A Short Review on Polymer, Metal and Ceramic Based Implant Materials

Deepika Shekhawat¹, Amit Singh¹, Ashray Bhardwaj², Amar Patnaik¹

¹Mechanical Engineering Department, MNIT Jaipur, 302017, Rajasthan, India
²Department of Mechanical Engineering, Thapar Institute of Technology, Patiala 147003, India

Email: deepikashekhawat91@gmail.com

Abstract. The present work focuses on the evaluation of polymer, metal and ceramic based biomaterials with particular emphasis on success rate of these materials till date along with the merits and demerits of these material system. Currently, the search for the materials with improved performance is on rise for biomedical (mainly total hip replacement, THR) applications owing to increase in the number of orthopedic patients worldwide. The clinicians utilized polymer and metal-based implants in ancient times to heal and treat the bone imperfections as well as fractures. The next generation materials required an update on properties, cell material interactions, repair and regeneration, that can only be acquired from recent knowledge related to materials. The commonly employed polymers (natural based polymers, proteins or polysaccharides; and synthetic polymers, poly (lactic acid), poly (glycolic acid), poly (ε-caprolactone), poly(3-hydroxybutyrate) (PHB)) and metals (SS, Mg-alloy, Ti-alloys, Co-alloy, silver, and nickel-titanium alloys) failed to fulfill the long-term durability and lacked in generating adequate bonding with the bones. It is intended that the facts and details abridged in this review article ought to be a beneficial tool in the development of progressively eminent implant materials like ceramic based materials against premature failure, cyclic stress generation, wear, corrosion fatigue, implant loosening and ultimate fracture.

1. Introduction

Biomaterials were in early days classified as materials employed in a medical device, which is designed to interact with biological structure [1]. The improvement in the implant materials is of considerable importance to heal and cure bone related deficiencies and fractures. The cases of revision hip surgery dramatically increased by 26 percent in past five years and this is expected to touch 137 percent by 2030 [2]. Hip surgeries are expected to face a rise from 1.8 million (2015) to 2.8 million by the year 2050 [3]. The current focus is on producing more durable implants with more success rate. Till date, there is no evidence of 100% success rate of implants made of polymer and metals. Human tissue mainly comprised of proteins (polymers) and bone mineral (ceramics) along with the elemental traces of metals. Bone in human body basically represents a bio-nanocomposite arrangement that has advanced and improved over billions of years. The hip joint bears a load of 3 times the body weight and peak load of 10 times the body weight is faced during rigorous activities which may include running, exercising, cycling, jumping, etc. There’s a general criterion before selecting any material for bone replacement applications which is as follows [4]:
- The selected material is highly biocompatible and it does not provoke any toxic reaction in the biological system.
- It must possess near about or close to bone physical and mechanical properties.
- Fabrication and processing of the selected material must be economically viable.
- Material must not wear out in any circumstances.

The selected material is said to be compatible with the existing tissue when it is compatible with the surface, osteocompatible, and mechanically compatible inside the human body. This review comprises of the different implant material types and their merits and demerits. The intention of this paper is also to point out the potential implant materials so far being investigated for total hip replacement (THR) applications. Polymer biomaterials are rarely used alone in bone replacement applications as they are responsible for generating immunogenic reactions, poor mechanical strength and implant loosening due to wear which ultimately causes early failure. On the other hand, metallic biomaterials face untimely mechanical failure resulting from cyclic stress generation. Secondly, many investigations have been carried out till date to understand the mechanism between fatigue and corrosion generation in the metallic implants under physiological environment. Moreover, the in-vitro and in-vivo investigation reveals the biological performance of any implant material that is responsible for determining the immune response, cell growth, physicochemical characteristics, and biodegradability rate [5]. Final comparison of these materials with the ceramic-based biomaterials is established on the basis of past literature as ultimate goal of all these bearings is to minimize the overall circumstances of the revision surgery. The three principal determinants responsible for the overall total joint performance are illustrated in Figure 1.

Figure 1. The three main determinants responsible for overall total joint performance [6,7]
1.1. Polymer based biomaterials

Polymer based biomaterials have been employed in the human body soon after its invention in the form of synthetic polymers. Clinical practice started exploiting polymer biomaterials owing to their strong, inert, and biocompatible nature for eliminating the burden of injured or infected bone in order to improve the patient’s life. Polymer biomaterials find implementation in multiple tissues like in cardiovascular [8], neural [9], musculoskeletal [10], and dermal tissues [11]. Before choosing any material for the biomedical implant system, it needs to have certain set of properties namely surface topography [12], free energy [13], and functional group [14]. Polymers unlock tailorableness with exceptional flexibility (chemical and physical surface behavior) as it provides a window of opportunity to precisely regulate the bulk properties (porosity, mechanical properties, biocompatibility, and biodegradation) [15]. In line with the previous studies carried out, the polymeric biomaterials for implants with their merits and demerits have been illustrated in Table 1.

Table 1. Polymeric biomaterials employed in implants and their characteristics

| S. No. | Polymer based biomaterial | Merits                                                                 | Demerits                                                                 | Reference |
|-------|--------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------|-----------|
| 1     | Ultra-High Molecular Weight Polyethylene | Superior mechanical properties, enhanced modulus, and creep resistance as compared to other polymer biomaterials | Releases debris, Adverse tissue biological reactions | [16] |
| 2     | Polyethylene (PE)       | Low friction coefficient, fracture toughness, low density, high impact strength | Over prolonged period, wear debris are released | [17,18] |
| 3     | Polymethylmethacrylate (PMMA) | Superior osseointegration, Absence of no interim fibrous tissue around cemented elements | Faces microfractures, Releases cement particles, Causes localized foreign-body response | [19,20] |
| 4     | High-density polyethylene (HDPE) | Good processability, Biocompatible, Lower cost and good mechanical properties Better creep resistance than UHMWPE | Lower wear resistance with long term use Can be used in combination with UHMWPE for best results | [21] |
| 5     | Polytetrafluoroethylene (PTFE) | Chemically inert, Nontoxic, Nonflammable | Very low resistance and high rate of wear More susceptible to creep, Causes compression syndromes | [22–26] |
| 6     | Polyacetal              | Good wear resistance, Polyacetal-polyethylene combination mostly used in artificial joints | Degrade to form formaldehyde and exaggerates in the presence of moisture, elevated temperature or mechanical force applied for prolonged time | [27–29] |
1.2. Metal based biomaterials

Millions of people throughout the world suffer from hip arthritis, and total hip replacement (THR) is the efficacious treatment for this end-stage arthritis responsible for joint pains or joint diseases. According to an updated projection, US alone possessed 52.5 million arthritis patients in the year 2010 and this number is going to touch 78.4 million by 2040 [30]. Patients confronting problem of arthritis undergo total hip replacement surgery that replaces the hip joint with a ball and socket joint mimicking its complete biomechanics. This ball and socket configuration can be made of metallic head articulating against metal cup (Metal-on-Metal, MoM) or polymer lining (Metal-on-Polymer, MoP) [31].

On the other hand, with the advantages of metal-based implants and successful surgeries, there comes some severe disadvantages too that needs to be considered before selecting them for the final application. They require further progress and advancements. With the increasing life-expectancy, the need for long lasting and durable implants with no adverse reaction is also rising at a faster pace. At present, less than 1 percent of the implant bearings have metal-on-metal (MoM) articulations [32,33]. In a study conducted by Laaksonen and teammates [34] found that out of all 56 studies, adverse local tissue reactions and rate of revision surgeries were found to be very high in numbers. Some of the metal-based implants used are titanium and titanium alloys, cobalt-chromium alloy, stainless steel, cobalt-chromium-molybdenum alloys, and tantalum. In line with the previous studies carried out, the metallic biomaterials for implants with their merits and demerits have been illustrated in Table 2.

Table 2. Metallic biomaterials employed in implants and their characteristics

| S. No. | Metal based | Merits | Demerits | Reference |
|--------|-------------|--------|----------|-----------|
| 1      | Titanium    | Superior mechanical properties, Great biocompatibility, light weight, biocompatible, lower young’s modulus | Causes allergic reactions, poor tribological properties, expensive, lower shear strength | [35–38] |
| 2      | Stainless steel (bio-steels) | Inexpensive to fabricate, high elastic modulus, high wear resistance, low cost, good fatigue resistance | Crevise and pitting corrosion in long-term applications, Ni and Cr allergy, stress shielding effect | [38,39] |
| 3      | Cobalt-Chromium-based alloys | Highly corrosion resistant with a minimal susceptibility, high wear resistance, biocompatibility, load bearing materials | Early implant loosening rate, limited use, difficult to machine and expensive to process, Ni and Cr allergy | [38,40,41] |
| 4      | Ti-6Al-4V    | With proper surface treatments, fatigue strength could be improved | Release of ions, intoxication, bone resorption, fracture of implant, restricted mobility | [42–44] |
| 5      | Ti-Nb-Ta-Zr (TZNT) alloy | Good mechanical properties, Superior biological properties, Enhanced wear characteristics, Biocompatibility, Great corrosion resistance, | Lower strength | [45][46] |
1.3. Ceramic based biomaterials

Implants these days are expected to deliver a lifetime of more than 30 years due to rising population and demand for surgery is growing at faster pace in young patients. All these selected implants must be very reliable and fracture resistant in in-vivo environment. Polymer-based and metal-based implants didn’t meet these requirements, hence researchers and doctors shifted to ceramics as an alternative material to these. Ceramic materials are generally suited for bone replacement bearings owing to their high hardness, high wear resistance and superb biocompatibility. In addition to these, ceramic produces a negligible amount of wear debris in comparison to metals and polymer-based implants. In comparison to micro-sized, nano-ceramic composites possess lower grain size which aids in executing higher overall mechanical, tribological as well as biological performance inside human body. Bioceramics, a sub-category of biomaterials are basically of three types, i.e. bioinert (does not interact with the living tissues and are non-toxic), biodegradable (that are absorbed and dissolved inside the body), and bioactive ceramics (capable in forming bonding with the hard and soft tissues). Ceramic-on-ceramic (ceramic femoral head and ceramic cup inserts) combination is also helpful in reducing abrasion [50]. A lot of work has been conducted in this area to find out the most compatible ceramic material for joint prosthesis applications. In line with the previous studies carried out, the ceramic biomaterials for implant applications with their merits and demerits have been illustrated in Table 3.

| S. No. | Ceramic based | Merits | Demerits | Reference |
|--------|---------------|--------|----------|-----------|
| 1      | Bioinert      | Reduces wear, long term risk of dislocation, higher biocompatibility, tissue regeneration | Slow crack growth, hydrothermal aging, phase transformation, expensive | [51,52] |
| 6      | Mg based alloys | Mechanically very strong, biocompatible | Presence of unprotected oxide film leads to corrosion of the implant, Growth of H2 bubbles during corrosion | [38,47] |
| 7      | NiTi shape memory alloy | Low Young’s modulus, returns to its original shape after a temperature change, superelastic, biocompatible | Ni causes allergy due to wear debris | [48,49] |
| 8      | Noble Metals (gold (Au), silver (Ag), platinum (Pt) and iridium (Ir)) | Resistant to chemical and electrochemical corrosion | Susceptible to corrosion during in-vivo and in-vitro environment | [38] |

**Table 3. Ceramic biomaterials employed in implants and their characteristics**
biocompatible nature, higher mechanical characteristics hence faces catastrophic failure, expensive, problem of squeaking

Tantulum oxide

Superior biocorrosion and wear resistance, decreases osteolysis and mechanical properties, low ion release, Dislocation, instability

[57–59]

2 Biodegradable

Calcium phosphates

High stiffness, mechanical properties similar to trabecular bone Not stable at high temperatures, low tensile strength

[60]

Hydroxyapatite

Non-toxic to living tissues, promotes bone growth, cheaper, highly biocompatible, better bonding and fixation, high osseointegration properties Used as coating over metallic implants hence may face delamination and wear by abrasion

[61,62]

3 Bioactive

Bioactive glass

High rate of bone formation, enhanced fixation, better cell growth and enhanced stability Difficult to fabricate, brittle nature, low bending and fatigue strength, lower fracture toughness, low ductility

[53,63]

Conclusion

In this review, all the three implant materials were taken into account, showing their merits and demerits faced in actual applications inside the body. This also indicated that single matrix materials were not sufficient enough to meet the desirable demand of hip joint. This paper summarizes in short, the findings and contributions made by all the three biomaterials that suggests that the only way is to fabricate multi-phase components. Polymers and metallic implants failed in presenting bioactivity in in-vivo environment and were unable to uphold mechanical properties in corrosive media, that ultimately ended in reduced durability. Besides this, previous studies have also indicated release of hazardous ions (metallic implants) near implant site and in blood stream. Polymer implants also face debris release issue that reduces durability of the implant in long run.

On the contrary, ceramic based implants demonstrated excellent bioactivity and biocompatibility characteristics in in-vivo environment, and were also resistant to corrosion. In comparison to polymer-based and metal-based implants, ceramic implants resulted in superior osseointegration and osseoconduction behavior inside human body that promoted fast healing of fractured and infected bones. The only shortcomings with the ceramic biomaterials is their brittleness and they tend to fail under tensile or cyclic loading condition that limits their complete utilization in load bearing bones. With designs prompted by natural biological structures, different combinations like bioceramic/polymer composites have instigated enhanced strength and fracture toughness in comparison to ‘parent’ metal and polymer biomaterials used alone. The current age of biomaterial composites belongs to 4th generation biomaterials that combines more than two different phases which
results in better control of properties like mechanical, antibacterial, osteoconductivity, degradation rate, physicochemical, interaction with cells, surface topography and wettabi
tility.

To conclude, bio-composite materials offers an opportunity to adopt a multidesign/multistage approach that provides better control of material and biological properties as compared to the polymers, metals and ceramics alone.

**Future direction**

Clinical use of ceramic biomaterials is limited owing to difficulty of producing intricate, complex and modified surfaces. A continuous effort in the fabrication of novel and improved biomaterials is crucial with the insight of attaining improved biological, tribological, chemical and mechanical properties as identical as possible to that of the original bones or tissues that need to be replaced. Bio-composites are emerging with advanced combination of desirable properties originating from mixing dissimilar materials. In comparison to polymer and metal-based implants, ceramic based bearings exhibit adequate compression strength, tribological characteristics, biocompatibility, and corrosion resistance ensuring its widespread use in medical implants with enhanced longevity. The following areas can be recommended for further work:

1. The structure-property-mechanism relationship of an implant system is of prime importance in terms of future research. Also, precise regulation of the nanoparticles incorporated in the base ceramic matrix is of paramount concern for obtaining desirable mechanical and microstructural properties in the synthesized material.
2. Further research is required to develop new ceramic based composite materials with negligible wear and prove to be a successful alternative bearing material and check for its interaction with the cell response and antibacterial properties.
3. More investigations must concentrate towards finding new methodologies, processes and growths in the field of manufacturing techniques (like 3D printing, fused deposition modeling, selective laser sintering, bioprinting, etc.) along with their advantages and limitations.
4. More studies are required in the direction of surface modification techniques to improve and enhance the reliability of implants to be implanted inside human body.
5. Limited literature is available for the impact of high and low temperature variations in the final synthesized bio-composite material that is an important aspect from a technological point of view.

**References**

[1] D.F. Williams, Definitions in Biomaterials, 1987. https://doi.org/10.1177/0001848182032002006.

[2] I. Sanli, J.J.C. Arts, J. Geurts, Clinical and Radiologic Outcomes of a Fully Hydroxyapatite-Coated Femoral Revision Stem: Excessive Stress Shielding Incidence and its Consequences, J. Arthroplasty. 31 (2016) 209–214. https://doi.org/10.1016/j.arth.2015.08.037.

[3] C. Pabinger, H. Lothaller, N. Portner, A. Geissler, Projections of hip arthroplasty in OECD countries up to 2050, HIP Int. 28 (2018) 498–506. https://doi.org/10.1177/1120700018757940.

[4] K.S. Katti, Biomaterials in total joint replacement, Colloids Surfaces B BioInterfaces. 39 (2004) 133–142. https://doi.org/10.1016/j.colsurfb.2003.12.002.

[5] P. Ducheyne, Comprehensive Biomaterials, Elsevier. 1 (2015). https://doi.org/10.1016/B978-0-08-055294-1.00275-0.
[6] X. Zhang, G. Shi, X. Sun, W. Zheng, X. Lin, G. Chen, Factors Influencing the Outcomes of Artificial Hip Replacements, Cells Tissues Organs. 206 (2018) 254–262. https://doi.org/10.1159/000500518.

[7] J. Alvarado, R. Maldonado, J. Marxuach, R. Otero, Biomechanics of hip and knee prostheses 1, Appl. Eng. Mech. Med. (2003) 6–22.

[8] M. Sarem, F. Moztarzadeh, M. Mozafari, How can genipin assist gelatin/carbohydrate chitosan scaffolds to act as replacements of load-bearing soft tissues?, Carbohydr. Polym. 93 (2013) 635–643. https://doi.org/10.1016/j.carbpol.2012.11.099.

[9] A. Yazdanpanah, G. Amoabediny, P. Shariatpanahi, J. Nourmohammadi, Synthesis and Characterization of Polylactic Acid Tubular Scaffolds with Improved Mechanical Properties for Vascular Tissue Engineering, Trends Biomater. Artif. Organs. 28 (2014) 99–105.

[10] P. Zarrintaj, A.M. Urbanska, S. Seyed, V. Goodarzi, M. Reza, M. Mozafari, A facile route to the synthesis of anilinic electroactive colloidal hydrogels for neural tissue engineering applications, J. Colloid Interface Sci. 516 (2018) 57–66. https://doi.org/10.1016/j.jcis.2018.01.044.

[11] M. Gholipournalekabadi, A. Samadikuchaksaraye, A.M. Seifalian, A.M. Urbanska, H. Ghanbarian, Silk fibroin/amniotic membrane 3D bi-layered artificial skin, Biomed. Mater. (2017) 1–36.

[12] A. Ranella, M. Barberoglou, S. Bakogianni, C. Fotakis, E. Stratakis, Tuning cell adhesion by controlling the roughness and wettability of 3D micro/nano silicon structures, Acta Biomater. 6 (2010) 2711–2720. https://doi.org/10.1016/j.actbio.2010.01.016.

[13] M. Hoefling, F. Iori, S. Corni, K. Gottschalk, Interaction of Amino Acids with the Au (111) Surface: Adsorption Free Energies from Molecular Dynamics Simulations, Langmuir. 26 (2010) 8347–8351. https://doi.org/10.1021/la904765u.

[14] F. Meder, T. Daberkow, L. Treccani, M. Wilhelm, M. Schowalter, L. Mädler, K. Rezwan, Protein adsorption on colloidal alumina particles functionalized with amino,carboxyl,sulfonate and phosphate groups, Acta Biomater. 8 (2012) 1221–1229. https://doi.org/10.1016/j.actbio.2011.09.014.

[15] M. Rahmati, C.P. Pennisi, E. Budd, A. Mobasher, M. Mozafari, Biomaterials for Regenerative Medicine: Historical Perspectives and Current Trends, Cell Biol. Transl. Med. 4 (2018) 1–19.

[16] S. Affatato, S.A. Jaber, P. Taddei, Polyethylene based polymer for joint replacement, Biomater. Clin. Pract. Adv. Clin. Res. Med. Devices. (2017) 149–165. https://doi.org/10.1007/978-3-319-68025-5_6.

[17] M.A. Mcgee, D.W. Howie, S.D. Neale, D.R. Haynes, M.J. Pearcy, The role of polyethylene wear in joint replacement failure, Proc. Inst. Mech. Eng. 211 (1997) 65–72.

[18] V. Premnath, W.H. Harris, M. Jasty, E.W. Merrill, Gamma sterilization of UHMWPE articular implants: an analysis of the oxidation problem, Biomaterials. 17 (1996) 1741–1753.

[19] E. Gibon, L.A. Cordova, L. Lu, T.-H. Lin, Z. Yao, M. Hamadouche, S.B. Goodman, The
biological response to orthopedic implants for joint replacement. II: Polyethylene, ceramics, PMMA, and the foreign body reaction, J. Biomed. Res. (Part B Appl. Biomater. 105 (2016) 1–7. https://doi.org/10.1002/jbm.b.33676.

[20] S.B. Goodman, R. Chin, Prostaglandin E2 Levels in the Membrane Surrounding Bulk and Particulate Polymethylmethacrylate in the Rabbit Tibia A Preliminary Study, Clin. Orthop. Relat. Res. 257 (1990) 305–309.

[21] H. Fouad, R. Elleithy, High density polyethylene/graphite nano-composites for total hip joint replacements: Processing and in vitro characterization, J. Mech. Behav. Biomed. Mater. 4 (2011) 1376–1383. https://doi.org/10.1016/j.jmbbm.2011.05.008.

[22] D. Dowson, N.C. Wallbridge, Laboratory wear tests and clinical observations of the penetration of femoral heads into acetabular cups in total replacement hip joints: I: Charnley prostheses with polytetrafluoroethylene acetabular cups, Wear. 104 (1985) 203–215.

[23] Polytetrafluoroethylene, Meyler’s Side Eff. Drugs (Sixteenth Ed. (2016) 872–873. https://doi.org/10.1016/B978-0-444-53717-1.01318-4.

[24] L.L. Radulovic, Z.W. Wojcinski, PTFE (Polytetrafluoroethylene; Teflon®), Third Edit, Elsevier, 2014. https://doi.org/10.1016/B978-0-12-386454-3.00970-2.

[25] A.A. Edidin, S.M. Kurtz, Influence of Mechanical Behavior on the Wear of 4 Clinically Relevant Polymeric Biomaterials in a Hip Simulator, J. Arthroplasty. 15 (2000) 321–331.

[26] R. Kumar, B. Malaval, M. Antonov, G. Zhao, Performance of polyimide and PTFE based composites under sliding, erosive and high stress abrasive conditions, Tribol. Int. 147 (2020) 106282. https://doi.org/10.1016/j.triboint.2020.106282.

[27] H.A. Mckellop, G. Bradley, Evaluation of Wear in an All-Polymer Total Knee Replacement. Part 1: Laboratory Testing of Polyethylene on Polyacetal Bearing Surfaces, Clin. Mater. 14 (1993) 117–126.

[28] J.R. Martin, R.J. Gardner, Effect of Long Term Humid Aging on Plastics, Polym. Eng. Sci. 21 (1981) 557–565.

[29] V. V. Pchelintsev, A.Y. Sokolov, Kinetic Principles and Mechanisms of Hydrolytic Degradation of Mono- and Polyacetals-A Review, Polym. Degrad. Stab. 21 (1988) 285–310.

[30] J.M. Hootman, C.G. Helmick, K.E. Barbour, K.A. Theis, M.A. Boring, Updated Projected Prevalence of Self-Reported Doctor-Diagnosed Arthritis and Arthritis-Attributable Activity Limitation Among US Adults, 2015 – 2040, Arthritis Rheumatol. 68 (2016) 1582–1587. https://doi.org/10.1002/art.39692.

[31] S. Balachandran, Z. Zachariah, A. Fischer, D. Mayweg, M.A. Wimmer, D. Raabe, M. Herbig, Atomic Scale Origin of Metal Ion Release from Hip Implant Taper Junctions, Adv. Sci. 7 (2020) 1–10. https://doi.org/10.1002/advs.201903008.

[32] C.L. Peters, J.A. Erickson, J.M. Gililland, Clinical and Radiographic Results of 184 Consecutive Revision Total Knee Arthroplasties Placed with Modular Cementless Stems, J. Arthroplasty. 24 (2009) 48–53. https://doi.org/10.1016/j.arth.2009.04.033.
[33] A. Mirzajavadkhan, S. Rafieian, M.H. Hasan, Toxicity of Metal Implants and Their Interactions with Stem Cells: A Review, Int. J. Eng. Mater. Manuf. 5 (2020) 2–11.

[34] I. Laaksonen, G.S. Donahue, R. Madanat, K.T. Makela, H. Malchau, Outcomes of the Recalled Articular Surface Replacement Metal-on-Metal Hip Implant System: A Systematic Review, J. Arthroplasty. 32 (2016) 341–346. https://doi.org/10.1016/j.arth.2016.06.060.

[35] M. Takemoto, S. Fujibayashi, M. Neo, J. Suzuki, Mechanical properties and osteoconductivity of porous bioactive titanium, Biomaterials. 26 (2005) 6014–6023. https://doi.org/10.1016/j.biomaterials.2005.03.019.

[36] T.R. Rautray, R. Narayanan, K. Kim, Ion implantation of titanium based biomaterials, Prog. Mater. Sci. 56 (2011) 1137–1177. https://doi.org/10.1016/j.pmatsci.2011.03.002.

[37] R.P. Verma, Titanium based biomaterial for bone implants: A mini review, Mater. Today Proc. 26 (2020) 3148–3151. https://doi.org/10.1016/j.matpr.2020.02.649.

[38] Q. Chen, G.A. Thouas, Metallic implant biomaterials, Mater. Sci. Eng. R. 87 (2015) 1–57. https://doi.org/10.1016/j.mser.2014.10.001.

[39] 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. 26 (2005) 3557–3563. https://doi.org/10.1016/j.biomaterials.2004.09.049.

[40] A. Aherwar, A.K. Singh, A. Patnaik, Cobalt Based Alloy: A Better Choice Biomaterial for Hip Implants, Trends Biomater. Artif. Organs. 30 (2016) 50–55. https://doi.org/10.13140/RG.2.1.2501.5284.

[41] B. Moretti, V. Pesce, G. Maccagnano, G. Vicenti, P. Lovreglio, L. Soleo, P. Apostoli, Peripheral neuropathy after hip replacement failure: is vanadium the culprit?, Elsevier Ltd, 2012. https://doi.org/10.1016/S0140-6736(12)60273-6.

[42] H. Matusiewicz, Potential release of in vivo trace metals from metallic medical implants in the human body: From ions to nanoparticles – A systematic analytical review, Acta Biomater. 10 (2014) 2379–2403. https://doi.org/10.1016/j.actbio.2014.02.027.

[43] Y.Y. Sun, S.L. Lu, S. Gulizia, C.H. Oh, D. Fraser, M. Leary, M. Qian, Fatigue Performance of Additively Manufactured Ti-6Al-4V: Surface Condition vs. Internal Defects, J. Mater. (2020). https://doi.org/10.1007/s11837-020-04025-7.

[44] R. Kumar, M. Antonov, Y. Holovenko, A. Surzenkov, Erosive Wear Resistance of Nature-inspired Flexible Materials, Tribol. Lett. 68:51 (2020) 1–8. https://doi.org/10.1007/s11249-020-01296-8.

[45] S. Nasibi, K. Alimohammadi, L. Bazli, S. Eskandarinezhad, A. Mohammadi, N. Sheysi, TZNT alloy for surgical implant applications: A systematic review, J. Compos. Compd. 2 (2020) 62–68.

[46] W. Xu, X. Lu, J. Tian, C. Huang, M. Chen, Y. Yan, L. Wang, X. Qu, C. Wen, Microstructure, wear resistance, and corrosion performance of Ti35Zr28Nb alloy fabricated by powder metallurgy for orthopedic applications, J. Mater. Sci. Technol. (2019).
https://doi.org/10.1016/j.jmst.2019.08.041.

[47] F. Findik, Recent developments of metallic implants for biomedical applications, Period. Eng. Nat. Sci. 8 (2020) 33–57.

[48] M.B. and B. Bin Sahari, NiTi Shape Memory Alloys, Promising Materials in Orthopedic Applications, in: Shape Mem. Alloy. Process. Charact. Appl., 2014: p. 261. https://doi.org/10.13140/2.1.3388.2247.

[49] M.H. Elahinia, M. Hashemi, M. Tabesh, Manufacturing and processing of NiTi implants: A review, Prog. Mater. Sci. 57 (2012) 911–946. https://doi.org/10.1016/j.pmatsci.2011.11.001.

[50] B.G. Willmann, Ceramic Femoral Heads for Total Hip Arthroplasty, Adv. Eng. Mater. 29 (2000) 114–122.

[51] M.H. Maneshian, M.K. Banerjee, Reverse martensitic transformation in alumina-15 vol% zirconia nanostructured powder synthesized by high energy ball milling, J. Alloys Compd. 459 (2008) 531–536. https://doi.org/10.1016/j.jallcom.2007.05.024.

[52] M.H. Maneshian, M.K. Banerjee, Effect of sintering on structure and mechanical properties of alumina-15 vol% zirconia nanocomposite compacts, J. Alloys Compd. 493 (2010) 613–618. https://doi.org/10.1016/j.jallcom.2009.12.166.

[53] M.Z. Ibrahim, A.A.D. Sarhan, F. Yusuf, M. Hamdi, Biomedical materials and techniques to improve the tribological, mechanical and biomedical properties of orthopedic implants- A review article, J. Alloys Compd. 714 (2017) 636–667. https://doi.org/10.1016/j.jallcom.2017.04.231.

[54] P. Hernigou, C. Bouthors, What every surgeon should know about Ceramic-on-Ceramic bearings in young patients, EFORT Open Rev. 1 (2016) 107–111. https://doi.org/10.1302/2058-5241.1.000027.

[55] C. Goswami, I.K. Bhat, A. Patnaik, Fabrication of Ceramic Hip Implant Composites : Influence of Silicon Nitride on Physical , Mechanical and Wear Properties, Silicon. (2019) 19–20. https://doi.org/10.1007/s12633-019-00222-5.

[56] C. Goswami, A. Patnaik, I.K. Bhat, T. Singh, Synthesis and Characterization of Al2O3–Cr2O3-Based Ceramic Composites for Artificial Hip Joint, Springer Singapore, 2018. https://doi.org/10.1007/978-981-13-2718-6.

[57] B. Rahmati, A.A.D. Sarhan, W.J. Basirun, W.A.B.W. Abas, Ceramic tantalum oxide thin film coating to enhance the corrosion and wear characteristics of Ti-6Al-4V alloy, J. Alloys Compd. (2016). https://doi.org/10.1016/j.jallcom.2016.03.188.

[58] B. Rahmati, A.A.D. Sarhan, E. Zalnezhad, Z. Kamiab, A. Dabbagh, D. Choudhury, Development of tantalum oxide (Ta-O) thin film coating on biomedical Ti-6Al-4V alloy to enhance mechanical properties and biocompatibility, Ceram. Int. 42 (2016) 466–480. https://doi.org/10.1016/j.ceramint.2015.08.133.

[59] A. Brüggemann, E. Fredlund, H. Mallmin, N.P. Hailer, A. Brüggemann, E. Fredlund, H. Mallmin, N.P. Hailer, A. Brüggemann, E. Fredlund, H. Mallmin, N.P. Hailer, Are porous
tantalum cups superior to conventional reinforcement rings?, Acta Orthop. (2016). https://doi.org/10.1080/17453674.2016.1248315.

[60] A.D. Speirs, T.R. Oxland, B.A. Masri, A. Poursartip, C.P. Duncan, Calcium phosphate cement composites in revision hip arthroplasty, Biomaterials. 26 (2005) 7310–7318. https://doi.org/10.1016/j.biomaterials.2005.05.062.

[61] H. Zhou, J. Lee, Nanoscale hydroxyapatite particles for bone tissue engineering, Acta Biomater. 7 (2011) 2769–2781. https://doi.org/10.1016/j.actbio.2011.03.019.

[62] P. Choudhury, D.C. Agrawal, Sol–gel derived hydroxyapatite coatings on titanium substrates, Surf. Coat. Technol. 206 (2011) 360–365. https://doi.org/10.1016/j.surfcoat.2011.07.031.

[63] M.N. Rahaman, D.E. Day, B.S. Bal, Q. Fu, S.B. Jung, L.F. Bonewald, A.P. Tomsia, Bioactive glass in tissue engineering, Acta Biomater. 7 (2011) 2355–2373. https://doi.org/10.1016/j.actbio.2011.03.016.