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Review

Insight of magnesium alloys and composites for orthopedic implant applications – a review

R Radha *, D Sreekanth

School of Mechanical and Building Sciences, VIT University, Chennai, India

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Abstract

Magnesium (Mg) and its alloys have been widely researched for orthopedic applications recently. Mg alloys have stupendous advantages over the commercially available stainless steel, Co-Cr-Ni alloy and titanium implants. Till date, extensive mechanical, in-vitro and in-vivo studies have been done to improve the biomedical performance of Mg alloys through alloying, processing conditions, surface modification etc. This review comprehensively describes the strategies for improving the mechanical and degradation performance of Mg alloys through properly tailoring the composition of alloying elements, reinforcements and processing techniques. It also highlights the status and progress of research in to (i) the selection of nutrient elements for alloying, reinforcement and its effects (ii) type of Mg alloy system (binary, ternary and quaternary) and composites (iii) grain refinement for strengthening through severe plastic deformation techniques. Furthermore it also emphasizes on the importance of Mg composites with regard to hard tissue applications.

Keywords: Orthopedic implants; Magnesium; Alloy system; Composites; Grain refinement; Processing, degradation, strengthening

1. Introduction

Orthopedic surgery in recent times depends profoundly on the development of biomaterials used for fixation of fractures and joint replacement. Biomaterials contribute significantly to the improvement of the health and well-being of humankind. The human bodies are often susceptible to painful and disabling injuries such as strains, sprains, dislocation and fractures. Fractures are simply a break in bone which is caused by the forces that exceed the strength of osseous tissue in the bone. The risk of fracture is affected by age, gender, and bone strength and pre-existing medical conditions apart from accidents. Most fractures are caused by excessive external forces and are classified as traumatic fractures. Orthopedic biomaterials can be implanted in to or near a bone fracture to facilitate healing or to compensate for a lack or loss of bone tissue. The ends of the fractured bone may be fixed in place by metal pins connected to an external frame; once the fracture has healed, the pins and frame are removed. In other cases, an operation is performed to open up the injury site and fasten together the bone pieces with metal screws, nails, plates, rods or wires. These implants are generally left in the body even after the bone has healed which may lead to infections caused by the degradation of the implant in the physiological environment. This is of the major interest in the development of orthopedic implant with the good corrosion resistance and adaptations to biological environments. Besides this, the implant material has to have sufficient mechanical strength to withstand various biomechanical forces. The mechanical properties of interest for an implant material are yield strength, elastic modulus and ultimate tensile strength for load bearing applications. Other properties which are expected in implant materials are low weight, good wear resistance and osseointegration. The use of increasing number of orthopedic devices such as joint prostheses and internal fixations helps in increasing the expectancy of human life span. Explorations in the biodegradable materials are required to enhance device performance, to improve function, deliver bioactive compounds and achieve the goal of tissue regeneration. There are mainly three kinds of biological implant materials: metallic materials, ceramic materials and polymeric materials. Owing to their mechanical strength, metallic materials have been widely used in orthopedic applications of which commonly used are:

* Corresponding author. School of Mechanical and Building Sciences, VIT University, Chennai, India

E-mail address: radha8vit@gmail.com (R. Radha).

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stainless steel, cobalt-chromium alloy and titanium alloy etc. The development of metallic biomaterials has gained interest and their advantages and disadvantages are outlined in Table 1. However, the biggest drawback is the non-degradability of these materials in the body environment which demands the secondary surgical procedure for the removal of implants after the bone heals. Therefore, at present, great amount of research is focused on developing biodegradable, low density and highly bioactive implants without compromising on strength. One such material which meets these requirements is Mg and its alloys. The research on biodegradable implant metal materials was born at the right moment. In the 1930s, magnesium alloy has been found biodegradable in the human body. Therefore, magnesium alloys become the study hot-spot in the field of medical implant materials. Compared with biodegradable polymer material, magnesium alloys have good mechanical compatibility, and can provide higher initial stability and initial support. Their modulus and density approach the human bones. As implant materials, they can reduce the shielding of implants. They are also lighter than other medical metal. But they are difficult to process, corrode rapidly, need a better biocompatibility. This review aims to provide a comprehensive description on the research status of Mg alloys and Mg based composites targeted for orthopedic applications. This is followed by the generic design rules entailed for developing the orthopedic biomaterials in terms of biocompatibility, mechanical characteristics, ease of processing and cost factor. The effect of alloying elements and reinforcements on the mechanical/biodegradation performance on Mg alloys and Mg based composites are discoursed in detail. Finally, the critical challenges and difficulties are summarized with importance on the promising research on Mg based materials for implant applications.

2. Evolution of metallic implants

Metallic materials have a drastic growth in orthopedic surgery intended for development of orthopedic devices, including permanent implants (total joint replacement, hip prosthesis etc.) and temporary implants (pins, bone plates, screws etc.) [1]. The potency of Mg as biodegradable implant has existed for more than a century [2]. To serve as biomaterials in vivo, magnesium and its alloys should have good biocompatibility. Mg2+, is an essential nutrient for life and is the fourth most abundant element present in the human body [3–7]. Mg/Mg alloys are beneficial over the present-day implant materials viz. Stainless steel, Co-Cr alloys and Titanium are outlined in Table 2 [5,8–14]. The surface response of commercially available AZ91 and AZ31 alloys in Hank's solution are investigated intended to use for clinical applications [15]. The rapid corrosion of Mg associated with the release of Hydrogen (H_2) gas was observed in few studies in mid of last century inhibits the idea of using Mg. However, the research was kindled in the early 2000s, with the better understanding of corrosion kinetics in Mg. The strategies are developed to control the degradation of Mg provided the healing of fractures without the need of removal of implant by secondary surgery. The research of biodegradable Mg based materials is evolving to design the implants intended for orthopedic applications. Mg and its alloys should have good biocompatibility to serve as biomaterials. The uncertain toxicity of commercial Mg alloying elements has a potential threat that may exasperate the application of such alloys in the biomaterial field. The major drawbacks of Mg must be overcome are listed in Table 3 [10,16,17]. In this circumstance, utmost care in selection of biocompatible elements, optimized composition design for new biodegradable Mg alloys with desired bio-mechanical properties and feasible processing

Table 1
Metallic materials advantages, disadvantages and applications.

Materials	Advantages	Disadvantages	Applications
316L Stainless steel	Easily available and Low cost Excellent fabrication properties Accepted Biocompatibility and toughness	High modulus Poor corrosion resistance Poor wear resistance Allergic reaction in surrounding tissue Stress shielding effect	Bone Plates, Bone screws and pins, Wires etc.
Co-Cr alloys	Superior in terms of resistance to corrosion, fatigue and wear. High strength Long term biocompatibility	Expensive Quite difficult to machine Stress shielding effect High Modulus Biological toxicity due to Co, Cr and Ni ions release.	Shorter term implants-Bone plates and wires, Total hip replacements (THR)-Stem or hard-on-hard bearing system
Ti alloys	Excellent resistance to corrosion Lower Modulus Stronger than stainless steels Light weight Biocompatible	Poor wear resistance Poor bending ductility Expensive	Fracture Fixation plates, Fasteners, nails, rods, screws and wires, Femoral hip stems, Total Joint Replacement (TJR) arthroplasty-hips and knees.
Mg alloys	Biocompatible Biodegradable Bioresorbable Similar density and young's modulus of bone (E = 10–30GPa) Less stress shielding effect Light weight	Hydrogen evolution during degradation Less resistance to corrosion	Bone screws, Bone plates, bone pins etc.

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