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A Critical Review on the Applications of Metal Materials for Medical Implants

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Abstract

This review was focusing on different types of metallic materials that are used as an implant due to their chemical, thermal, electrical, and mechanical properties. Therefore, to design and manufacture new as well a cost-effective metal-alloy having higher bio-compatibility that can be used as implant specific properties should be considered before their manufacturing. Also, using common alloys for creating a strategy to minimize the use of some rare metals is considered as one of the challenges in using metals as an implant. In order to ensure long human life, especially when using implants on young patients, the need for developing a novel method and strategy of using a metallic alloy in the bio-medical field is aimed at giving structural metallic materials having suitable mechanical, chemical and biomedical biocompatibility. Therefore, metallic alloys that can be used in the future and for the next generation should have less toxic effects. Elements that can cause severe and adverse health menace, such as tumor-causing agents, neurological disorder, and coronary disorder agents, should be avoided. Therefore, these metals and their alloys should have low cost having lower melting points such as Mg, Fe, Ti, Mn, and their alloys. Finally, the need for designing chemically, biologically, mechanically, and electrically biocompatible metal alloys are significantly recommended, especially those having longer-term implantation.

Keywords: *Implant, metal, alloy, biocompatibility, chemical, mechanical and biodegradable*

I. INTRODUCTION

Technological advancements resulted in the practical usage of metallic materials in medical aspects in the replacement of joints and bones. It is also used in devices to fixed broken bones and for teeth implantation. For a relatively long time, it is known by man that metals possess significantly high strength, toughness as well as elongation, especially when compared with polymeric and ceramic biomaterials. One of the vital and significant advantages of metal and metallic materials is their ease in manipulating manufacturing and processing by applying highly modified technological methods such as casting, extrusion, rolling, and forging.

Implantation is a significant area in medical fields, especially in the area of traumatology and orthopedics. And the most common materials used are stainless steel, Ti-based alloys, and Co-based alloys. Stainless steels are used in implantation for tubular stents to restore destroyed and affected blood cells. Furthermore, some noble metals and their alloys, i.e., Au, pd, Nitinol, and stainless steel, are applicable in dental treatments. These metals are used for a more extended period due to their resistive nature to corrosion and their inertness in the body fluids, and these made them very useful to use in the medical field.

Apart from the corrosive resistance nature of these kinds of metals and their alloys [1], It has also been reported that in engineering, the biodegradability of metallic materials is very useful and has also attracted the attention of the medical practitioners many years ago. Among the criteria to be fulfilled by these metals and their alloys for them to be efficiently used in medical fields is that they should be degradable in the body and be able to produce non-cancer producing agents, non-toxic and non-allergic chemical materials as metabolites which can be easily, readily and successfully excreted out of the body. Metallic alloys with biodegradable properties have some suitable properties for implantation, having temporary advantages such as fixing fractured bones, stents, nails, and plates. Generally, if this kind of noble alloys is to be used for medical reasons, another secondary surgery is most needed and necessary to get rid of them after the patient has recovered and healed. Though these materials should decompose and degrade naturally after treatment, and no secondary surgery should be applied to get rid of the materials from the body. Which later can be very expensive in terms of cost as well as makes the treatment inconvenience to the patients due to multiple steps and tendencies of causing other problems.

Because of these reasons, this area needs to be devoted, and extensive research should be done to elucidate the mechanism responsible for the biodegradable properties of metals and their alloys; also, their strength, corrosive resistance, and hardness should be checked and examined because these metals are more biocompatible than polymers and ceramics. And it has been reported that the most suitable analytes for producing implants with biodegradable nature are zinc, titanium, magnesium, iron, and their alloys [2], [3].

II. APPLICATIONS OF METAL MATERIALS FOR MEDICAL IMPLANTS

A. Magnesium, zinc, and iron alloys for medical applications in biodegradable implants

a) Biocompatibility

Magnesium is one of the significant elements which aids and assist for the right and proper functioning of the body. It strongly assists numerous enzymatic processes in the human body, in the circulatory system, digestive and neurological functions. It equally promotes and assists the proper growth of the bone. It has also been reported that the body of an adult human being possesses almost thirty grams of magnesium, which are found mainly in the bones and the human muscles. It has also been recommended that the daily magnesium amount should be 400 mg. The deficiency of this macro element can lead to vascular and heart diseases. This is one reason why this element should be included in such various food and other medical supplements. Though, the over-dose of the element is very rare because the body has some mechanisms and the ability to regulate its amount in the human body.

It has also been reported that numerous bio-compatibility test was conducted using Mg and Mg-alloys. And most of the results, both from in vivo experiments using laboratory animals and vitro analysis, shows that bio-compatibility of this element is in perfect agreement with the positive results based on the WHO recommendation. Mg-alloy is the only alloy which represents materials that have been used in pre-clinical analysis using human patients.

Zinc, also like magnesium, is a vital macro element for the right and proper functioning of the body. At its trace level, it can protect the immune system of the body and in the manufacturing of enzymes. It is also regarded as a non-toxic macro element having a daily recommended amount of forty milligrams, which is relatively lower than that of magnesium. Its over-dosage also was not reported to have caused any severe menace. And researches that show the bio-compatibility of zinc is very low and is limited. The primary and first study was conducted recently, whereby Zinc wire has been implanted in a laboratory animal. And the result shows no adverse effect, especially inflammation of the aorta of the animal was not seen, which proved the bio-compatibility of Zinc element. But more studies should be conducted to reprove this fact to validate the use of zinc in implantation.

Iron also was regarded as a non-toxic element. Its helps in transferring oxygen in the human body to other tissues and part of the bodies.

It is recommended for the body to have a daily in taking off 10 mg of the iron element. Many studies reported that this element's biocompatibility based on using chemicals and on laboratory animals was found to be very good. However, more experiments are also needed, as in zinc [4]–[6].

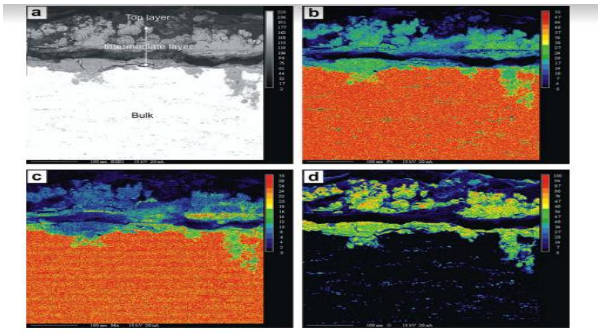

Fig. 1. Images of the cross-section area of Fe35Mn specimens after 3 months of degradation test: (a) BSE image and (b, c, and d) EPMA maps for iron, manganese, and oxygen, respectively. The color represents the intensity of the mapped elements [8].

b) Mechanical properties

The densities and other primary mechanical characteristics of these metals and their alloys are seen in the table below. The range of their mechanical characteristics is seen for every set of metals because mechanical characteristics lie mainly on the alloy's chemical constitution and physical states. Additionally, the mechanical characteristics of some polymers that are biodegradable, noble metal materials. One of the most essential and significant parameters to be observed is that almost all 3 elements have high strength than the biodegradable polymeric materials. This shows that they should be applied to produce implants primarily in fractured bones and teeth.

Table 2.0.1: Comparison of Mechanical Properties of Some Biomaterials [6]–[9]

Material/tissue	Density (g/cm^3)	Tensile strength (MPa)	Young modulus of elasticity (GPa)
Ti-based alloys	~4.5	600-1200	110
Stainless steels	~8	600-1000	200
Polylactid acid (PLA)	~1	~30	~2
Bone tissue	~2	30-280	5-20
Mg-based alloys	~2	100-400	50
Zn-based alloys	~7	100-400	90
Fe-based alloys	~8	200-1400	200

c) Magnesium

Positive characteristics of magnesium-based alloys show lower density as well lower or the least modulus of electricity that is nearer to the human bone tissues when compared to that of the remaining metallic materials. The lower modulus of the electricity helps in a good transfer of mechanical load among bone load and the implants. And this gave an avenue for a proper and well-being process to heal the bone. But, if we assume that the modulus was high, the mechanical load is more involved by the implant than the bone tissues and subsequently leads to slower growth of the new bone tissues.

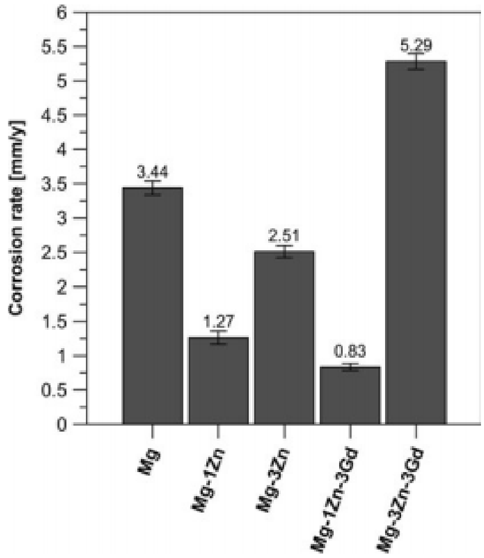

Figure: 2 Corrosion rates of the investigated alloys

d) Zinc

The Zn based alloys also have shown similar strength as that of Mg alloy, even though its density and the modulus of electricity seems to be relatively larger, whereby it can affect the healing process negatively because of non-identical transferring of load among the new bone and the implant.

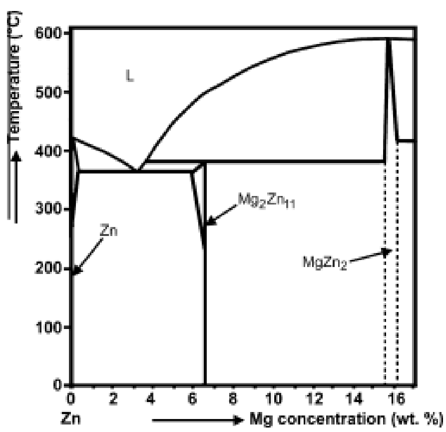

Figure 3: Zn-rich region of the Zn-Mg equilibrium phase diagram [3]

E. Iron

The iron-based alloys have shown the highest strength among the other metal-based alloys. And because of these characteristics, it's suitable for making implants, especially to higher mechanical load such as in fixing bone tissues, plantar, and in dental treatment.

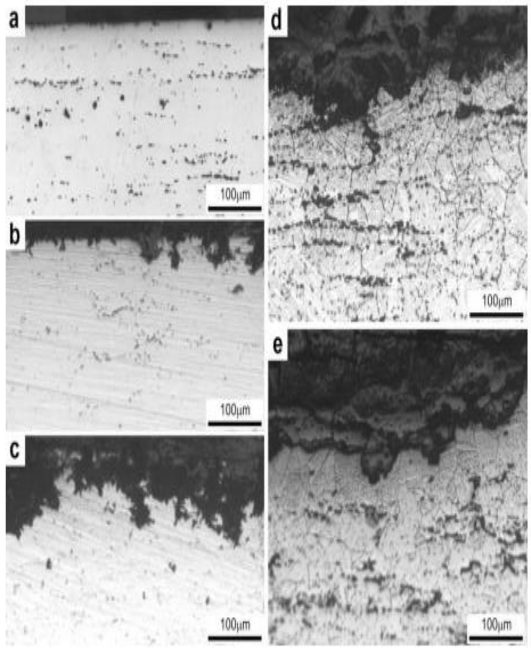

Figure 4: Cross-sectional profile of polished Fe specimens: (a) before and (b and c) after 1 week and 3 months of degradation test respectively, and (d and e) etched Fe25Mn [8] and Fe35Mn specimens after 3 months of degradation test respectively (etchant: Nital 2%).

But its modulus was larger, especially when compared with the prominent growing bone, causing severe issues during the healing process.

1) Corrosion properties

In table 2, the rate by which zinc, iron, and zinc-based alloys are corroding were summarized in human body fluids. Generally, they are all corrosive, and it occurs quickly in samples having chlorides. Such as in stimulating physiological solutions. These chlorides are known to contain some properties that can solubilize the surface of these metallic biomolecules.

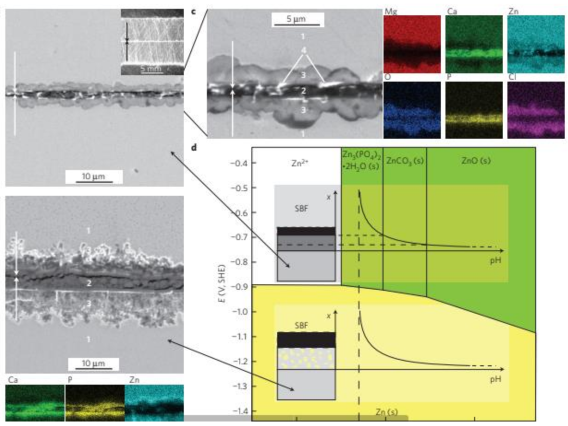

Figure 5: SEM micrographs of surface corrosion and model explaining this corrosion behavior.

Table 2.0.2: Corrosion rates of three alloys in simulated body-fluids [2], [10]–[13]

Material	Corrosion rates in SBFs (in mm per year)
Mg-based alloys	0,3 – 20
Zn-based alloys	0,1 – 0,5
Fe-based alloys	0,1 – 0,9

It has been shown in table 2 that Mg-based alloy corrodes quickly, having a high rate than the other 3 metallic materials. Zinc and iron alloys show significantly lower corrosion rates in comparison with magnesium.

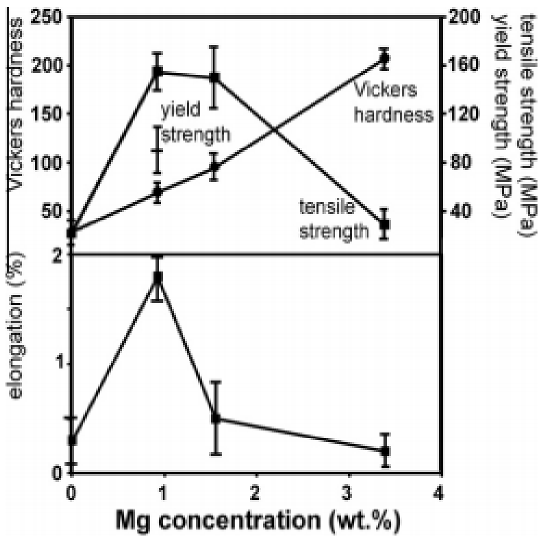

Figure 6: Mechanical properties of the Zn–Mg alloys versus Mg content (average Values were obtained from three measurements) [3].

Magnesium: The corrosion process of magnesium involves anodic and cathodic reactions:

Anodic reaction : Mg → Mg2+ + 2e(1)

Cathodic reaction : 2H2O + 2e- → H2 + 2OH

For zinc also.

Zinc: The mechanism of zinc corrosion is the following:

Anodic reaction : Zn → Zn2+ + 2e(3)

Cathodic reaction : O2 + 2H2O + 4e - → 4OH

For iron also.

Iron: The mechanism of iron corrosion resembles that of zinc:

Anodic reaction : Fe → Fe2+ + 2e

Cathodic reaction : O2 + 2H2O + 4e - → 4OH

Among the significant issues which are associated with iron, alloys are a result of their lower corrosive rates that were determined and which was conducted using laboratory animals. It is, therefore, necessary to speed up the corrosive methods and ways of Fe based alloy, which is hugely needed [2], [6].

Table 2.3 summarizes the positive and negative features of the three groups of biodegradable materials. It can be concluded from this table that there is no biodegradable material that can be considered as entirely optimal. Although the polymeric material (PLA) possesses a suitable combination of elasticity, corrosion rate in vivo, and biocompatibility, its drawback is low strength and other mechanical characteristics. Magnesium based alloys have a higher strength than polymer but still suffer from too high in vivo corrosion rates. The advantages of zinc alloys are higher strength than polymers and a lower corrosion rate than magnesium. Iron exhibits high strength, low corrosion rate, but too high modulus of elasticity. Regarding the biocompatibility of Zn and Fe, many questions remain unanswered, and much more in vitro and in vivo tests are needed to solve them.

Table 0.3: Advantages and disadvantages of some biodegradable materials

Material	Strength	Modulus of elasticity	Corrosion rate	Biocompatibility
PLA	--	+	+	+
slitiny hořčíku	-	+	-	+
slitiny zinku	-	-	+	+?
slitiny železa	+	--	+	+?

Table 3 Summary of advantages and disadvantages of biodegradable materials (the mark + means that a material is advantageous, the mark - suggests a less advantageous material and the mark - - indicates that a material's characteristic is disadvantageous). PLA = polylactid acid, i.e., the commercial biodegradable material utilized for bone fixations.

B. Titanium-alloys for long-term implantation

The creation of a highly cost-effective Titanium alloy having higher bio-compatibility and strength that can be used for implantation, with the aid of using naturally found alloying materials for the creation of new methods to abolish the used of rare metallic material is a hot cake and highly challengeable topic. But to meet the target of human life as well in the implant for kids, the manufacturing and creation of new metal alloy for medical uses are essential to provide metallic biomaterials having good mechanical, medical and chemical biocompatibility.

Therefore, the discovery of titanium alloys having excellent biological, chemical, and mechanical biocompatibility with low cost is so much needed in the market for commercial purposes and medical applications [14].

Below is a diagram that summarizes the significant reasons that serve as the driving force towards the progress and need for metallic materials implantation research in the last twenty years ago, which lead to the birth of new and highly developed metallic alloys.

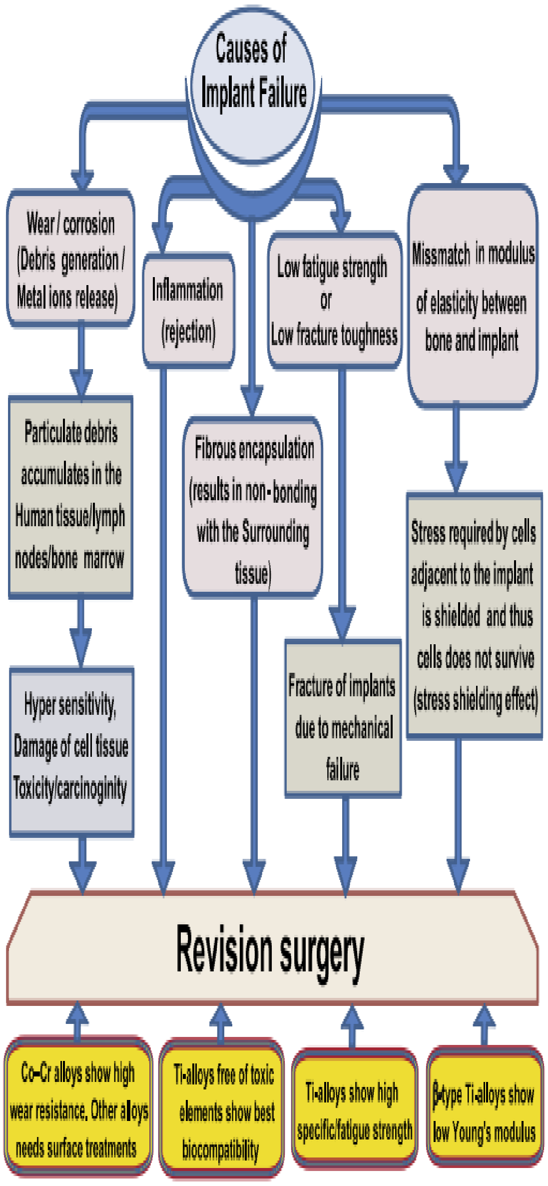

Figure 7: Various causes for failure of implants that lead to revision surgery, footed with a proposed system for better performance

a) Stiffness of Titanium-based metals as implants

The stiffness of this metal and its metal-based alloys is significantly lower than that of other local metallic-based implants, for example, stainless steel Co-Mo alloys. So, in comparison with these examples, Titanium alloys are exquisite materials that can be used for quite a long time as an implant due to its lower modulus properties, excellent resistance to fatigue as well as perfect medical passivity. Nevertheless, the most standard alloy of these metal that is mostly used as an implant is of a and aþb type alloys, which still showed higher elastic modulus when compared with the new bone tissue growing [21].

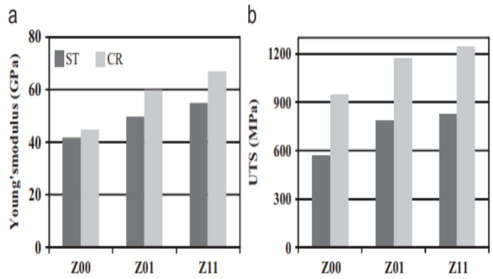

Figure 8: Effect of phase stability and thermomechanical treatment on Young's modulus (a), and the ultimate tensile strength (UTS) (b) of theTi67Zr20Nb10Ta3, Z00, Ti66Zr20Nb10Ta3O1, Z01, and Ti65Zr20Nb10Ta3Fe1O1, Z11, alloys after solution treatment (ST) and after 90%CR (CR).

b) Mechanical biocompatibility titanium-based alloys used for implant

When choosing and considering a metallic-based alloy, we shouldn't just consider avoiding short-term rejections and infections; instead, it should also provide longer-term bio-compatibility to avoid long term biomaterial issues. Apart from the medical compatibility described above, the mechanical biocompatibility of titanium-based alloys provides used a longer-term implant. Therefore it clearly shows that it has higher strength, high wear resistance, longer life-time, and low modulus [16].

c) Fatigue and wear resistance

The load usually applied to the bones of an implant while moving the body can result in alternating plastic deformation of some smaller zones of frictional concentrations that can be resulted through notches and micro-structural non-homogeneities [17].

Titanium-based alloys have excellent fatigue resisting ability and a significant strength as compared to other metallic based alloys and that of the growing bone tissues. Additionally, excellent wear resistance can be achieved by these metallic based materials by microstructural control. And therefore, it is so suitable to be used as an implant [18-20].

III. CONCLUSION

It is essential to consider the chemical, biochemical, availability, medical and mechanical bio-compatibility of any metal or metallic based alloy before it is used as an implant. The cost of the metal or metallic based alloy also should be considered to minimize the use of highly expensive and rare metals in the production of implants.

Finally, an alloy having higher strength, excellent workability, and high resistivity to fatigue and wear and with lower modulus should be considered and chosen as the best candidate in producing implants.

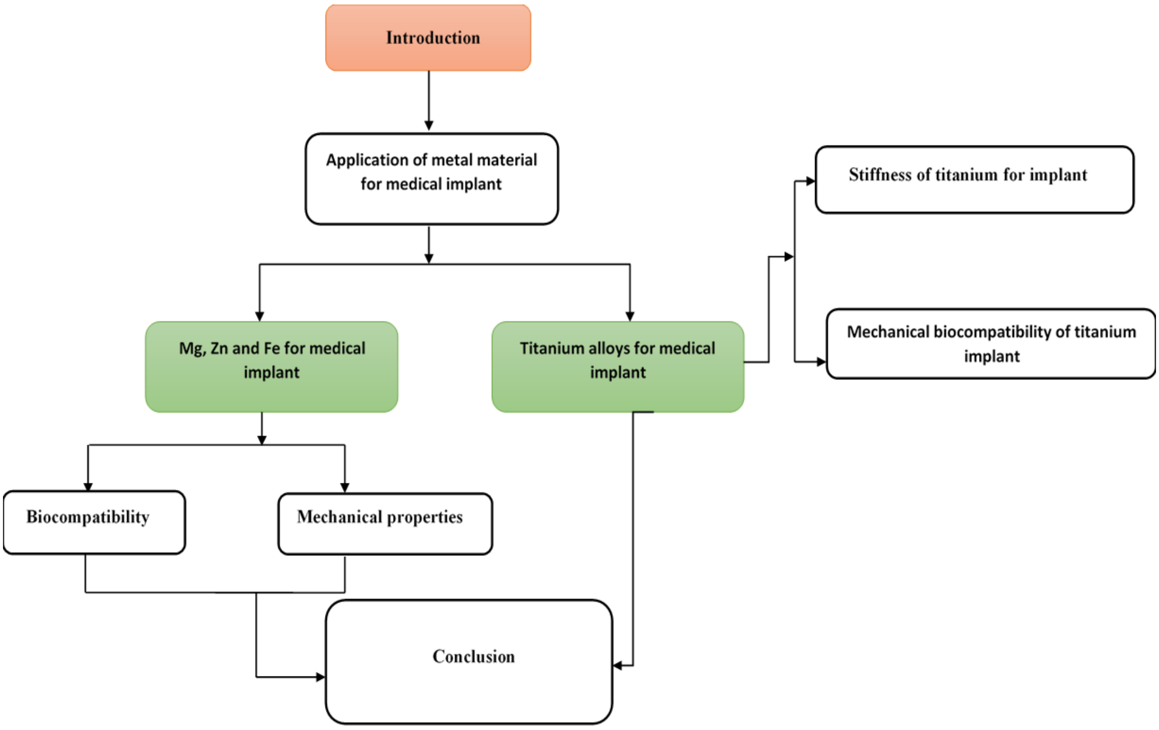

Figure 3.0 Flow chart showing the summary of the review

References

[1] J. R. Davis, *"HANDBOOK OF MATERIALS FOR MEDICAL DEVICES"*. United States of America: ASM International, Materials Park, 2003.

[2] D. Vojtěch, J. Kubásek, J. Šerák, and P. Novák, *"Mechanical and corrosion properties of newly developed biodegradable Zn-based alloys for bone fixation,"* Acta Biomater., vol. 7, no. 9, pp. 3515–3522, 2011.

[3] M. Schinhammer, A. C. Hänzi, J. F. Löffler, and P. J. Uggowitzer, *"Design strategy for biodegradable Fe-based alloys for medical applications,"* Acta Biomater., vol. 6, no. 5, pp. 1705–1713, 2010.

[4] B. Zberg, P. J. Uggowitzer, and J. F. Löffler, *"MgZnCa glasses without clinically observable hydrogen evolution for biodegradable implants.,"* Nat. Mater., vol. 8, no. 11, pp. 887–91, 2009.

[5] L. Zhang, F. X. Gu, J. M. Chan, A. Z. Wang, R. S. Langer, and O. C. Farokhzad, "*<Campa_2008_Association of ABCB1 and OPRM1 with Morphine.pdf>,"* no. June, 2008.

[6] P. K. Bowen, J. Drelich, and J. Goldman, *"Zinc exhibits ideal physiological corrosion behavior for bioabsorbable stents,"* Adv. Mater., vol. 25, no. 18, pp. 2577–2582, 2013.

[7] N. Hort et al., "*Magnesium alloys as implant materials- Principles of property design for Mg-RE alloys,"* Acta Biomater., vol. 6, no. 5, pp. 1714–1725, 2010.

[8] H. Hermawan, A. Purnama, D. Dube, J. Couet, and D. Mantovani, *"Fe-Mn alloys for metallic biodegradable stents: Degradation and cell viability studies,"* Acta Biomater., vol. 6, no. 5, pp. 1852–1860, 2010.

[9] J. R. Davis, Properties and Selection: *"Nonferrous Alloys and Special-Purpose Materials"*. ASM International, Materials Park, 1990.

[10] X. Gu, Y. Zheng, Y. Cheng, S. Zhong, and T. Xi, "*In vitro corrosion and biocompatibility of binary magnesium alloys,*" Biomaterials, vol. 30, no. 4, pp. 484–498, 2009.

[11] M. Moravej, F. Prima, M. Fiset, and D. *"Mantovani, "Electroformed iron as new biomaterial for degradable stents: Development process and structure-properties relationship,"* Acta Biomater., vol. 6, no. 5, pp. 1726–1735, 2010.

[12] D. Vojtech, J. Kubasek, J. ?apek, and I. Pospisilova, "*Magnesium, zinc and iron alloys for medical applications in biodegradable implants,"* in International Conference on Metallurgy and Materials, Conference Proceedings, 2014, pp. 1–6.

[13] J. Kubásek, D. Vojtěch, J. Lipov, and T. Ruml, *"Structure, mechanical properties, corrosion behavior and cytotoxicity of biodegradable Mg-X (X = Sn, Ga, In) alloys,"* Mater. Sci. Eng. C, vol. 33, no. 4, pp. 2421–2432, 2013.

[14] Kurtz, S., Ong, K., Lau, E., Mowat, F., Halpern, M., 2007. "*Projections of primary and revision hip and knee arthroplasty in the United States from 2005 to 2030*". The Journal of Bone and Joint Surgery 89, 780–785.

[15] Md. Masud Rana, Naznin Akhtar, Md. Zahid hasan and S.M. Asaduzzaman, *"Preparation And Evaluation Of Biocompatible Composite For Bone Tissue Engineering"* SSRG International Journal Of Pharmacy And Biomedical Engineering 4.3 (2017): 7-14.

[16] He, G., Hagiwara, M., 2006. "*Ti alloy design strategy for biomedical applications. Materials Science and Engineering"* C 26, 14–19

[17] Niinomi, M., Nakai, M., 2011. "*Titanium-based biomaterials for preventing stress shielding between implant devices and bone"*. International Journal of Biomaterials 2011, 836587 - 10

[18] J.C.M., 2000. *"Microsctructure and properties of materials. World Scientific"* 2, 49–55.

[19] Mansour, H.A., Ray, J.D.,"*Mukherjee, D.P., 1995. Proceeding of the Biomedical Engineering Conference"*, 7–9 Apr, 53.

[20] Song, Y., Xu, D.S., Yang, R., Li, D., Wu, W.T., Guo, Z.X., 1999a. *"Theoretical study of the effects of alloying elements on the strength and modulus of beta-type bio-titanium alloys"*. Materials Science and Engineering A 260 (1–2), 269–274

[21] Oshida, Y., 2006. *"Bioscience and Bioengineering of Titanium Materials"*. Elsevier Science, Oxford.