STUDY ON THE MECHANICAL BEHAVIOR OF SILICA NANOPARTICLE REINFORCED MAGNESIUM BIO-NANOCOMPOSITE

NORFATIHAH BINTI ISMAIL

MASTER OF SCIENCE

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

TS. DR. NAFRIZUAN BIN MAT YAHYA
PENSYARAH KANAN
FAKULTI TEKNOLOGI KEJURUTERAAN
PEMBUATAN & MEKATRONIK ,
UNIVERSITI MALAYSIA PAHANG

____

(Supervisor's Signature)

Full Name : TS. DR NAFRIZUAN MAT YAHYA

Position : SENIOR LECTURER

Date : 07 MARCH 2022

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institution.

fatihah
____

(Student's Signature)

Full Name : NORFATIHAH BINTI ISMAIL

ID Number : MFI19005

Date : 07 MARCH 2022

STUDY ON THE MECHANICAL BEHAVIOR OF SILICA NANOPARTICLE REINFORCED MAGNESIUM BIO-NANOCOMPOSITE

NORFATIHAH BINTI ISMAIL

Thesis submitted in fulfilment of the requirements
for the award of the degree of
Master of Science

Faculty of Manufacturing and Mechatronic Engineering Technology

UNIVERSITI MALAYSIA PAHANG

MARCH 2022

ACKNOWLEDGEMENTS

First, I would like to express my deep thanks to Allah Almighty for putting me up to complete this Master of Science and this thesis as well. I am also grateful to Allah Almighty for the good health and well-being necessary for this thesis to be achieved.

I would like to portray my deepest appreciation to my supervisor, Ts. Dr. Nafrizuan Mat Yahya who always supporting and providing me with his insight, invaluable guidance, continuous encouragement and constant support in making this research possible. I am truly thankful for his tolerance, constructive criticism when I do the mistake and his commitment in assist me to complete my thesis.

My sincere thanks go to all my lab mates and members of the staff of the Manufacturing Engineering Department, UMP, especially Mr Aidil Shafiza Bin Shafiee who helped me in many ways and made my stay at UMP pleasant and unforgettable.

Biggest appreciation to my family who always been my source of affection, support and strength all these years. Their constant prayers have always been a gift to overcome any challenges and difficulties to achieve my goal. They will always be the reason behind my success. Lastly, special thanks to my friends who always motivate and support me through my master research. I would like to acknowledge their comments and suggestions, which was crucial for the successful completion of this study.

ABSTRAK

Tahun kebelakangan ini, keperluan biomaterial logam canggih untuk implan tiruan telah meningkat secara berperingkat dan pasaran bagi orang-orang yang mempunyai keretakan tulang dan degenerasi yang berpunca daripada perlanggaran, kecederaan olahraga atau proses penuaan normal, kebiasaannya memerlukan implant bahan bio untuk mendapatkan semula fungsi, dijangka berterusan. Magnesium (Mg) dan aloinya telah menarik minat yang besar untuk menjadi alternatif yang mungkin bahan implan ortopedik tradisional kerana sifat terbiodegradasi dan mekanikal mereka yang sangat baik. Bahan Mg ini menunjukkan rintangan kakisan yang rendah dalam persekitaran fisiologi walaupun manfaat besar mereka. Untuk meningkatkan tingkah laku kakisan dan mengekalkan kemerosotan pada kadar terkawal, bahan pengisi digunakan untuk aloi Mg untuk menghasilkan komposit. Selain daripada bahan oksida lain, slica (SiO_2) adalah satu lagi pilihan bahan pengisi yang boleh digunakan untuk menghasilkan bio-komposit berasaskan Mg kerana bioserasi yang tinggi. Teknik aloi mekanikal (MA) telah digunakan secara meluas dalam pembuatan bahan komposit, memerlukan transformasi bahan-bahan kerana pelbagai kimpalan sejuk, patah dan proses kimpalan semula zarah serbuk gilingan di penggilingan bola yang sangat bertenaga, menjadikan serbuk lebih seragam kerana keupayaannya untuk mengintegrasikan zarah pengukuhan ke dalam acuan logam pada jarak yang dekat. Oleh itu, dalam kajian ini, magnesium-nanosilica (Mg-SiO_2) sistem komposit telah dibuat oleh proses aloi mekanikal dengan peratusan berat yang berbeza daripada pengukuhan nanosilika untuk mencapai komposisi pengukuhan optimum. Untuk mendapatkan penggubalan, serbuk mentah peratusan yang dikehendaki telah diadun, dipadat dan disinter. Sampel yang dibuat kemudiannya disediakan untuk pencirian mikrostruktur, ujian mekanikal dan kakisan. Analisis mikrostruktur mendedahkan mikrostruktur sampel nanokomposit yang hampir sempurna dengan fasa baru pembentukan magnesium silisida (Mg_2Si). Sifat-sifat mekanikal komposit, termasuk kekerasan dan kekuatan tegangan, telah diperiksa. Ia diperhatikan dari sifat mekanikal yang diperolehi bahawa kekerasan dan kekuatan tegangan nanokomposit bertambah baik secara mendadak kerana pengeluaran fasa Mg_2Si dalam komposit. Di samping itu, nanokomposit yang dibuat mempunyai sifat rintangan kakisan yang lebih kuat daripada bahan Mg tulen. Penambahan 5 berat % nanosilica ke dalam acuan Mg mendedahkan sifat mekanikal dan kakisan menonjol berbanding dengan bahan acuan dan komposisi lain nanokomposit Mg-SiO_2. Nanokomposit Mg-5% SiO_2 ini menunjukkan potensinya untuk menjadi bahan bio-implan yang berkesan

ABSTRACT

In recent years, the need for advanced metallic biomaterials for artificial implants has gradually risen and the market for people with bone fractures and degeneration attributable to collisions, athletic injuries or normal ageing processes, often requiring biomaterial implants to regain function, is expected to continue. Magnesium (Mg) and its alloys have drawn tremendous interest in becoming possible alternatives to traditional orthopaedic implant materials due to their excellent biodegradable and mechanical properties. These Mg materials demonstrate low corrosion resistance in a physiological environment despite their great benefits. In order to improve corrosion behaviour and sustain degradation at a controlled rate, filler materials are applied to the Mg alloys to produce composites. Apart from other oxide materials, silica (SiO_2) is another option of filler material that can be used to produce Mg-based bio-composite due to its high biocompatibility. Mechanical alloying (MA) technique has been widely used in the manufacturing of composite materials, requiring the transformation of materials due to various cold welding, fracturing and re-welding processes of milled powder particles in a highly energetic ball mill, making the powder more homogeneous due to its ability to integrate the reinforcing particle into the metal matrix at a close distance. Therefore, in this study, magnesium- nanosilica (Mg-SiO_2) composite system has been fabricated by the mechanical alloying process with different weight percentages of nanosilica reinforcement in order to achieve an optimal reinforcement composition. In order to get the formulation, the raw powders with the desired percentage were blended, compacted and sintered. The fabricated samples were then prepared for microstructural characterization, mechanical and corrosion testing. Analysis of the microstructure revealed an almost flawless microstructure of nanocomposite samples with a new phase of magnesium silicide formation (Mg_2Si). Mechanical properties of the composites, including hardness and tensile strength, have been examined. It is observed from the obtained mechanical properties that the hardness and tensile strength of the nanocomposites improve dramatically due to the production of the Mg_2Si phase in the composite. In addition, the fabricated nanocomposite has stronger corrosion resistance properties than the pure Mg material. The addition of 5 wt. % nanosilica into the Mg matrix reveals superior mechanical and corrosion properties relative to the matrix material and other compositions of the Mg-SiO_2 nanocomposites. This Mg-5%SiO_2 nanocomposite demonstrated its potential to be an effective bio-implant material.

TABLE OF CONTENT

REFERENCES

Aboudzadeh, N., Dehghanian, C., & Shokrgozar, M. A. (2018). In vitro degradation and cytotoxicity of Mg − 5Zn − 0 . 3Ca / nHA biocomposites prepared by powder metallurgy. *Transactions of Nonferrous Metals Society of China*, *28*(9), 1745–1754.

Agarwal, S., Curtin, J., Duffy, B., & Jaiswal, S. (2016). Biodegradable magnesium alloys for orthopaedic applications: A review on corrosion, biocompatibility and surface modifications. In *Materials Science and Engineering C* (Vol. 68, pp. 948–963). Elsevier Ltd.

Ajith Kumar, K. K., Pillai, U. T. S., Pai, B. C., & Chakraborty, M. (2013). Dry sliding wear behaviour of Mg-Si alloys. *Wear*, *303*(1–2), 56–64.

Al-maamari, A. E. A., Iqbal, A. A., & Nuruzzaman, D. M. (2019). Wear and mechanical characterization of Mg–Gr self-lubricating composite fabricated by mechanical alloying. *Journal of Magnesium and Alloys*, *7*(2), 283–290.

Ali, M., Hussein, M. A., & Al-Aqeeli, N. (2019). Magnesium-based composites and alloys for medical applications: A review of mechanical and corrosion properties. In *Journal of Alloys and Compounds* (Vol. 792, pp. 1162–1190). Elsevier Ltd.

Alves, M. M., Prošek, T., Santos, C. F., & Montemor, M. F. (2017). Evolution of the: In vitro degradation of Zn-Mg alloys under simulated physiological conditions. *RSC Advances*, *7*(45), 28224–28233.

Amaravathy, P., Sathyanarayanan, S., Sowndarya, S., & Rajendran, N. (2014). Bioactive HA/TiO2 coating on magnesium alloy for biomedical applications. *Ceramics International*, *40*(5), 6617–6630.

Amiri, H., Mohammadi, I., & Afshar, A. (2017). Electrophoretic deposition of nano-zirconia coating on AZ91D magnesium alloy for bio-corrosion control purposes. *Surface and Coatings Technology*, *311*, 182–190.

Arifin, A., Sulong, A. B., Muhamad, N., Syarif, J., & Ramli, M. I. (2014). Material processing of hydroxyapatite and titanium alloy (HA/Ti) composite as implant materials using powder metallurgy: A review. In *Materials and Design* (Vol. 55, pp. 165–175). Elsevier Ltd.

Bakhsheshi-Rad, H. R., Abdellahi, M., Hamzah, E., Ismail, A. F., & Bahmanpour, M. (2016). Modelling corrosion rate of biodegradable magnesium-based alloys: The case study of Mg-Zn-RE-xCa (x = 0, 0.5, 1.5, 3 and 6 wt%) alloys. *Journal of Alloys and Compounds*, *687*, 630–642.

Bakhsheshi-Rad, H. R., Hamzah, E., Kasiri-Asgarani, M., Saud, S. N., Yaghoubidoust, F., & Akbari, E. (2016). Structure, corrosion behavior, and antibacterial properties of nano-silica/graphene oxide coating on biodegradable magnesium alloy for biomedical applications. *Vacuum*, *131*, 106–110.

Bansal, S., & Saini, J. S. (2015). Mechanical and wear properties of SiC/Graphite reinforced Al359 alloy-based metal matrix composite. *Defence Science Journal*, *65*(4), 330–338.

Beck, G. R., Ha, S. W., Camalier, C. E., Yamaguchi, M., Li, Y., Lee, J. K., & Weitzmann, M. N. (2012). Bioactive silica-based nanoparticles stimulate bone-forming osteoblasts, suppress bone-resorbing osteoclasts, and enhance bone mineral density in vivo. *Nanomedicine: Nanotechnology, Biology, and Medicine*, *8*(6), 793–803.

Bhakta, G., Sharma, R. K., Gupta, N., Cool, S., Nurcombe, V., & Maitra, A. (2011). Multifunctional silica nanoparticles with potentials of imaging and gene delivery. *Nanomedicine: Nanotechnology, Biology, and Medicine*, *7*(4), 472–479.

Bhat, D., Shabadi, R., Tingaud, D., Touzin, M., & Ji, G. (2019). Biocompatible silica-based magnesium composites. *Journal of Alloys and Compounds*, *772*, 49–57.

Bhat Panemangalore, D., Shabadi, R., Tingaud, D., Touzin, M., & Ji, G. (2019). Biocompatible silica-based magnesium composites. *Journal of Alloys and Compounds*, *772*, 49–57.

Biber, R., Pauser, J., Geßlein, M., & Bail, H. J. (2016). Magnesium-Based Absorbable Metal Screws for Intra-Articular Fracture Fixation. *Case Reports in Orthopedics*, *2016*, 1–4.

Biesiekierski, A., Wang, J., Abdel-Hady Gepreel, M., & Wen, C. (2012). A new look at biomedical Ti-based shape memory alloys. In *Acta Biomaterialia* (Vol. 8, Issue 5, pp. 1661–1669). Elsevier.

Bommala, V. K., Krishna, M. G., & Rao, C. T. (2019). Magnesium matrix composites for biomedical applications: A review. *Journal of Magnesium and Alloys*, *7*(1), 72–79.

Bornapour, M., Celikin, M., & Pekguleryuz, M. (2015). Thermal exposure effects on the in vitro degradation and mechanical properties of Mg-Sr and Mg-Ca-Sr biodegradable implant alloys and the role of the microstructure. *Materials Science and Engineering C*, *46*, 16–24.

Brooks, E., & Ehrensberger, M. (2017). Bio-Corrosion of Magnesium Alloys for Orthopaedic Applications. *Journal of Functional Biomaterials*, *8*(3), 38.

Chen, Qizhi Thouas, G. A. (2015). Metallic implant biomaterials. *Materials Science and Engineering R: Reports*, *87*, 1–57.

Chen, Shangsi Shi, Y., & Zhang, Xin Ma, J. (2019). 3D printed hydroxyapatite composite scaffolds with enhanced mechanical properties. *Ceramics International*, *45*(8), 10991–10996.

Chen, Yongjun Xu, Z., Smith, C., & Sankar, J. (2014). Recent advances on the development of magnesium alloys for biodegradable implants. In *Acta Biomaterialia* (Vol. 10, Issue 11, pp. 4561–4573). Elsevier Ltd.

Chen, X. (2017). Magnesium-based implants: Beyond fixators. *Journal of Orthopaedic*

Translation, *10*, 1–4.

Cheng, X. Y. Li, S. J. Murr, L. E., Zhang, Z. B., Hao, Y. L., Yang, R., Medina, F., & Wicker, R. B. (2012). Compression deformation behavior of Ti-6Al-4V alloy with cellular structures fabricated by electron beam melting. *Journal of the Mechanical Behavior of Biomedical Materials*, *16*(1), 153–162.

Cheng, W., Bai, Y., Wang, L., Wang, H., Bian, L., & Yu, H. (2017). Strengthening Effect of Extruded Mg-8Sn-2Zn-2Al Alloy: Influence of Micro and Nano-Size Mg2Sn Precipitates. *Materials*, *10*(7), 822.

Chiu, K. Y., Wong, M. H., Cheng, F. T., & Man, H. C. (2007). Characterization and corrosion studies of fluoride conversion coating on degradable Mg implants. *Surface and Coatings Technology*, *202*(3), 590–598.

Cho, D. H., Lee, B. W., Park, J. Y., Cho, K. M., & Park, I. M. (2017). Effect of Mn addition on corrosion properties of biodegradable Mg-4Zn-0.5Ca-xMn alloys. *Journal of Alloys and Compounds*, *695*, 1166–1174.

Datta, M. K., Chou, D. T., Hong, D., Saha, P., Chung, S. J., Lee, B., Sirinterlikci, A., Ramanathan, M., Roy, A., & Kumta, P. N. (2011). Structure and thermal stability of biodegradable Mg-Zn-Ca based amorphous alloys synthesized by mechanical alloying. *Materials Science and Engineering B: Solid-State Materials for Advanced Technology*, *176*(20), 1637–1643.

Deaquino-Lara, R., Gutiérrez-Castañeda, E., Estrada-Guel, I., Hinojosa-Ruiz, G., García-Sánchez, E., Herrera-Ramírez, J. M., Pérez-Bustamante, R., & Martínez-Sánchez, R. (2014). Structural characterization of aluminium alloy 7075-graphite composites fabricated by mechanical alloying and hot extrusion. *Materials and Design*, *53*, 1104–1111.

Ding, P., Liu, Y., He, X., Liu, D., & Chen, M. (2019). In vitro and in vivo biocompatibility of Mg–Zn–Ca alloy operative clip. *Bioactive Materials*, *4*, 236–244.

Draxler, J., Martinelli, E., Weinberg, A. M., Zitek, A., Irrgeher, J., Meischel, M., Stanzl-Tschegg, S. E., Mingler, B., & Prohaska, T. (2017). The potential of isotopically enriched magnesium to study bone implant degradation in vivo. *Acta Biomaterialia*, *51*, 526–536.

Durai, T. J., Sivapragash, M., & Sahayaraj, & M. E. (2017). Effect of sintering temperature on mechanical properties of mg-zr alloy. *International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) ISSN*, *7*(5), 117–122.

Echeverry-rendon, M., Paul, J., Robledo, S. M., Echeverria, F., & Harmsen, M. C. (2019). Coatings for biodegradable magnesium-based supports for therapy of vascular disease : A general view. *Materials Science & Engineering C*, *102*(52), 150–163.

Fan, X. (2019). Preparation and performance of hydroxyapatite/Ti porous biocomposite scaffolds. *Ceramics International*, *45*(13), 16466–16469.

Farraro, K. F., Kim, K. E., Woo, S. L. Y., Flowers, J. R., & McCullough, M. B. (2014). Revolutionizing orthopaedic biomaterials: The potential of biodegradable and bioresorbable magnesium-based materials for functional tissue engineering. *Journal of Biomechanics*, *47*(9), 1979–1986.

Ferreira, P. C., Piai, K. D. A., Takayanagui, A. M. M., & Segura-Muñoz, S. I. (2008). Aluminio como factor de riesgo para la enfermedad de Alzheimer. In *Revista Latino-Americana de Enfermagem* (Vol. 16, Issue 1, pp. 151–157). Escola de Enfermagem de Ribeirão Preto / Universidade de São Paulo.

Ghasali, E., Alizadeh, M., & Ebadzadeh, T. (2016). Mechanical and microstructure comparison between microwave and spark plasma sintering of Al-B4C composite. *Journal of Alloys and Compounds*, *655*, 93–98.

Ghasali, E., Alizadeh, M., Niazmand, M., & Ebadzadeh, T. (2017). Fabrication of magnesium-boron carbide metal matrix composite by powder metallurgy route: Comparison between microwave and spark plasma sintering. *Journal of Alloys and Compounds*, *697*, 200–207.

Gu, X. N., & Zheng, Y. F. (2010a). A review on magnesium alloys as biodegradable materials. In *Frontiers of Materials Science in China* (Vol. 4, Issue 2, pp. 111–115). Springer.

Gu, X. N., & Zheng, Y. F. (2010b). A review on magnesium alloys as biodegradable materials. In *Frontiers of Materials Science in China* (Vol. 4, Issue 2, pp. 111–115). Springer.

Guo, W., Wang, D., Fu, Y., Zhang, L., & Wang, Q. (2016). Dry Sliding Wear Properties of AZ31-Mg2Si Magnesium Matrix Composites. *Journal of Materials Engineering and Performance*, *25*(10), 4109–4114.

Gupta, M., & Meenashisundaram, G. K. (2015a). Insight into designing biocompatible magnesium alloys and composites :processing, mechanical and corrosion characteristics. In *National Library*.

Gupta, M., & Meenashisundaram, G. K. (2015b). Insight into Designing Biocompatible Magnesium Alloys and Composites Processing, Mechanical and Corrosion Characteristics. In *Springerbriefs in Materials*. Springer Singapore.

Harrison, R., Maradze, D., Lyons, S., Zheng, Y., & Liu, Y. (2014). Corrosion of magnesium and magnesium-calcium alloy in biologically-simulated environment. *Progress in Natural Science: Materials International*, *24*(5), 539–546.

Höhn, S., Virtanen, S., & Boccaccini, A. R. (2019). Protein adsorption on magnesium and its alloys: A review. *Applied Surface Science*, *464*(September 2018), 212–219.

Hornberger, H., Virtanen, S., & Boccaccini, A. R. (2012). Biomedical coatings on magnesium alloys - A review. In *Acta Biomaterialia* (Vol. 8, Issue 7, pp. 2442–2455). Elsevier.

Huang, S. J., & Ali, A. N. (2018). Effects of heat treatment on the microstructure and microplastic deformation behavior of SiC particles reinforced AZ61 magnesium metal matrix composite. *Materials Science and Engineering A*, *711*, 670–682.

Jayasathyakawin, S., Ravichandran, M., Baskar, N., Chairman, C. A., & Balasundaram, R. (2019). Magnesium matrix composite for biomedical applications through powder metallurgy – Review. *Materials Today: Proceedings*, *7*(1), 72–79.

Kang, M. H., Jang, T. S., Kim, S. W., Park, H. S., Song, J., Kim, H. E., Jung, K. H., & Jung, H. Do. (2016). MgF2-coated porous magnesium/alumina scaffolds with improved strength, corrosion resistance, and biological performance for biomedical applications. *Materials Science and Engineering C*, *62*, 634–642.

Katsuyoshi, K., Umeda, J., Kenshi, K., Yoshikazu, S., & Yoshihito, K. (2008). Wear Behavior of Sintered Magnesium Matrix Composites Reinforced with Mg2Si Particle under Wet Sliding Conditions. In *Transactions of JWRI* (Vol. 37, Issue 1).

Kaushik, Nc., Sri Chaitanya, C., & Rao, R. (2018). Abrasive grit size effect on wear depth of stir cast hybrid Al–Mg–Si composites at high stress condition. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, *232*(6), 672–684.

Kaynar, Ü. H., Şabikoğlu, I., Kaynar, S. Ç., & Eral, M. (2016). Modeling of thorium (IV) ions adsorption onto a novel adsorbent material silicon dioxide nano-balls using response surface methodology. *Applied Radiation and Isotopes*, *115*, 280–288.

Kazemi, A., Faghihi-Sani, M. A., & Alizadeh, H. R. (2013). Investigation on cristobalite crystallization in silica-based ceramic cores for investment casting. *Journal of the European Ceramic Society*, *33*(15–16), 3397–3402.

Khalajabadi, S. Z., Abdul Kadir, M. R., Izman, S., Bakhsheshi-Rad, H. R., & Farahany, S. (2014). Effect of mechanical alloying on the phase evolution, microstructure and bio-corrosion properties of a Mg/HA/TiO2/MgO nanocomposite. *Ceramics International*, *40*(PB), 16743–16759.

Khamkongkaeo, A., Bootchanont, A., Klysubun, W., Amonpattaratkit, P., Boonchuduang, T., Tuchinda, N., Phetrattanarangsi, T., Nuntawong, N., Kuimalee, S., & Lohwongwatana, B. (2019). Effect of phosphate compound on physical and mechanical properties of SiO2 ceramic. *Ceramics International*, *45*(1), 1356–1362.

Khan, M. U. F., Mirza, F., & Gupta, R. K. (2018). High hardness and thermal stability of nanocrystalline Mg–Al alloys synthesized by the high-energy ball milling. *Materialia*, *4*(August), 406–416.

Kirkland, N. T., Birbilis, N., Walker, J., Woodfield, T., Dias, G. J., & Staiger, M. P. (2010). In-vitro dissolution of magnesium-calcium binary alloys: Clarifying the unique role of calcium additions in bioresorbable magnesium implant alloys. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, *95B*(1), 91–100.

Kokubo, T., & Takadama, H. (2006). How useful is SBF in predicting in vivo bone bioactivity? *Biomaterials*, *27*(15), 2907–2915.

Krämer, M., Schilling, M., Eifler, R., Hering, B., Reifenrath, J., Besdo, S., Windhagen, H., Willbold, E., & Weizbauer, A. (2016). Corrosion behavior, biocompatibility and biomechanical stability of a prototype magnesium-based biodegradable intramedullary nailing system. *Materials Science and Engineering C*, *59*, 129–135.

Kumar, N., Bharti, A., & Saxena, K. K. (2020). A re-analysis of effect of various process parameters on the mechanical properties of Mg based MMCs fabricated by powder metallurgy technique. *Materials Today: Proceedings*, *26*, 1953–1959.

Li, Xuan Wang, Y., & Chu, Chenglin Han, Linyuan Bai, Jing Xue, F. (2020). A study on Mg wires/poly-lactic acid composite degradation under dynamic compression and bending load for implant applications. *Journal of the Mechanical Behavior of Biomedical Materials*, *105*(October 2019), 103707.

Li, J., Tan, L., Wan, P., Yu, X., & Yang, K. (2015). Study on microstructure and properties of extruded Mg-2Nd-0.2Zn alloy as potential biodegradable implant material. *Materials Science and Engineering C*, *49*, 422–429.

Li, X., Liu, X., Wu, S., Yeung, K. W. K., Zheng, Y., & Chu, P. K. (2016). Design of magnesium alloys with controllable degradation for biomedical implants: From bulk to surface. In *Acta Biomaterialia* (Vol. 45, pp. 2–30). Elsevier Ltd.

Liang, Y. X., Wu, Z. M., Fu, E. G., Du, J. L., Wang, P. P., Zhao, Y. B., Qiu, Y. H., & Hu, Z. Y. (2017). Refinement process and mechanisms of tungsten powder by high energy ball milling. *International Journal of Refractory Metals and Hard Materials*, *67*, 1–8.

Liu, Yong Kang, Z. X., Zhang, Jun Yi Wang, F., & Li, Y. Y. (2016). Influence of Pre-Solution Treatment on Microstructure and Mechanical Properties of Mg-Gd-Nd-Zn-Zr Alloy Processed by ECAP. *Advanced Engineering Materials*, *18*(5), 833–838.

Liu, L., Koo, Y., Collins, B., Xu, Z., Sankar, J., & Yun, Y. (2017). Biodegradability and platelets adhesion assessment of magnesium-based alloys using a microfluidic system. *PLOS ONE*, *12*(8), 20.

Michel, M. D., Serbena, F. C., & Lepienski, C. M. (2006). Effect of temperature on hardness and indentation cracking of fused silica. *Journal of Non-Crystalline Solids*, *352*(32–35), 3550–3555.

Mitić, Ž., Stolić, A., Stojanović, S., Najman, S., Ignjatović, N., Nikolić, G., & Trajanović, M. (2017). Instrumental methods and techniques for structural and physicochemical characterization of biomaterials and bone tissue: A review. *Materials Science and Engineering C*, *79*, 930–949.

Mohamad Rodzi, S. N. H., Zuhailawati, H., & Dhindaw, B. K. (2019). Mechanical and degradation behaviour of biodegradable magnesium–zinc/hydroxyapatite composite with different powder mixing techniques. *Journal of Magnesium and Alloys*, *7*(4), 566–576.

Mondal, A. K., & Kumar, S. (2009). Dry sliding wear behaviour of magnesium alloy based hybrid composites in the longitudinal direction. *Wear*, *267*(1–4), 458–466.

Munir, K., Wen, C., & Li, Y. (2020). Graphene nanoplatelets-reinforced magnesium metal matrix nanocomposites with superior mechanical and corrosion performance for biomedical applications. *Journal of Magnesium and Alloys*, *8*(1), 269–290.

Nagels, J., Stokdijk, M., & Rozing, P. M. (2003). Stress shielding and bone resorption in shoulder arthroplasty. *Journal of Shoulder and Elbow Surgery*, *12*(1), 35–39.

Nair, L. S., & Laurencin, C. T. (2007). Biodegradable polymers as biomaterials. In *Progress in Polymer Science (Oxford)* (Vol. 32, Issues 8–9, pp. 762–798). Pergamon.

Narayanasamy, P., Selvakumar, N., & Balasundar, P. (2018). Effect of weight percentage of TiC on their tribological properties of magnesium composites. *Materials Today: Proceedings*, *5*(2), 6570–6578.

Narayansamy P., & Selvakumar, N. (2017). Tensile, compressive and wear behaviour of self-lubricating sintered magnesium based composites. *Transactions of Nonferrous Metals Society of China (English Edition)*, *27*(2), 312–323.

Ng, W. F., Chiu, K. Y., & Cheng, F. T. (2010). Effect of pH on the in vitro corrosion rate of magnesium degradable implant material. *Materials Science and Engineering C*, *30*(6), 898–903.

Nie, K. B., Wang, X. J., Hu, X. S., Xu, L., Wu, K., & Zheng, M. Y. (2011). Microstructure and mechanical properties of SiC nanoparticles reinforced magnesium matrix composites fabricated by ultrasonic vibration. *Materials Science and Engineering A*, *528*(15), 5278–5282.

Niu, X., & Lu, L. (1997). Formation of magnesium silicide by mechanical alloying. *Advanced Performance Materials*, *4*(3), 275–283.

Parai, R., & Bandyopadhyay-ghosh, S. (2019). Engineered bio-nanocomposite magnesium sca ff old for bone tissue regeneration. *Journal of the Mechanical Behavior of Biomedical Materials*, *96*(April), 45–52.

Penther, D., Fleck, C., Ghasemi, A., Riedel, R., & Kamrani, S. (2017). Development and characterization of Mg-Sic nanocomposite powders synthesized by mechanical milling. *Key Engineering Materials*, *742 KEM*, 165–172.

Pereda, M. D., Alonso, C., Burgos-Asperilla, L., Del Valle, J. A., Ruano, O. A., Perez, P., & Fernández Lorenzo De Mele, M. A. (2010). Corrosion inhibition of powder metallurgy Mg by fluoride treatments. *Acta Biomaterialia*, *6*(5), 1772–1782.

Prakash, C., Kansal, H. K., Pabla, B., Puri, S., & Aggarwal, A. (2016). Electric discharge machining – A potential choice for surface modification of metallic implants for orthopedic applications: A review. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *230*(2), 331–353.

Prakash, C., Kansal, H. K., Pabla, B. S., & Puri, S. (2015). Processing and Characterization of Novel Biomimetic Nanoporous Bioceramic Surface on β-Ti Implant by Powder Mixed Electric Discharge Machining. *Journal of Materials*

Engineering and Performance, *24*(9), 3622–3633.

Prakash, C., Kansal, H. K., Pabla, B. S., & Puri, S. (2016). Multi-objective optimization of powder mixed electric discharge machining parameters for fabrication of biocompatible layer on β-Ti alloy using NSGA-II coupled with Taguchi based response surface methodology. *Journal of Mechanical Science and Technology*, *30*(9), 4195–4204.

Prakash, C., Kansal, H. K., Pabla, B. S., & Puri, S. (2017). Experimental investigations in powder mixed electric discharge machining of Ti–35Nb–7Ta–5Zrβ-titanium alloy. *Materials and Manufacturing Processes*, *32*(3), 274–285.

Prakash, C., Singh, S., Verma, K., Sidhu, S. S., & Singh, S. (2018). Synthesis and characterization of Mg-Zn-Mn-HA composite by spark plasma sintering process for orthopedic applications. *Vacuum*, *155*(May), 578–584.

Radha, R., & Sreekanth, D. (2017). Insight of magnesium alloys and composites for orthopedic implant applications – a review. In *Journal of Magnesium and Alloys* (Vol. 5, Issue 3, pp. 286–312). National Engg. Reaserch Center for Magnesium Alloys.

Rai, P., Rai, A., Kumar, V., Chaturvedi, R. K., & Singh, V. K. (2019). Corrosion study of biodegradable magnesium based 1393 bioactive glass in simulated body fluid. *Ceramics International*, *45*(14), 16893–16903.

Rajan, A. V., Sundaram, C. M., & Rajesh, A. V. (2020). Mechanical and morphological investigation of bio-degradable magnesium AZ31 alloy for an orthopedic application. *Materials Today: Proceedings*, *21*, 272–277.

Rashad, M., Pan, F., Asif, M., & Tang, A. (2014). Powder metallurgy of Mg-1%Al-1%Sn alloy reinforced with low content of graphene nanoplatelets (GNPs). *Journal of Industrial and Engineering Chemistry*, *20*(6), 4250–4255.

Rashad, M., Pan, F., Tang, A., Asif, M., Hussain, S., Gou, J., & Mao, J. (2015). Improved strength and ductility of magnesium with addition of aluminum and graphene nanoplatelets (Al+GNPs) using semi powder metallurgy method. *Journal of Industrial and Engineering Chemistry*, *23*, 243–250.

Razzaghi, M., Kasiri-Asgarani, M., Bakhsheshi-Rad, H. R., & Ghayour, H. (2020). Microstructure, mechanical properties, and in-vitro biocompatibility of nano- NiTi reinforced Mg–3Zn-0.5Ag alloy: Prepared by mechanical alloying for implant applications. *Composites Part B: Engineering*, *190*(September 2019).

Richards, A. M., Coleman, N. W., Knight, T. A., Belkoff, S. M., & Mears, S. C. (2010). Bone Density and Cortical Thickness in Normal, Osteopenic, and Osteoporotic Sacra. *Journal of Osteoporosis*, *2010*, 1–5.

Roa, J. J. Fargas, G. Jiménez-Piqué, E., & Mateo, A. (2014). Deformation mechanisms induced under high cycle fatigue tests in a metastable austenitic stainless steel. *Materials Science and Engineering A*, *597*, 232–236.

Sabetghadam-Isfahani, A., Abbasi, M., Sharifi, S. M. H., Fattahi, M., Amirkhanlou, S.,

& Fattahi, Y. (2016). Microstructure and mechanical properties of carbon nanotubes/AZ31 magnesium composite gas tungsten arc welding filler rods fabricated by powder metallurgy. *Diamond and Related Materials*, *69*, 160–165.

Salernitano, E., & Migliaresi, C. (2003). Composite Materials for Biomedical Applications: A Review. *Journal of Applied Biomaterials & Functional Materials*, *1*(1), 3–18.

Sanchez, A. H. M., Luthringer, B. J. C., Feyerabend, F., & Willumeit, R. (2015). Mg and Mg alloys: How comparable are in vitro and in vivo corrosion rates? A review. In *Acta Biomaterialia* (Vol. 13, pp. 16–31). Elsevier Ltd.

Seth, P. P., Singh, N., Singh, M., Prakash, O., & Kumar, D. (2020). Formation of fine Mg2Si phase in Mg–Si alloy via solid-state sintering using high energy ball milling. *Journal of Alloys and Compounds*, *821*, 153205.

Sezer, N., Evis, Z., Kayhan, S. M., Tahmasebifar, A., & Koç, M. (2018). Review of magnesium-based biomaterials and their applications. In *Journal of Magnesium and Alloys* (Vol. 6, Issue 1, pp. 23–43). National Engg. Reaserch Center for Magnesium Alloys.

Sezer, N., Evis, Z., Murat, S., Tahmasebifar, A., & Koç, M. (2018). Review of magnesium-based biomaterials and their applications. *Ournal of Magnesium and Alloy*, *6*, 23–43.

Shahin, M., Munir, K., Wen, C., & Li, Y. (2020). Magnesium-based composites reinforced with graphene nanoplatelets as biodegradable implant materials. *Journal of Alloys and Compounds*, *828*, 154461.

Sharma, S., Susan, D., Kothiyal, N. C., & Kaur, R. (2018). Graphene oxide prepared from mechanically milled graphite: Effect on strength of novel fly-ash based cementitious matrix. *Construction and Building Materials*, *177*, 10–22.

Simsek, I., & Ozyurek, D. (2019). Investigation of the wear and corrosion behaviors of Ti5Al2.5Fe and Ti6Al4V alloys produced by mechanical alloying method in simulated body fluid environment. *Materials Science and Engineering C*, *94*(September 2018), 357–363.

Song, G. Atrens, A. (2007). Recent Insights into the Mechanism of Magnesium Corrosion and Research Suggestions. *Advanced Engineering Materials*, *9*(3), 177–183.

Song, G. (2005). Recent progress in corrosion and protection of magnesium alloys. In *Advanced Engineering Materials* (Vol. 7, Issue 7, pp. 563–586). John Wiley & Sons, Ltd.

Song, G., & Atrens, A. (2007). Recent insights into the mechanism of magnesium corrosion and research suggestions. *Advanced Engineering Materials*, *9*(3), 177–183.

Song, G., & Song, S. (2007). A Possible Biodegradable Magnesium Implant Material. *Advanced Engineering Materials*, *9*(4), 298–302.

Soorya Prakash, K., Balasundar, P., Nagaraja, S., Gopal, P. M., & Kavimani, V. (2016). Mechanical and wear behaviour of Mg–SiC–Gr hybrid composites. *Journal of Magnesium and Alloys*, *4*(3), 197–206.

Sotoudeh Bagha, P., Khakbiz, M., Safaie, N., Sheibani, S., & Ebrahimi-Barough, S. (2018). Effect of high energy ball milling on the properties of biodegradable nanostructured Fe-35 wt.%Mn alloy. *Journal of Alloys and Compounds*, *768*, 166–175.

Tahmasebifar, A., Kayhan, S. M., Evis, Z., Tezcaner, A., Çinici, H., & Koç, M. (2016). Mechanical, electrochemical and biocompatibility evaluation of AZ91D magnesium alloy as a biomaterial. *Journal of Alloys and Compounds*, *687*, 906–919.

Tian, Y., Lu, C., Shen, Y., & Feng, X. (2019). Microstructure and corrosion property of CrMnFeCoNi high entropy alloy coating on Q235 substrate via mechanical alloying method. *Surfaces and Interfaces*, *15*(February), 135–140.

Tian, Y., Shen, Y., Lu, C., & Feng, X. (2019). Microstructures and oxidation behavior of Al-CrMnFeCoMoW composite coatings on Ti-6Al-4V alloy substrate via high-energy mechanical alloying method. *Journal of Alloys and Compounds*, *779*, 456–465.

Torabi, H., Hoseini, M., Sadrkhah, M., Faraji, G., & Masoumi, A. (2020). Microstructure, mechanical properties and bio-corrosion properties of Mg-HA bionanocomposites fabricated by a novel severe plastic deformation process. *Ceramics International*, *46*(3), 2836–2844.

Tun, Khin Sandar Gupta, M. (2007). Improving mechanical properties of magnesium using nano-yttria reinforcement and microwave assisted powder metallurgy method. *Composites Science and Technology*, *67*(13), 2657–2664.

Tun, K., Wong, W., Nguyen, Q., & Gupta, M. (2013). Tensile and Compressive Responses of Ceramic and Metallic Nanoparticle Reinforced Mg Composites. *Materials*, *6*(5), 1826–1839.

Vahid, A., Hodgson, P., & Li, Y. (2017). Reinforced magnesium composites by metallic particles for biomedical applications. *Materials Science and Engineering A*, *685*, 349–357.

Vassal, M. F., Nunes-Pereira, J., Miguel, S. P., Correia, I. J., & Silva, A. P. (2019). Microstructural, mechanical and biological properties of hydroxyapatite - CaZrO 3 biocomposites. *Ceramics International*, *45*(7), 8195–8203.

Waizy, H., Seitz, J. M., Reifenrath, J., Weizbauer, A., Bach, F. W., Meyer-Lindenberg, A., Denkena, B., & Windhagen, H. (2013). Biodegradable magnesium implants for orthopedic applications. In *Journal of Materials Science* (Vol. 48, Issue 1, pp. 39–50). Springer.

Wang, Shunfeng Wang, X., Draenert, F. G., Albert, O., Schröder, H. C., Mailänder, V., Mitov, G., & Müller, W. E. G. (2014). Bioactive and biodegradable silica biomaterial for bone regeneration. *Bone*, *67*, 292–304.

Wang, X., Schröder, H. C., Wiens, M., Ushijima, H., & Müller, W. E. G. (2012). Bio-silica and bio-polyphosphate: Applications in biomedicine (bone formation). In *Current Opinion in Biotechnology* (Vol. 23, Issue 4, pp. 570–578). Elsevier Current Trends.

Willumeit, R., Fischer, J., Feyerabend, F., Hort, N., Bismayer, U., Heidrich, S., & Mihailova, B. (2011). Chemical surface alteration of biodegradable magnesium exposed to corrosion media. *Acta Biomaterialia*, *7*(6), 2704–2715.

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

Witte, F. (2015). Reprint of: The history of biodegradable magnesium implants: A review. In *Acta Biomaterialia* (Vol. 23, Issue S, pp. S28–S40). Elsevier Ltd.

Witte, F., Hort, N., Vogt, C., Cohen, S., Kainer, K. U., Willumeit, R., & Feyerabend, F. (2008). Degradable biomaterials based on magnesium corrosion. *Current Opinion in Solid State and Materials Science*, *12*(5–6), 63–72.

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

Xin, Yunchang Liu, Chenglong Huo, K., Tang, G., Tian, X., & Chu, P. K. (2009). Corrosion behavior of ZrN/Zr coated biomedical AZ91 magnesium alloy. *Surface and Coatings Technology*, *203*(17–18), 2554–2557.

Xiong, G., Nie, Y., Ji, D., Li, J., Li, C., Li, W., Zhu, Y., Luo, H., & Wan, Y. (2016). Characterization of biomedical hydroxyapatite/magnesium composites prepared by powder metallurgy assisted with microwave sintering. *Current Applied Physics*, *16*(8), 830–836.

Xu, Liping Pan, F., Yu, Guoning Yang, L., Zhang, E., & Yang, K. (2009). In vitro and in vivo evaluation of the surface bioactivity of a calcium phosphate coated magnesium alloy. *Biomaterials*, *30*(8), 1512–1523.

Yazdimamaghani, M., Razavi, M., Vashaee, D., Moharamzadeh, K., Boccaccini, A. R., & Tayebi, L. (2017). Porous magnesium-based scaffolds for tissue engineering. In *Materials Science and Engineering C* (Vol. 71, pp. 1253–1266). Elsevier Ltd.

Ye, Xiaoxin Tse, Zion T.H. Tang, G., & Song, G. (2015). Mechanical properties and phase transition of biomedical titanium alloy strips with initial quasi-single phase state under high-energy electropulses. *Journal of the Mechanical Behavior of Biomedical Materials*, *42*, 100–115.

Yildirimer, Lara Thanh, Nguyen T.K. Loizidou, M., & Seifalian, A. M. (2011). Toxicological considerations of clinically applicable nanoparticles. In *Nano Today* (Vol. 6, Issue 6, pp. 585–607). Elsevier.

Yu, H., Zhou, H., Sun, Y., Ren, L., Wan, Z., & Hu, L. (2018). Microstructures and mechanical properties of ultrafine-grained Ti/AZ31 magnesium matrix composite prepared by powder metallurgy. *Advanced Powder Technology*, *29*(12), 3241–3249.

Yusop, A. H., Bakir, A. A., Shaharom, N. A., Abdul Kadir, M. R., & Hermawan, H. (2012). Porous biodegradable metals for hard tissue scaffolds: A review. In *International Journal of Biomaterials* (p. 10).

Zeng, R. Dietzel, W. Witte, F. Hort, N. Blawert, C. (2008). Progress and Challenge for Magnesium Alloys as Biomaterials. *Advanced Engineering Materials*, *10*(8), B3–B14.

Zeng, F., Cai, Q., Liu, X., Yao, Y., Zhuo, F., Gao, Q., Xie, Y., & Wang, Y. (2017). Fabrication and mechanical properties of mesoporous silica nanoparticles reinforced magnesium matrix composite. *Journal of Alloys and Compounds*, *728*, 413–423.

Zhang, Erlin Xu, L., Yu, Guoning Pan, F., & Yang, K. (2009). In vivo evaluation of biodegradable magnesium alloy bone implant in the first 6 months implantation. *Journal of Biomedical Materials Research. Part A*, *90*(3), 882–893.

Zhang, J., Kong, N., Shi, Y., Niu, J., Mao, L., Li, H., Xiong, M., & Yuan, G. (2014). Influence of proteins and cells on in vitro corrosion of Mg-Nd-Zn-Zr alloy. *Corrosion Science*, *85*, 477–481.

Zhang, L. N., Hou, Z. T., Ye, X., Xu, Z. Bin, Bai, X. L., & Shang, P. (2013). The effect of selected alloying element additions on properties of Mg-based alloy as bioimplants: A literature review. In *Frontiers of Materials Science* (Vol. 7, Issue 3, pp. 227–236). Springer.

Zhao, D., Wang, T., Hoagland, W., Benson, D., Dong, Z., Chen, S., Chou, D. T., Hong, D., Wu, J., Kumta, P. N., & Heineman, W. R. (2016). Visual H2 sensor for monitoring biodegradation of magnesium implants in vivo. *Acta Biomaterialia*, *45*, 399–409.

Zheng, Y. F., Gu, X. N., & Witte, F. (2014). Biodegradable metals. In *Materials Science and Engineering R: Reports* (Vol. 77, pp. 1–34). Elsevier Ltd.

Zheng, Y., Li, Y., Chen, J., & Zou, Z. (2015). Effects of tensile and compressive deformation on corrosion behaviour of a Mg-Zn alloy. *Corrosion Science*, *90*, 445–450.