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A brief review on titanium alloy for dental, biotechnology and biomedical applications

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Abstract

Titanium (Ti) is used for various application due to its light, durable and polished silver-white element. Titanium has two forms of allotropy called rutile and anatase, due to white color, slow-melting point and high power and high power in uniform distribution and diffusion in other compounds, is the main raw material of white color in the dyeing industry. It is known for making paper, plastics, rubber and various other materials. Therefore, regarding its use and high application in this paper we reviewed the conventional and advance application of Ti. The presence of small amounts of impurities such as oxygen, nitrogen, carbon and hydrogen in which are soluble in the metal, causes the mineral fragility of the metal and prevents its commercial exploitation. At the same time, it is very light and does not cause skin allergies and have scratch-resistant properties. The purpose of this study is to introduce and application of titanium in various industries. The main use of titanium in the industry is in the form of metal and titanium dioxide, the use of metal is not used much due to problems in its preparation and purification, but instead, the use of oxide in the form of TiO_2 is widely used in industry; So that 90% of the primary industries are consuming titanium oxide. The human body easily accepts titanium because it has been proven to be more biocompatible than stainless steel or cobalt chromium (CoCr). In addition, titanium has a higher fatigue strength than many other metals which helps to transform it as a desired material in dental and orthopedic applications.

Keywords: Titanium, Alloys, Production technology, Biomedical application, Dentistry

1- Introduction

The purpose of this study is to introduce the application of titanium in various industries such as dentistry as dental implant or filler. The main use of titanium in the industry is in the form of metal and titanium dioxide (titanium nanoparticles), the use of metal is not used much due to problems in its preparation and purification, but the use of oxide in the form of TiO_2 is widely used in industry application. Therefore, 90% of the primary industries are consuming titanium oxide in different form [1-7]. Recently, many researchers work on titanium nanoparticles for bone and orthopedic applications [8-14]. The titanium is a strategic metal in aircraft engines and in-house construction, transportation equipment, chemical industries, power generation units, alloy industries, submarine construction, chemical plants, nuclear and thermal power plant cooling devices [15-18]. The main use of titanium dioxide in the paint industry is as a pigment, and it is also used in the ceramic, plastic, paper, and electronics industries. Consumption of this substance in developed countries is almost ten times that of developing countries. Titanium metal is very resistant to corrosion environments and the pure titanium or its low-impurity alloys are used in petroleum desulfurization plants, in oil well equipment, and in required joints, as well as in medical applications [19-21]. On the other hand, titanium-coated steel sheets are now produced in the world, which due to their anti-erosion properties are widely used in the oil industry. These products used in the desulfurization stages of oil derivatives in refineries [4]. Principles of extraction of titanium such as aluminum and other similar metals are done by electrolytic methods. In the last 50 years, a lot of investment has been made to make soluble titanium compounds in a molten electrolyte and settle on the cathode of the electrolyte solution [5]. Titanium is produced in this way in the form of a sponge, porous materials or powder form. In various cases, their microscopic structure consists of spherical particles that are between 1 and 100 micrometers [6-11]. The titanium sponge processed is structurally similar to the Kroll sponge**.** FFC processing is more economical than Kroll**.**

2- Physical properties of titanium

Titanium is a relatively light metal with a density of 4.54 gr/cm^3, which is located between the density of aluminum (2.71 gr/cm3) and iron (7.87 gr/cm^3). The melting point of titanium is 1668°C, which is higher than the melting point of iron, and its elastic modulus is between the values of iron and aluminum. It has a high melting point due to the formation of TiO_2 nanoparticles which is used for corrosion resistance. These forms are alpha which has a compact hexagonal structure, and B, which has a centered cubic crystal structure. In pure titanium, phase alpha is stable up to 883°C and at more than 883°C in which this phase becomes phase b [15-32].

3-Applications of titanium nanoparticles

3-1-Titanium in the industry

The main advantages of titanium nanoparticles in various engineering applications such as high specific strength, high temperature strength over a wide temperature range, and corrosion resistance in most corrosive environments. Titanium nanoparticles used in various industry typically as an alloy that has greater mechanical strength, higher temperature strength, and other beneficial properties than pure titanium. Titanium alloys are most used at very low temperatures up to a temperature range of 500-600°C. One of the things that are considered in the development of new titanium alloys is the percentage of alloying. Alloying the titanium increases the strength of alloys, but it causes a decrease in ductility. Ti-6Al-4V alloy is limited in terms of temperature, which limits its application to a temperature of about 400°C, and for high temperatures, another alloy such as Ti-6Al-2Sn-4Zr-2Mo+Si must be used. Ti-6Al-4V climbing alloy is widely used in turbine engines and aircraft structures [33-39].

3-2-Titanium in mechanical application

Easy machining properties of titanium and its alloying properties facilitate the combination of high-quality alloys with aluminum, vanadium, and other elements. Titanium alloys in aircraft, ships, missiles, and spacecraft appear in high performance components such as firewalls, helicopter exhaust ducts, and sensitive structural components. The surface of the material contains non-chemical oxides that increase the corrosion resistance to mineral acids and chlorides. In the many industrial, biomedical and biomaterials challenges, titanium sheet tensile and fatigue strength also contribute to fatigue and fracture resistance. Its tensile strength changes from 20,000 to 200,000 psi and heat resistance above 600°C enable it to play a role in any environment. The high alloying properties of titanium ensure that the demand for metal industrial application.

3-3-Titanium in cosmetics

Titanium nanoparticles is also used in the production of synthetic fibers in which the pure titanium dioxide powder is used as a pigment in food products. Titanium dioxide is used in sunscreens (lotions) due to its ability to protect the skin and it is a superior white pigment. Rutile is composed of a denser crystal lattice than anatase and is denser and has a higher refractive index. The pigment should be usable in the sulfated pathway (rutile or synthetic rutile should not be used) and has a higher FeO/Fe_2O_3 ratio (ferric acid and sulfur) [6, 10-17].

3-4-Titanium in orthopedics field

Titanium was first used in orthopedic applications in the 1950s. Orthopedic branches of surgery are related to the musculoskeletal system. Orthopedic surgeons use both surgical and non-surgical methods to treat musculoskeletal injuries, spinal diseases, and sports injuries. Currently, titanium alloys are a top priority for orthopedic equipment such as hip joints, skeletal joints, knee joints, spinal fluid shelf, shoulder and elbow joints, and bone plates and scaffold. Titanium is a popular metal for orthopedic specialists because of its overall resistance to iron corrosion. In addition, it has been shown to be compatible with bone density, strength, and has a small elastic modulus. Hence, it is an excellent material for the orthopedic field.

Fig. 1 The screw and spine produced by Titanium with mechanical process

3-5-Titanium in dentistry field

Most dental implant bases are made of titanium with a non-allergic metal that is biocompatible which means that the immune system does not consider it as an external attacker and therefore may not attack it [40-44]. Titanium nanoparticles has been used successfully for many years, not only for dental implants however also for bone, arm, back, and bone replacement.

The titanium fuses well with the jawbone during a process called implantation in which during this process, titanium becomes part of the bone and attached to the host bone as shown in Fig. 2 [38-44].

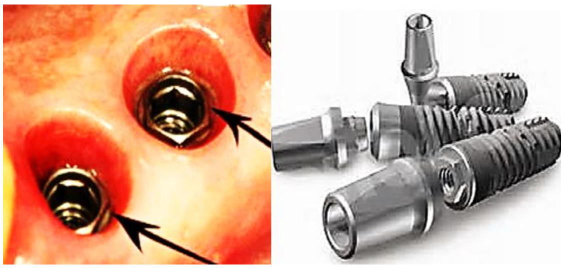

Fig. 2 The screw and titanium implant for dental application

Titanium is extremely strong but much lighter than gold alloys, therefore: it is ideal for patients who need strong and comfortable dental implants. This mechanical feature reduces the risk of pain or discomfort during changes in ambient temperature. The success rate of titanium as a dental implant is more than 95% for tooth implants remain in place and in case that the patient can use them for the rest of his life. One or more implants can be used to support a denture crown or overdenture [31-45]. Titanium-based dental implants have both cosmetic and therapeutic applications with none toxic properties in the human body which can tolerate high doses of titanium. However, some studies have shown that titanium and titanium dioxide is slightly toxic in animal laboratories, especially in mice exposed to titanium dioxide [45-52]. A small black spot has been observed in the lungs. Titanium is generally recognized as one of the safest metals for dental implant use. But some studies have shown that titanium has caused many problems in the area implanted in the mouth [52-53]. Of course, these reported problems account for less than one percent of implanted cases. One of the reasons for the failure of dental implants can be related to the allergic reactions of the human body to the metal titanium. Some reports of severe allergic reactions such as arrhythmia or eczema, swelling, inflammation, necrosis, and bone resorption due to titanium tooth implant base implantation have been reported. Titanium is a metal that has a very long lifespan in the human body [36-47]. Titanium is implanted in various types in the form of rods or dental implant screws inside the human body, which lasts for more than 20 years in the human body. Even if the patient takes good care of the dental implants, especially the titanium implant bases, even for more than 20 years. One of the reasons for dental implant failure may be the occurrence of allergies and allergic reactions to the titanium base of the dental implant, so it is better to inform your implantologist in case of side effects such as swelling, pain, burning, and itching of the implanted area [38-44]. The bases of titanium implants, which are used as the roots of dentures, are chemically and physically welded to the jawbone tissue. The lower part of the titanium root is implanted in a small hole in the bone so that it can fuse well with the jawbone. It can also be used as a heart patch booster [45-49].

4- Other aspects of Titanium

4-1- Titanium alloy systems

To explain the different microstructures observed in titanium alloys, it is necessary to be aware of the different stabilization systems and fuzzy diagrams of titanium binary alloys [26-33]. However, it should be noted that binary fuzzy diagrams are considered for near-equilibrium conditions. In a stable binary system, a, the alloying elements are mostly soluble in phase a and the metamorphic line B moves upwards.

Some of the substituents that stabilize the titanium phase are aluminum, gallium, and germanium. Of these three elements, aluminum is the most important. In fact, almost all titanium alloys contain aluminum because aluminum is added to titanium for formability and lightness. Some interstitial alloying elements also stabilize phase alpha. Oxygen, nitrogen, and carbon are all stabilizing elements [8]. Because oxygen is an impurity found in all commercial titanium alloys, it is an important stabilizing element. Sometimes the strength can be determined using the amount of oxygen. In titanium, the fast constituents of eutectoids are the elements silicon and copper. These elements cause phase B to decompose very quickly into a compound and phase. The mild constituents of eutectoid are elements such as chromium, manganese, iron, nickel, and cobalt. These elements are very slow in the rate of eutectoid decay. These elements have high solubility in both solid phases alpha and beta but do not have much effect on phase stabilization. These elements are useful because they participate in the solidification of the solid solution and slow down the formation of a harmful phase in titanium such as the phase [10].

4-2- Classification of titanium alloys

Titanium alloys are classified according to the phases in their structure. Finally, thiamine alloys, which are stabilized at room temperature after phase B after leaving the temperature of the dissolution operation, are classified as alloy B. Titanium alloys can generally not be heated and welded on and near alloys. These alloys have medium strength, good toughness and good creep resistance at high temperatures [11].

4-3- Titanium alloys

Chemical composition and specific applications due to Ti-%5 Al-%2.5Sn. Today, there is only one major alloy that has a commercial application, and its nominal composition is aluminum and tin are both stabilizers in titanium. Oxygen, which is present in almost all titanium alloys, is as strong a stabilizer as aluminum and increases the strength of titanium. The alloy is weldable and has good stability and oxidation resistance at high temperatures. Nevertheless, its mechanical strength and chemical stability is moderate [12].

4-4- Microstructure

Titanium alloys have a complete crystal structure. Aluminum is the most important substituent alloy in titanium because it stabilizes phase to a large extent while increasing the strength and decreasing the density of titanium. However, the amount of aluminum used for titanium is limited to 5 wt% to 6 wt% because it makes the alloy brittle [13]. According to Rosenberg's theory, the maximum equivalent of these alloying elements that must be added to titanium to prevent the formation of too much of phase 2 is

$$Al + \frac{Sn}{3} + \frac{Zr}{6} + 10(O) \leq \%9 \quad (1)$$

4-5-Chemical composition

This alloy is also used in the many industry applications. This alloy is capable of heat treatment to achieve maximum strength and is stable from a metallurgical point of view up to 2482. One of the disadvantages of this alloy is its low hardness, and only sections up to an inch thick can be completely hardened [14-21].

4-6-Titanium alloys B: Chemical composition and specific applications

Titanium B alloys, due to their centered cubic crystal structure, are easily cooled under dissolved and hydrated conditions and can be aged immediately to provide greater strength. However, their density is relatively high because the percentage of heavy metals such as vanadium and molybdenum are high. These alloys have low ductility when high strength [15]. In thick sections, large grain size and chemical separation occur, which leads to low ductility in ductility and short life in fatigue. As a result, semi-stable B-titanium alloys are not widely used at present. Heat treatment of titanium alloys includes stress relief, annealing, annealing and ageing. Stress relief operations are performed to reduce stresses created during the manufacturing process, annealing operations are performed to optimize flexibility, machinability, dimensional and structural stability, dissolution annealing and ageing operations increase its strength and optimize fracture toughness, fatigue strength and creep strength increase at high temperatures.

Heating titanium and its alloys in conventional furnaces can contaminate the surface and absorb oxygen and hydrogen, resulting in brittleness in the alloy [16-21]. Due to the rapid cooling and relatively narrow hot working range, the cooling effect of the tool should be reduced as much as possible by reducing the contact time, in which the preheating of the tool is also effective. In addition, performing multiple preheats with minor deformations at each stage is also harmful because it causes the grain structure to become larger, microstructure to become rougher, and mechanical properties to decrease. Removal of appendages should be done in conditions where the temperature of the part is high**.** Therefore, in order to reduce preheating and prevent waste of time and heat, hammering and removal of appendages should be done with the shortest time interval from each other, and then stress relief operations are recommended [16-24]. The sheet that has been dissolved annealed can be subjected to stretching, pressing, etc., but the maximum amount of deformation depends on the amount of load applied. The use of hydraulic presses has good results. To produce parts with complex designs from titanium sheets, the falling hammer forming method is mainly used, in which the sheets are preheated before forming. The bites used in cold forming can be prepared by cutting or sawing at low cutting speeds [24-36]. All sharp protrusions should be removed and the edges of the cut should be scraped or polished for complex forming processes. Simple shapes can be formed at room temperature. The change in form depends on the strength and elasticity of the material. Solid lubricants such as soap, molybdenum disulfide or graphite are preferable to mineral oils and greases. Informing parts with complex designs, the part and the mold must be preheated in order to facilitate the forming process [26-41].

4-7-Welding of titanium alloys

Commercial pure titanium and most titanium alloys can be welded using a variety of welding methods. The most common welding methods used for titanium alloys are gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW). Other methods used include electron beam, laser welding, friction welding and resistance welding**.** In order to obtain a healthy weld, it is essential to clean the surface of the workpiece and to properly use the shielding neutral gas. Titanium melt reacts easily with oxygen and hydrogen, these elements can be absorbed by the titanium melt through contact with air or contaminated surfaces and have adverse effects on the properties of the weld metal. Also, mainly titanium cannot be welded to other metals because it is possible to form brittle intermetallic compounds in the weld zone, which can cause cracks in the weld zone [19]. Titanium and its alloys can be machined using conventional machining tools.

Using the following recommendations may result in good machining and long machine life such as use of sharp cutting blades to reduce heat and wear and using a large volume of cooling fluid to maximize the amount of heat removed. Major uses of titanium: Titanium metal is very resistant to erosion environments. Pure titanium or its low-impurity alloys are used in petroleum desulfurization plants, in oil well equipment and in required fittings, as well as in medical applications. On the other hand, steel sheets or titanium coatings have been produced, which due to their anti-erosion properties, have been widely used in the oil industry and in the desulfurization stages of oil derivatives in refineries [32-39]. Other major uses of titanium can be summarized as follows. Manufacture of titanium carbide, ceramic, in chemical and electrochemical processes, fabrication of metal sheets and construction of special warehouses for storage of materials such as nuclear waste reinforcing fibers for use in metal compounds, industrial ligaments, jewelry, making alloys, energy storage, increasing thermal conductivity alloys, fillers for synthetic gemstones [42-53].

5- Conclusion

Titanium is often alloyed with aluminum, iron, manganese, molybdenum and other metals. Medicinal and cosmetic uses of titanium is used to heal skin burns and reflects the sun's ultraviolet rays, and is therefore used in the manufacture of sunscreens and lotions. Titanium oxide powder is also used in the manufacture of drug capsules and tablets. Titanium is a non-toxic substance and is not considered toxic even in large quantities. Also, this substance does not play any role in the natural system of the human body. The annual consumption of titanium and its compounds is 105 to 106 tons. Approximately 95% of titanium is consumed in the form of titanium oxide TiO_4 and is a permanent, highly white pigment with good coating strength in paper and plastic. Paints with titanium oxide make an excellent infrared reflector and are therefore widely used by astronomers. Since, this metal has high strength and lightweight with abnormal resistance to corrosion and has the ability to withstand high temperatures.

References

[1] Abdellahi, M., Jabbarzare, S., Ghayour, H., & Khandan, A. (2018). Thermal and X-ray analyses of aluminum–titanium nanocomposite powder. *Journal of Thermal Analysis and Calorimetry*, *131*(2), 853-863.

[2] Salimi, K., Eghbali, S., Jasemi, A., Shokrani Foroushani, R., Joneidi Yekta, H., Latifi, M., ... & Khandan, A. (2020). An Artificial Soft Tissue Made of Nano-Alginate Polymer Using Bioxfab 3D Bioprinter for Treatment of Injuries. *Nanochemistry Research*, *5*(2), 120-127.

[3] Khandan, A., Abdellahi, M., Ozada, N., & Ghayour, H. (2016). Study of the bioactivity, wettability and hardness behaviour of the bovine hydroxyapatite-diopside bio-nanocomposite coating. *Journal of the Taiwan Institute of Chemical Engineers*, *60*, 538-546.

[4] Jamnezhad, S., Asefnejad, A., Motififard, M., Yazdekhasti, H., Kolooshani, A., Saber-Samandari, S., & Khandan, A. (2020). Development and investigation of novel alginate-hyaluronic acid bone fillers using freeze drying technique for orthopedic field. *Nanomedicine Research Journal*, *5*(4), 306-315.

[5] Khandan, A., Karamian, E., & Bonakdarchian, M. (2014). Mechanochemical synthesis evaluation of nanocrystalline bone-derived bioceramic powder using for bone tissue engineering. *Dental Hypotheses*, *5*(4), 155.

[6] Shayan, A., Abdellahi, M., Shahmohammadian, F., Jabbarzare, S., Khandan, A., & Ghayour, H. (2017). Mechanochemically aided sintering process for the synthesis of barium ferrite: Effect of aluminum substitution on microstructure, magnetic properties and microwave absorption. *Journal of Alloys and Compounds*, *708*, 538-546.

[7] Kordjamshidi, A., Saber-Samandari, S., Nejad, M. G., & Khandan, A. (2019). Preparation of novel porous calcium silicate scaffold loaded by celecoxib drug using freeze drying technique: Fabrication, characterization and simulation. *Ceramics International*, *45*(11), 14126-14135.

[8] Baneshi, N., Moghadas, B. K., Adetunla, A., Yusof, M. Y. P. M., Dehghani, M., Khandan, A., ... & Toghraie, D. (2021). Investigation the mechanical properties of a novel 3D multicomponent scaffold coated with a new bio-nanocomposite for bone tissue engineering: Fabrication, simulation and characterization. *Journal of Materials Research and Technology*.

[9] Aghdam, H. A., Sanatizadeh, E., Motififard, M., Aghadavoudi, F., Saber-Samandari, S., Esmaeili, S., ... & Khandan, A. (2020). Effect of calcium silicate nanoparticle on surface feature of calcium phosphates hybrid bio-nanocomposite using for bone substitute application. *Powder Technology*, *361*, 917-929.

[10] Salmani, M. M., Hashemian, M., Yekta, H. J., Nejad, M. G., Saber-Samandari, S., & Khandan, A. (2020). Synergic effects of magnetic nanoparticles on hyperthermia-based therapy and controlled drug delivery for bone substitute application. *Journal of Superconductivity and Novel Magnetism*, *33*, 2809-2820.

[11] Razavi, M., & Khandan, A. (2017). Safety, regulatory issues, long-term biotoxicity, and the processing environment. In *Nanobiomaterials Science, Development and Evaluation* (pp. 261-279). Woodhead Publishing.

[12] Khandan, A., Nassireslami, E., Saber-Samandari, S., & Arabi, N. (2020). Fabrication and characterization of porous bioceramic-magnetite biocomposite for maxillofacial fractures application. *Dental Hypotheses*, *11*(3), 74.

[13] Li, X., Saeed, S. S., Beni, M. H., Morovvati, M. R., Angili, S. N., Toghraie, D., ... & Khan, A. (2021). Experimental measurement and

simulation of mechanical strength and biological behavior of porous bony scaffold coated with alginate-hydroxyapatite for femoral applications. *Composites Science and Technology*, *214*, 108973.

[14] Raisi, A., Asefnejad, A., Shahali, M., Doozandeh, Z., Kamyab Moghadas, B., Saber-Samandari, S., & Khandan, A. (2022). A soft tissue fabricated using a freeze-drying technique with carboxymethyl chitosan and nanoparticles for promoting effects on wound healing. *Journal of Nanoanalysis*, *7*(4), 262-274.

[15] Foroutan, S., Hashemian, M., Khosravi, M., Nejad, M. G., Asefnejad, A., Saber-Samandari, S., & Khandan, A. (2021). A Porous Sodium Alginate-CaSiO 3 Polymer Reinforced with Graphene Nanosheet: Fabrication and Optimality Analysis. *Fibers and Polymers*, *22*(2), 540-549.

[16] Jasemi, A., Moghadas, B. K., Khandan, A., & Saber-Samandari, S. (2021). A porous calcium-zirconia scaffolds composed of magnetic nanoparticles for bone cancer treatment: Fabrication, characterization and FEM analysis. *Ceramics International*.

[17] Mohammadzadeh Rad, M., Saber-Samandari, S., Sadighi, M., Tayebi, L., Mohammadi Aghdam, M., & Khandan, A. (2021). Macro-and micromechanical modelling of HA-Elastin scaffold fabricated using freeze drying technique. *Journal of Nanoanalysis*, *8*(1), 17-31.

[18] Doozandeh, Z., Saber-Samandari, S., & Khandan, A. (2020). Preparation of novel Arabic gum-C6H9NO biopolymer as a bedsore for wound care application. *Acta Medica Iranica*, 520-530.

[19] Raisi, A., Asefnejad, A., Shahali, M., Kazerouni, Z. A. S., Kolooshani, A., Saber-Samandari, S., ... & Khandan, A. (2020). Preparation, characterization, and antibacterial studies of N, O-carboxymethyl chitosan as a wound dressing for bedsore application. *Archives of Trauma Research*, *20*.

[20] Qian, W. M., Vahid, M. H., Sun, Y. L., Heidari, A., Barbaz-Isfahani, R., Saber-Samandari, S., ... & Toghraie, D. (2021). Investigation on the effect of functionalization of single-walled carbon nanotubes on the mechanical properties of epoxy glass composites: Experimental and molecular dynamics simulation. *Journal of Materials Research and Technology*, *12*, 1931-1945.

[21] Akbari-Aghdam, H., Bagherifard, A., Motififard, M., Parvizi, J., Sheikhbahaei, E., Esmaeili, S. & Khandan, A. (2021). Development of porous photopolymer resin-SWCNT produced by digital light processing technology using for bone femur application. *Archives of Bone and Joint Surgery*, *9*(4), 445.

[22] Maghsoudlou, M. A., Barbaz Isfahani, R., Saber-Samandari, S., & Sadighi, M. (2021). The Response of GFRP Nanocomposites Reinforced with Functionalized SWCNT Under Low Velocity Impact: Experimental and LS-DYNA Simulation Investigations. *Iranian Journal of Materials Science and Engineering*, *18*(2), 0-0.

[23] Sahranavard, M., Rezayat, A. A., Bidary, M. Z., Omranzadeh, A., Rohani, F., Farahani, R. H. & Mosaed,

R. (2021). Cardiac complications in COVID-19: a systematic review and meta-analysis. *Archives of Iranian Medicine*, *24*(2), 152.

[24] Maghsoudlou, M. A., Nassireslami, E., Saber-Samandari, S., & Khandan, A. (2020). Bone regeneration using bio-nanocomposite tissue reinforced with bioactive nanoparticles for femoral defect applications in medicine. Avicenna *Journal of Medical Biotechnology*, *12*(2), 68.

[25] Maghsudlurad, M., BarbazIsfahani, R., Saber-Samandari, S., & Sadighi, M. (2017). Prediction of elastic modulus of epoxy/single wall carbon nanotube composites by considering interfacial debonding. *Advanced Materials and New Coatings*, *5*(19), 1371-1379.

[26] Mirsasaani, S. S., Hemati, M., Dehkord, E. S., Yazdi, G. T., & Poshtiri, D. A. (2019). Nanotechnology and nanobiomaterials in dentistry. In *Nanobiomaterials in Clinical Dentistry* (pp. 19-37). Elsevier.

[27] Raisi, A., Asefnejad, A., Shahali, M., Kazerouni, Z. A. S., Kolooshani, A., Saber-Samandari, S. & Khandan, A. (2020). Preparation, characterization, and antibacterial studies of N, O-carboxymethyl chitosan as a wound dressing for bedsore application. *Archives of Trauma Research*, *20*.

[28] Khoroushi, M., Ghasemi, M., Abedinzadeh, R., & Samimi, P. (2016). Comparison of immediate and delayed light-curing on nano-indentation creep and contraction stress of dual-cured resin cements. *Journal of the mechanical behavior of biomedical materials*, *64*, 272-280.

[29] Khandan, A., & Esmaeili, S. (2019). Fabrication of polycaprolactone and polylactic acid shapeless scaffolds via fused deposition modelling technology. *Journal of Advanced Materials and Processing*, *7*(4), 12-20.

[30] Abedinzadeh, R., Safavi, S. M., & Karimzadeh, F. (2015). Finite Element modeling of Microwave-Assisted Hot Press process in a multimode furnace. *Applied Mathematical Modelling*, *39*(23-24), 7452-7468.

[31] Li, G., Chen, D., You, Y., Ding, C., Pei, G., Chen, Y., ... & Lv, X. Andradite titanium: Preparation, characterization and metallurgical performance. *Journal of the American Ceramic Society*.

[32] Zarei, M. H., Pourahmad, J., Aghvami, M., Soodi, M., & Nassireslami, E. (2017). Lead acetate toxicity on human lymphocytes at non-cytotoxic concentrations detected in human blood. *Main Group Metal Chemistry*, *40*(5-6), 105-112.

[33] Ferraris, S., Cochis, A., Cazzola, M., Tortello, M., Scalia, A., Spriano, S., & Rimondini, L. (2019). Cytocompatible and anti-bacterial adhesion nanotextured titanium oxide layer on titanium surfaces for dental and orthopedic implants. *Frontiers in bioengineering and biotechnology*, *7*, 103.

[34] Ziental, D., Czarczynska-Goslinska, B., Mlynarczyk, D. T., Glowacka-Sobotta, A., Stanisz, B., Goslinski, T., & Sobotta, L. (2020). Titanium dioxide nanoparticles: prospects and applications in medicine. *Nanomaterials*, *10*(2), 387.

[35] Manßen, M., & Schafer, L. L. (2020). Titanium catalysis for the synthesis of fine chemicals–development and trends. *Chemical Society Reviews*, *49*(19), 6947-6994.

[36] Zhang, L. C., Chen, L. Y., & Wang, L. (2020). Surface modification of titanium and titanium alloys: technologies, developments, and future interests. *Advanced Engineering Materials*, *22*(5), 1901258.

[37] Pan, L., Ai, M., Huang, C., Yin, L., Liu, X., Zhang, R., ... & Mi, W. (2020). Manipulating spin polarization of titanium dioxide for efficient photocatalysis. *Nature communications*, *11*(1), 1-9.

[38] Sahmani, S., Khandan, A., Saber-Samandari, S., & Aghdam, M. M. (2020). Effect of magnetite nanoparticles on the biological and mechanical properties of hydroxyapatite porous scaffolds coated with ibuprofen drug. *Materials Science and Engineering*: *C*, *111*, 110835.

[39] Abdellahi, M., Najfinezhad, A., Saber-Samanadari, S., Khandan, A., & Ghayour, H. (2018). Zn and Zr co-doped M-type strontium hexaferrite: Synthesis, characterization and hyperthermia application. *Chinese journal of physics*, *56*(1), 331-339.

[40] Qin, W., Kolooshani, A., Kolahdooz, A., Saber-Samandari, S., Khazaei, S., Khandan, A. & Toghraie, D. (2021). Coating the magnesium implants with reinforced nanocomposite nanoparticles for use in orthopedic applications. Colloids and Surfaces A: *Physicochemical and Engineering Aspects*, *621*, 126581.

[41] Asadpoori, A., Keshavarzi, A., & Abedinzadeh, R. (2021). Parametric study of automotive shape memory alloy bumper beam subjected to low-velocity impacts. *International Journal of Crashworthiness*, *26*(3), 322-327.

[42] Talebi, M., Abbasi-Rad, S., Malekzadeh, M., Shahgholi, M., Ardakani, A. A., Foudeh, K., & Rad, H. S. (2021). Cortical Bone Mechanical Assessment via Free Water Relaxometry at 3 T. *Journal of Magnetic Resonance Imaging*.

[43] Liang, H., Saber-Samandari, S., Yusof, M., Esfahani, M. M., Shahgholi, M., Hekmatifar, M., ... & Toghraie, D. (2021). Investigation of the effect of Berkovich and Cube Corner indentations on the mechanical behavior of fused silica using molecular dynamics and finite element simulation. Ceramics International.

[44] Fada, R., Shahgholi, M., & Karimian, M. (2021). Improving the mechanical properties of strontium nitrate doped dicalcium phosphate cement nanoparticles for bone repair application. *Ceramics International*, *47*(10), 14151-14159.

[45] Fada, R., Farhadi Babadi, N., Azimi, R., Karimian, M., & Shahgholi, M. (2021). Mechanical properties improvement and bone regeneration of calcium phosphate bone cement, Polymethyl methacrylate and glass ionomer. *Journal of Nanoanalysis*, *8*(1), 60-79.

[46] Mirsasaani, S. S., Bahrami, M., & Hemati, M. (2016). Effect of Argon laser Power Density and Filler content on Physico-mechanical properties of

Dental nanocomposites. Bull. *Env. Pharmacol. Life Sci*, *5*, 28-36.

[47] Iranmanesh, P., Gowdini, M., Khademi, A., Dehghani, M., Latifi, M., Alsaadi, N., & Khan, A. (2021). Bioprinting of three-dimensional scaffold based on alginate-gelatin as soft and hard tissue regeneration. *Journal of Materials Research and Technology*, *14*, 2853-2864.

[48] Sahmani, S., Saber-Samandari, S., Khandan, A., & Aghdam, M. M. (2019). Nonlinear resonance investigation of nanoclay based bio-nanocomposite scaffolds with enhanced properties for bone substitute applications. *Journal of Alloys and Compounds*, *773*, 636-653.

[49] Esmaeili, S., Khandan, A., & Saber-Samandari, S. (2018). Mechanical performance of three-dimensional bio-nanocomposite scaffolds designed with digital light processing for biomedical applications. Iranian *Journal of Medical Physics*, *15*(Special Issue-12th. Iranian Congress of Medical Physics), 328-328.

[50] Pirmoradian, M., Naeeni, H. A., Firouzbakht, M., Toghraie, D., & Darabi, R. (2020). Finite element analysis and experimental evaluation on stress distribution and sensitivity of dental implants to assess optimum length and thread pitch. *Computer methods and programs in biomedicine*, *187*, 105258.

[51] Eslami, M., Mokhtarian, A., Pirmoradian, M., Seifzadeh, A., & Rafiaei, M. (2020). Design and fabrication of a passive upper limb rehabilitation robot with adjustable automatic balance based on variable mass of end-effector. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *42*(12), 1-8.

[52] Eslami, M., Mokhtarian, A., Pirmoradian, M., Seifzadeh, S. A., & Rafiaei, S. M. (2020). Designing and creating a virtual reality environment and a wearable glove with control and evaluation capability to rehabilitate patients. *Journal of Health and Biomedical Informatics*, *7*(2), 161-170.

[53] Torkan, E., & Pirmoradian, M. (2019). Efficient higher-order shear deformation theories for instability analysis of plates carrying a mass moving on an elliptical path. *Journal of Solid Mechanics*, *11*(4), 790-808.