Material Perspectives of the Dental Implants: A Review

Gui Wang, Matthew Dargusch, and Nghiem Doan

Abstract

A dental implant is an artificial tooth root, similar to a screw, inserted into the jawbone at the site of the missing tooth. The crucial requirements have taken upon on dental implants including mechanically assembly with the abutment, permanently locked with jaw bone, appropriate mechanical properties, excellent corrosion resistance, compatible to the surrounding hard/soft tissue biologically to mechanically. The aim of this paper is to provide a short literature review on the topic of β titanium alloys with electrochemical treatment techniques to produce nano and micro level roughness and porous.

Keywords

Dental implant • Titanium • Compatibilities • Surface modification

1 Introduction

A dental implant is an artificial tooth root, similar to a screw, inserted into the jawbone at the site of the missing tooth. From structure point of view, a typical implant is as simple as a metallic screw, but it is still a complicated integrated system of multiple disciplines science and today's advanced engineering technologies [1]. The crucial requirements have taken upon on dental implants including mechanically assembly with the abutment, permanently locked with jaw bone through osseointegration, appropriate mechanical properties, excellent corrosion resistance, compatible to the surrounding hard/soft tissue biologically and mechanically. The favorable long-term clinical survival rates reported for titanium and its biomedical alloys have made titanium the "gold standard" material for the fabrication of dental implants due to their high specific strength, excellent biocompatibility, and corrosion resistance [2].

The development of titanium and its alloys used as implant material perfectly reflect the research goal of biomaterials. Commercial Purity Titanium (CP Ti) has long been used for biomedical devices, such as spinal/trauma fixation devices, however the mechanical properties of CP Ti is generally considered to lie below that desired for many of load bearing application such as hard tissue replacement. Indeed the desire for enhanced strength has led to the introduction of Ti–6Al–4V, which today remains the largest single titanium alloy used for biomedical device manufacturing because of its excellent properties and commercial available. Continued concern with respect to the long term biological response of vanadium and aluminium containing materials has moreover led to the development and introduction of Ti–6Al–7Nb and Ti–5Al–2.5Fe, which show good mechanical and metallurgical behaviour comparable to those of Ti–6Al–4V [3]. Recent interest in reduced modulus α-β titanium alloys has resulted in the development of Ti–13Nb–13Zr and many other β titanium alloys [4].

It is well known that surface plays a vital role, research and development of bioactive surface modifications for improving the biocompatibility of titanium alloys keeps increasing, and among of surface modification techniques, anodic oxidation has been successfully to achieve either nano or micro porous surface along with other treatments. They have been proposed to improve the bone conductivity or bioactivity of titanium.

G. Wang (✉) · M. Dargusch · N. Doan
Centre for Advanced Materials and Manufacturing,
The University of Queensland, Jocks Road, St Lucia,
Brisbane, Australia
e-mail: gui.wang@uq.edu.au

T. Vo Van et al. (eds.), *6th International Conference on the Development of Biomedical Engineering in Vietnam (BME6)*, IFMBE Proceedings 63, https://doi.org/10.1007/978-981-10-4361-1_76

The present paper builds on many excellent prior reviews [5, 6] and provides a snap-shot of several areas of current exploration focusing on the synthesis and understanding required for successful application of titanium alloys for dental implants.

2 Mechanical Compatibility of Implant

Many investigations on jaw bones have revealed the connective hard tissues bone and teeth are highly porous on a micrometer scale even they appear to be made of solid materials. These pores are filled with fluid and cells, making bone a viscoelastic material with remarkable regenerative capacity. This regenerative capacity is secured by cells that are present in the pores of bone tissue. Vascular canals ramify within bone, providing its cells with metabolic support. Therefore bone can be characterized as viscoelastic composites with gradient and organised porous structure.

Biomechanics involved in implantology should include at least (1) the nature of the biting forces on the implants, (2) transferring of the biting forces to the interfacial tissues, and (3) the interfacial tissues reaction, biologically, to stress transfer conditions. Interfacial stress transfer and interfacial biology represent very difficult, interrelated problems because of totally different mechanical behaviors between bone and metal. A critical aspect affecting the success or failure of an implant is the manner in which mechanical stresses are transferred from the implant to bone smoothly [5]. It is essential that neither implant nor bone be stressed beyond the long-term fatigue capacity. It is also necessary to avoid any relative motion that can produce abrasion of the bone or progressive loosening of the implants. Therefore, materials for implant or surface zone of implants should be mechanically compatible to mechanical properties of receiving tissues to minimize the interfacial discrete stress.

2.1 Mismatched Stiffness Between Titanium Alloys and Bone

A significant stiffness mismatch exists between metal and bone, for example CP Ti and Ti–6Al–4V have a Young's modulus of around 105 and 110 GPa respectively, well too higher than that of jaw bones. β titanium alloys are advantageous for the development of titanium alloys with low Young's modulus and continuously achievements have been made on reducing Young's moduli by introducing toxicity-free alloying elements over decades. The lowest value of Young's modulus reported for the polycrystal β titanium alloy Ti–35Nb–4Sn or Ti–24Nb–4Zr–7.9Sn, subjected to severe cold working, is around 40 GPa [4].

Apart from Young's modulus of the material, stiffness also depends on geometrical factor of a structure, for example, reducing the cross section area and increasing length of the structure lead to lower structure stiffness which then requires material to have higher strength.

2.2 Strengthening Titanium and Its Alloys

Most metals are strong enough to withstand the maximum possible oral forces, however the fracture occurs in some cases. In the literature, the proposed mechanism of titanium implant failure is fatigue fracture from high cyclic occlusal loading. Accelerated peri-implant marginal bone loss is suggested to result in an increase in the bending moments and torque force on the implants. This, in turn, contributes to increased implant mobility and an eventual structural failure of the implant [3]. Unlike the natural bone, metal used implantology behaviors like a rigid body and stress concentration often occurs in the geometry rapid change area. It has been reported that the most of the fractures in dental implant is compatible with signs of fatigue failure that appeared to initiate from the stress concentration associated with the thread and typically initiated in the section of the implant that was not internally supported by the abutment screw. The strength is a very important factor for their long-term use in implants for biomedical applications, in fact, a small receiving area in jaw bones for implant requires a small size of the implant, therefore material with high strength is critical, and this can be achieved by alloying strengthening and deformation strengthening.

Strengthening through alloying: Titanium can be alloyed with a variety of elements to alter its properties for improving mechanical properties and formability. Practically, β titanium alloys contain 10–15% of β stabilizers, in the solution treated condition, they generally have moderate strength, and they can be aged to obtain very high strength due to the precipitation of fine α phase upon aging. The most important, these alloys can be tailored by selecting appropriate ageing temperature and time to achieve an excellent combination of many properties.

Paladugu et al. reported a good age hardening response of a biomedical β Ti–25Nb–3Mo–3Zr–2Sn alloy in the as-cast condition, and enhanced strengthening of the alloy was due to precipitation of fine scale α laths throughout the β matrix [7]. In general, β alloys are capable to be strengthened significantly due to 100% heat treatable of the β phase. The high alloying content of the β alloys can be strengthened though solid solution mechanism of the β phase matrix and the fine α phase precipitation by ageing treatment further enhance the mechanical properties. These strengthening mechanisms provide opportunity to tailor mechanical properties of materials to suit a variety of different applications.

Strengthening through Severe Plastic Deformation (SPD): Processes with SPD are defined as metal forming processes in which an ultra-large plastic strain is introduced into a bulk metal in order to create Ultra-Fine Grained (UFG) metals with grain sizes between 100 nm and 1 μm. UFG materials exhibit unique and superior properties to that of otherwise identical coarse grained materials.

Valiev et al. have investigated the strengthening of grade 2 CP Ti utilizing equal channel angular pressing (ECAP), and a 140% increase in ultimate tensile strength being observed while maintaining an elongation to failure of 9%. A comparison between the UFG grade 2 CP Ti indicates that its strength, ductility and fatigue limit are comparable to Ti–6Al–4V ELI. This suggests that substitution of the UFG grade 2 CP Ti should be capable to replace Ti–6Al–4V. Kent et al. have investigated the microstructure and mechanical property evolution of a Ti–25Nb–3Zr–3Mo–2Sn biomedical β Ti alloy in a modified accumulative roll-bonding (ARB) process, and revealed that a heavily refined UFG microstructure composed primarily of β grains heavily elongated in the rolling direction together with a fine dispersion of nanocrystalline α phase precipitates located on the β grain boundaries, After 4 cycles the ARB-processed material exhibited an UTS of 1220 MPa with 70% improvement of the coarse-grained solution treated alloy and ductility of 4.5% [8].

2.3 Challenges of Mechanical Properties of Titanium Alloys

A material subject to a cyclic loading can fracture far below its UTS and even below the yield strength of the material. Fatigue fractures are dangerous because they occur under normal service conditions with no warning prior to rupture. Medical devices manufactured from any material that are expected to survive millions of cyclic deformations over their lifetime require scrutiny of the fatigue and fracture resistance, with fatigue fracture being the major cause of premature failure in dental implants.

One drawback of β titanium alloys is their unsatisfactory fatigue strength, compared with Ti–6Al–4V alloys. Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture. In general, β titanium alloys have better fracture toughness which retains its high strength than that in Ti–6Al–4V, this has been recognised in the aerospace structure. However for the medical grade β titanium, there is not enough data to support it.

The challenge confronting the material scientists is that many properties must be controlled almost simultaneously. For example, developing the fatigue strength and simultaneously lowering Young's modulus is difficult because they are opposite natures when the bonding force between atoms is considered. In term of fracture toughness, the ability of a material to undergo limited deformation is a critical aspect of conferring toughness, as this feature enables the local dissipation of high stresses that would otherwise cause the material to fracture; this is the reason that hard materials tend to be brittle and lower strength materials, which can deform more readily, tend to be tougher. The optimization of strength and fracture toughness is often a goal in the development of structural materials.

3 Biological Compatibility

Osseointegration is critical for implant stability and is considered a prerequisite for implant loading and long term clinical success of dental implants. Since implant surface properties have long been identified as an important factor to promote osseointegration, research has focused on optimizing the potential for osseointegration, and surface modifications have been extensively investigated.

3.1 Surface Structure and Biocompatibility of Titanium

The excellent chemical inertness, corrosion resistance, repassivation ability, and even biocompatibility of titanium and its alloys are thought to result from the chemical stability and structure of the titanium oxide film. However, a normal implant manufacturing route including thermomechanical processing and machining usually lead to an oxidized, contaminated surface layer that is often stressed and plastically deformed, non-uniform and rather poorly defined. Such "native" surfaces are clearly not appropriate for biomedical applications and surface treatment must be performed.

In bones, titanium heals in close apposition to the mineralized tissues under the proper conditions, however, titanium and bones are generally separated by a thin non-mineral layer and the bond associated with osteointegration is believed to attribute to mechanical interlocking of the titanium untreated surface asperities and pores in the bones. In order to make titanium biologically bond to bones, surface modification methods have been proposed to improve the bone conductivity or bioactivity of titanium.

Roughening surface is the natural step to increase mechanical interlocking by increasing contact surface between implant and bone. The studies have focused on modifying titanium surface at both microscale and nanoscale level. Many techniques have been investigated to modify the surface of titanium and its alloys, and anodization was the most investigated in decades due to its simplicity and low-cost.

3.2 Anodic Oxidation and TiO_2 Nanotube

Oxide film formed in nature for titanium is only several nanometres thick, which is too thin to protect metal in general. Anodic oxidation is a well-established method to produce protective oxide films on metals in the metal industry, and it encompasses electrode reactions in combination with electric field driven metal and oxygen ion diffusion leading to the formation of an oxide film on the anode surface as illustrated in Fig. 1.

Anodization of titanium leads to an oxidation of titanium species that form a solid oxide on the surface, and depending on conditions such as mainly potential, electrolyte, and temperature, the oxide layer can be either compact or nanotubular [9]. The structure of the oxide film formed on titanium is amorphous at low voltages (below 20 V) and crystalline at higher voltages. A self-organized and ordered nanotubular and nanoporous structures of TiO_2 can been obtained when electrolytes containing fluoride ions and suitable anodization conditions were used.

Specific surface area to achieve a maximum overall efficiency, in particular nanotubes may allow for a much higher control of the chemical or physical behaviour. By diminishing dimensions to the nanoscale, not only the specific surface area increases significantly but also the electronic properties may change considerably owing for example to quantum size effects, strong contribution of surface reconstruction, or surface curvature. These effects may also contribute to drastically improve the reaction/interaction between a device and the surrounding media, thereby making the system more effective or even allow for entirely novel reaction pathways. *In vitro* study of osteoblasts on anodized nanotubular titanium substrates has been reported to enhance cell adhesion and proliferation.

Using controlled anodization in dilute fluoride electrolytes, nanotubes of biomedical alloys such as Ti–29Nb–13Ta–4.6Zr were successfully fabricated. Attempts have also been made to grow self-organized anodic nanotube layers on technologically relevant substrates such as Ti–6Al–4V and Ti–6Al–7Nb for dental and orthopedic implant applications. Further investigation on utilising this nanotube as an effective carrier for osteoinductive growth factors and antibacterial drugs has been conducted and evaluated in preclinical animal studies with favorable results.

3.3 Micro Arc Oxidation (MAO) and Porous Ceramic Coating

MAO is an electrochemical surface treatment process for generating oxide coatings on metals. Similar to anodizing, but it employs higher potentials usually in the range of 150–1000 V, so that discharges occur and the resulting plasma modifies the structure of the oxide layer. This process can be used to grow tens or hundreds of micrometres thick, largely crystalline, oxide coatings on titanium. In particular, this technique has been used to grow ceramic coatings on metal surface, and high quality coatings can be synthesized using

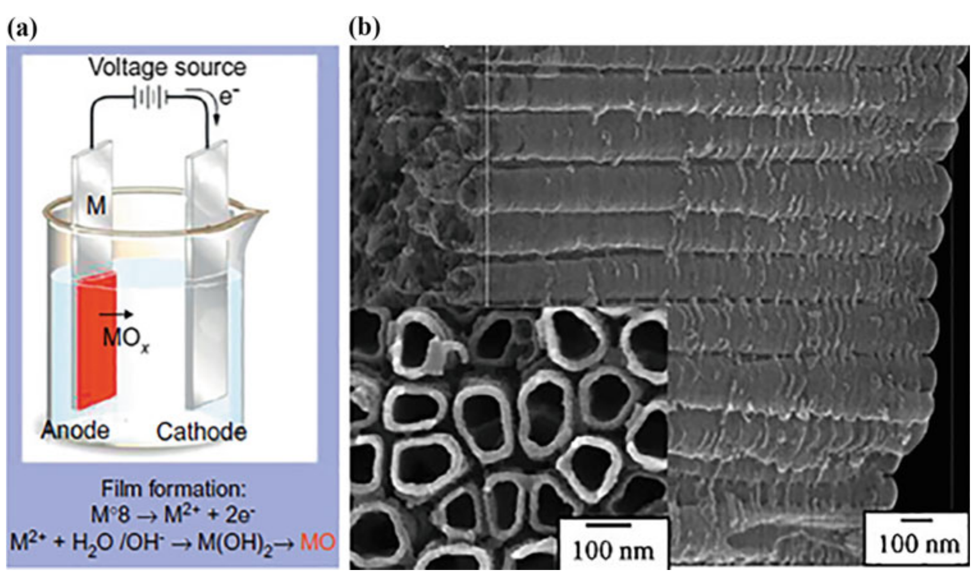

Fig. 1 **a** Electrochemical anodization process and **b** anodic self-ordered nanotubes

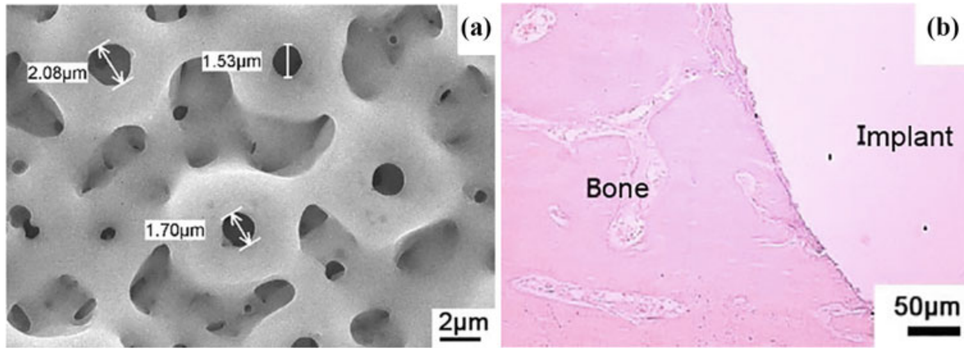

Fig. 2 **a** Porous surface generated by MAO on Ti–25Nb–3Mo–3Zr–2Sn alloy and **b** vigorous bone formation on the surface in 2 weeks

properly selected deposition parameters, as well as creating the desired porosity for the anchorage of bone tissue in implant applications. Yu et al. have produced activated porous TiO_2 on surface of a near β Ti–Nb–Mo–Zr–Sn alloy using MAO in an electrolytic solution containing Ca- and P-subsequently, and apatite formation can be induced on these active porous layers by immersion in simulated body fluid [10]. The active porous surface offers an environment with a strong osteoblast-affinity, as demonstrated by the enhanced attachment, spreading, proliferation and differentiation of the MC3T3-E1 cells. The results suggest that the alloy with a surface modified to incorporate an active porous calcium–phosphate film has excellent corrosion resistance, good biocompatibility and osteoconduction (see Fig. 2).

4 Conclusions

The requirements for dental implants include mechanically assembly with the abutment, permanently locked with jaw bone through osseointegration, appropriate mechanical properties, excellent corrosion resistance, compatible to the surrounding hard/soft tissue biologically and mechanically. β titanium alloys are premising for this application. However, it is still challenge that many properties including low Young's modulus, high strength, good fatigue properties and fracture toughness must be controlled simultaneously, and severe plastic deformation provides a possible pathway to further enhance mechanical properties of titanium. The electrochemical surface treatments such as anodic oxidation and micro arc oxidation are methods to produce nanotube and micro porous features which can accommodate the surface rugophilicity and promote bony cell growth.

References

1. Elias CN, Lima JHC et al (2008) Biomedical applications of titanium and its alloys. JOM 60(3):46–49
2. Adell R, Eriksson B et al (1990) A long-term follow-up study of osseointegrated implants in the treatment of totally edentulous jaws. Int J Oral Maxillofac Implants 5:347–359
3. Osman RB, Swain MV (2015) A critical review of dental implant materials with an emphasis on titanium versus zirconia. Materials 8:932–958
4. Niinomi M (2008) Biologically and mechanically biocompatible titanium alloys. Mater Trans 49:2170–2178
5. Yoshiki O, Tuna EB et al (2010) Dental implant systems. Int J Mol Sci 11:1580–1678
6. Shibata Y, Tanimoto Y et al (2015) A review of improved fixation methods for dental implants. J prosthodontic research 59:20–33
7. Paladugu M, Kent D et al (2010) Strengthening of cast Ti-25Nb-3Mo-3Zr-2Sn alloy through precipitation of α in two discrete crystallographic orientations. Mat Sci and Eng A527:6601–6606
8. Kent D, Wang G et al (2011) Strength enhancement of a biomedical titanium alloy through a modified accumulative roll bonding technique. J Mech Behav Biomed Mater 4:405–416
9. Ercan B, Webster TJ (2008) Greater osteoblast proliferation on anodized nanotubular titanium upon electrical stimulation. Int J Nanomed 3(4):477–485
10. Yu S, Yu Z et al (2011) Biocompatibility and osteoconduction of active porous calcium–phosphate films on a novel Ti–3Zr–2Sn–3Mo–25Nb biomedical alloy. Colloids Surf, B 85:103–115