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Magnesium Alloys for Biomedical Applications

Advances and Challenges

EDITED BY
DEEPAK KUMAR AND NOORUDDIN ANSARI

Magnesium Alloys for Biomedical Applications

Magnesium alloys have enormous potential for use in biomedical implants. *Magnesium Alloys for Biomedical Applications* delves into recent advances and prospects for implementation and provides scientific insights into current issues posed by Mg alloy materials. It provides an overview of research on their mechanical and tribological characteristics, corrosion tendencies, and biological characteristics, with a particular emphasis on biomedical implants.

- Details the fundamentals of Mg alloys as well as necessary surface modifications of Mg alloys for biomedical use.
- Discusses emerging Mg alloys and their composites.
- Covers mechanical, tribological, and chemical properties, as well as fatigue and corrosion.
- Highlights emerging manufacturing methods and advancements in new alloy design, composite manufacturing, unique structure design, surface modification, and recyclability.
- Helps readers identify appropriate Mg-based materials for their applications and select optimal improvement methods.
- Summarizes current challenges and suggests a roadmap for future research.

Aimed at researchers in materials and biomedical engineering, this book explores the many breakthroughs achieved with these materials and where the field should concentrate to ensure the development of safe and reliable Mg alloy-based implants.

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Edited by

Deepak Kumar and Nooruddin Ansari

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About the Editors

Dr. Deepak Kumar boasts an impressive academic journey. He obtained his B.Tech. in Mechanical Engineering from Uttar Pradesh Technical University, India, in 2013 and went on to earn his M.Tech. in Mechanical System Design from the National Institute of Technology, Srinagar, India, in 2016. During his Master's program, he had the privilege of being a visiting student at the esteemed Indian Institute of Technology, Delhi, and his dedication was rewarded with a Gold Medal for his Master of Technology achievement. In 2021, Dr. Kumar achieved a significant milestone by completing his doctorate from the Materials Science and Engineering Department at the Indian Institute of Technology, Delhi, India. His academic excellence was further showcased when he participated in a summer camp organized by the University of Tokyo, Japan, in 2019, where he received recognition for his innovative ideas. Moreover, he secured best presentation and paper awards in India for IEEE and AIP conferences. Driven by his passion for research and learning, he traveled to Germany after being awarded a travel scholarship by the Government of India, enabling him to attend an international conference. Dr. Kumar's contributions to the field are notable, as evidenced by his publication record. He has authored 36 papers in prestigious SCI journals and presented 6 conference proceedings. Notably, several articles are currently under review in renowned SCI journals. His doctoral dissertation delved into the nanoscale mechanical and tribological behavior of magnesium alloys. He conducted comprehensive investigations into the fundamental mechanisms of friction, wear, and deformation under both dry and lubricated conditions. Using a unique AFM setup, he probed the in situ tribofilm development mechanisms, particularly in localized regions/phases of magnesium alloy under distinct lubricative conditions. Additionally, Dr. Kumar has explored the mechanical and tribological properties of titanium alloys and high-entropy alloys (HEAs). His expertise extends to the field of corrosion, where he has conducted research on Ni-Ti shape memory alloys. Following the completion of his Ph.D. in the Department of Materials Science and Engineering at IIT Delhi, Dr. Kumar continued to expand his research horizons. He has investigated nanomechanical and tribological characteristics of 3D printed medium entropy alloys. Currently, Dr. Kumar serves as a postdoctoral research associate in the Department of Mechanical Engineering at Carnegie Mellon University, USA, a position he has held since September 2021. His work involves the development of thin conductive film, integration of these methods with devices using clean room technology, characterizing device behavior through a novel, in-house-built controlled characterization platform, and analyzing the results to unravel the mechanisms governing performance limits and failure modes.

Dr. Nooruddin Ansari earned his B. Tech. in Mechanical Engineering from Jamia Millia Islamia, India, in 2014, followed by an M. Tech. in Industrial and Production Engineering from Aligarh Muslim University, India, in 2017, where he was awarded the Silver Medal for his Master of Technology. In 2021, he successfully completed his doctorate from the Materials Science and Engineering Department at the Indian

Institute of Technology, Delhi, India. In 2018, he represented India as an Indian Youth Delegate in China, fostering collaborations in education. Dr. Ansari has an impressive publication record, with 12 papers in renowned SCI journals and 2 conference proceedings. His doctoral research focused on the thermomechanical processing and deformation behavior of Mg-Y alloys with varying Y concentrations. This involved the development of lightweight Mg-Y alloys through casting and hot rolling, as well as an exploration of recrystallization and deformation behavior at both room and high temperatures. Additionally, he has devoted attention to the mechanical behavior of steel, Al, and Ti alloys.

Presently, Dr. Ansari serves as Postdoctoral Research Associate in the Department of Mechanical Engineering at Texas A & M University, Qatar. His current work focuses on the development of steels, Ti, Al, and Mg alloys through additive manufacturing, with a focus on investigating their mechanical and corrosion behavior across different environments.

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1 Magnesium Alloys for Biomedical Applications

Scope and Opportunities

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1.1 INTRODUCTION

Tissue engineering is a multidisciplinary area dedicated to the regeneration of vital human tissues. Although living organs have inherent self-healing abilities, the extent of healing differs between tissues and can be compromised by the extent of injury [1–5]. Tissue engineering is the formation of bioengineered tissues in vitro and the modification of cell growth and function in vivo by the implantation of appropriate cells extracted from donor tissue and biocompatible scaffolds [2, 6–9]. Tissue engineering combines material and cell transplantation principles to create tissues and promote regeneration. The strategy was devised to bridge the gap between the enhancing number of patients due to end-stage failures and the limited number of donated organs [3, 10–13]. Tissue engineering is a branch of biomedical engineering discipline that integrates biology and ecological system with engineering to create tissues or cellular products outside the living body or to make use of gained knowledge to better manage the repair/reconstruction of tissues within the living body [12–15].

Biomaterials are an integral part of tissue engineering. The biodegradability, chemistry, and porosity of biomaterials used in tissue engineering must be controlled to promote optimum properties like cell adhesion and deposition of extracellular matrix materials by cells [10, 16]. The utilization of biocompatible materials for the development of implants has increased manifolds with the purpose to improve patients' health. Usage of such implants is commonly observed in the field of orthopedics (spinal fixation, bone fixation, tendon/ligament/cartilage replacement, etc.). Various biomaterials' properties that make them useful for medical applications include their ductility, high strength, fracture toughness, wear resistance, and corrosion resistance. Commonly used examples of implant materials include Co-Cr alloys, stainless steel, titanium alloys, magnesium alloys, etc. [17].

Biomaterials are used in a wide variety of industries for a variety of applications. There are many materials that can be used to create biomaterials, including metals, ceramics, polymers, glass, and living cells/tissues [18–20]. The basic function of a biomaterial implant is to replace the damaged biological part in the body so that it

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can perform its basic function well in coordination with other biological tissues and organs. Biomaterials should have biocompatible composition so that adverse chemical reactions can be avoided. Moreover, such materials should also offer excellent degradation resistance in terms of corrosion, biological, and wear resistance. Also, these biomaterials should have sufficient strength to withstand fluctuations arisen due to cyclic loads. Furthermore, in order to minimize resorption in bones, low modulus is required. Minimum wear in these implant materials result in minimum generation of debris as well [21]. Less wear debris accounts for presence of less foreign particles in the physiological system that hamper the working of various tissues. Present-day research studies show that there has been a substantial increase in the manufacturing methods of implants. Fabrication techniques like fused deposition modelling, investment casting, and vapor smoothing have also been in practice for the development of implant materials [22]. Moreover, it is evident from Figure 1.1 that research articles published in the field of biomaterials and biomedical magnesium alloys are continuously enhancing year-wise.

3D printing techniques have been extensively used for the development of the same. The life of the implant materials is generally hampered by corrosion. For prolonging the life of biomaterials, various coatings and surface modification techniques have been employed. For instance, ZrN/Cu coating has been successfully employed by the researchers on stainless steel and titanium materials for biomedical

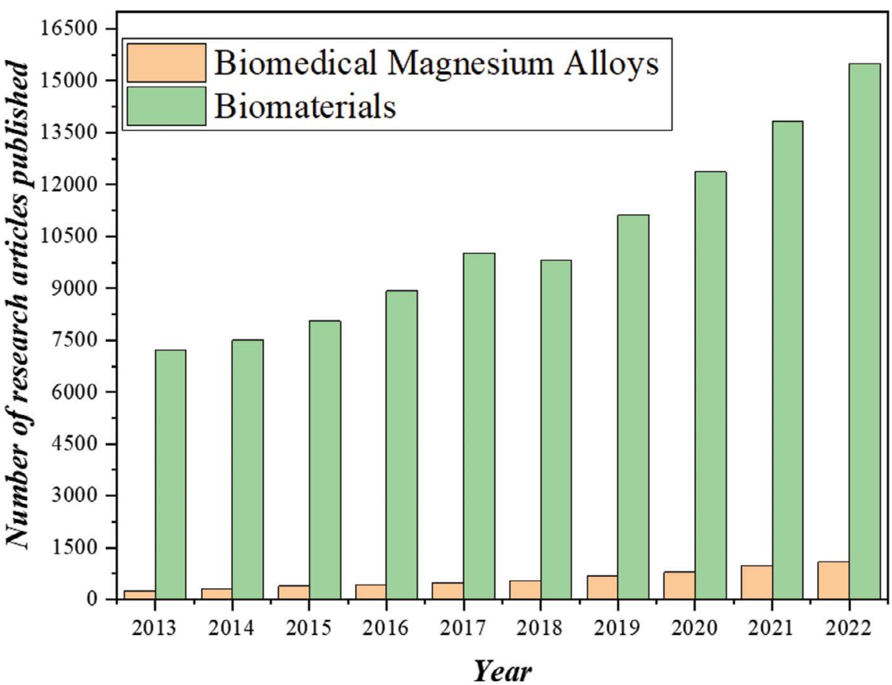

FIGURE 1.1 Yearwise distribution of research articles in biomaterials and biomedical magnesium alloys. (From ScienceDirect.)

purposes [23]. Coating techniques include thermal spraying, sputter coating, dip coating, sol–gel technique, electrophoretic deposition, pulsed layer deposition, biomimetic coating, etc. [24].

Different types of corrosion that affect conventional materials utilized for biomaterials development include pitting, crevice, stress corrosion cracking, corrosion fatigue, fretting, galvanic, and selective leaching. By-products arising out of corrosion of implant materials can cause dermatitis, anemia, ulcers, disturbance in central nervous system, Alzheimer's disease, etc.

The surface modification technique is one of the prominent solutions to reducing corrosion, thereby enhancing the life span of biomaterials [25]. Electrical discharge machining (EDM) process is also one of the potential choices for the surface modification of titanium alloys utilized for different orthopedic applications. In EDM process variants, powder-mixed EDM process is significantly used for modifying the surface of any material [26]. The complete structure of this chapter is shown in Figure 1.2.

1.1.1 Metal-based Biomaterials

Due to the increasing number of cardiovascular, orthopedic, dental, and neurological diseases that require implants and surgeries, metals are utilized at every stage, and there is a growing demand for biocompatible and biodegradable metals such as stainless steel, gold, chromium, titanium, cobalt, nitinol, and silver [27].

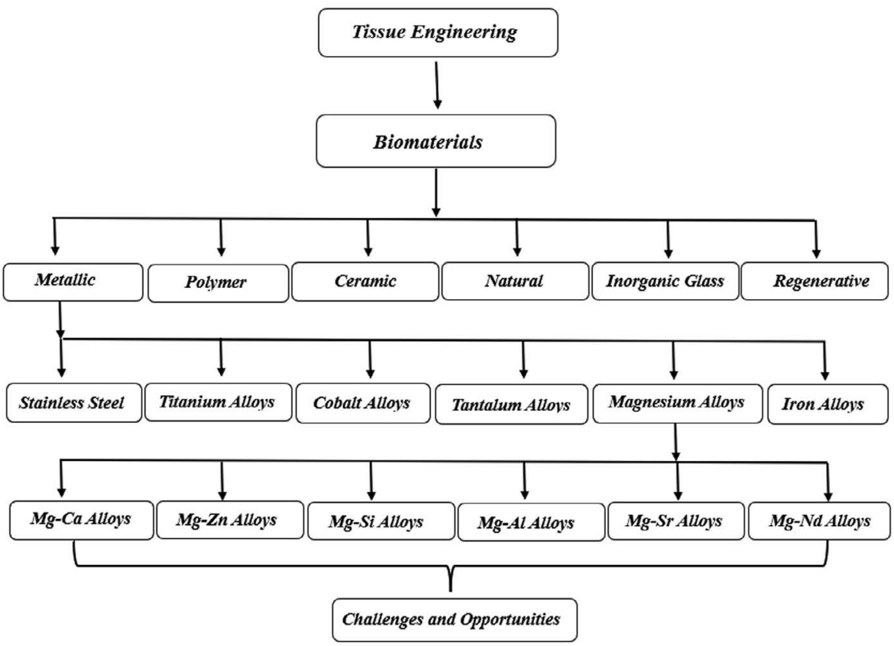

FIGURE 1.2 The schematic diagram depicting the complete structure of this chapter.

1.1.2 Polymer-based Biomaterials

Polymeric biomaterials are used in a variety of medical applications, including vascular grafts, implants applications, dressings, catheters, sutures, ligament repair, meshes, stents, tendon repair, and cardiac surgery valves. Polymeric (plastic) materials used in these areas can be synthetic or natural. For example, proteins, cellulose, deoxyribonucleic acid (DNA), ribonucleic acid (RNA), silk, wool, etc. are common among natural polymers derived from both plant and animal resources [27].

1.1.3 Ceramic-based Biomaterials

Bioceramics have specific properties such as chemical stability, stiffness, wear resistance, and hardness, and are biocompatible. The biocompatibility of bioceramics varies depending on the composition of the ceramic oxides (alumina, hydroxyapatite, zirconia, etc.), which are chemically inactive in the human body, and on the biodissolvable materials, which are to be finally replaced by the human tissues after carrying out repair work. These biomaterials are widely used in implants for teeth and bones, surgical crowns, and arthroplasty surgery (Table 1.1) [28].

1.1.4 Natural Biomaterials

Natural biomaterials can be classified into chitin, hyaluronic acid, cellulose, silk, gelatin, chitosan, and fibrin. They are commonly used to replace and restore the function and structure of injured organs, as drug delivery systems, and as medical biases similar to surgical sutures [18, 20, 27].

TABLE 1.1
List of Biomaterials and Its Characteristics and Applications

S. No.	Biomaterials	Characteristics	Applications	References
1.	Metal	Ductile, high wear resistance, impact resistance, low biocompatibility and corrosion resistance in physiological environment, mechanical properties different from biological tissues	Plates and wires, joint prostheses, dental implants, cranial plaques, artificial hip joints, knee joints, screw, plates	Kumar [29] dos Santos [30] Niinomi [31] Minnath [32]
2.	Polymer	Low density, easy to produce, easily degradable	Sutures, arteries, tendons, veins, artificial, implants	Love [33] Dutta [34] Chen [35]
3.	Ceramic	High biocompatibility, corrosion resistance, low thermal and electrical conductivity, low impact strength, difficult in manufacturing implants	Medical equipment and tools, coatings, bone filling	Punj et al. [36] Moshiri et al. [37] Migonney [38]