Chapter 22
Recent Progress in Mechanically Biocompatible Titanium-Based Materials

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ABSTRACT

Mechanical and biological biocompatibility is important consideration for materials that are used as metallic implants. During the past two decades, many β-type titanium alloys composed of non-toxic and hypoallergenic elements with low Young's moduli have been developed worldwide. Recently, the development of new titanium-based materials to improve the mechanical and biological biocompatibility of metallic implants has progressed under advanced concepts. This chapter focuses on the improvement of mechanical biocompatibility, and recent research topics on such material developments are reviewed.

INTRODUCTION

Metals are not intrinsically included as components of the human body; therefore, they are treated as foreign substances. However, metals are widely employed as materials for implants to substitute for or to rebuild hard tissues that maintain large loads, such as bones and teeth, because their mechanical reliability (e.g., fatigue strength and toughness) is higher than that of ceramics and polymers. For example, almost all (approximately 80%) artificial hip joints, bone plates, spinal fixation devices, and artificial dental roots are currently composed of metals (Hanawa, 2010). Therefore, high mechanical reliability is one of the most important properties of metals that are used for implants and general structural applications. Moreover, metals that are used for implants must be biocompatible because they are exposed to an anomalous atmosphere inside the human body. There are two types of biocompatibility, mechanical and biological biocompatibility. For the former (mechanical biocompatibility), the metals that are used for implants should be harmonized

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mechanically with hard tissues. For example, the Young's modulus of bone is approximately 10–30 GPa (Niinomi, 2008; Rho, Tsui, & Pharr, 1997; Zioupos & Currey, 1998); however, the Young's moduli of metals used for implants are much higher. Specifically, a stainless steel (SUS316L) and a titanium alloy (Ti-6Al-4V ELI), both of which are commonly used for implants, exhibit Young's moduli of approximately 200 GPa and 110 GPa, respectively (Navarro, Michiardi, Castano, & Planell, 2008; Niinomi, 2002). Accordingly, the load transfer between a metallic implant and a bone is non-homogeneous. As a result, stress stimulation of the bone is reduced (stress shielding effect). Under such conditions, bone atrophy is likely to occur, leading to a loosening of the metallic implant and a re-fracturing of the bone. To mitigate the stress shielding effect, metals with Young's moduli equal to that of bone are thought to be ideal for the fabrication of metallic implants. However, to ensure biological biocompatibility, toxins and allergens should be removed from the metals that are used in the implants. Additionally, it is often desirable for metals not to be treated as foreign substances in the human body so that they are able to spontaneously connect with hard tissues. This chapter focuses on research regarding the improvement of mechanical biocompatibility, and recent reports on this topic are reviewed.

FURTHER REDUCING YOUNG'S MODULUS

As mentioned above, a low Young's modulus equal to that of bone is desired for metallic implants. Among titanium alloys, β-type titanium alloys tend to exhibit lower Young's moduli than α- or (α + β)-type titanium alloys (Niinomi, 1998). Therefore, extensive efforts have been made to develop β-type titanium alloys with a Young's modulus close to that of bone. Over the past two decades, controlling β-phase stability via optimization of the chemical composition of the alloys has enabled a reduction of the Young's modulus to approximately 40–60 GPa in some β-type Ti-Nb based titanium alloys (Ahmed, Long, Silvestri, Ruiz, & Rack, 1996; Hao, Li, Sun, & Yang, 2006; Kuroda, Niinomi, Morinaga, Kato, & Yashiro, 1998; Matsumoto, Watanabe, & Hanada, 2005; Saito et al., 2003. The advantage of a low Young's modulus for suppressing the stress shielding effect has been demonstrated in animal experiments (Sumitomo et al., 2008). However, even using β-type Ti-Nb-based titanium alloys with a low Young's modulus, the stress shielding effect could not be completely eliminated. Therefore, a further reduction in the Young's modulus is desired for metals that are to be used in metallic implants. To accomplish this reduction, the following two methods have been investigated: (1) controlling the crystal orientation using single crystals and (2) controlling porosity using porous materials.

Single Crystal

Figure 1 shows the dependence of the crystal orientation on the Young's modulus of the Ti-29Nb-13Ta-4.6Zr (TNTZ) single crystal (Tane et al., 2008). It has been reported that the TNTZ polycrystal exhibits a low Young's modulus of approximately 60 GPa, which is the minimum value for this alloy when it is subjected to solution treatment (Akahori, Niinomi, Fukui, Ogawa, & Toda, 2005; Kuroda, et al., 1998). However, for the TNTZ single crystal, a further reduction of the Young's modulus to approximately 35 GPa, which is much closer to the Young's modulus of bone (similar to the upper limit of the Young's modulus of bone), could be obtained along the direction parallel to $<100>_\beta$. It is believed that the lowest Young's modulus could be obtained using this method because the distance between atoms along the direction parallel to $<100>_\beta$ is the largest along any direction. Moreover, it is expected that the Young's modulus can be reduced by controlling the crystallographic texture, even in the polycrystal of each β-type titanium alloy.