

Machinability of Experimental Ti-Ag Alloys

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This study investigated the machinability of experimental Ti-Ag alloys (5, 10, 20, and 30 mass% Ag) as a new dental titanium alloy candidate for CAD/CAM use. The alloys were slotted with a vertical milling machine and carbide square end mills under two cutting conditions. Machinability was evaluated through cutting force using a three-component force transducer fixed on the table of the milling machine. The horizontal cutting force of the Ti-Ag alloys tended to decrease as the concentration of silver increased. Values of the component of the horizontal cutting force perpendicular to the feed direction for Ti-20%Ag and Ti-30%Ag were more than 20% lower than those for titanium under both cutting conditions. Alloying with silver significantly improved the machinability of titanium in terms of cutting force under the present cutting conditions.

Keywords: Titanium alloy, Machinability, CAD/CAM

INTRODUCTION

Although titanium is well suited for dental prostheses because of its combination of excellent corrosion resistance and biocompatibility, it is difficult to machine. The relative ease of machining a material, that is, the material's machinability, is considered good if the tool life is long, the cutting forces are low, the surface finish is good, and the chips are well formed. Machinability is a result of complex interactions among various properties of a material. The intrinsically poor machinability of titanium is a serious practical problem in the milling of this material with dental CAD/CAM systems. This is because it not only affects the quality of prostheses, but also leads to low economic efficiency.

Another problem with titanium is that its strength is insufficient for dental prostheses that need comparatively high strength, such as partial dentures, bridges, and superstructures of implants. Alloying titanium is one method of improving its properties. To date, industrial free-cutting titanium and titanium alloys have been developed¹⁾. However, they were not developed for dental use. They contain sulfur and rare-earth metals as free-cutting additives, which are less-familiar elements in conventional dental alloys. It has been reported that their corrosion resistance is inferior to that of pure titanium and that further consideration is needed before these alloys can be applied to dentistry²⁾.

Since most currently available dental alloys have been developed to facilitate the dental casting process and few have been developed for enhanced machinability, we believe that there is room for improvement. In our previous studies³⁻⁷⁾, the properties of experimental Ti-Ag alloys were examined. Silver was selected as an alloying element because it

has a long history of use in dentistry. Our results showed that when titanium was alloyed with silver, the tensile strength and hardness of titanium could be significantly improved³⁾ without significantly reducing the corrosion resistance^{5,6)}. As for biocompatibility, Wang and Li reported that there was no significant difference between Ti-25%Ag alloy and titanium⁸⁾. In addition, the grindability of Ti-20%Ag was significantly higher than that of titanium under certain grinding conditions⁷⁾.

In this paper, the machinability of experimental titanium alloys with 5–30 mass% silver was evaluated through cutting force with the hope of developing a new titanium alloy suitable for dental CAD/CAM applications.

MATERIALS AND METHODS

Chemical compositions of experimental alloys

Silver is a β -stabilizing element that reduces the allotropic transformation temperature from β (bcc) to α (hcp) of titanium. Ti-Ag alloy is classified as a titanium alloy with a eutectoid transformation and a eutectoid point at 15.6 mass% Ag (hereafter, "mass%" will be referred to as "%")⁹⁾. The experimental Ti-Ag alloys in the present study (5%, 10%, 20%, and 30% Ag) were selected from both hypoeutectoid and hypereutectoid regions.

Preparation of specimens

Buttons (15 g each) of the Ti-Ag alloys were prepared by melting titanium sponge (>99.8%, grade S-90, Sumitomo Titanium, Amagasaki, Japan) and silver (99.9%, Ishifuku, Tokyo, Japan) using an argon-arc melting furnace (TAM-4S, Tachibanariko, Sendai, Japan). The chamber was evacuated to 5 mPa, and high-purity argon gas (>99.9999%, Nipponso, Japan)

Kawasaki, Japan) was introduced until the pressure reached 50 kPa prior to melting. A titanium getter was melted before the material was melted. Each ingot was inverted five times during melting and was melted a total of six times. The titanium ingots were made in the same way.

Although the experimental alloys were made for machining and not for casting, the buttons were cast and formed into small plates. Wax patterns (3.5 mm × 8.5 mm × 30.5 mm) were invested in a magnesia investment material (Selevest CB, Selec, Osaka, Japan). The molds were burnt out according to the investment manufacturer's instructions. Each button was arc-melted and cast into the mold using a dental titanium-casting unit (Castmatic-S, Iwatani, Osaka, Japan). After being cast, the molds were kept at room temperature. Prior to testing, the entire hardened surface layer of each casting was ground using SiC abrasive paper, producing specimens measuring approximately 3 mm × 8 mm × 30 mm. All surfaces subjected to cutting were polished to a 1000-grit surface finish. Three specimens were made for each metal.

Machinability test

The specimens were slotted using a milling machine (MDX-500/ZS-500T, Roland DG, Hamamatsu, Japan) and square end mills (mill diameter: 3 mm, 2 flutes; FX-MG-EDS, OSG, Toyokawa, Japan)¹⁰. The axial direction of the tool was parallel to the vertical axis of the milling machine. The tool was fed in the horizontal direction of the machine. A three-component force transducer (LSM-50KBS, Kyowa, Tokyo, Japan), which had a left-handed coordinate system, was fixed on the table of the milling machine so that the positive x direction and positive z direction of the transducer matched the feed direction and the tool tip direction, respectively, as shown in Fig. 1. The direction of rotation of the tool was from the positive x direction to the negative y direction of the transducer. Three strain amplifiers (DPM-711B, Kyowa) were used for signal conditioning.

The outputs of the strain amplifiers were acquired for 2^{14} samples (3.3 s) at a sampling rate of 5 kHz using a computer (AT-690C, Epson, Matsumoto, Japan) equipped with a 16-bit A/D interface (6034E, National Instruments, Austin, TX, USA) during cutting. The three component forces (F_x , F_y , and F_z) were determined by calculating the average forces. Each specimen was gripped in a vise mounted on the transducer so that the surfaces to be cut on all specimens were even with the top of the vise. A cutting test was performed under two cutting conditions, as shown in Table 1, for each specimen. Condition A was close to the tool manufacturer's recommended milling condition for heat-resistant alloys, which are difficult to machine¹¹. Under condition B, the cutting

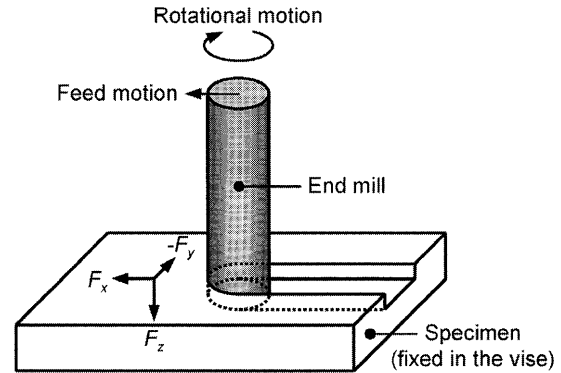


Fig. 1 Coordinates of the cutting force measurement system.

Table 1 Cutting conditions

Condition	Cutting speed		Feed rate		Depth of cut mm
	rev s ⁻¹	m s ⁻¹	mm s ⁻¹	μm rev ⁻¹	
A	50	0.47	1	20	0.2
B	100	0.94	2	20	0.2

rev: revolution of tool

speed and feed rate were doubled. The test was performed twice for each specimen and cutting condition. Two tools were used for each metal, and no cutting fluid or coolant was used. The cut surfaces and metal chips were observed using a scanning electron microscope (JSM-6060, JEOL, Tokyo, Japan). The results were analyzed using ANOVA and the Scheffé's test at a significance level of $\alpha = 0.05$ and were compared with those of titanium.

RESULTS

Cutting forces

Figure 2 shows the cutting forces of the Ti-Ag alloys. Under condition A, except for that of Ti-5%Ag ($p < 0.05$), the F_x values of titanium and Ti-Ag alloys were not significantly different; under condition B, there were no significant differences at all (Fig. 2(a)). The absolute value of F_y tended to decrease as the concentration of silver increased (Fig. 2(b)). For all Ti-Ag alloys, the absolute value of F_y was significantly lower than that of titanium under condition A ($p < 0.01$ for 5%Ag and 10%Ag; $p < 0.001$ for 20%Ag and 30%Ag). Under condition B, Ti-20%Ag and Ti-30%Ag exhibited significantly lower absolute values of F_y than titanium (both $p < 0.05$). It is noteworthy that the values for Ti-20%Ag and Ti-30%Ag were more than 20% lower than those for titanium under both conditions. The absolute values of F_z were well

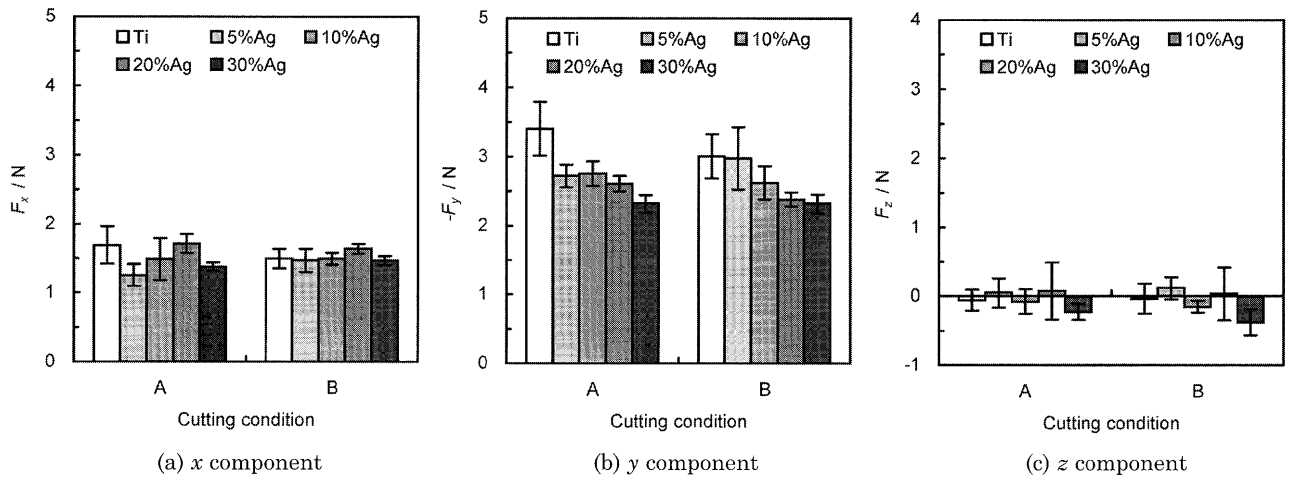


Fig. 2 Cutting forces of the Ti-Ag alloys.

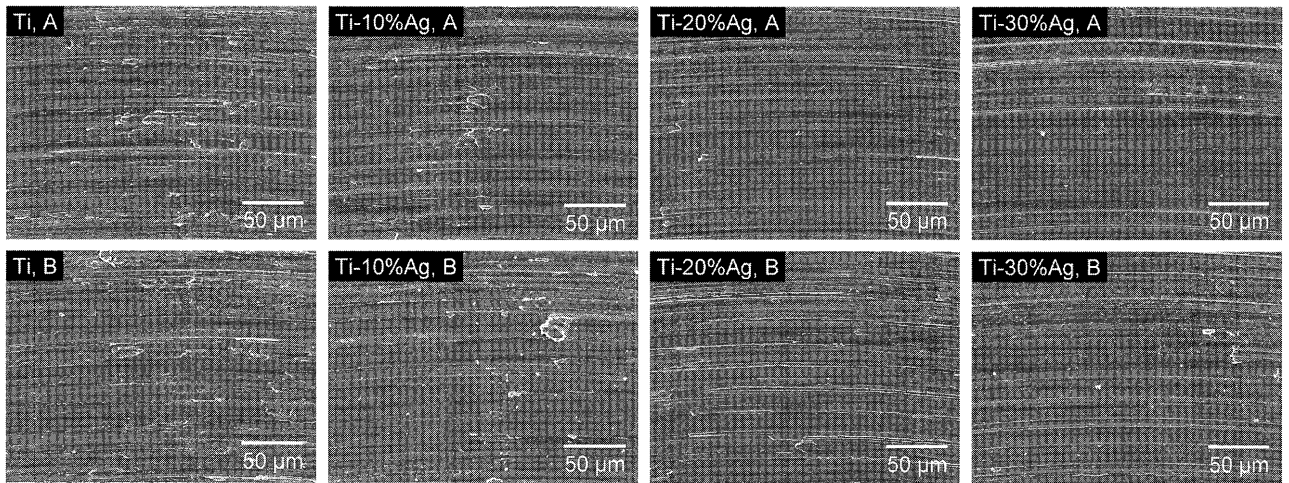


Fig. 3 Cut surfaces of the Ti-Ag alloys.

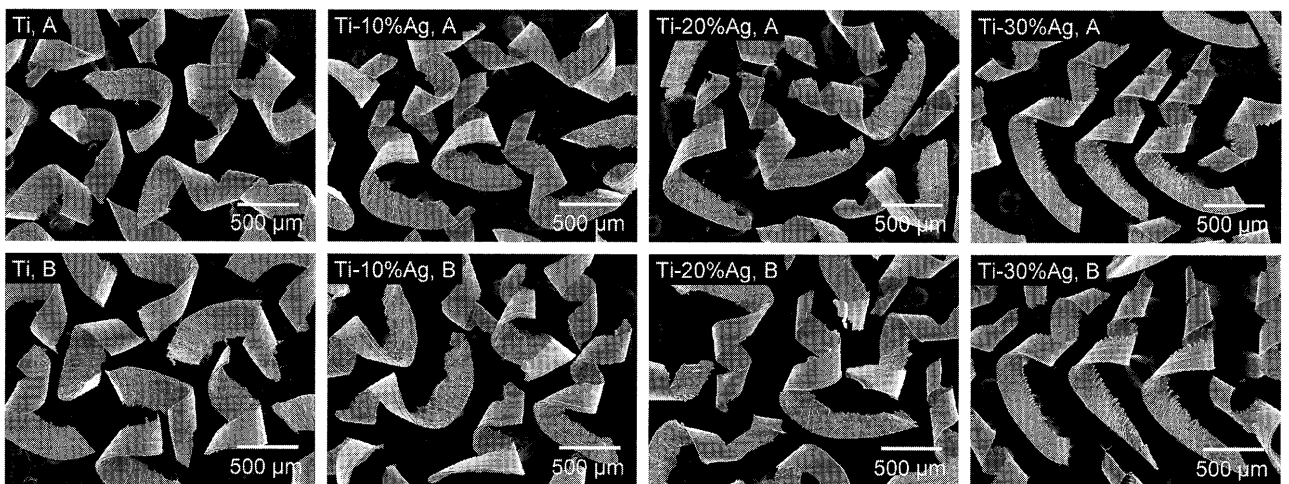


Fig. 4 Metal chips cut from the Ti-Ag alloys.

below those of the horizontal cutting forces (Fig. 2(c)). No statistical differences in F_z were found among the metals.

Cut surfaces and metal chips

Figure 3 shows the cut surfaces of the Ti-Ag alloys. The feed direction was from the bottom to the top, and the rotational direction was from the left to the right of each image. Cutting marks were observed on all the cut surfaces. The coarsest pitch length was 20 μm and matched the feed per revolution of the tool in the present study. Adhesion of metal chips to the cut surface was observed in some places. However, there were no marked differences in the appearance of the cut surfaces among the metals and cutting conditions.

Figure 4 shows the metal chips resulting from cutting. The shape of the titanium chips was, in general, a short spiral. The extremity lying inside the spiral was formed when the cutting edge of tool entered the metal. The chips appeared thinner and longer as the concentration of silver increased. For each metal, there were no pronounced differences in the appearance of metal chips between the two cutting conditions.

DISCUSSION

The cutting force determines the cutting power requirements for removal of a material. In the present study, the horizontal cutting forces were related to the cutting power. The rotational power was proportional to the product of the torque (related to F_x and F_y) and the angular speed, and the feed power was proportional to the product of F_x and the feed rate. The majority of the cutting power is predicted to turn into thermal energy and raise the temperature of the tips of a tool, thus shortening its life. This is especially so when the work material has a thermal conductivity as low as that of titanium. The cutting force also affects the dimensional accuracy and surface integrity of the workpiece because a higher cutting force results in greater deformation of the machining system (machine, tool, and workpiece). It is, therefore, desirable to reduce the cutting force.

The absolute value of F_y tended to decrease with the concentration of silver. The absolute values of F_y for Ti-20%Ag and Ti-30%Ag were more than 20% lower than those for titanium under both conditions. In our previous study on the machinability of titanium alloys¹⁰⁾, the machinability of free-cutting brass, well known for its superior machinability, was used as a benchmark. The absolute values of the horizontal cutting forces (both F_x and F_y) of brass were significantly lower (approximately 50%) than those of titanium. The cutting forces of Ti-20%Ag and Ti-30%Ag were

between those of titanium and brass, rendering them as good candidates for dental machining alloys for CAD/CAM use. Considering its corrosion resistance, Ti-20%Ag was thus far the most promising Ti-Ag alloy^{5,6)}.

The mechanical properties and machinability of a metal are affected by its microstructure¹²⁾. Based on the Ti-Ag equilibrium phase diagram⁹⁾, the alloy phases of 10%Ag, 20%Ag, 30%Ag, and possibly 5%Ag alloys should be α and the intermetallic compound Ti_2Ag at room temperature. However in reality, as shown in previous studies^{5,6)}, Ti-Ag alloys with a small amount of silver consisted of an α phase only because of non-equilibrium cooling. The precipitation of the intermetallic compound in the Ti-Ag alloy seemed to result from a silver concentration of around 20%. Our previous study³⁾ revealed that the tensile strength and Vickers hardness of Ti-Ag alloy increased with an increase in silver concentration. It was thought to be due to solid solution strengthening and the inclusion of a small amount of intermetallic compound Ti_2Ag . The strength and hardness of Ti-20%Ag were about 1.6 and 1.8 times higher than those of titanium, respectively.

A high degree of strength and hardness in a material often results in low machinability¹²⁾. The cutting forces of Ti-6Al-4V and Ti-6Al-7Nb were significantly higher than those of titanium¹⁰⁾, which coincided with the higher degree of tensile strength and hardness of these two titanium alloys than those of titanium. On the other hand, although the Ti-Ag alloys also had higher tensile strength and hardness than titanium, their machinability in terms of cutting force was comparable to or even better than that of titanium. This showed that the machinability of a material cannot be determined only by its tensile strength and hardness.

It is known that lower ductility is generally beneficial to machinability¹³⁾. Cutting a ductile alloy requires that the tool have a sharp cutting edge¹⁴⁾. In industry, it is common to improve the machinability of a metal by adding free-cutting additives^{1,15-17)}. These additives are dispersed in the metal as elements or as compounds and reduce the ductility of metals, thereby enhancing the notch effect in metal chips and improving chip breakability.

In our previous study, the elongation of Ti-Ag alloy decreased from 36% to 19% with an increase in the concentration of silver from 0% to 20%³⁾. Although no elongation value was available for Ti-30%Ag, an explanation for the favorable machinability of the Ti-Ag alloys was the decrease in elongation caused by microstructural changes through alloying. The reduced ductility was probably the primary contributor to the decreased chip thickness and cutting force^{14,18)}.

It should also be noted that in general, lower ductility promotes shorter chips. In the present study, however, the chip length became longer with decreased elongation. Assuming that the chip was strong enough to maintain its original length, it is understandable that the chip length increased with decreased thickness because the volume of material removed by a cutting tooth at one time was constant under the present milling condition.

It was possible that not only reduced ductility contributed to improved machinability, but that the intermetallic compound dispersed in the matrices of Ti-20%Ag and Ti-30%Ag had the same effect as free-cutting additives. In this connection, it should be possible to control the machinability of Ti-Ag alloys by controlling the precipitation of the intermetallic compound through a heat treatment.

In terms of testing modes, tools, and processing speeds, there were indeed differences between the present study and a previous grinding experiment⁷⁾. In the present study, the cutting test was performed at a constant feed rate, while the grinding test was performed at a constant load. TiAlN-coated carbide end mills were used in the present study, whereas carborundum wheels were used previously. Further, the cutting speed used in the current study was well below the previous grinding speed (8.3 ms^{-1} or more). Despite these differences, Ti-20%Ag showed favorable results in both the cutting and grinding experiments, which seemed natural because cutting and grinding are essentially the same process on a microscopic scale. However, there was a noteworthy difference between the results for cutting and grinding. Although the grindability of Ti-20%Ag was grinding-speed dependent and equivalent to that of titanium at a low grinding speed, the machinability of the alloy in terms of cutting force was better than that of titanium at an even lower cutting speed. This finding thus suggested that the mechanism for improved machinability in terms of cutting force was not exactly the same as that for improved grindability.

The current explanation of the machinability of the experimental alloys in view of the previously studied mechanical properties is somewhat limited because the properties are likely to be affected by strain, strain rate, and temperature. Therefore, further investigations are necessary for a more thorough understanding on the underlying mechanism that accounts for an improved machinability.

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REFERENCES

- 1) Nakamura S. Free-machining titanium. Sixth World Conference on Titanium, France, 1988, pp. 1415-1420.
- 2) Oda Y, Kitamura T, Kawada E, Yoshinari M, Hasegawa K, Hattori M, Matsumoto M. Electrochemical behavior of free-machining titanium alloy. *J J Dent Mater* 2001; 20: 249-255.
- 3) Takahashi M, Kikuchi M, Takada Y, Okuno O. Mechanical properties and microstructures of dental cast Ti-Ag and Ti-Cu alloys. *Dent Mater J* 2002; 21: 270-280.
- 4) Kikuchi M, Takahashi M, Okuno O. Elastic moduli of cast Ti-Au, Ti-Ag, and Ti-Cu alloys. *Dent Mater* 2006; 22: 641-646.
- 5) Takada Y, Nakajima H, Okuno O, Okabe T. Microstructure and corrosion behavior of binary titanium alloys with beta-stabilizing elements. *Dent Mater J* 2001; 20: 34-52.
- 6) Takahashi M, Kikuchi M, Takada Y, Okabe T, Okuno O. Electrochemical behavior of cast Ti-Ag alloys. *Dent Mater J* 2006; 25: 516-523.
- 7) Kikuchi M, Takahashi M, Okabe T, Okuno O. Grindability of dental cast Ti-Ag and Ti-Cu alloys. *Dent Mater J* 2003; 22: 191-205.
- 8) Wang RR, Li Y. In vitro evaluation of biocompatibility of experimental titanium alloys for dental restorations. *J Prosthetic Dent* 1998; 80: 495-500.
- 9) Murray JL, Bhansali KJ. The Ag-Ti (silver-titanium) system. In: Phase diagrams of binary titanium alloys, ASM International, Metals Park, OH, 1990, pp.6-11.
- 10) Kikuchi M, Okuno O. Machinability evaluation of titanium alloys. *Dent Mater J* 2004; 23: 37-45.
- 11) Recommended milling conditions for carbide end mills. In: Milling Tools 2000-2001, OSG Corp., Toyokawa, 2001, p.121.
- 12) Zlatin N, Christopher J. Machining characteristics of difficult to machine materials. In: Materials/Metalworking Technology Series, No. 7: Influence of metallurgy on machinability, ASM, Metals Park, OH, 1975, pp.296-307.
- 13) Guy AG. Elements of physical metallurgy, Addison-Wesley, Cambridge, 1951, pp.127-130.
- 14) López de lacalle LN, Pérez J, Llorente JI, Sánchez JA. Advanced cutting conditions for the milling of aeronautical alloys. *J Mater Process Tech* 2000; 100: 1-11.
- 15) Finn ME. Machining of carbon and alloy steels. In: Metals Handbook, 9th ed., Vol. 16: Machining, ASM International, Metals Park, OH, 1989, pp.666-677.
- 16) ASM International Handbook Committee. Machining of aluminum and aluminum alloys, *ibid.*, pp.761-804.
- 17) ASM International Handbook Committee. Machining of copper and copper alloys, *ibid.*, pp.805-819.
- 18) Nakayama K. On the formation of "saw-toothed chip" in metal cutting. *J Japan Soc Prec Eng* 1977; 43: 117-122.