Development and characterization of bio Compatible Magnesium Scaffold

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ABSTRACT

This study emphasizes on the application of Mg alloys and potential replacement of existing steel and titanium alloys with Magnesium. This study necessitates the combination of Ca, Zn, and Mn with Mg. The use of Mg based alloys is increasing at an exponential rate due to its high strength to weight ratio compared with other alloys. The Mg alloys used today have good corrosion resistance and thermal stability. Bio compatible implants play a vital role in bio medical applications. In general stainless steel implant are as substitute materials for bone and its connectors, then drawback of stainless steel is that its density does not match with the density of bone and also it is heavy which gives pain for the patients. This research work is focused on developing a new material to overcome the above said disadvantages. Mg alloys can be a substitute which is also one of the nutritional elements to the human body. Mg-based implants can be used as an alternative over Fe-based and Ti-based implants.

KEYWORDS: Bio materials, Inflammation, Mg alloys, Mg-Mn-Ca-Zn, Titanium alloys,

1. INTRODUCTION

A tissue scaffold is a three-dimensional (3D) structure made from biological materials and biomaterials, which is used to facilitate cell/tissue growth and the transport of nutrients and wastes while degrading gradually itself. Current commercially available permanent metallic implants made of medical grade titanium, stainless steel, or cobalt-chromium alloys often cause stress shielding. Stress shielding can lead to secondary revision or removal surgeries that impose a heavy burden and affect an individual's quality of life. Bio compatible metallic implants are proposed as a suitable alternative to permanent metallic implants. Magnesium is the lightest metal that is in use today having density of 1.74 g/cm3 which is its density is closer to that of natural bone. Its high specific strength and specific stiffness can meet the strength performance requirements of biological implant materials. As biodegradable implant material magnesium provides both biocompatibility and sufficient mechanical properties the characteristic properties of Mg alloys, low density, high strength stiffness to weight ratio, good damping capacity can be increased by addition ofother metals. A composite of Mg-Mn-Ca-Zn has the properties to improve the above properties. Mg shear loss can be checked by addition of Ca in proportions which in turn increases the ultimate strength of the alloy. By addition of Zn improved corrosion resistance can be achieved. Thermal stability can be increased by the addition of Mn.

Literature review: Since metallic biomaterials possess a good combination of high mechanical properties and fracture toughness, they are widely being used in load-bearing bio-medical applications. However, some clinical limitations of these materials such as cobalt chromium alloy stainless steel 316L, pure titanium and titanium alloys Singh, 2009 and confine their application. For instance, the stress shielding effect is induced due to the much higher elastic modulus of metal in-service in comparison with that of natural bone. This phenomenon could contribute to accelerate the resorption of bone in vicinity of the implant, resulting in unbalanced load supported by the metal instead of the surrounding bone. Eventually, the implant will fail to satisfy the requirement of load-bearing fixation. Moreover, the surface of metallic implants is impossible to match perfectly with bone surface, while the toxic ions released by corrosion or mechanical wear could cause deleterious influence on the bone and tissue response (e.g. less bone formation and inflammation) Abraham, 2015. On the basis of those negative effects, biodegradable polymers and resorbable ceramics have widely been developed as alternatives to permanent metallic implants, whereas the low mechanical properties retarded their clinical application the bio-medical implant based on magnesium and its alloys offer a novel vehicle to relieve the patient's pain by avoiding second surgery for removing the bone fixation. Depending on the pre operation and post-operation investigation of Mg alloys, as cardiovascular stents in animals, the hydrogen evolution seems to rarely cause remarkable inflammation. The hydrogen is completely eliminated within two months due to less weight of implants and good transportation by blood circulation

Corrosion mechainism of magnesium: Magnesium and its alloys undergo electrochemical reaction easily in aqueous conditions. Magnesium hydroxide and hydrogen are generally observed as corrosion products. The entire corrosion equation of magnesium in aqueous solution is: $Mg(s) + 2H_2O\ (aq)\ Mg\ (OH)_2\ (s) + H2(g)$

This reaction could be divided into three partial equations: $Mg\ (s)\ Mg_2+\ (aq) + 2e-$ (anodic reaction)

$2H_2O\ (aq) + 2e-\ H2\ (g) + 2OH-\ (aq)$ (cathodic reaction)

$Mg_2+\ (aq) + 2OH-\ (aq)\ Mg\ (OH)_2\ (s)$ (product formation)

Although the $Mg\ (OH)_2$ film formed on the surface of Mg could temporarily retard the corrosion to some extent, it will become susceptible when the concentration of aggressive chloride ions increases above 30 mmol/l and eventually transform into MgCl2 with high solubility. Therefore, it is worth mentioning that Mg alloys as bio-degradable implants will be subjected to serious corrosion due to the presence of high Cl- concentration (150 mmol/l) in physiological conditions.

Corrosion properties of mg alloy:

Cacontent: The corrosion resistance of Mg-xCa (x=1-3%) alloy showed that the anticorrosion properties decreased and the hydrogen evolution increased with increasing calcium content. In Mg-0.6%Si alloy by adding different low Ca content it is shown that the addition of 0.18% Ca shifted the corrosion potential towards higher position but the anticorrosion behavior has not improved because of high corrosion density. The corrosion resistance significantly increased with 0.44% Ca content the corrosion resistance improved significantly and the corrosion density decreased when the content of Ca increased from 0.5 wt% to 1.0 wt %.

Zn–content: Zinc can improve the corrosion resistance by increasing its mass fraction in magnesium. The addition of 1.5% Zn to Mg-0.6%Si alloy dramatically increased the anticorrosion performance in comparison with the alloy without zinc. Compared to the corrosion resistance of pure magnesium, an extruded Mg-6Zn alloy with the absence of second phase (γ-MgZn) possessed an excellent corrosion property. The existence of a Zn-rich layer on the surface of Zn-containing magnesium alloy could protect alloys from further corrosion under aggressive environment. But, if the content of Zn element exceeds its maximum solubility in the magnesium matrix, the presence of a massive fraction of second phase (MgZn) accelerates the rate of corrosion and deteriorates the property of anti-corrosion

Re-content: RE (Rare Earth) element was regarded as an effective potential candidate to optimize anti-corrosion property. The result demonstrated that the corrosion resistance can be improved remarkably due to the formation of a protective Y2O3 film on the surface of magnesium alloy after addition of Y element. The corrosion performance of Gd-containing magnesium alloys can be improved with the additive amount of Gd up to 10wt% which improves anti corrosion properties. The significant increasing trend of corrosion rate was found when the Gd content is 15%. The highest content of Ni was discovered in the 15wt% Gd-containing Mg alloy as an impurity, which deteriorated the corrosion property.

Table.1.Physical properties of Mg

Property	Magnesium
Density at 293 K (g/cm^3)	1.74
Thermal expansion coefficient 293-373K (x10^6/C)	25.2
Elastic modulus (x10^{6}Mpa)	44.126
Tensile strength (x10^{6}Mpa)	274
Melting point (K)	923

Mechanical properties of mg alloys and human bone: To completely meet the requirements of adequate clinical implants, the maintenance of mechanical integrity is widely regarded as a crucial parameter accompanied with corrosion resistance. Therefore, the bio-degradable material under in vivo service should possess appropriate strength in sync with the process of bone healing, although it can experience corrosion reaction. Mechanical properties of various bone types, bio-metallic materials, polymers and Mg alloys are summarized in Table 2

Table.2.Polymers and Mg alloys

Material	Yield strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)
Bone		35-283	5-23
Stainless steel	190	490	193
Magnesium	170	220	41-45

Chemical additions to mg alloys and its relevance to biological properties:

Ca- addition: In the present work, calcium is regarded as a favorable bio-alloying element for the following considerations. (1) It is well known that calcium is a major component in human bone (2) Magnesium is necessary for the calcium incorporation into the bone which might be expected to be beneficial to bone healing with the co-release of Mg and Ca ions In vivo, biocompatibility studies discovered newly formed bone. It is characterized by high activity and good alignment of osteocytes around the Mg-1Ca alloy pins.

Zn- addition: Zinc is one of the most abundant nutritionally essential elements in the human body, and has basic safety for biomedical applications. The consequence of cytotoxicity assessment confirmed that the *in vitro* cytotoxicity of Mg-6Zn alloy was found to be Grade 0-1 according to ISO 10993-5: 1999. In addition, although a gap between the implant and surrounding bone tissue occurred during animal implant experiments due to a rapid degradation, the newly formed trabeculae and osteoblasts were still observed. Meanwhile, no disorders of the heart, kidney, liver and spleen existed because of the release of Zn ions. Therefore, it indicates that Zn element is safe as an important potential bio-medical candidate.

Re- addition: Excessive yttrium ions (Y3+) have been shown to change the expression of some rat genes and have adverse effects on DNA transcription factors, while many authors stated that gadolinium is highly toxic.

Nevertheless, if we successfully manipulate and control the concentration of Y or Gd ions released by Y or Gd containing Mg alloys in the physiological condition below the harmful level through specific and efficient post treatment method, they are employable for bio-medical applications

Physical and chemical properties of magnesium: Magnesium is among the alkaline earth metals and its average atomic mass is 24.305 g/mol. The melting temperature is 649oC. It possesses excellent thermal and electrical conductivity. The free state of magnesium hardly exists under natural atmosphere due to its high chemical activity, tending to react with water, oxygen, nitrogen, phosphorous and chlorine. Normally, Magnesium reveals an appearance of a silvery and white shade. It is worth mentioning that Mg is the lightest of all structural metals which are used in building and the automobile industry. Pure magnesium possesses a hexagonal closed-packed (h.c.p.) crystal structure under atmospheric pressure. The atomic locations in the magnesium unit cell, and the principal planes as well as directions are illustrated in Fig. 2.4. The lattice parameters of pure Mg at 25ºC are a = 0.32092 nm and c = 0.52105 nm within marginal error (± 0.01%). Since the ideal value of c/a ratio for the ABAB close-packed layers of atoms is 1.633, the h.c.p. structure of pure magnesium is almost perfectly ideal (c/a = 1.6236). If the Mg crystal undergoes plastic deformation, primarily, it happens on the (0001) basal plane and in the close-packed <11-20 > direction of the plane. Secondary slip occurs in the <11-20> direction on the {10-12} perpendicular face planes. Twinning of pure magnesium can be observed most frequently across the {10-10} series planes, and the occurrence of secondary twinning is across the {30-34} planes.

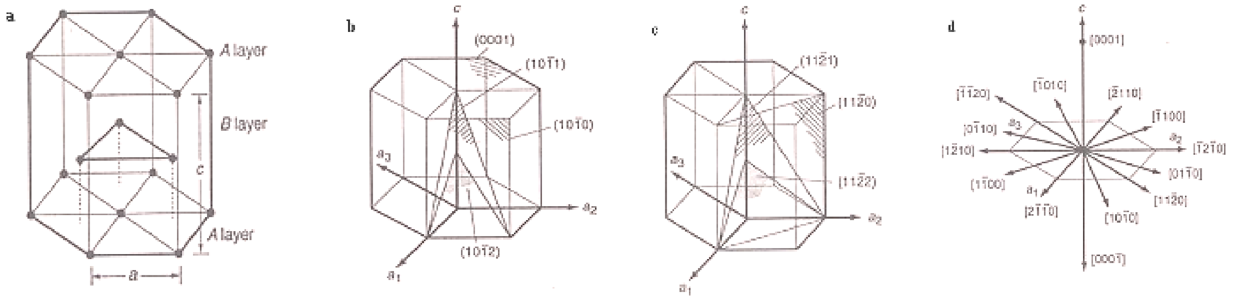


Figure.1a. Stage 1 **Figure.1b. Stage 2** **Figure.1c. Stage 3** **Figure.1d. Stage 4**

2. EXPERIMENTAL PROCEDURE

Design criteria of biocompatible materials: Biocompatible materials are designed to provide temporary support during healing process of diseased or damaged tissues. This concept requires the materials to provide appropriate mechanical properties for the intended use and suitable corrosion resistance for its compatibility. It also requires the materials to possess acceptable biocompatibility and bioactivity within the human body as a new generation biomaterials. The specific design and selection criteria of biocompatible materials depend on the intended applications. Screws, pins, needles and other load bearing orthopedic applications are implanted in the bone to maintain mechanical integrity over 12-18 weeks while the bone tissue heals (Staiger, 2006). Thus dedicated Mg-based alloys should combine both high strength and a low modulus close to that of bone that avoid “stress shielding”. The specific mechanical and corrosion requirements for biomaterials proposed for bone fixtures are: the corrosion rate needs to be less than 0.5 mm year-1 in simulated body fluid at 37ºC, the strength should be higher than 200MPa and the elongation greater than 10%. The material requirements for the experimental purpose, the various powders such as Atomized Mg powder, Zinc, manganese and calcium powders were supplied by S.H Metal India Ltd., Kalpakam, India. In Table-2, the chemical composition of the Mg-Zn-Ca powder is shown. The basic characteristics of powder blend such as flow, apparent density, compressibility, and sieve analysis have been carried out using standard rate methods of testing.

Element selection: There are several considerations for element selection in developing bio-Mg alloys, as shown schematically in Fig. 3.1. The first consideration is elemental toxicity. The degradation products of the designed alloys should be non-toxic and absorbable by the surrounding tissues or dissolvable for excretion via the kidneys. Elements can be classified into the following groups (Staiger, 2006): (i) well-known toxic elements: Be, Ba, Pb, Cd, Th; (ii) elements that are likely to cause severe hepatotoxicity or other allergic problems in human: Al, V, Cr, Co, Ni, Cu, La, Ce, Pr; (iv) nutrient elements found in the human body: Ca, Mn, Zn, Sn, Si; and (iv) nutrient elements found in plants and animals: Al, Bi, Li, Ag, Sr, Zr. The second consideration is the strengthening ability of the elements. Four groups can be categorized Li, 2008: (i) impurities: Fe, Ni, Cu, Co; (ii) elements that can improve the strength and ductility simultaneously: ranging in increasing strength, they are Al, Zn, Ca, Ag, Ce, Ni, Cu, Th; ranging in increasing ductility, they are Th, Zn, Ag, Ce, Ca, Al, Ni, Cu; (iii) elements that can only improve ductility with little effect on the strength of magnesium: ranging in increasing ductility, they are Cd, Tl, Li; and (iv) elements that decrease the ductility but increase the strength of magnesium: ranging in increasing strength, they are Sn, Pb, Bi, Sb.

The third consideration is the influence on the corrosion behavior. Alloying elements that have a close electrochemical potential to form intermetallic phases with a similar potential to that of magnesium (-2.37 V) which will improve the corrosion resistance by reducing the internal galvanic corrosion.

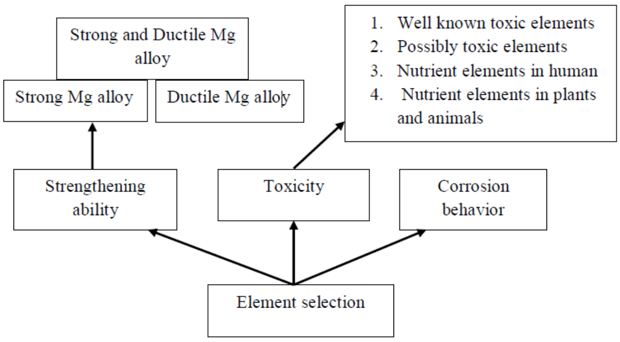


Figure.2.Considerations for element selection in developing bio-Mg alloys

Material preparation: Mg shear loss can be checked by addition of Calcium in proportions which in turn increases the ultimate strength of the alloy. Addition of Zn imparts micro structure refinement of Mg-Zn phase.The production of Mg alloy is based on power metallurgy test. The standard practices for production and preparation of powder metallurgy test specimens is ASTM B 925-03 . A flow chart for powder metallurgy is shown in fig.2. The metals are powdered and mixed well and compact. The sintering temperature is found to be 450^0c.The tensile test specimen with a gauge section of 89.7 mm x 3.56 mm x 8.6 mm were made from die. A solid cylindrical test specimen for compressibility test is produced by compacting a test portion of powder metallurgy of size 25.4 mm diameter and 7.11 mm compact thickness .A test specimen with a size of 75 mm x 10 mm x 10 mm were made for the powder metallurgy impact test. The micro structural analysis was carried out by using an optical microscope, and was carried out by inductively coupled Etchant: Picric Acid+ Hydrogen peroxide+ Acetic acid.

Table.2.Weight composition

Elements	%Composition
Copper	0.005
Manganese	3.25
Zinc	1.4
Calcium	0.92
Iron	0.004
Nickel	0.005
Magnesium	Remainder

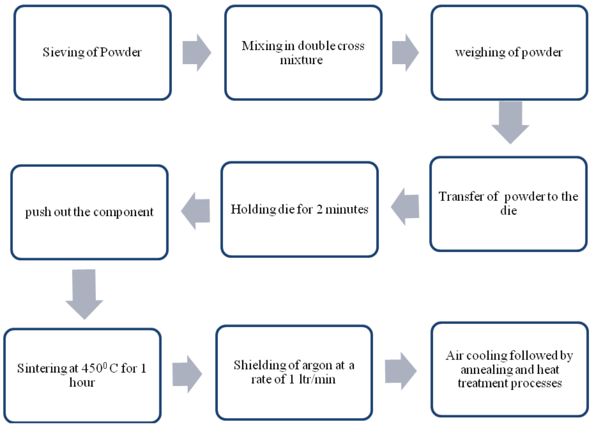
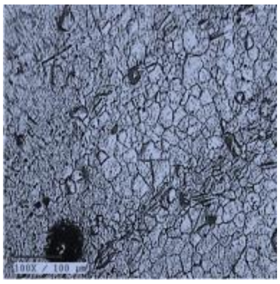


Figure.3.Process flow sheet for Mg powder metallurgy

3. RESULTS AND DISCUSSION

Microstructure: The microstructure development during the process is shown in figure 1and2. The mean grain size in the as-received soft condition of Mg alloy is 100 µm. The microstructure shows pores between grains of the magnesium alloy powder that undergone fusion in almost all the areas of the field. Some precipitate of $Mg_{17}Al_{12}$ eutectics present in the primary magnesium solid solution.



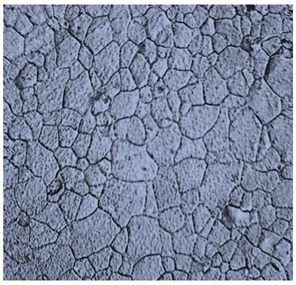


Figure.4.Magnification 100x   Figure.5.Magnification 200x

Mechanical Properties: The mechanical properties of the alloy Mg-3.4Mn-.9Ca-1.4Zn are compared with that of titanium scaffold used in femur bone regeneration scaffold. It can be seen that Ca addition to the alloy causes worthwhile effect on improving the mechanical properties ofMg-3.4Mn-.9Ca-1.4Zn alloy. Both ultimate tensile strength and yield strength are also improved with a addition of Zn imparts microstructure refinement of Mg-Zn phase and change in morphology, since long cracks nucleate along Mg-Zn particles and Mg matrix. It is also found that age hardening response of the alloy is significantly improved. It is experimentally found that adding Mn increases corrosion resistance under ambient and working conditions.

Tensile and compressive strength: At homogenized state, tensile yield strength is about 95 MPa, and this sample ruptures as strain reaches 53% with the tensile strength being approximately 274 MPa.also, the ultimate compressive stress is relatively high, about 480MPa. The existence of microstuctural texture has significant impact on compressive and tensile symmetry. For the Mg-3.4Mn-.9Ca-1.4Zn with texture on the basal plane in homogenized condition, the tensile yield strength is decided by the basal texture density. Higher texture density will cause more difficulties in deformation and greater yield strength.The compressive yield strengthis higher than the tensile yield strength. When being annealed, the Mg-3.4Mn-.9Ca-1.4Znthe texture intensity decreases due to larger grain size. So annealing of the alloy does not have tremendous effecton the tensile and compressive symmetry. When compared with titanium scaffold having ultimate tensile strength of 230 MPa, the Mg-3.4Mn-.9Ca-1.4Zn has much superior ultimate tensile and compressive strength.

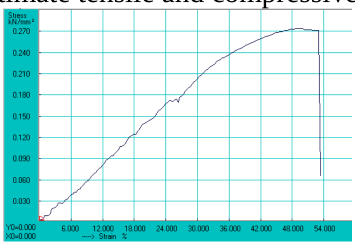


Figure.6a. stress-strain (tensile)

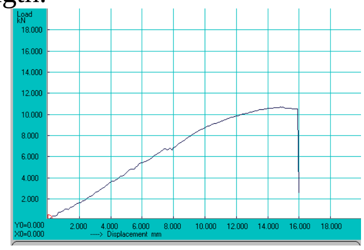


Figure.6b.load-displacement (tensile)

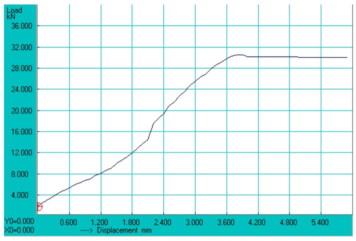


Figure.6c.load-displacement (compression)

Fracture Strenght: Due to addition of calcium in the alloy, the fractured surface exhibits fine scale indentations with no obvious chasm as shown in figure 5. This type of microstructure prohibits shearing along grain boundaries. The grain boundaries after impact and tensile test is shown in figure 5.a and 5.b. The micro hardness test based on Vickers hardness test ranges between 56 to 61 at 0.5 kg load.

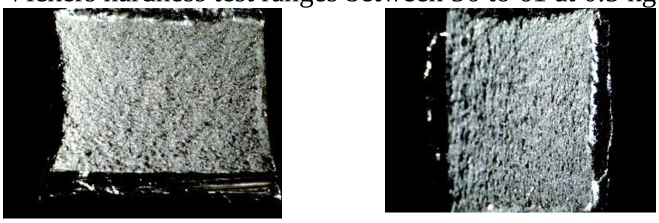


Figure.7a.Grain boundary after impact test

Figure.7b. Grain boundary after tensile test

4. CONCLUSION

A new type of magnesium alloy based on Mg-Mn-Ca-Zn sytem has been developed for biomedical application. The Mg-3.4Mn-.9Ca-1.4Zn has good inclusive mechanical properties and its corrosion resistance is much better than common biomaterials. Addition of calcium were found to be methodical in refining the microstructure of Mg-3.4Mn-.9Ca-1.4Zn alloys and caused a morphological change. Addition of Zn imparts microstructure refinement of Mg-Zn phase. Mg shear loss can be checked by addition of Ca in proportions which in turn increases the ultimate strength of the alloy.

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