Bioactive titanium composites for bone implant applications

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Abstract: Development of titanium (Ti) based implants has revolutionized the application of materials engineering to address several challenges associated with other metallic implants. Ti exhibit excellent biocompatibility, nontoxicity and lowers the stress shielding effect. However, bio-inert nature of titanium is a limitation and therefore, several surface engineering strategies are adopted to promote bioactivity. Higher bioactivity helps to improve the healing rate by accelerating the implant tissue interactions. On the other hand, developing Ti based composites by incorporating bioactive ceramic phases is another promising route to develop bioactive Ti implants. In the present review, the role of addition of bioactive ceramic phases on tailoring the properties of Ti for bone implant applications is presented. Different processing routes to incorporate bioceramic particles into Ti are also discussed with a brief discussion on future scope of Ti based composites for biomedical implant applications.

Keywords: FSP, MMCs, hybrid composites, machining, hardness.

1. Introduction

Metal are the best candidates to produce bio-implants particularly for load bearing applications in orthopaedics and allied fields. Among the available metallic implants, Titanium (Ti) has emerged as a potential load bearing material to manufacture bone fixing implants and joint replacement implants [1]. Titanium possesses excellent biocompatibility, nontoxicity and noncarcinogenicity properties [2, 3]. Titanium also exhibits lower stress shielding effect compared with steels and Co based implants when used in load bearing orthopaedic applications. Stress shielding is a phenomena in which the bone that is supported by a metallic implant is subjected to lower level of bone remodelling due to the lower stresses developed in the bone compared with the implant. This phenomenon is profound when the difference between the young’s modulus of the implant material and the bone is higher. Among the available metallic implants, Ti shows mechanical properties close to that of natural bone and hence the mismatch in the mechanical properties of bone and the implant is lower which reduces the stress shielding effect [4]. Fig 1 compares the young’s modulus of different metals used in bio-implant applications [4].

Fig 1: Comparison of Young’s Modulus of Various Metallic Implants
Compared with Co-alloys and steels, pure Ti exhibits nearly 50% reduction in the elastic modulus value. Further by alloying certain elements such as Ni, Ta and Nb, the developed Ti alloys demonstrate elastic modulus values close to that natural bone. Hence, from the mechanical properties point of view, Ti based implants decreases stress shielding in load baring implant applications. However, Ti suffers from lack of bioactivity which influences the interactions between the tissue and the implant surface. There are several strategies such as developing nanostructured surfaces, providing surface coatings, introducing bioactive phases into the surface reported in the literature to improve the bioactivity of Ti [5, 6, 7, 8, 9]. On the other hand, several other reports also demonstrated the superior bioactivity resulted from the addition of ceramic particles as dispersing phases in Ti [10, 11, 12, 13]. The present review provides a brief summary of the state of the art in developing Ti based composites with enhanced bioactivity for bone fixing implant applications in biomedical engineering.

2. Titanium based composites as bio-implants

Interest on Ti as suitable candidate to manufacture biomedical implants arose from its excellent biocompatibility and corrosion resistance in the highly corroding environment. The formation of a thin oxide layer on the surface of Ti implant provides corrosion resistance against the aggressive chemical events in the biological environment. Additionally, the oxide layer that is developed on the Ti surface helps to enhance the bonding ability of the tissue with the implant surface by which, bioactivity of the surface is accelerated. Among the available Ti alloys, commercial grade -2 pure Ti (medical grade) and Ti-6Al-4V alloys are used to manufacture medical implants. Ti based implants are mainly used to support the hard tissue or to replace the hard tissue in bone implant applications. Furthermore, Ti based materials are used in total joint replacement, dental and maxillofacial implants. Composites exhibit hybrid properties and offer more flexibility to choose different composition to achieve desired properties in the end product. The dispersing fibre in the form of particles or fine powder imparts specific properties to the bulk composite. The main objective in developing Ti based composites targeted for biomedical applications is to introduce additional properties which are inferior in Ti such as bioactivity, bio-mineralization and ability to develop strong bonding with the local host tissue.
Therefore, the selection of reinforcing particles to develop the composite is crucial. It is well established fact that the dispersing particle size, shape and chemical composition influence the bulk properties of the composite materials. When it comes to biomedical applications, the dispersing phase that is used to develop the composite also must have the necessary properties to be used as a biomaterial. Hence, it is always better to select approved materials to be used in biomedical applications. Calcium based ceramic phase are well accepted and widely used in the biomedical applications. Among the available bioceramic phases, apatite is the most promising material due to its close resemblance with the natural calcium based phase that is available in the bone. By using apatite as a dispersing phase into Ti, Additional properties such as bioactivity and improved osseointegration can be achieve for the implant. Other ceramic phases such as TiN, TiB, TiC, Nb2O5 TiO2, SiO2, ZrO2 and SrO were also used to develop Ti based composites for biomedical applications.

Thirugnanam et al. [10] developed Ti based composites by using nano-hydroxyapatite (nHA) as the dispersing phase. The powders were mixed in appropriate compositions and subjected to high energy ball milling followed by sintering. The crystallite size after ball milling was found to be influenced by milling speed (rpm), milling medium and time, ball to power ratio etc. From the XRD studies, broader peaks were identified which is an indication of decreased crystallite size. The authors have studied the role of added nHA on bioactivity by conducting immersion studies in simulated body fluid (SBF) for one week. The studies demonstrated the promising effect of addition of nHA on enhancing the deposition of apatite from the SBF which is an indication of enhanced bioactivity. From the cell adhesion studies by using human osteoblast cells showed excellent cell adhesion and growth on the surface of Ti-nHA composites compared with commercial pure Ti.

Calin et al., [14] added Nb in Ti75Zr10Si15 and Ti60Nb15Zr10Si15 alloys and studied the role of addition of Nb on the bioactivity by conducting immersion studies in Ringer’s solution. From the observations, they have reported superior bioactivity for the Ti based metallic glasses compared with commercial pure Ti. Furthermore, pitting corrosion was found to be insignificance on the produced metallic glasses compared with the commercial pure Ti. Zhang et al. [15] developed Ti-TiC functionally graded composites with different amount of TiC addition. It was observed that the change in yield strength and ultimate tensile strength was insignificant with the increased amount of TiC. On the other hand, ductility was significantly measured as decreased with the increased TiC content.

Developing in-situ composites by promoting chemical reaction within the material is another way of producing Ti based composites. There are several reports in producing Ti based in-situ composite. Developing in-situ composites offer additional benefits compared with the conventional processes to develop the composites where externally reinforcements are added. Higher level of strong bonding can be achieved in the Ti based composites produced by in-situ route. Furthermore, Thermodynamic stability is also increased with better interfacial bonding between the secondary phase particles and the matrix. The uniform distribution of the particles within the matrix resulted from in-situ reaction helps to achieve better mechanical properties and other bulk properties in the Ti composites [16, 17]. Gu et al., [18] developed in-situ Ti composite that has Ti5Si3-TiN dispersing phases. From the investigations, they found that the microhardness of the developed in-situ composite is 4 times higher than the base Ti due to the strengthening effect introduced by the intermetallic produced during the in-situ reaction. Attar et al., [19, 20, 21, 22] have done extensive studies on developing in-situ Ti based composites and various studies have been carried out such as the effect of powder morphology, mechanical behaviour, wear properties and demonstrated the superior behaviour of these composites compared with their counterpart parts.

Balla et al. [23] developed Ti-TiO2 functionally graded composites by LENS techniques and the efficacy of these composites as biomaterials was studied. From the results, higher wettability, and enhanced tissue – implant interactions and better wear resistance were demonstrated. On the other hand, Bandyopadhyay et al. [24] incorporated calcium phosphate (CaP) mineral phase into titanium by
LENS with an aim to produce bioactive implants. From their observations, it was clearly shown that the presence of Ca-P decreases the rate of material loss due to wear by developing a Ca-P tribofilm on the surface of the implant. Additionally, the incorporated Ca-P has also enhanced the yield strength (compressive) and ultimate strength (compressive) and also hardness. The wear test data clearly demonstrate the superior wear resistance for the composites. Studies were also reported in the literature to incorporate hydroxyapatite (HA) into Ti and Ti6Al7Nb to promote osseointegration and higher bioactivity at the surface [25, 26].

Recently, Li et al., [27] developed Ti- Nb_2O_5 composite by powder metallurgy route. Increased strength was measured for the composites compared with Ti. When the composites are exposed to human osteoblast like cells, excellent tissue implant interactions and cell adhesion was observed for the composites. Improved mechanical properties and bioactivity for the composites were attributed to the presence of Nb_2O_5.

Fig 2 a) 3D modal of the network connectors, b) scaffolds with different % of porosity, c) Scaffolds subjected to compressive loads, d) SEM image of Ti with 0% porosity and e) SEM image of Ti with 25% porosity (Source: Soro et a., [28]).

Several successful attempts were also made to develop porous scaffold structures of Ti based composites as demonstrated in the literature. Soro et al., [28] studied the promising benefits of porous Ti scaffolds for biomedical applications by selecting three levels of porosity (25 %, 42% and 64%). Three dimensional model was created as shown in Fig 2 (a) and the same has been used to produce 3D porous structures as shown in Fig 2 (b). Then the porous scaffolds were produced by selective laser melting (SLM) technique and subjected to compression (Fig 2 (c)). The scaffolds after compression test were observed by using SEM as shown in Fig 2 (d) and (e). Similarly, Xiang Li et al. [29] also
developed a composite scaffold contains a silk fibroin (SF) sponge on functionally graded titanium (FG-Ti). With the same level of porosity, FG-Ti exhibited better radial gradation and enhanced mechanical properties compared with homogeneous porous Ti. The composite structure was observed as similar to that of bone structure. The bio-mimicking nature of the developed composite scaffold improved the bioactivity as observed from the cell adhesion studies. Fig 3 shows comparison of rat osteoblast cells cultured on the surface of homogeneous porous Ti and FG-Ti. It can be observed that the cell spreading was higher in the FG-Ti.

Fig 3 Rat osteoblast cells on the surface of the samples: a) SEM image of Ti, b) SEM image of FG-Ti composite scaffold, c) Confocal laser scanning microscopy of Ti and d) FG-Ti composite scaffold (Source: Li et al., [29]).

3. Challenges and future perspectives

The available literature demonstrates the promising benefits which can be obtained by incorporating appropriate ceramic phases in the form of particles and discontinuous fibres. The selection of reinforcing phase is crucial to impart specific properties to the developed Ti composite. Several ceramic phases are available as reinforcing materials to develop conventional composites. However, limited number of reinforcements only can be used as dispersing phases due to the restriction from the biocompatibility and toxicity issues as the intended use of these composites is for medical applications. Furthermore, the concentration and the distribution of the dispersing phases in Ti are also crucial as the higher amounts of reinforcements may alter the bulk properties of the composite. On the other hand, if liquid processing routes are selected to develop Ti composites, stability of the ceramic phases that are reinforced into the liquid Ti is crucial to study. For example, hydroxyapatite (HA) is a calcium phosphate ceramic phase that can be used as dispersing phase into Ti to improve the bioactivity and osseointegration. However, the stability of HA at higher temperatures is an important concern as the HA is unstable if heated above 1000°C, particularly if Ca fraction is decreased in the HA phase. On the other hand, solid state processing routes such as powder metallurgy can help to complete the manufacturing of Ti based composites without affecting the phase stability of reinforcements. Developing porous structures can be an advantage with powder metallurgy as implants with porosity can perform well in bone fixing applications to promote higher healing rate. However, shape and size of the produced composite are the limitations with powder metallurgy routes. Developing Ti based composites by allowing in-situ chemical reactions is another promising strategy.
which helps to obtain stronger bond between the resulted secondary phase and Ti. However, the limitation with in-situ process is from the restrictions of number of phases that can be produced by chemical reactions. Certain bio-ceramic phases which are attractive to alter the Ti matrix properties cannot be produced by in-situ reactions such as calcium-phosphorous based phases. Very recently, additive manufacturing (AM) techniques are widely adopted to produce highly porous, network structures with different cell (open or close) morphologies suitable for bone implant applications [30]. Adopting AM techniques help to produce functionally graded composites with multi phases to impart combination of properties into the Ti composite. By adopting AM techniques, complex shapes of Ti based implants can be manufactured. Even though the AM techniques have demonstrated excellent results, the developments are gradual compared with developments in conventional Ti alloy studies.

4. Conclusions

Developing Ti based composites addresses several issues associated with the bio-inert nature of Ti implants in the biomedical industry. Introducing secondary phases into Ti matrix and achieving phase stability is challenging if the processing routes involve heating of the materials to higher temperatures. In-situ chemical reaction helps to develop matrix compatible intermetallic phases and excellent matrix-fibre bonding can be achieved. However, the number of phase combinations is limited. On the other hand, powder metallurgy route and advanced manufacturing methods such as additive manufacturing facilitate to produce novel Ti based composites by using wide range of secondary phases. From the available information in the literature, addition of reinforcements improves the performance of Ti as biomaterial and future developments certainly help the engineers to produce new age Ti based implants with hybrid properties with higher healing rate for the biomedical applications particularly for load bearing bone implant applications.

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