Wear resistance of cast dental Ti-Fe alloys

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Binary Ti-Fe alloys with 5–25 mass% Fe were prepared, and subjected to reciprocating wear test. The aim of this study was to investigate the relationship between mechanical properties and the wear resistance of titanium and Ti-Fe alloys. The dimensions (length, width and depth) of wear marks on Ti-Fe alloys were less than those observed on pure Ti specimen. Wear resistance of Ti-Fe alloys was better than that of pure titanium. It was established that hardness was the main factor that influenced wear resistance of Ti-Fe alloys. Single β Ti-Fe alloys showed better wear resistance than α+β Ti-Fe alloys. Increase in concentration of Fe in the β phase of Ti-Fe alloys leads to improved wear resistance of the alloy. Ti-Fe alloys with 11–15 mass% Fe form ideal candidates for fabrication of dental titanium alloys with excellent wear resistance.

Keywords: Ti-Fe alloy, Wear resistance, Mechanical property, Alloy phase, Titanium alloy

INTRODUCTION

Titanium and titanium alloys have high specific strength and good corrosion resistance, thus applicable in aerospace, chemical, sporting goods and leisure industries1–3). Titanium and its alloys demonstrate excellent biocompatibility, making them suitable for use in the medical field as substitute material for hard tissues as well as fixation devices implanted in the body for a long duration4). Applications in the dental field include: making of dental implants, denture metal frames, and clasps. Unfortunately, titanium exhibits poor wear resistance mainly due to its low hardness5). Moreover, its high chemical activity and low thermal conductivity worsens wear resistance causing it to adhere to other materials6,7). High wear resistance is an important aspect especially if the material application involves being incorporated in a device that is under continuous motion. High wear resistance is therefore a desirable quality in constantly sliding or rotating device.

Wear is material loss due to physical forces between two objects that are in contact. Wear can be classified in to four forms: adhesive, abrasive, fatigue and corrosive wear8–10). The four forms of wear are complex and occur in an intricate fashion. It is difficult to predict wear resistance through assessment of hardness or surface properties only.

Attempts to improve wear resistance of titanium through several surface treatment methods have been reported. Surface treatment such as chemical or physical vapor deposition and thermal spraying methods lead to formation of super-hard coatings (of more than 2,000 Hv)11–13). However, these super-hard coatings are generally brittle, and associated with formation of a distinct interphase between the layer of coating and base material14). As a result, the coating easily detaches from the base material. Contrastingly, thermal diffusion treatment method involves formation of a solid-solution layer with oxygen, nitrogen or carbon on titanium surface whose hardness is very high (about 1,200 Hv)14–16). There is no distinct interphase or separation between the solid-solution layer and base material for thermal diffusion treated surfaces. However, the solid-solution layers formed are brittle and the thickness of the layers formed is uncontrollable17).

Although hardness is the main contributing factor of wear resistance; other factors such as toughness and elongation, influence wear resistance5). If two materials are of equal hardness; the metal with higher elongation or toughness shows better wear resistance18,19). It is well known that dental Co-Cr casting alloys shows excellent wear resistance18,20). Despite the high hardness of Co-Cr alloys (350–390 Hv) in comparison to both hardened type 4 dental gold casting (237–264 Hv) and Ti-6Al-4V (320–341 Hv) alloys20,21), it is less than that of the coatings or the layer formed on titanium after surface treatment. However, Co-Cr alloys additionally show good elongation. Developing titanium alloys with excellent wear resistance is possible by incorporating suitable hardness and elongation qualities of Co-Cr alloys through alloying.

In our previous study22), we investigated the existent alloy phases and mechanical properties of Ti-Fe alloys in addition to determination of the composition range with improved wear resistance. Titanium alloys with 8–11 mass% Fe showed potential for good wear resistance like a Co-Cr alloy. They demonstrated high hardness (350–400 Hv) that matches Co-Cr alloy (350–390 Hv)20) and ductility. Alloys with 5–7 mass% Fe (more than 400 Hv) and 20–25 mass% Fe (more than 500 Hv) that showed higher hardness but poor elongation may also be excellent in wear resistance. As illustrated above; factors that determine wear are complex making it difficult to predict wear resistance solely by studying
the mechanical properties. Therefore, it was necessary to perform the actual wear test on Ti-Fe alloys. In this study; binary Ti-Fe alloys with 5–25 mass% Fe were prepared, and subjected to wear test. The aim of this study was to investigate the relationship between mechanical properties and the wear resistance of titanium and Ti-Fe alloys.

MATERIALS AND METHODS

Preparation of specimen

Ti-Fe alloys with the composition of 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 20, and 25 mass% Fe were prepared. The desired amounts of Ti sponge (>99.8%, grade S-90, Osaka Titanium technologies, Amagasaki, Japan) and pure Fe (>99.95%, Hirano Seizaemon Shoten, Tokyo, Japan) were melted in an argon-arc melting furnace (TAM-4S, Tachibana Riko, Sendai, Japan) to form the alloy ingots (15 g each). Each ingot was melted six times to make evenly distributed and uniform composition. Pure Ti ingots were made in the same manner. The quality corresponds to that of commercially available pure titanium Grade 1.

Using magnesia investment (Symbion-TC, i-Cast, Kyoto, Japan) at 200ºC in an argon gas-pressure dental casting machine (Autocast HC-III, GC, Tokyo, Japan); slabs of test specimen (11×30×1.6 mm) were cast and then bench-cooled. All the cast slabs were abraded to a depth of 300 µm using 180–1000 grit SiC paper to remove the superficial hardened surface layer. Afterwards, the slabs were cut into square specimen of 10×10 mm and embedded in epoxy resin (EpoFix, Struers, dallerup, Denmark). Cast pure Ti specimens were prepared in a similar manner.

Wear test

Sliding type two-body wear testing device (Model C320, Yoshimitsu Seiki, Tokyo, Japan) was used to perform the reciprocating wear test. A schematic drawing of the wear test set up is shown in Fig. 1. A spherical indenter was prepared by attaching a 3.0 mm diameter steel ball (SUJ2: 844 Hv) to one end of a cylindrical stainless-steel pipe with a 3.1 mm external diameter and 20 mm length using dental adhesive resin cement (Super-Bond C&B, Sun Medical, Shiga, Japan). The indenter was fixed in a manner to apply the load vertically onto the test specimen. The test was applied at a rate of 60 cycles per minute and strokes of 1.5 mm each under water to mimic wet conditions. The wear test was carried out in two different conditions; 4.9 N weight, 20,000 cycles (herein reported as [4.9N]) and 0.49 N weight, 86,400 cycles (=24 h) (herein reported as [0.49N]). After the wear test, the depth of the wear marks was measured using a surface profilometer (Surfcom 480A, Tokyo Seimitsu, Tokyo, Japan), whereas the length and width was captured using a profile projector (V-12B, Nikon, Tokyo, Japan) (n=18). The wear marks were observed under a scanning electron microscope (SEM; JSM-6060, JEOL, Tokyo, Japan). Wear resistance was evaluated from the results of the above assessments.

Statistical analysis

The data obtained was statistically analyzed using one-way ANOVA and Tukey HSD tests at a significance level of α=0.05.

RESULTS

Wear marks patterns

SEM images of wear marks observed in [4.9N] are shown in Fig. 2. The dimensions (length and width) of wear marks on Ti-Fe alloys are smaller than those observed on pure Ti. The size of wear marks of 5–11 mass% Fe alloys was almost the same. The size of the wear marks decreased with increase in Fe content of the alloys with more than 11 mass% Fe. There was remarkable size reduction in wear marks of alloys with Fe concentration range of 11–15 mass%.

SEM images of wear marks found in [0.49N] are shown in Fig. 3. The wear marks were clear and distinct on pure Ti, unlike those observed on Ti-Fe alloys. The length of wear marks on all the Ti-Fe alloys was hardly different from that of pure Ti. However, the width of the wear marks showed a slight decrease with increase in Fe content of the alloys.

Depth of wear marks

The depth of wear mark of [4.9N] are shown in Fig. 4. Ti-Fe alloys demonstrated significantly shallow marks compared to those of pure titanium (p<0.01). There was no difference in the depth of marks found in alloys with 5–11 mass% Fe (p>0.05). Marks on 5–11 mass% Fe alloys measured about 60% the value of those on pure titanium. The depth of marks found in alloys with 6 mass% Fe was shallow compared to those with 5 mass% Fe and 7 mass% Fe. There was an abrupt decrease in depth of wear marks examined on Ti-Fe alloys with Fe concentration of 11–15 mass% Fe. The actual depth on 11 mass% Fe and 15 mass% Fe alloys was 53.5% and 15.5% of the value of pure titanium, respectively. The depth of wear marks on Ti-Fe alloys gradually decreased with increase in Fe concentration for alloys with 15–25 mass% Fe.
Fig. 2  SEM images of the wear marks (4.9 N, 20,000 cycles).

Fig. 3  SEM images of the wear marks (0.49 N, 86,400 cycles).
The depth of wear marks of [0.49N] are shown in Fig. 5. With the exception of 5 mass% Fe and 7 mass% Fe alloys; all the other concentration of alloys had marks that were shallower than those of pure titanium. Alloys with 6, 8–10 mass% Fe showed wear marks that were about 10–20 µm deep. Ti-Fe alloys with 11 mass% Fe and more were less than 5 µm in depth even though there was no significant difference across the different concentrations ($p>0.05$). The average depth of marks in Ti-Fe alloys with 11 mass% Fe and more was about 15.9% that of pure titanium. This shallowness compared to that of pure titanium was statistically significant ($p<0.01$).
some slight ductility. On the other hand, mass% Fe whose alloy phases were also influenced the wear resistance. Elongation of 5–7 mass% Fe whose alloy phases were α+β was almost zero when subjected to the tensile test. On the other hand, 8–11 mass% Fe whose alloy phase was single β showed some slight ductility. Even though both 6 mass% Fe (α+β) and 25 mass% Fe (β+TiFe) showed significantly high hardness (of more than 500), the depth of wear marks borne by two alloys was remarkably different. From such results in this study, it was demonstrated that alloy phases besides hardness influence the wear resistance of Ti-Fe alloys.

It was expected that Ti-Fe alloys with 8–11 mass% Fe would have excellent wear resistance since the alloys showed good ductility and had high hardness that matched the Co-Cr alloys. However, the wear resistance on carrying out the experiment only improved conspicuously in the alloys with more than 11 mass% Fe. Dimples, typical of ductile fracture, were not observed in any of these compositions during the previous study conducted. An increase in amounts of Fe in the solid-solution of β, rather than the ductility feature, may have contributed towards improvement of wear resistance of Ti-Fe alloys. Additionally, there was a linear increase in hardness of the alloys from 11 mass% Fe to 25 mass% Fe. Interestingly, the depth of wear marks decreased steeply across alloys with 11 mass% Fe to 15 mass% Fe, and then decreased gradually across the alloys with 15 mass% Fe to 25 mass% Fe. The improved hardness of alloys from 11 mass% Fe to 15 mass% Fe was as a result of solid-solution hardening of the β phase, whereas that of 15 mass% Fe to 25 mass% Fe was due to precipitation hardening of TiFe. The results of this study, reveal that the solid-solution of Fe to the β phase is more effective towards improved wear resistance of Ti-Fe alloys than precipitation of Ti-Fe.

The depth of wear marks of [0.49N] was small with a large standard deviation. It was difficult to detect statistically significant difference in the depth of marks formed among the low Fe content alloys. The condition of [4.9N] was more sensitive to the difference in the wear resistance among the various compositions than that of [0.49N]. The relationship between the different compositions and depth in [0.49N] condition showed similar pattern to that of [4.9N]. Although the 5–7 mass% Fe whose alloy phases were α+β had high hardness of more than 400, their wear resistance was not equally good. On the other hand, although the alloys with 8 mass% Fe and more whose alloy phase was single β had lower hardness than 5–7 mass% Fe, their wear resistance was better. Ductility of their bcc structures most likely contributed towards their good wear resistance. The depth of wear marks on Ti-Fe alloys decreased remarkably when the alloy composition exceeded 11 mass% Fe. Increase of concentration of Fe in β phase positively influenced wear resistance, in both [0.49N] and [4.9N].

**Dental Ti-Fe alloys with excellent wear resistance**

Because the depth of wear-marks formed on Ti-Fe alloys with single β phase was shallow under both test conditions, we propose that the wear resistance of Ti-Fe alloys with single β phase is better than that of titanium. Specifically, wear resistance of the alloys with 11 mass% Fe and more was excellent. The wear resistance of alloys with 20 mass% Fe and 25 mass% Fe was good due to the increased hardness caused by precipitation hardening of TiFe, but almost similar to 15 mass% Fe. Intermetallic compound such as TiFe are generally brittle, thus alloy compositions from which an intermetallic compound is precipitated are not recommended for dental use. Additionally, corrosion resistance is one of the important properties for dental alloys. It has been reported that the corrosion resistance of Ti-Fe alloys with up to 20 mass% Fe, whose phases were single β phase, was as good as that of pure titanium. Furthermore, unlike Ti-6Al-7Nb or Ti-6Al-4V, Ti-Fe alloys contain neither vanadium nor aluminum, which pose safety concerns. Iron is an essential element in the body of human beings and has relatively low risk of inducing allergic reactions. Therefore, Ti-Fe alloys with 11–15 mass% Fe form ideal candidates for dental titanium alloy with excellent wear resistance.

**CONCLUSIONS**

In this study, Ti-Fe alloys designed to bear improved wear resistance compared to titanium, were prepared and subjected to wear test under two conditions. The following statements were established from the results:

1. The wear resistance of Ti-Fe alloys was better than that of pure titanium.
2. Hardness was the main factor that influenced wear resistance of Ti-Fe alloys.
3. Single β Ti-Fe alloys showed better wear resistance than α+β Ti-Fe alloys.
4. Increase in concentration of Fe in the β phase of Ti-Fe alloys leads to improved wear resistance of the alloy.
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