JURNAL POLIMESIN
Unit Penelitian dan Pengabdian Kepada Masyarakat (P2M)
Politeknik Negeri Lhokseumawe
ISSN Print: 1693-5462, ISSN Online: 2549-1199
Website: http://e-jurnal.pnl.ac.id/index.php/polimesin

Application of magnesium alloys in orthopedic implant

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Abstract

Technological updates in the field of advanced materials research are now tend to focuses on biomedical materials application and utilization of Magnesium and its' alloys. Magnesium (Mg) has been widely studied as an alternative material for biodegradable orthopedic implant applications. Recent studies regarding the potential application of Mg have been done related to its' mechanical properties, biodegradation profile, and the in-vitro and in-vivo testing. This study aims to review the Mg properties, production process, biomaterial roadmap, and the concern of chemical composition of Mg alloy in orthopedic application. Future potential improvement of the magnesium alloys properties is also highlighted.

Keywords: *Magnesium alloys; biodegradable; orthopedic implant; biomaterial roadmap*

1. Introduction.

Orthopedic implants are now closely related to the concept of developing biomaterials, especially in human bones. Human bones are very susceptible to pain, dislocation and fracture. In general, fractures that occur can be caused by external factors such as accidents. However, it is possible for fractures to be caused by disease or conditions of bone abnormalities from birth. Bone fractures are generally caused by excessive external loads or forces applied to the bone [1]. Orthopedic biomaterials can be implanted into the body as an alternative to healing or replacing damaged or lost tissue. The implantation process is generally done with two surgeries when the second surgery found problems such as infection due to the degradation of the implant.

The main requirements for implant material candidates must be degraded, adapt to their biological environment and have adequate mechanical properties. Mechanical properties for implant materials in terms of yield strength, Young's modulus, wear resistance and tensile or compressive strength. Another characteristic of implant materials is that they have a relatively light density and low manufacturing costs. Observation of implant materials that have biodegradable properties is needed to improve performance, function and to achieve the goal of tissue regeneration [2].

There are three main types of materials for implants: ceramic-based, metals and polymers. Stainless steel and titanium alloys are kind of metallic materials that have been widely used in orthopedic implants [3]. The biggest drawback of those implant materials is that they are not completely degraded, and there must be a second surgery after the bone is declared healed.

Most researchers focus on the development of implant materials that have biodegradable properties. Therefore, magnesium and its alloys are the best candidates for implant materials. Magnesium generally contains alloying elements: aluminum, zinc and manganese [4].

Magnesium alloys have a relatively low density, a Young's modulus that is close to bone morphology with high initial stability. This review aims to provide an overview of research on magnesium alloys as orthopedic implants with more descriptive mechanical characteristics, factors and costs.

The effect of alloying elements or chemical composition on biodegradation effects and mechanical performance will be discussed in detail. The expectation of this review is to help research of implant materials based on magnesium alloys.

2. Magnesium for orthopedic implant.

The development and use of magnesium as an implant have been around for more than a century. Formerly, the materials applied for biomaterials in particular were materials found in industry or society and not special materials, after that the material was modified and tested for biocompatibility.

There are three types of biomaterial implants such as ceramics, metals and polymers. Metallic materials have been widely used in orthopedic applications such as Co-Cr, titanium, and stainless-steel alloys. Disadvantage of metallic biomaterials is that they are not properly degraded in the body and require secondary surgery after the bone heals; as presented on Table 1.

Table 1. Advantages, disadvantages and applications of implant materials

No.	Material	Advantages	Disadvantages	Applications	References
1	316L Stainless Steel	• Easily Available • Low cost • Accepted biocompatibility and toughness • Easily fabricate	• High modulus • Poor corrosion resistant • Poor wear - resistant Elements can cause allergies	Bone plates, bone screws and pins, wires.	[5,6]
2	Co-Cr Alloys	• Resistant to corrosion, fatigue and wear • High strength Long term biocompatibility	• Expensive • Difficult to fabricate • High modulus Toxic when Co, Cr and Ni ions are released	Shorter term implants-Bone plates and wires, Total hip replacements (THR)-Stem or hard-on-hard bearing system	[7]
3	Mg Alloys (solid)	• Biocompatible • Biodegradable • Bioresorbable • Density and Young's modulus similar to bone • Light • Similar to tibial and cortical bone	• Low corrosion resistance • Control of hydrogen gas must be carried out during the degradation process	Bone screws, bone plates, bone pins	[8-10]
4	Mg Alloys (porous)	• Low cost • Easily to control pore formation • The product is close to the mold in shape • Similar to cancellous bone for bone scaffold applications	• Low corrosion resistance • Ratio of the composition must be balanced • Pores resulted are sometimes different	Bone screws, bone plates, bone pins	[11,12,13]

Magnesium and its alloys also have a good biocompatibility, magnesium is a very abundant element in the human body. Since the beginning of 1878, magnesium and its alloys have been studied for the utility of modern or advanced materials as biomaterials [14,15].

However, developments only started in the beginning of 2000s, such as corrosion control, and controlled degradation time to provide a healing process without surgical removal of the implant. The toxicity percentage of magnesium alloying elements is one of the main disadvantages of magnesium alloys.

The selection process of alloying elements must be very careful to optimize the revolutionary magnesium alloys in the future. The density and Young's modulus of magnesium are in the same range as natural human bone, making it an alternative for orthopedic implant applications.

The Young's modulus of magnesium is 40 – 50 GPa [16]. This value tends to resemble the stiffness of human bone, which is around ~40 GPa.

Theoretically, Magnesium has a tensile strength unlike the steel, but magnesium has the properties and abilities when used as a human bone implant material, not only safe but reducing costs significantly compared to the price of other implant materials used in the market now.

The selection for biomedical application of magnesium is not only based on its mechanical properties, but also related to its' degradation and biocompatibility that mostly depend on the alloying elements.

Additional alloying elements in Mg may improve the mechanical properties through the development of hexagonal closed-pack (HCP) matrix and precipitation hardening [17,18].

2.1. Production Process

Powder metallurgy is a synthesis technique in the solid state, followed by a sintering process with an adjustable temperature but tends to be expensive with some risks such as the difficulty of transporting metal in powder form and needing a mold. Casting is the most economical way of production magnesium but there are high risks such as porosity, poor mechanical properties and high impact on the environment [19].

The process of production degradable magnesium is classified into 2 conditions, they are solid or liquid conditions. In the molten state, magnesium can be formed by casting; stir casting, squeeze casting and disintegrated melt deposition, while the solid condition was formed by a powder metallurgy process [20,21]. The type of Mg alloys, production process, chemical composition, and their applications in biomedical is shown in table 2.

Table 2. Types, formation, chemical composition, and applications of magnesium alloys

No.	Alloy Type	Production Process	Chemical Composition						Applications
			Al	Zn	Mn	Si	RE	Zr	
1	AM60	Die Casting	6		>0,13				Bioresorbable Stent
2	AZ31B	Extrusion and rolling	3	1	0,3				Bone screws, bone plates, bone pins
3	AZ80A	Extrusion	8	0,5	0,2				Bone screws, and pins
4	HK31A	Rolling						0,7	Bone plates
5	AZ91B	Die Casting	9	0,7	>0,13				
6	AZ91D	Die Casting	9	0,7	0,2				Long term biocompatibility
7	EZ33A	Sand Casting		3			3	0,8	
8	AS41A	Die Casting	4		0,3	1	0,3		

The hot or cold working metal is divided into two parts: rolling and extrusion. Rolling is a production process that uses a pair of rollers in order to reduce the thickness of the material by compressing it to a certain size with hot or cold conditions, while extrusion of metal production uses the compressive force of a mold and produces metal that has been reduced or has reduced cross-section

The production process is expected to be easy, along with the development of current biomaterial technology. The potential application of magnesium alloys for orthopedic implant applications has not been said perfect, because there are several problems such as controlling hydrogen gas during the degradation process, the level of toxicity that must be identified, corrosion and mechanical behavior that must be anticipated before in-vitro, also studied during in-vivo.

2.2. Alloy Elements and Mechanical Properties

The elements of magnesium that are commonly used are including: aluminum (Al), zinc (Zn), manganese (Mn), and calcium (Ca). Elements can be classified into three types, they are toxic elements, nutritional elements and elements that cause allergies. Cadmium, beryllium, lead, barium, thorium, and iron are some examples for clumps of toxic elements. The elements contained in the alloy have their respective roles in human bones. Magnesium is a mineral that is needed by the human body and is evenly distributed in tissues, blood, body fluids, and other organs [22].

Magnesium has been shown to promote the process of bone establishment after being damaged. Previous research has shown that calcium plays an important role in the process of enhancing bone mineral density, strength, stretch ability, and calcium also gives bone hard properties for forming bone structure to support the human body. The zinc element in the alloy acts as a reinforcement and to overcome corrosive. The density and Young's modulus of zinc is slightly higher than that of magnesium, this will delay the healing process. The role of manganese as a stimulant of bone metabolism and it is able to create bone-forming enzymes, and also can prevent osteoporosis [23].

Also, other alloying elements that may contribute to improve the mechanical properties of Mg are including: aluminum, zinc, nickel and copper can increase the value of strength and ductility. Elements such as lead can increase its strength but decrease its ductility. The addition of alloying elements such as nickel and iron should be as minimal as possible.

Nickel and iron are considered as unnecessary substances because they cause toxicity to the implant material. The alloy not only supports its mechanical properties, but also must be degraded over time during the implantation process. Research that focuses on corrosion rate and density has been done to obtain efficient results. Alloys of magnesium and calcium have mechanical properties and biocompatibility similar to cortical bone, the addition of calcium to magnesium can suppress the rate of oxidation during the casting process and improve the mechanical properties, also corrosion resistance according to the percentage of calcium.

Zinc and nickel can reduce toxic elements such as iron, thereby increasing the value of tensile strength, hardness, ductility, and corrosion resistance. However, high levels of zinc will form pores and a eutectic phase which reduces the strength value. Total percentage of lead is less than 5% will improve the strength and ductility of magnesium.

The mechanical properties of magnesium alloys depend on the percentage of alloying elements, grain size, and intermetallic phase formed. The orthopedic implant material must have sufficient strength to support the bone structure during the healing process. The yield strength and maximum strength of magnesium are obtained from tensile testing. The series of stages of magnesium biocompatibility testing must be done in stages according to the biomaterial roadmap.

3. Roadmap of Mg Alloy

Biomaterials considers as materials that produce or synthesized for the purpose of applications related to contact with the human body. Biomedical material is aims to repair, replace, support, and to restore the function of organs or the human body. It can be in the form of materials with special technical specifications or in the form of some medical devices and biomaterials also have other purposes such as producing a product that is biocompatible, economical and produced easily in order to reduce very expensive costs.

Biomaterials are also one of the hopes for alternative biomedical materials that have high potential to be developed, particularly orthopedic implant materials [24]. The material which will be used as implant material will be modified and tested for biocompatibility with different sub-fields of science.

In the field of materials science and engineering, the implant material is tested for the first stage, in the in vitro Lab. At this stage, testing of strength, hardness, microstructure, fatigue, density, porosity, and corrosion rate of the candidate materials have to be done. Also, the material must be characterized related to the targeted implant site. For example, Mg may be tested as solid materials for the bone implant purposes, as well as in porous structure for bone scaffolding material. Following the success of the in vitro test, the second stage is the animal or in vivo testing.

One this second stages, the biocompatibility of implant material should be tested using a scarifying animal. This in vivo test needs to be handled by animal husbandry doctors and will be carried out in the group of knowledge of tissue engineering and animal cell culture technology.

Once its' results show a biocompatibility and have no rejection by the animal, the further test may be runs using a clinical test. to determine the biocompatibility level of the material inside the human's body.

This clinical testing should be runs by the medical doctors in the respected research hospital. The testing of biomaterial candidate inside the human body is the last step before the approval may be given to the biomaterial candidate [25].

4. Conclusions

Magnesium and its alloys have the potential to be used as orthopedic implant materials. The alloying elements which are used in improving the mechanical properties of magnesium need attention because the low or high percentage of alloying elements greatly affects the biocompatibility of magnesium. Cost factors, risks, and the process of production magnesium which will be used as an alternative implant material must follow the standards that have been tested or have been carried out in previous research. This review is expected to highlight the potential of Magnesium and its' alloying elements as orthopedic implant material. The production processes, mechanical properties and the biocompatibility of Mg and its' alloys open a potential application as biomedical material for orthopedic implants.

Acknowledgement

This study is supported by Hibah Penelitian Kerja sama Internasional DIPA FT Universitas Lampung, International Cooperative Research grant of FT UNILA No. 4062/UN26.15/LK.03/2021.

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