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Review article

Recent advances in bulk metallic glasses for biomedical applications

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ABSTRACT

With a continuously increasing aging population and the improvement of living standards, large demands of biomaterials are expected for a long time to come. Further development of novel biomaterials, that are much safer and of much higher quality, in terms of both biomedical and mechanical properties, are therefore of great interest for both the research scientists and clinical surgeons. Compared with the conventional crystalline metallic counterparts, bulk metallic glasses have unique amorphous structures, and thus exhibit higher strength, lower Young's modulus, improved wear resistance, good fatigue endurance, and excellent corrosion resistance. For this purpose, bulk metallic glasses (BMGs) have recently attracted much attention for biomedical applications. This review discusses and summarizes the recent developments and advances of bulk metallic glasses, including Ti-based, Zr-based, Fe-based, Mg-based, Zn-based, Ca-based and Sr-based alloying systems for biomedical applications. Future research directions will move towards overcoming the brittleness, increasing the glass forming ability (GFA) thus obtaining corresponding bulk metallic glasses with larger sizes, removing/reducing toxic elements, and surface modifications.

Statement of Significance

Bulk metallic glasses (BMGs), also known as amorphous alloys or liquid metals, are relative newcomers in the field of biomaterials. They have gained increasing attention during the past decades, as they exhibit an excellent combination of properties and processing capabilities desired for versatile biomedical implant applications. The present work reviewed the recent developments and advances of biomedical BMGs, including Ti-based, Zr-based, Fe-based, Mg-based, Zn-based, Ca-based and Sr-based BMG alloying systems. Besides, the critical analysis and in-depth discussion on the current status, challenge and future development of biomedical BMGs are included. The possible solution to the BMG size limitation, the brittleness of BMGs has been proposed.

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1. Introduction

With the improvement of the living standards and the development of science and technology, biomaterials have developed rapidly and helped in improving the quality of life and longevity of human beings greatly. Metallic biomaterials have the longest history among the various kinds of biomaterials. It has been reported that people began to use metal dental implants thousand years ago, which can be tracked back to 200 CE [1]. Stainless steel, vitallium (Co-Cr alloys), pure Ti and Ti alloys, pure Zr and Zr alloys are widely used as artificial hip joints, cardiovascular stents, artificial knee joints, bone plates, dental implants, etc. Besides, pure Mg and Mg alloys, pure Zn and Zn alloys have been studied and developed as biodegradable materials aiming to be useful in the clinical cases that need temporary supporting or fixation (such as plates and screws for bone fracture fixation, stents for cardiovascular repair), without second operation to be removed after finishing their functions [2,3]. However, these conventional crystalline metallic alloys have disadvantages such as low strength, high elastic modulus, low wear resistance, prone to crevice corrosion, pitting corrosion as well as stress corrosion cracking (SCC) and high cycle fatigue failure, incompatibility with X-ray or magnetic resonance imaging, which cause various problems in clinical application [4]. For instance, poor corrosion resistance can cause relatively high toxic ion release, such as Ni^{+}, Cr^{3+} and Co^{2+} into human and it is well known that these ions usually lead to adverse reactions when their concentrations rise above certain thresholds. Most of the conventional metallic biomaterials possess much higher elastic modulus compared to that of human bone. And the mismatching modulus can cause stress shielding of bone, resulting in bone resorption and loosening of the implant after a period of implantation [5]. Further development of novel biomaterials, that are much safer and of much higher quality, in terms of both biomedical and mechanical properties, are therefore of great interest for both the research scientists and clinical surgeons.

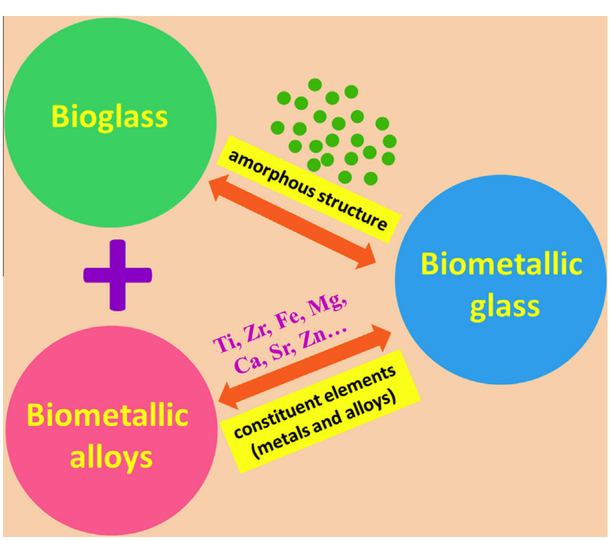

Fig. 1. Illustration of the relationship of the three materials, i.e. bioglasses, biometallic alloys and biomedical BMGs.

Efforts to discover alternatives to conventional biometals led to the discovery of bioglass in the early 1970s [6], since which time various kinds of bioglasses have been developed. Key bioglass systems include the typical S45P7 (SiO_2-CaO-Na_2O-P_2O_5-B_2O_3), 45S5 (SiO_2-CaO-Na_2O-P_2O_5) and S52P3 (SiO_2-CaO-Na_2O-P_2O_5-B_2O_3-Al_2O_3) systems, all of which have been widely used in biomedical applications, in contexts ranging from otology to cancer treatment [7]. Unfortunately, most of the bioglasses developed did not represent a real alternative to biometals, since they had unsatisfactory mechanical properties and thus remained unsuitable for clinical applications that need place them in load-bearing sites.

Metallic glasses (MGs), also known as amorphous alloys and liquid metals, emerged as a newcomer to the clubs of metallic materials in 1960, with the formation of the first metallic glass of Au75Si25 being reported in Nature journal by Duwez P's research team at Caltech, USA [8]. MGs have excellent physical and chemical functions such as high toughness and corrosion resistance, but the limited specimen sizes originally achievable (normally in the range of microns) severely restricted the study and application of MGs. These limitations were overcome by the development of bulk metallic glasses (BMGs) with much lower critical cooling rates (<100 K/s).

BMGs had received a lot of attention during the last two decades for their high strength and elasticity which are the consequences of their amorphous structure and concomitant lack of dislocations and associated slip planes. From the early 1990s, a series of new kinds of BMGs with the multicomponent chemistry and excellent glass forming ability (GFA) have been discovered in Zr-, Mg-, La-, Pd-, Ti-, and Fe-based systems by various solidification methods. These BMGs exhibited strong resistance to crystallization in the super-cooled liquid state and demonstrated excellent mechanical and physical properties.