Grindability of Cast Ti-6Al-4V Alloyed with Copper

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Abstract

Purpose: This study investigated the grindability of cast Ti-6Al-4V alloyed with copper.
Materials and Methods: The metals tested were commercially pure titanium (CP Ti), Ti-6Al-4V, experimental Ti-6Al-4V-Cu (1, 4, and 10 wt% Cu), and Co-Cr alloy. Each metal was cast into five blocks ($3.0 \times 8.0 \times 30.0$ mm^3). The 3.0-mm wide surface of each block was ground using a hand-piece engine with an SiC wheel at four circumferential speeds (500, 750, 1000, and 1250 m/min) at a grinding force of 100 g. The grindability index (G-index) was determined as volume loss (mm^3) calculated from the weight loss after 1 minute of grinding and the density of each metal. The ratio of the metal volume loss and the wheel volume loss was also calculated (G-ratio, %). Data (n = 5) were statistically analyzed using ANOVA ($\alpha = 0.05$).
Results: Ti-6Al-4V and the experimental Ti-6Al-4V-Cu alloys exhibited significantly ($p < 0.05$) higher G-indexes compared with CP Ti and Co-Cr at any rotational speed except for the lowest speed (500 m/min). At 500 m/min, the G-index of Ti-6Al-4V-Cu increased as the amount of alloyed copper increased. The 4% Cu and 10% Cu alloys had significantly greater G-indexes than did 1% Cu and Ti-6Al-4V at the highest rotational speed (1250 m/min). Increasing the percentage of alloyed copper and the circumferential speed also increased the G-ratio.
Conclusions: A slight reduction in ductility due to alloying Ti-6Al-4V with copper improved the grindability of some of the resultant Ti-6Al-4V-Cu alloys.

Titanium and titanium alloys are materials of choice for prosthetic devices used by patients with sensitivity to traditional dental alloys, because these alloys have excellent corrosion resistance and biocompatibility in the oral environment.[1,2] To make cast titanium prostheses clinically applicable, investigators have rigorously worked to improve these prostheses' grinding, cutting, and polishing characteristics.[3–11] The grindability of titanium is generally considered to be poor, owing to several inherent properties such as its high chemical reactivity at high temperature, relatively low thermal conductivity, and high ductility.[11] Titanium is chemically reactive, which means it tends to adhere to metal tools, thus leading to shortened tool life.[3] The low thermal conductivity of titanium also damages tools, because the heat generated during grinding cannot escape through the titanium metal framework, resulting in dullness of the metal cutting tools and delamination of the abrasive particles in these tools.[3,7,8] The high ductility of titanium causes these delaminated abrasive particles to adhere to the grinding surface, preventing further effective grinding.

Among various titanium alloys, Ti-6Al-4V is one of the most studied titanium alloys and has been used for the fabrication of denture bases and multiple unit bridges because of its higher strength compared with pure titanium.[2] In general, the grindability of Ti-6Al-4V is much better than that of CP Ti.[7,9] The main reason for this is considered to be the two-phase $\alpha + \beta$ microstructure of the as-cast Ti-6Al-4V. This type of microstructure has a higher resistance to plastic deformation with less ductility, which generates broken metal chips more easily. Kikuchi et al.[10] investigated the grindability of cast Ti alloyed with Cu and reported that the grindability was improved by increasing the amount of Cu (up to 10%). This improvement was due to the introduction of the Ti_2Cu eutectoid in their microstructure. Similar to the two-phase lamellar structure, this microstructure increases resistance to plastic deformation, which should work favorably for the improvement of grinding efficiency. Thus, introducing the eutectoid into the $\alpha + \beta$ Ti-6Al-4V was thought to improve the grindability of the Ti-6Al-4V, which already has better grinding characteristics than does CP Ti. Therefore, the purpose of this study was to investigate the grindability of cast Ti-6Al-4V alloyed with copper and to compare the results with those of CP Ti and a commercial dental casting alloy, the Co-Cr alloy.

Materials and methods

The six metals used in this study were commercially pure titanium (ASTM Grade 2, Titanium Industries, Grand Prairie, TX), Ti-6Al-4V (ASTM Grade 5, Titanium Industries), three experimental Ti-6Al-4V-Cu alloys, and Co-Cr alloy (Vitallium, Austenal, Chicago, IL). The experimental alloys were made by melting together 30 g discs of Ti-6Al-4V (KS6-4, Kobelco Steel Ltd., Kobe, Japan) and pieces of pure copper (Oxygen Free Cu, 99.99 mass%, The Research Institute for Electric and Magnetic Materials, Sendai, Japan) in the following chemical compositions: 1.0 wt% Cu (hereafter, Ti64-1% Cu), 4.0 wt% Cu (Ti64-4% Cu), and 10.0 wt% Cu (Ti64-10% Cu). Note that these copper percentages are based on the concentration of titanium in the alloy. The Ti-6Al-4V disc and a designed amount of Cu were arc-melted and inverted five times to ensure the alloy homogeneity on a water-cooled hearth in a furnace (ACM-01 Diavac Limited, Chiba, Japan). Usually a hardened reaction layer (α-case) on the cast surface forms, consisting of the stabilized α-Ti with elements contaminated by investment materials.[12] In the present study, the grindability was investigated in the bulk interior structure. Therefore, the α-case, which is usually a maximum of 200 μm, was removed from all the surfaces of the cast specimens before testing. A rectangular parallel-piped wax pattern (3.5 × 8.5 × 30.5 mm^3) was invested in a magnesia-based investment material (Selevest CB, Selec Co., Osaka, Japan) for CP Ti and Ti-6Al-4V. Each metal was cast using a centrifugal casting machine (Ticast Super R, Selec Co.). Approximately 250 μm was removed from the cast surfaces, which made the dimensions of the test specimens 3.0 × 8.0 × 30.0 mm^3. For the Co-Cr alloy, plates (3.0 × 8.0 × 30.0 mm^3) were cast using phosphate-bonded investment (V.R. Investment, Austenal) and an induction-casting machine (ECM III, Nobelpharma Inc., Chicago, IL). The surfaces of the cast Co-Cr alloy specimens were cleaned by air abrasion with 50 μm Al_2O_3.

Prior to the grindability testing, the microhardness of the interior structure was measured on the surfaces metallurgically polished using 1 μm alumina slurry. Vickers microhardness was measured with a load of 100 g and a dwell time of 15 seconds (Model FM-7, Future-Tek Corp., Tokyo, Japan). Three indentations were measured for the five specimens of each metal and averaged.

The 3.0-mm wide surface of each metal block was ground with a SiC wheel (703-120, Brasseler, Savannah, GA) (13-mm diameter, 1.5-mm thick, 120 μm grit SiC particles) using a hand-piece engine (UP500, Brasseler) set in the custom-made apparatus used in our previous studies.[7] Four circumferential speeds (500, 750, 1000, 1250 m/min) and a grinding force of 100 gf were used. The grindability index was determined as volume loss (mm^3) estimated from the weight loss after 1 minute of continuous grinding and the density of each metal. The mean density (g/cm^3) determined for each metal used (one standard deviation, n = 5) were: 4.52 (0.04) for CP Ti; 4.42

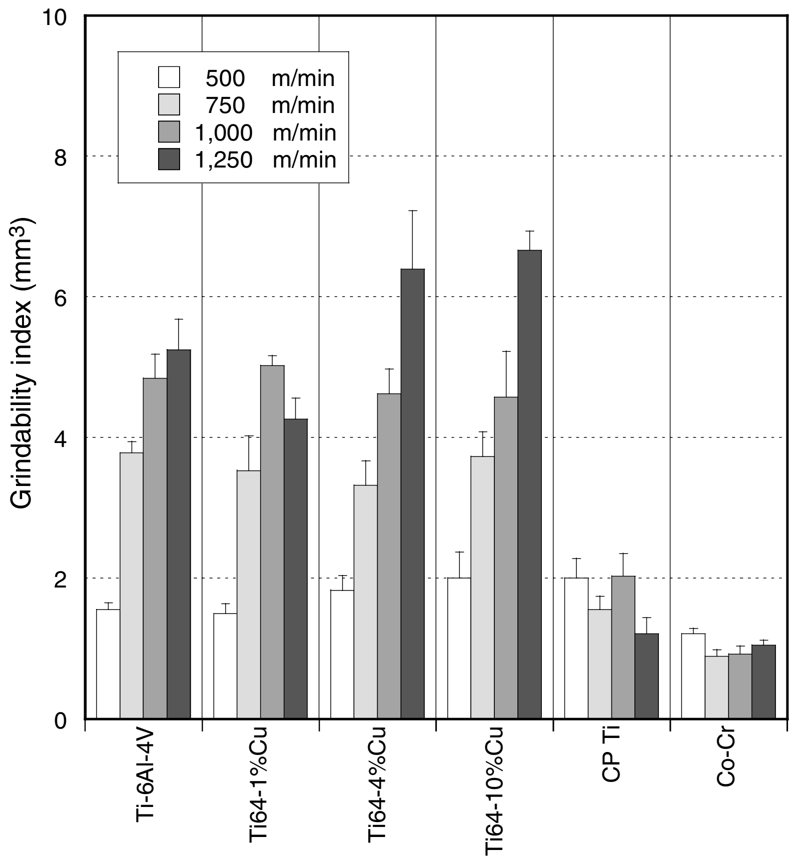

Figure 1 Grindability indexes (mm^3) of metals tested.

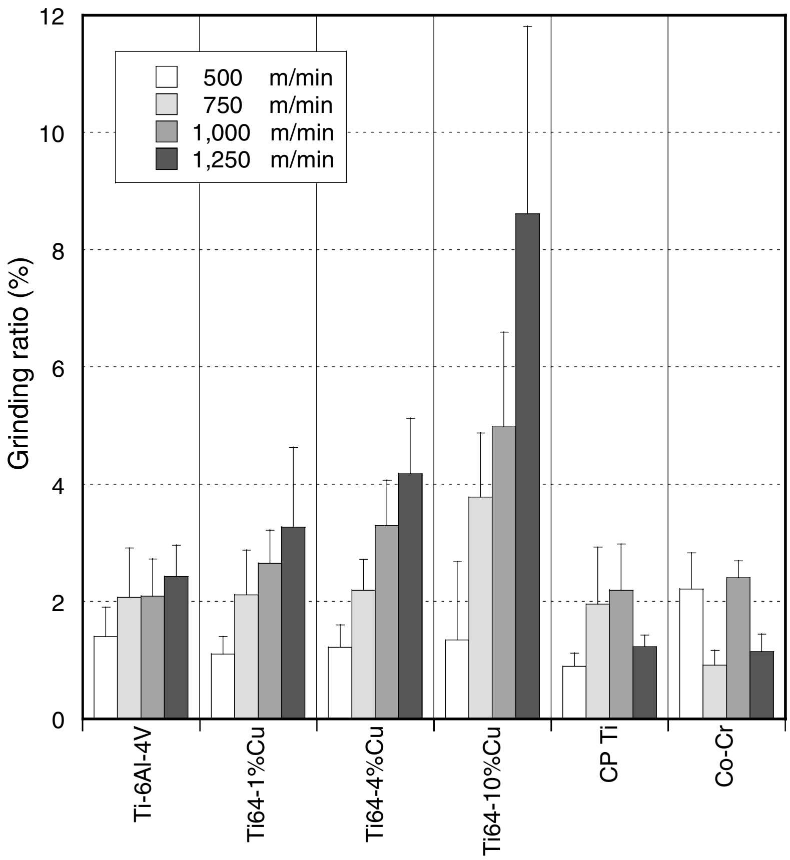

Figure 2 Grinding ratios (%) of metals tested.

(0.03) for Ti-6Al-4V; 4.43 (0.01) for Ti64-1% Cu; 4.47 (0.01) for Ti64-4% Cu; 4.64 (0.02) for Ti64-10% Cu; and 8.25 (0.05) for Co-Cr. The grinding ratio (%) was also estimated as the ratio of the metal volume loss and the wheel volume loss [(amount of metal removed)/(amount of wheel lost)]. The volume loss of the wheel was obtained by measuring the changes of diameter before and after testing. The diameters were measured at three arbitrarily chosen sites and averaged. Both data of grindability index and grinding ratio (n = 5) were statistically analyzed (ANOVA and Scheffé test: $\alpha = 0.05$).

Results

The bulk hardness (Hv, mean ± standard deviation) of each cast metal was obtained in the following order: Co-Cr alloy (576 ± 38) > Ti64-10% Cu (508 ± 8) > Ti64-4% Cu (404 ± 23) > Ti64-1% Cu (389 ± 6) > Ti-6Al-4V (380 ± 12) > CP Ti (211 ± 13).

The grindability indexes (mm^3) and the grinding ratios (%) of all kind of metals at four circumferential speeds used are summarized in Figures 1 and 2, respectively. The grindability indexes of the Ti-6Al-4V and three Ti64-Cu alloys were significantly higher compared to the CP Ti and Co-Cr alloy at all speeds except for the lowest speed (500 m/min) (Fig 1). At the lowest speed (500 m/min), there were no significant differences ($p > 0.05$) in the grindability index among the Ti-6Al-4V and Ti64-Cu alloys except between Ti64-1% Cu and Ti64-10% Cu. Ti64-4% Cu and Ti64-10% Cu indicated significantly greater grindability indices than any other metals tested at the highest wheel speed (1250 m/min). Increasing the Cu content and circumferential speed increased the grinding ratios of the Ti64-Cu alloys (Fig 2); however, there were no significant differences in the grinding ratio among the CP Ti, Ti-6Al-4V, and Ti64-Cu alloys at the lower speeds (500 and 750 m/min) (Fig 2). At the highest speed (1250 m/min), the grinding ratio of Ti64-10% Cu was significantly higher ($p < 0.05$) than those of the Ti-6Al-4V, Ti64-1% Cu, and Ti64-4% Cu alloys.

Discussion

The study revealed that the grindability of Ti-6Al-4V and Ti-6Al-4V alloyed with Cu exhibited much better grindability than CP Ti and the Co-Cr alloy, except for the slowest grinding speed. Also notable is an exceptional high grindability of the Ti64-4% Cu and Ti64-10% Cu compared to that of the rest of the metals at higher circumferential speeds. A similar trend was found in the previous study on the grindability of a series of Ti-Cu alloys.[10] As found earlier, it is apparent the two-phase $\alpha + \beta$ structure of Ti-6Al-4V and the Ti-Cu eutectoid structure, both of which increase the resistance to plastic deformation, help to improve grindability by breaking more easily in forming metal chips. For both the Ti-Cu alloys[13] and Ti-6Al-4V alloyed with Cu,[14] the hardness increased and ductility (percent elongation) decreased with the amount of Cu. Earlier we found an excellent negative correlation between grindability and the ductility for various titanium alloys.[9,10] Certainly the higher grindability of CP Ti did not bring out the high ductility because of an easy plastic deformation on the ground surfaces. Apparently, the mechanism of the grinding processes of Co-Cr alloys is different from titanium, and they exhibited a very low grindability. As observed in our earlier studies,[8,15] the ground Co-Cr chips showed similar debris, which is very fine and thin compared with those of CP Ti and Ti-6Al-4V, and the ground Ti-6Al-4V chips were coarser than those of CP Ti. These observations and the highest hardness among the metals tested indicate the extreme stiffness of Co-Cr alloy, resulting in the lowest grindability of this metal.

As for the grinding ratio, the trend for each metal with the grinding speed resembled that for the grindability. In general, a grinding ratio, thus efficient grinding with less wear of the grinding wheel, was realized with the increased amount of Cu in Ti-6Al-4V. The effect of additive Cu on grinding ratio (Fig 2) was more apparent than on grindability index (Fig 1). These results indicated that increasing the amount of Cu in Ti-6Al-4V decreases the damage to the grinding tool and lengthens the tool life. CP Ti is known to increase damage to the grinding tool and to shorten tool life due to its low thermal conductivity. Heat generated during grinding cannot be released through the titanium specimen and accumulates around the ground surface, resulting in damage to the grinding tool. This is another possible effect of Cu on the increased grinding ratio, since increasing the copper content could increase the thermal conductivity of the alloy. Although gold alloys (which usually are easily machined) were not employed in this study, our previous study[15] indicated that there was no significant difference in grindability and the grinding ratio between a Ti-6Al-4V alloy and a Type IV gold alloy. The results of grindability and the grinding ratio obtained for CP Ti and Ti-6Al-4V are similar to the results of this study, that is, lower grindability and grinding ratio of CP Ti than Ti-6Al-4V.

One concern brought up by adding copper to Ti-6Al-4V is the change of biocompatibility of the alloy. In our previous study,[16] the cytotoxicity of commercial and novel binary titanium alloys (including Ti-6Al-4V) was investigated, and the addition of 10% copper to CP Ti did not show any cytotoxicity, which was the same as CP Ti. Therefore, the addition of copper to Ti-6Al-4V will probably not change the biocompatibility of Ti-6Al-4V when alloyed with copper. Unfortunately, titanium alloys with copper are not commercially available for dental use; however, this alloy system shows promise for dental applications under the limits of this study.

Conclusions

The highest grindability indexes were obtained for Ti64-4% Cu and Ti64-10% Cu at the highest wheel speed employed. The grinding ratio increased as the concentrations of alloyed copper and wheel speed increased. Based on two criteria (grindability index, grinding ratio), the grindability of the Ti-6Al-4V-Cu alloys improved as the percentage of alloyed copper increased.

References

1. Kononen M, Rintanen M, Waltimo A, et al: Titanium framework removable partial denture used for patients allergic to other metals. J Prosthet Dent 1995;73:4-7
2. Wakabayashi N, Ai M: A short-term clinical follow-up study of superplastic titanium alloy for major connectors of removable partial dentures. J Prosthet Dent 1997;77:583-587
3. Miyazaki T, Tamaki Y, Suzuki E, et al: Polishing of titanium prosthetics (Part 1) Mechanical polishing by dental laboratory rotary wheels. J Jpn Dent Mater 1987;6:917-922
4. Miyakawa O, Watanabe K, Okawa S, et al: Grinding of titanium. Part 1. Commercial and experimental wheels made of silicon carbide abrasives. J Jpn Dent Mater 1990;9:30-41
5. Miyakawa O, Watanabe K, Okawa S, et al: Grinding of titanium. Part 2. Commercial vitrified wheels made of alumina abrasives. J Jpn Dent Mater 1990;9:42-52
6. Miyawaki H, Taira M, Wakasa K, et al: Dental high-speed cutting of four cast alloys. J Oral Rehabil 1993;20:653-661
7. Ohkubo C, Watanabe I, Ford JP, et al: The machinability of cast titanium and Ti-6Al-4V. Biomaterials 2000;21:421-428
8. Watanabe I, Ohkubo C, Atsuta M, et al: Cutting efficiency of air-turbine burs on cast titanium and dental casting alloys. Dent Mater 2000;16:420-425
9. Watanabe I, Kiyosue S, Ohkubo C, et al: Machinability of cast commercial titanium alloys. J Biomed Mater Res 2002;63:760-764
10. Kikuchi M, Takada Y, Kiyosue S, et al: Grindability of cast Ti-Cu alloys. Dent Mater 2003;19:375-381
11. Ozugwu O, Wang M: Titanium alloys and their machinability. J Mater Proc Tech 1997;68:262-274
12. Watanabe I, Watkins JH, Nakajima H, et al: Effect of pressure difference on the quality of titanium casting. J Dent Res 1997;76:773-779
13. Kikuchi M, Takada Y, Kiyosue S, et al: Mechanical properties and microstructures of cast Ti-Cu alloys. Dent Mater 2003;19:174-181
14. Aoki T, Okafor ICI, Watanabe I, et al: Mechanical properties studies of Ti-6Al-4V-XCu alloys. J Oral Rehabil 2004;31:1109-1114
15. Ohkubo C, Hosoi T, Ford JP, et al: Effect of surface reaction layer on grindability of cast titanium alloys. Dent Mater 2006;22:268-274
16. Watanabe I, Wataha JC, Lockwood PE, et al: Cytotoxicity of commercial and novel binary titanium alloys with and without surface-reaction layer. J Oral Rehabil 2004;32:185-189