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ORIGINAL ARTICLE

Tailoring Properties of Fe-based Biodegradable Stent Materials by Grain Refinement: A Review

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ABSTRACT

Overtime, researchers on biodegradable stent materials are challenged to develop a material having adequate mechanical properties and degradation rate matching tissue healing rate. This study attempted to show that biodegradation rate of pure iron (Fe)-stent material in physiological fluid depends on effective grain size just like its mechanical properties by reviewing some pertinent works on pure Fe-based biometals. This study reviewed the works of some researchers who used different processing methods that altered the microstructure and extracted information on the dependence of degradation rates and mechanical properties of pure iron on average grain sizes. The major outcome of this survey is that finer grain size led to lower degradation rate of pure iron in near-neutral simulated body fluid while strength increased with decrease in grain size. Strength and ductility are mutually exclusive as extreme grain refinement of Fe-based metal improves strength at the expense of ductility but enhances corrosion resistance and biocompatibility. On the other hand, extreme grain refinement followed by annealing heat treatment increases grain size, lowers strength and restores ductility. This survey indicates strongly that grain refinement is a promising route of striking a balance among the required properties of iron-based stent material.

1 Introduction

Pure iron (Fe) has been in front of biodegradable stent materials research since its first clinical trial in 2001. A biodegradable metallic coronary stent is made to function as a short-term mechanical support for a severely obstructed or narrowed coronary arterial wall during healing and to degrade in vivo gradually and completely after implantation and completion of its intended purpose without causing toxicity in the human body [1, 2].

Sufficient strength and ductility, uniform in vivo degradation rate and adequate biocompatibility are the major property requirements that affect performance of stent materials. Specifically, a stent material should have uniform in vivo dissolution and corrosion rate of about 20 µm/year [3] in body fluids and a maximum grain size that ranges from 10 – 30 µm [1, 4].

Additionally, it should have sufficient strength (yield strength > 200 MPa; tensile strength > 300 MPa) to preserve its load-bearing function and adequate ductility (> 15 – 18 %) to enable easy and safe deployment during implantation [1].

For close to two decades, pure iron (Fe) - and magnesium (Mg) and their alloys have been studied as biodegradable metallic stent materials, until recently when the focus shifted to zinc (Zn) and its alloys due to the shortcomings of Fe and Mg.

Animal studies have revealed that pure Fe is fairly biocompatible, degrades uniformly but slowly in physiological media [5, 6, 7]. Fe also has sufficient mechanical properties of strength and ductility closer to the biodegradable metal design criteria [8]. Pure Mg possesses good biocompatibility, but has limitations of low strength, ductility, and very rapid

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degradation rate in physiological media [9, 10]. Zn degrades faster than Fe, but much slower than Mg [11]. Although, pure zinc displays an outstanding ductility (60 – 80 %), it has a low tensile strength of about 120 MPa [12].

The challenge facing the biodegradable metal research community has been how to increase corrosion rate of pure Fe while improving its mechanical characteristics further; how to improve pure Mg's mechanical properties while also increasing its corrosion resistance; and how to increase strength of pure Zn. Research on biodegradable metals has been prompted by the need to find answers to the aforementioned problems, targeted at striking strength-ductility-degradation rate balance without compromising biocompatibility.

Some of the materials' design strategies that have been employed to adjust mechanical properties and the degradation kinetics of pure Fe in order to enhance its bio-performance include selective alloying with active and nontoxic elements [13, 14, 15, 16], powder metallurgy [17, 18], additive manufacturing (direct metal printing [19], selective laser melting and laser metal deposition [20]), electro-deposition/electroforming [5], bulk or surface modification [21, 22, 23, 24, 25, 26], equal channel angle pressure (ECAP) technique [27], spark plasma sintering [28, 29] and magnetron sputtering [30, 32]. All these techniques affect microstructure developed in pure Fe both in the bulk and on the surface. The microstructural parameters affected include the crystallographic texture, grain size, grain shape and their distribution in the microstructure, which singly or collectively moderate the degradation kinetics of pure Fe.

Grain size is adjudged the outstanding microstructural parameter that moderates the physical, mechanical and dissolution behaviour of polycrystalline metals [33]. Grain refinement is a process of obtaining or inducing small grains in the structure of materials. Grain size is an important parameter influencing the biodegradation rate of biodegradable metals in physiological environments [20, 34].

As earlier stated, many workers have worked on how to improve both the mechanical properties and degradation rate of pure Fe stent materials, but very few have endeavoured to consider the influence of grain size on biodegradation specifically. The objective of this study is to show that biodegradation rate of pure iron depends on effective grain size just like its mechanical properties by reviewing some pertinent works on Fe-based biometals. The result of this survey could enable the optimalization of the required stent material properties of pure iron as a function of grain size.

2 Methodology

This study reviewed the works of three researchers [32, 27, 33, 30, 20] who used different processing methods to moderate the grain sizes of biodegradable pure iron and extracted information on the effect of grain size on the mechanical properties and degradation rates in simulated body fluid (SBF).

It has earlier been established that there is a relationship between the average grain size and corrosion rate of a metal [34], similar to the Hall-Petch relation that relates grain size to strength as shown in Equation 1 and graphically in Figure 1.

$$i_{corr} = A + Bd^{-1/2} \quad (1),$$

where i_{corr} is the corrosion current, *A* and *B* are constants and their values depend on the material (composition or impurity level) and on the nature of the media, respectively, and *d* is the average grain size.

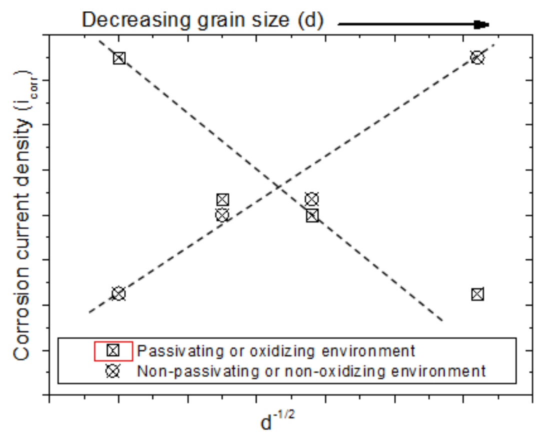

Figure 1: Relationship between corrosion current density and grain size in passivating and non-passivating environments [34]

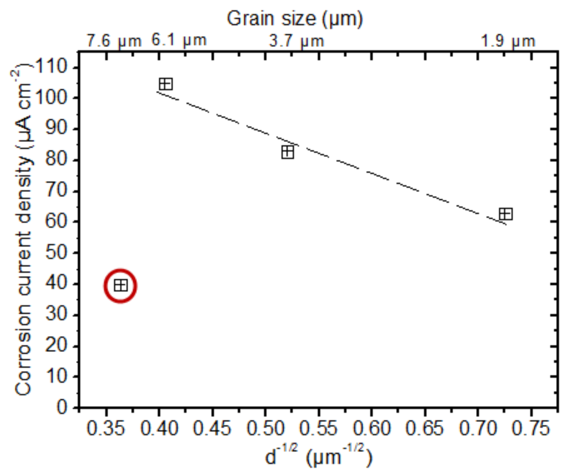

Figure 2: Grain size versus corrosion current density extracted from ref. [32]

Maryam Moravej, et al [32] studied the effect of deposition current density on the microstructure and degradation behaviour of electroformed pure iron (E-Fe) sheets in Hank's solution. The E-Fe sheets were produced using current densities of 1, 2, 5 and 10 Adm^{-2}. The as-electrodeposited Fe displayed weak textures corresponding to (101), (111) and (112) with average grain sizes less than 3 µm.

However, after annealing at 550 °C for 1 hr., the microstructure of iron samples changed because of the induced recrystallization, but the annealing texture remained the same as the as-electrodeposited. The results of the corrosion tests showed that among the deposited and annealed samples, the sample with a grain size of 6.1 µm exhibited uniform and higher corrosion rate than pure Fe. Annealing decreased the corrosion current density of the pure E-Fe samples as shown in Table 1.

Table 1: Average grain sizes, corrosion current densities of as-deposited and annealed electrodeposited Fe at different deposition current densities [32]

Deposition current density (Adm^{-2})	**1**	**2**	**5**	**10**
As-deposited				
Average grain size (µm)	2.5	4.4	2.5	3.0
corrosion current density i_{corr} (μAcm^{-2})	120	81	161	107
As-deposited annealed at 550 °C for 1 hr.				
Average grain size (µm)	3.7	7.6	6.1	1.9
corrosion current density i_{corr} (μAcm^{-2})	83	40	105	63

Table 2: Summary of the mechanical and dissolution behaviour of ECAPed pure iron [27]

Equal channel angular pressure (ECAP)	**Zeroth pass (0^{th} Fe)**	**2^{nd} pass (2^{nd} Fe)**	**4^{th} pass (4^{th} Fe)**	**8^{th} pass (8^{th} Fe)**
Average grain size	50 µm	40 µm	80 nm	200 nm
corrosion current density i_{corr} (μAcm^{-2})	7.79	7.11	2.32	1.66
Tensile strength (MPa)	262	313	381	470
Micro-hardness value ($kgfmm^{-2}$)	114	351	397	444

Table 3: Summary of the mechanical and dissolution behaviour of cold rolled and annealed pure iron [33]

Cold rolling and annealing	**85%UR-550**	**75%UR-800**	**85%UR-1000**
Average grain size (µm)	14.1	28.1	168.0
corrosion current density i_{corr} ($\mu A\ cm^{-2}$)	14.88	18.50	21.05
Tensile strength (MPa)	287	238	173

Table 4: Summary of the mechanical and dissolution behaviour of pure iron produced by magnetron sputtering [30]

Magnetron sputtering	**As-deposited pure Fe**	**s-Fe annealed at 400 °C for 2 hrs.**	**s-Fe annealed at 600 °C for 2 hrs.**	**s-Fe annealed at 800 °C for 2 hrs.**
Average grain size (µm)	0.5	0.58	0.8	3
Corrosion rate (mm/yr.)	0.06	0.07	0.08	0.1
Tensile strength (MPa)	606	604	381	267
Ultimate tensile strength (MPa)	634	616	413	343
% elongation (%)	1.4	1.6	13	14

Table 5: Summary of the mechanical and dissolution behaviour of pure iron produced by SLM and LMD [20]

Selective laser melting (SLM) and laser metal deposition (LMD)	**Cast pure Fe**	**Pure Fe produced by LMD**	**Pure Fe produced by SLM**
Average grain size (µm)	350	114	8
Corrosion rate (mm/yr.)	47	66	72
Tensile strength (MPa)	157.1	241.9	421.1
Ultimate tensile strength (MPa)	497.8	580.6	760.2

The degradation behaviour of the Fe samples was attributed to factors such texture, stored energy, accumulation of defects, grain boundaries and effect of annealing. However, a deeper consideration of the annealed E-Fe samples indicates that corrosion current density is grain size-dependent.

Neglecting data at deposition current of 2 Adm^{-2}, which is very close to 1 Adm^{-2}, a plot of the corrosion current density versus average grain size shows that corrosion current density decreases as average grain size decreases (Figure 2). In another assessment, the E-Fe had superior yield and tensile strengths but lower ductility than Armco® pure iron [35]. It also exhibited adequate biocompatibility [36].

F. L. Nie and co-workers [27] studied the microstructure; degradation behaviour; cellular responses and hemocompatibility of bulk nanocrystalline pure iron, compared with microcrystalline pure iron (50 µm). The bulk nanocrystalline (80 – 200 nm) pure iron rods (> 99.8 wt. %) were fabricated by the equal channel angular pressure (ECAP) technique up to eight passes. The results indicated that both the mechanical properties and corrosion current density of the Fe samples scaled with grain size with tensile strength and hardness increasing and the corrosion current density decreasing with decrease in grain size as shown in Table 2.

The nano-crystallization of pure iron improved its tensile strength and enhanced its corrosion resistance without pitting unlike that of the microcrystalline pure iron. The biocompatibility test of the ECAPed samples revealed that the nanocrystalline pure iron had good *in vitro* biocompatibility and the properties were clearly grain size-dependent. Nanocrystalline pure iron also stimulated better proliferation of fibroblast cells, promoted preferable endothelialization, and effectively inhibited proliferation of vascular smooth muscle cells (VSMCs).

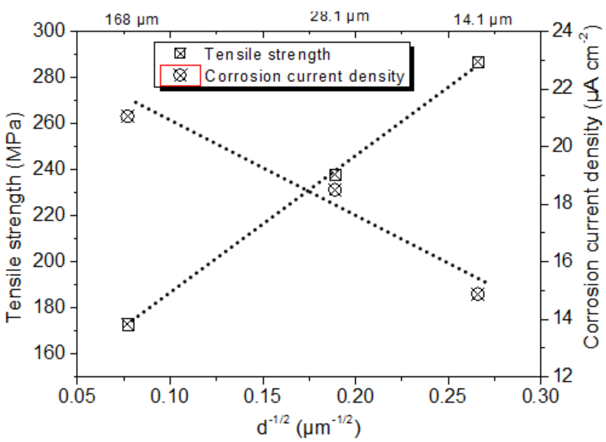

Figure 3: Grain size versus corrosion current density extracted from ref. [33]

Obayi, et al [33] investigated the effect of grain size (14.1 – 164.8 µm) on the mechanical and corrosion behaviour of pure Fe processed by cold rolling and annealing. The result demonstrated that dissolution rate decreases slightly with decrease in average grain size in Hank's solution while both the yield and tensile strength increased with decrease in average grain size according to Hall-Petch relation as shown in Table 3 and Figure 3.

The result also showed that percentage elongation or ductility decreased with decrease in grain size, but very big grain size was detrimental to ductility. Since mechanical properties increase and corrosion rate decreases with decrease in average grain size, the result shows that grain size moderation could be a tool for achieving a balance in the strength, ductility, and degradation rate of pure Fe as a candidate biodegradable material.

Till Jurgeleit, et al [30], produced free-standing, patterned, pure-iron foils (s-Fe) through magnetron sputtering. The s-Fe foils were annealed at 400 °C, 600 °C and 800 °C for 2 hrs. and their mechanical properties and degradation rates compared to the as-deposited s-Fe, cast iron and pure iron produced via other methods. The iron foils showed enhanced mechanical strengths, elongation at break and degradation rates that were grain size-dependent. The mechanical strengths decreased with increase in grain size while the ductility and degradation rate increased with increase in grain size as shown in Table 4. It is noteworthy that annealing led to the grain coarsening, which increased dissolution rate and ductility, but lowered mechanical strength.

Carluccio, et al [20], fabricated pure via selective laser melting (SLM) and laser metal deposition (LMD) and compared the mechanical properties and degradation rates with that of cast pure iron. The average grain sizes of SLM and LMD samples were much smaller than that of cast pure iron. This smaller grain size evolution of the SLM and LMD samples was attributed to the significantly higher cooling rates of the laser based additive manufacturing process. The smaller grain sizes led to higher mechanical properties of the SLM and LMD processed pure Fe.

It is evident here that decrease in grain size resulted in increase in corrosion rates of pure Fe manufactured by LMD and SLM as shown in Table 5. This display of increased corrosion rates of LMD and SLM samples with decrease in grain size is different from the works of others considered here. The degradation rates are far above the standard corrosion rate for biodegradable stents (20 µm/year). Though, a good technology for improving the degradation rate of pure iron, the adaptation of the method to produce cylindrical stents will need to put into consideration.

3 Outcome of grain refinement practice on properties of biodegradable Fe

The benefits of grain refinement to bio-performance of biodegradable Fe are enormous. The competing parameters that control the performance of bioabsorbable stents such as strength, degradation rate, ductility and biocompatibility are influenced strongly by effective average grain sizes. Strength and corrosion current density are inversely dependent on grain size with strength increasing and current density decreasing with decrease in grain size in most of the works reviewed here.

The dependence of strength and ductility on average grain size is mutually exclusive-strength increases while ductility decreases with decreasing grain size [31]. Ultrafine grained or nano-crystallized Fe exhibits homogeneous or uniform corrosion. However, very fine grained or nano grained Fe exhibit corrosion resistance in near-neutral SBF as shown in the work of F. L. Nie and co-workers [27].

Structurally, cardiovascular stent is a miniature and micron scale implant with a limitation on average grain size and strut thickness. The maximum average grain size ranges from 10-30 µm and strut thickness is in the range of 70 – 120 µm [4, 38, 39]. The importance of smaller grain size and strut thickness are adequately discussed in the work of Obayi et al [33].

More so, fine grained metallic implant materials exhibit better host-implant interactions and excellent biocompatibilities. The success of medical implants is dependent on level of interaction between the living tissue and implant's surface which is a surface phenomenon. This surface interaction which is a function of surface factors such as chemistry, energy, charge, wettability, and roughness, determines the extent of cell adhesion, protein adsorption, tissue healing rate, biocompatibility, and bio-functionality [40].

Since tissues in human body exist on a very small scale [40] and surface reactivity is more pronounced on this length scale, grain refinement benefits host-implant interactions and can lead to faster healing, better bonding of implant to anatomical sites and reduction in the rate of implant failure and revision surgeries.

Since yield and tensile strengths of Fe-based biometals increase with decrease in grain size and both corrosion current/corrosion rate in SBF and ductility decrease with decrease in average grain size, the expected compromise among these grain size-dependent properties is as shown in Figure 4. This compromise is achievable through controlled grain refinement processes.

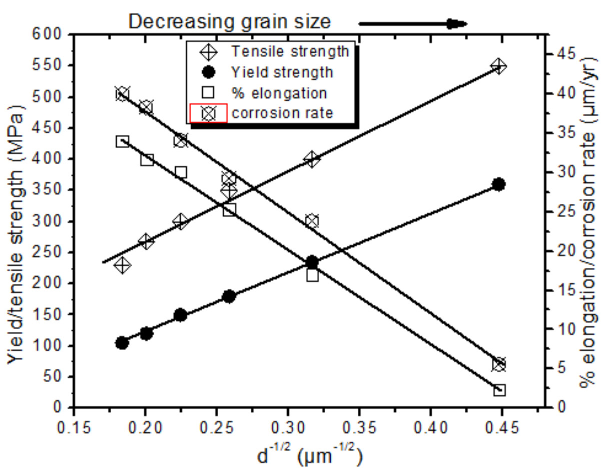

Figure 4: Expected compromise among grain size, mechanical and degradation properties of biodegradable Fe metal

4 Conclusion

This survey focused on the works of some researchers who used different processing methods to improve the mechanical properties and degradation rates of pure iron and extracted information on the dependence of these properties on average grain sizes. The major outcome of this review is as follows: the degradation rate/corrosion current density of pure Fe is grain size-dependent and decreases as grain size decreases in near-passive simulated body fluid; mechanical strength readily obeys the Hall-Petch relationship increasing with decrease in grain size while ductility decreases with decrease in average grain size; extreme grain refinement followed by annealing heat treatment increases grain size, lowers strength and restores ductility. This review indicates strongly that grain refinement is a promising route of tailoring and optimizing these grain size-dependent properties of pure iron for biodegradable stent application.

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Declaration of Competing Interest

Authors have declared that there is no existing conflict of interest.

References

[1] R. J. Werkhoven , W. H. Sillekens, J. B. J. M. van Lieshout, in Magnesium Technology 2011 , (Eds: W. H. Sillekens, S. R. Agnew, N. R. Neelameggham, S. N. Mathaudhu), The Minerals, Metals, and Materials Society, Warrendale, PA, USA 2011 , p. 419.

[2] Agung Purnama, Hendra Hermawan, Diego Mantovani. "Biodegradable Metal Stents: A Focused Review on Materials and Clinical Studies", Journal of Biomaterials and Tissue Engineering, Vol. 4, 2014, pp 1–6.

[3] F. Witte, N. Hort , F. Feyerabend , C. Vogt, in Corrosion of Magnesium Alloys (Ed: G. Song), Woodhead , Philadelphia, PA, USA, 2011, 403.

[4] M. Moravej, D. Mantovani, Biodegradable Metals for Cardiovascular Stent Application: Interests and New Opportunities, Int. J. Mol. Sci. 2011, 12(7), 4250-4270; https://doi.org/10.3390/ijms12074250

[5] Matthias Peuster; Carola Hesse; Tirza Schloo; Christoph Fink; Philipp Beerbaum; Christian von Schnakenburg. Long-term biocompatibility of a corrodible peripheral iron stent in the porcine descending aorta. Biomaterials. 2006, 27(28): 4955-4962.

[6] M. Peuster; P. Wohlsein; M. Brugmann; M. Ehlering; K. Seider; C. Fink; H. Brauer; A. Fischer; G. Hausdorf. A novel approach to temporary stenting: degradable cardiovascular stents produced from corrodible metal results 6-18 months after implantation into New Zealand white rabbits. Heart. 2001, 86(5): 563-569.

[7] R. Waksman; R. Pakala; R. Baffour; R. Seabron; D. Hellinga; F.O. Tio. Short-Term Effects of Biocorrodible Iron Stents in Porcine Coronary Arteries. Journal of Interventional Cardiology. 2008, 21(1): 15-20.

[8] H. Hermawan; D. Dube; D. Mantovani. Degradable metallic biomaterials for cardiovascular applications. Wood head Publishing Limited, Canada, 2010: 379-404.

[9] Carlo Di Mario; Huw Griffiths; Omer Goktekin; Nicolas peters; Jan Verbist; Marc Bosiers; Koen Deloose; Bernard Heublein; Roland Rohde; Victor Kasese; Charles Ilsley; Raimund Erbel. Drug-Eluting Bioabsorbable Magnesium Stent. Journal of Interventional Cardiology. 2004, 17(6): 391-395.

[10] F.Witte; V. Kaese; H. Haferkamp; E. Switzer; A. Meyer-Lindenberg; C.J. Wirth; H. Windhagen. In vivo corrosion of four magnesium alloys and the associated bone response. Biomaterials. 2005, 26(17): 3557-3563.

[11] Patrick K. Bowen, Jaroslaw Drelich, Jeremy Goldman, Zinc Exhibits Ideal Physiological Corrosion Behavior for Bioabsorbable Stents, Adv. Mater, 2013, 25, 2577-2582.

[12] E. A. Brandes, Ed. Smithells Metals Reference Book, Butterworths , London 1983.

[13] Schinhammer, M.; Anja C. Hanzi; Jorg F. Loffler; Peter J. Uggowitzer. Design strategy for biodegradable Fe-based alloys for medical applications. Acta Biomaterialia. 2010, 6(5): 1705-1713.

[14] Liu, B.; Y.F. Zheng. Effects of alloying elements (Mn, Co, Al, W, Sn, B, C and S) on biodegradability and in vitro biocompatibility of pure iron. Acta Biomaterialia. 2011, 7(3): 1407-1420.

[15] Liu, B.; Y.F. Zheng; L. Ruan. In vitro investigation of Fe30Mn6Si shape memory alloy as potential biodegradable metallic material. Materials Letters. 2010, 65(3): 540-543.

[16] Michael Schinhammer; Patrick Steiger; Frank Moszner; F. L¨offler; Peter J. Uggowitzer. Degradation performance of biodegradable Fe–Mn–C (-Pd) alloys, Materials Science & Engineering C. 2012, doi: 10.1016/j.msec.2012.10.013.

[17] Hermawan, H.; Alamdari, H.; D. Mantovani; Dominique Dube; Iron-manganese: new class of metallic degradable biomaterials prepared by powder metallurgy. Powder Metallurgy. 2008, 51(1): 38-45.

[18] Jaroslav Cˇapek, Dalibor Vojteˇch, Adela Oborna, Microstructural and mechanical properties of biodegradable iron foam prepared by powder metallurgy, Materials & Design 83 (2015) 468–482.

[19] Li, Y., Jahr, H., Lietaert, K., Pavanram, P., Yilmaz, A., Fockaert, L.I., Leeflang, M.A., Pouran, B., Gonzalez-Garcia, Y., Weinans, H., Mol, J.M.C., Zhou, J., Zadpoor, A.A., Additively manufactured biodegradable porous iron, Acta Biomaterialia (2018), doi: https://doi.org/10.1016/j.actbio.2018.07.011.

[20] Carluccio, Danilo; Bermingham, Michael; Kent, Damon; Demir, Ali Gökhan; Previtali, Barbara; Dargusch, Matthew S. (2019). Comparative Study of Pure Iron Manufactured by Selective Laser Melting, Laser Metal Deposition, and Casting Processes. Advanced Engineering Materials, (), adem.201900049–. doi:10.1002/adem.201900049

[21] Zhu, S.; Huang N.; Xu L.; Zhang Y.; Liu H,; Lei Y.; Sun H.; Yao Y. Biocompatibility of Fe-O films synthesized by plasma immersion ion implantation and deposition. Surface and Coatings Technology. 2009, 203(10-11): 1523-1529.

[22] Shengfa Zhu; Nan Huang; Hui Shu; Yanping Wu; Li Xu. Corrosion resistance and blood compatibility of lanthanum ion implanted pure iron by MEVVA. Applied Surface Science. 2009, 256(1): 99-104.

[23] Chen Chang-Zi, Shi Xing-Hua, Zhang Peng-Cheng, Bin Bai, Leng Yong-Xiang, Nan Huang, The microstructure, and properties of commercial pure iron modified by plasma nitriding. Solid State Ionics, 2008, 179, 971–974.

[24] Chen, H., Zhang, E., Yang, K. Microstructure, corrosion properties and biocompatibility of calcium zinc phosphate coating on pure ion for biomedical application. Materials Science and Engineering C, 2014, 34, 201-206.

[25] Tao Huang, Yufeng Zheng, Uniform and accelerated degradation of pure iron patterned by Pt disc arrays, Scientific Reports, 2016 | 6:23627 | DOI: 10.1038/srep23627.

[26] Lin W, Zhang G, Cao P, Zhang D, Zheng Y, Wu R, Qin L, Wang G, Wen T., Cytotoxicity, and its test methodology for a bioabsorbable nitrided iron stent. J Biomed Mater Res Part B 2015:103B:764–776.

[27] F.L. Nie; Y.F. Zheng; S.C. Wei; C. Hu; G. Yang. In vitro Corrosion, Cytotoxicity and Hemocmpatibility of Bulk Nanocrystalline Pure Iron. Biomedical Materials. 2010, 5, 065015.

[28] Cheng, J., Zheng, Y. In vitro study on newly designed biodegradable Fe-X composites (X=W, CNT) prepared by spark plasma sintering. Journal of Biomedical Materials Research Part B: Applied Biomaterials 101B, 2013, 485-497.

[29] T. Huang, J. Cheng, Y.F. Zheng, In vitro degradation and biocompatibility of Fe-P and Fe-Pt composites fabricated by spark plasma sintering, Mater. Sci. Eng. C35 (2014) 43–53, https://doi.org/10.1016/j.msec.2013.10.023.

[30] Jurgeleit, Till, Quandt, Eckhard, Zamponi, Christiane (2015). Magnetron Sputtering a New Fabrication Method of Iron Based Biodegradable Implant Materials. Advances in Materials Science and Engineering, 2015(), 1–9. doi:10.1155/2015/294686.

[31] Estrin, Y. and A. Vinogradov, Extreme grain refinement by severe plastic deformation: A wealth of challenging science. Acta Materialia, 2013. 61(3): p. 782-817.

[32] Maryam Moravej; Sofiene Amira; Frédéric Prima; Ahmed Rahem; Michel Fiset; Diego Mantovani. Effect of electrodeposition current density on the microstructure and the degradation of electroformed iron for degradable stents Mater. Sci. & Eng. B 176 (2011) 1812-1822.

[33] Camillus Sunday Obayi, Ranna Tolouei, Afghany Mostavan, Carlo Paternoster, Stephane Turgeon, Boniface Adeleh Okorie, Daniel Oray Obikwelu & Diego Mantovani. Effect of Grain Sizes on Mechanical Properties and Biodegradation Behavior of Pure Iron for Cardiovascular Stent Application. Biomatter, 2016, 6:1, e959874, DOI :10.4161/21592527.2014.959874

[34] K.D. Ralston; N.Birbilis; C.H.J. Davies. Revealing the relationship between grain size and corrosion rate of metal. Scripta Materialia. 2010, 63, 1201-1204.

[35] M. Moravej; F.Prima; M. Fiset; D. Mantovani. Electroformed iron as new biomaterial for degradable stents: Development process and structure-properties relationship. Acta Biomaterialia. 2010, 6(5): 1726-1735.

[36] M. Moravej; A. Purnama; M. Fiset; J. Couet; D. Mantovani. Electroformed pure iron as a new biomaterial for degradable stents: In vitro degradation and preliminary cell viability studies. Acta Biomaterialia. 2010, 6(5): 1843-1851.

[37] Serruys PW, Kutryk MJB. Handbook of coronary stents. Martin Dunitz Ltd, London, 2000.

[38] Murphy BP; Cuddy H; Harewood FJ; Connoley T. “The influence of grain size on the ductility of micro-scale stainless steel stent struts”, Journal of Materials Science: Materials in Medicine. 2006, Vol. 17, Number 1: pp 1-6.

[39] Paul Roach; David Eglin; Kirsty Rohde; Carole C. Perry. Modern Biomaterials: a review – bulk properties and implications of surface modifications, J. Mater Sci: Mater Med. 2007, 18, 1263-1277.

[40] Ayad S.; Boot-Handford; R., Humphries, M.J.; Kadler K.E.; Shuttleworth, A. The Extracellular Matrix Factsbook, Academic Press, San Diego, CA: 29, 1994.