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Mg–Zr–Sr alloys as biodegradable implant materials

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ABSTRACT

Novel Mg–Zr–Sr alloys have recently been developed for use as biodegradable implant materials. The Mg–Zr–Sr alloys were prepared by diluting Mg–Zr and Mg–Sr master alloys with pure Mg. The impact of Zr and Sr on the mechanical and biological properties has been thoroughly examined. The microstructures and mechanical properties of the alloys were characterized using optical microscopy, X-ray diffraction and compressive tests. The corrosion resistance was evaluated by electrochemical analysis and hydrogen evolution measurement. The in vitro biocompatibility was assessed using osteoblast-like SaOS2 cells and MTS and haemolysis tests. In vivo bone formation and biodegradability were studied in a rabbit model. The results indicated that both Zr and Sr are excellent candidates for Mg alloying elements in manufacturing biodegradable Mg alloy implants. Zr addition refined the grain size, improved the ductility, smoothed the grain boundaries and enhanced the corrosion resistance of Mg alloys. Sr addition led to an increase in compressive strength, better in vitro biocompatibility, and significantly higher bone formation in vivo. This study demonstrated that Mg–xZr–ySr alloys with x and $y \leqslant 5$ wt.% would make excellent biodegradable implant materials for load-bearing applications.

1. Introduction

Metallic biomaterials such as titanium alloys, SUS316L stainless steel and cobalt–chromium–molybdenum alloys are widely used as implant materials for load-bearing applications [1–4]. However, most metallic implant materials used today are much stiffer than human bone. For example, the elastic modulus of most Ti alloys ranges from 60 to 130 Gpa, although Hao et al. [5,6] reported the development of a β-type titanium alloy (Ti–24Nb–4Zr–7.9Sn (wt.%)) with a modulus of 33 GPa, which is higher than that of natural bone, which ranges from 0.1 to 30 GPa [7–10]. This mismatch in elastic modulus causes stress shielding, leading to implant loosening and eventually premature failure. Another concern is that these metallic implants are retained in the human body permanently and may cause adverse reactions due to ion release. Therefore, the ideal implant materials for load-bearing applications are biodegradable materials that possess adequate mechanical strength and perfect biocompatibility. On the other hand, biodegradable polymers such as poly(lactic acid) and poly(glycolic acid) are weak and may not be able to sustain the applied forces during the operating and healing processes [11–13].

Magnesium alloys are receiving increasing attention as new biodegradable implant materials for orthopaedic applications [14–16]. Mg is a natural ionic presence with significant functional roles in biological systems, and may stimulate the growth of new bone tissue [17–21]. Moreover, Mg and its alloys are lightweight, with mechanical properties similar to those of natural bone. The elastic modulus and compressive strength of Mg alloys are closer to those of natural bone than other commonly used metallic implants [9,14,22,23]. In particular, Mg and its alloys are biodegradable in the human body, where biodegradation of the Mg alloy implants involves the formation of a soluble, non-toxic oxide that is safely excreted in the urine [24,25].

However, there are three major concerns in using pure Mg and currently existing Mg alloys for load-bearing implant materials. One of the challenges is that pure Mg possesses poor mechanical performance. Its low mechanical strength and elastic modulus cannot satisfy the mechanical property requirements of an implant material because it cannot sustain the rigours of the daily activity of patients after implantation into the body [14,15,21,26]. Therefore, to develop new Mg alloys using strengthening alloying elements becomes an indispensable approach. The second challenge is that currently existing Mg alloys possess low corrosion resistance and therefore degrade too quickly in the human body. This process produces large volumes of hydrogen gas and leads

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