Mg/HAP composites was measured as approximately 30–60 μm.

Table 1
Mechanical properties of Mg compared to bone and metals [5].

Tissue/material	Density (g/cm^3)	UTS (MPa)	Yield stress (MPa)	Elastic modulus (GPa)
Cortical bone	1.8–2.0	35–283	104.9–114.3	5–23
Cancellous bone	1.0–1.4	1.5–38	–	0.01–1.57
Ti–6Al–4V	4.43	830–1025	760–880	114
316L stainless steel	8.0	450–650	200–300	190
Pure Mg, annealed	1.74	160	90	45
WE43 Mg alloy, T6	1.84	220	170	44

Please cite this article in press as: Meysam Haghshenas, Mechanical characteristics of biodegradable magnesium matrix composites: A review, Journal of Magnesium and Alloys (2017), doi: 10.1016/j.jma.2017.05.001