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Machinability of Experimental Ti-Cu Alloys

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This study is an investigation of the machinability of experimental Ti-Cu alloys (2, 5, and 10 mass% Cu) as new dental titanium alloy candidates for CAD/CAM use. The alloys were slotted with a vertical milling machine and carbide square end mills under two cutting conditions. Their machinability was evaluated through cutting force using a three-component force transducer fixed on the table of the milling machine. The horizontal cutting forces of the Ti-Cu alloys tended to increase as the concentration of copper increased. The feed force for Ti-10%Cu was more than twice as large as that for titanium under both cutting conditions. Alloying with copper reduced the machinability of titanium under the present cutting conditions. The adverse effect on the cutting force was attributed to the higher degree of tensile strength and hardness of the Ti-Cu alloys than of titanium. [doi:10.2320/matertrans.MRA2007285]

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1. Introduction

Machining is a process in which a shape is generated by removing unwanted material and includes both cutting and grinding processes. In the present study, the terms machinability and grindability are used to refer to the relative ease of cutting and grinding metal, respectively. Machining has become an important metal processing method next to dental casting ever since dental CAD/CAM systems were put into practical use. End mills and drills are commonly used as cutting tools to machine titanium by the dental CAD/CAM systems.

Although titanium has superior biocompatibility and corrosion resistance, it exhibits low machinability and grindability due to its intrinsic characteristics, such as low thermal conductivity, high chemical reactivity, and low modulus of elasticity. Better machinability and higher strength are still demanded for some applications. Alloying titanium is one of the ways to improve its properties. However, only a few titanium alloys have been developed for enhanced machinability.

In our previous studies,^{1,2)} the properties of a series of Ti-Ag (up to 20 mass% Ag) and Ti-Cu (up to 10 mass% Cu) alloys were examined (hereafter, “mass%” will be referred to as “%”). Both silver and copper are β -stabilizing elements, and Ti-Ag and Ti-Cu alloys are classified as titanium alloys with eutectoid transformation. The Ti-Ag alloy has a eutectoid point of α and Ti_2Ag at 15.6% Ag.³⁾ The Ti-Cu alloy has a eutectoid point of α and Ti_2Cu at 7.0% Cu.⁴⁾ Judging from previous studies,^{5–8)} the precipitation of the intermetallic compounds Ti_2Ag and Ti_2Cu in the experimental alloys seemed to occur at a silver concentration of around 20% and a copper concentration of around 5%, respectively.

As the concentration of silver or copper in the alloys increased, the tensile strength and hardness of the alloys became higher than those of titanium, and the elongation of the alloys became lower than that of titanium, which was considered to be due to solid solution strengthening/hardening and the inclusion of a small amount of Ti_2Ag or

Ti_2Cu .¹⁾ Ti-5%Cu and Ti-10%Cu possessed significantly better grindability than titanium, as Ti-20%Ag did, under certain grinding conditions,²⁾ in addition to significantly higher tensile strength and hardness than titanium. Furthermore, the machinability of the experimental Ti-Ag alloys with 5–30% silver in terms of the cutting force was comparable to or better than that of titanium.⁹⁾ Due to the above-mentioned similarities as an alloying element for titanium, copper is expected to have the same effect on the machinability as silver. In this paper, the machinability of experimental titanium alloys with 2–10% copper was evaluated through the cutting force with the hope of developing a new titanium alloy suitable for dental CAD/CAM applications.

2. Materials and Methods

2.1 Preparation of specimens

The experimental Ti-Cu alloys in the present study (2%, 5%, and 10% Cu) were selected from both hypoeutectoid and hypereutectoid regions. Buttons (15 g each) of the Ti-Cu alloys were prepared by melting a titanium sponge (>99.8%, grade S-90, Sumitomo Titanium, Amagasaki, Japan) and copper (99.99%, The Research Institute for Electric and Magnetic Materials, Sendai, Japan) using an argon-arc melting furnace (TAM-4S, Tachibanariko, Sendai, Japan), as in previous studies.^{1,2)} The titanium ingots were made in the same way by melting the titanium sponge only.

Although the experimental alloys were made for machining and not for casting, the buttons were cast in order to form 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 bench cooled. 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 1,000-grit surface finish. Three specimens were made for each metal.

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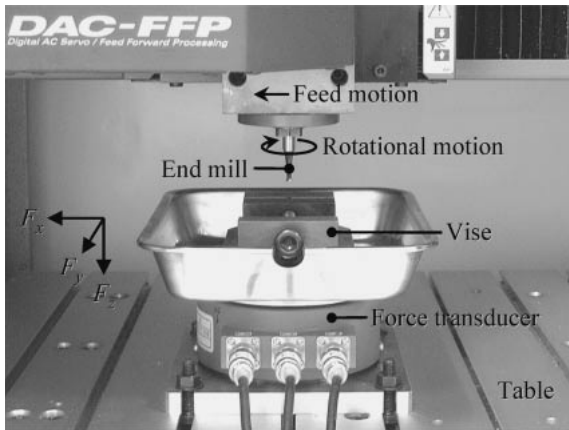


Fig. 1 Cutting force measurement system.

2.2 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), as shown in Fig. 1.¹⁰ 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 has 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. 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 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, shown in Table 1, for each specimen as in the previous study.⁹ 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 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 the titanium.

Table 1 Cutting conditions.

Condition	Cutting speed s^{-1}	Feed rate $mm s^{-1}$	Depth of cut mm
A	50	1	0.2
B	100	2	0.2

3. Results

3.1 Cutting forces

Cutting forces of the Ti-Cu alloys are shown in Fig. 2. The magnitude of both F_x [Fig. 2(a)] and F_y [Fig. 2(b)] tended to increase as the concentration of copper increased. Under condition A, the F_x value of Ti-10%Cu was significantly higher than that of titanium ($p < 0.05$); under condition B, the F_x and F_y values of Ti-10%Cu were significantly higher than those of titanium ($p < 0.01$ and $p < 0.05$, respectively). Ti-10%Cu showed F_x value more than two times larger and absolute F_y value about 1.3 times larger than those for titanium under both cutting conditions. The absolute value of F_z was well below that of the horizontal cutting forces [Fig. 2(c)]. No statistical difference in F_z was found among the metals. Figure 3 shows the relationship between the cutting force and the Vickers hardness of the Ti-Cu and Ti-Ag alloys.^{1,9} With the increase in the hardness, the absolute value of the horizontal cutting forces of the Ti-Cu alloys increased. It is noteworthy that the absolute value of F_y decreased with the increase in the concentration of silver despite the increase in the Vickers hardness.

3.2 Metal chips

Metal chips resulting from cutting are shown in Fig. 4. The shape of the titanium chips was, in general, a short spiral. The chips appeared thinner and longer as the concentration of copper increased, while their width decreased. The chip width for Ti-10%Cu was approximately 200 μm and matched the depth of cut. For each metal, there was no pronounced difference in the appearance of metal chips between the two cutting conditions.

4. Discussion

Although many attempts have been made to explain and predict the machinability or grindability of a material by its mechanical properties, no general consensus has been reached regarding an explanation. Hence, it is necessary to evaluate the machinability of materials one by one. The cutting force is often measured to evaluate the machinability of a material. A smaller cutting force brings benefits to tool life, cutting accuracy, and surface integrity. Against our expectations, the machinability of the Ti-Cu alloys in terms of the cutting force was equivalent to or lower than that of titanium under the present cutting conditions. In our previous study on the machinability of titanium alloys,¹⁰ the machinability of Ti-6Al-4V, which is the best-known high-strength titanium alloy, was evaluated. The magnitudes of F_x and F_y for Ti-6Al-4V were approximately two to three times larger and about 1.4 times larger than those of titanium, respectively, under cutting conditions equivalent to those in the present study. In comparison with these numbers, the machinability of Ti-10%Cu was low and close to that of Ti-6Al-4V.

The width of titanium chips was greater than the depth of cut because plastic deformation in the axial direction toward the shank of the end mill occurred by the peripheral helical cutting edges of the rotating end mill. The chip thickness and width decreased with the increase in the concentration of

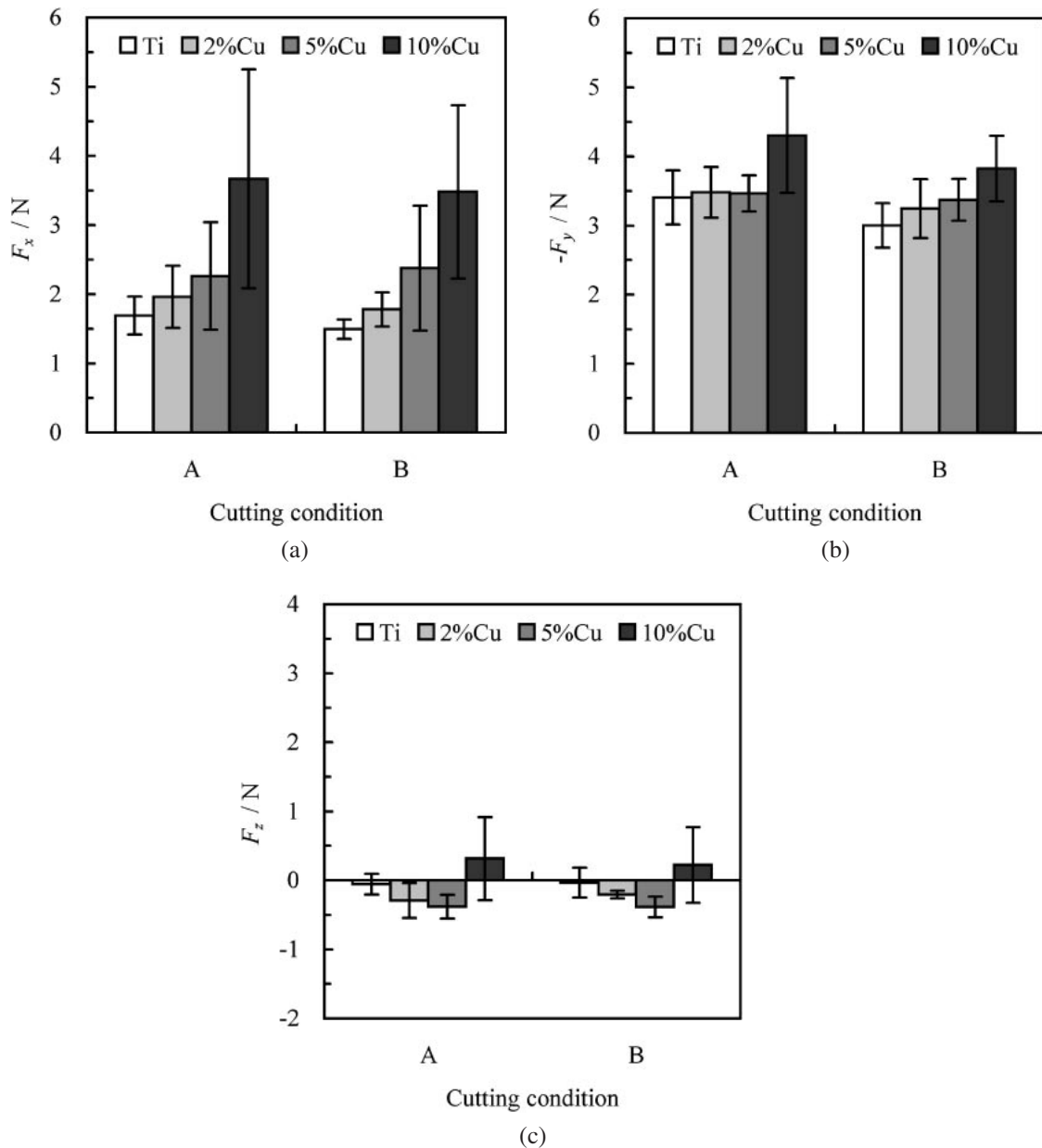


Fig. 2 Cutting force of the Ti-Cu alloys: (a) x component, (b) y component, and (c) z component.

copper. The decrease in the chip thickness can be explained by the reduced ductility through alloying. The decrease in the chip width can be explained in the same way. In fact, the chip width of Ti-10%Cu, which showed little elongation in the previous study,¹⁾ matched the value of the depth of cut.

A high degree of strength and hardness in a material is generally disadvantageous to machinability. However, although the Ti-Ag alloys had higher tensile strength and hardness than titanium, their machinability in terms of the cutting force was comparable to or better than that of titanium.⁹⁾ The magnitudes of F_y for Ti-20%Ag and Ti-30%Ag were more than 20% lower than those for titanium. The reduced ductility was considered to be the primary contributor to the decreased cutting force. Differently from Ti-Ag alloys, Ti-Cu alloys exhibited a cutting force that was equivalent to or higher than that of titanium. This result is probably due to the fact that the tensile strength and hardness

of Ti-Cu alloys were considerably higher than those of titanium¹⁾ and the benefit of lowering the cutting force by decreasing the elongation was cancelled.

The increased tensile strength and hardness were attributed to not only the solid solution strengthening/hardening but also the inclusion of a small amount of Ti_2Cu .¹⁾ It is known that inclusions in the matrix can affect the machinability of a metal, depending on their properties. If the inclusions are soft or brittle, they can act as free-cutting additives and enhance the machinability.¹¹⁻¹³⁾ For example, free-cutting brass contains lead as a free-cutting additive that rarely forms a solid solution with the matrix.¹³⁾ The spherical lead particles dispersed in the matrix enhance the notch effect in metal chips and improve chip breakability. They also act as a lubricant and reduce the cutting force. On the other hand, if the inclusions are hard, they make a material difficult to cut. Cementite (Fe_3C) in cast iron is a classic example.¹¹⁾ The

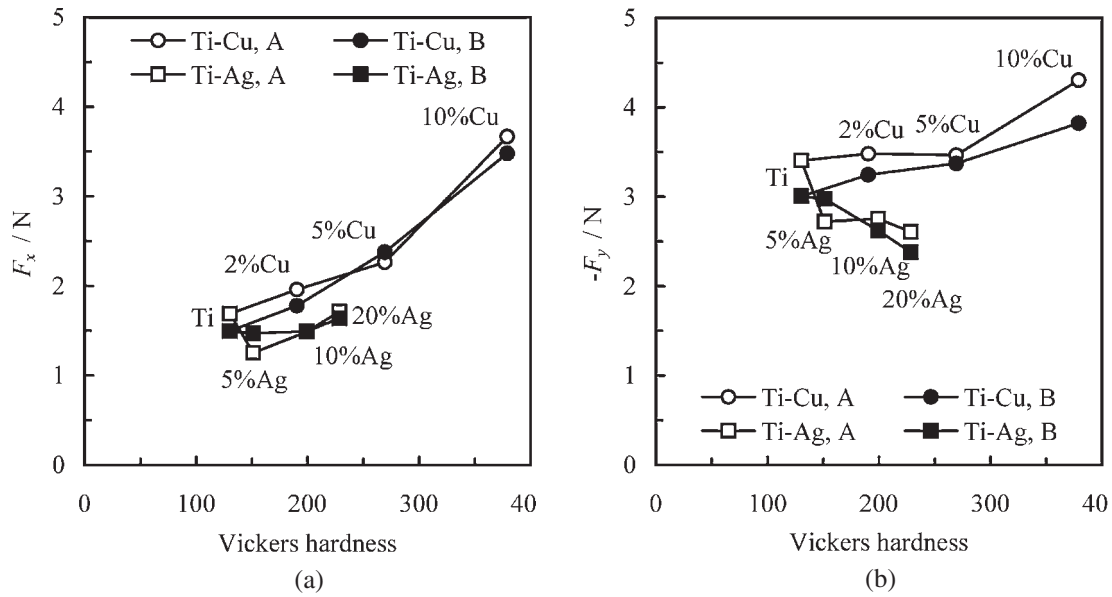


Fig. 3 Relationship between the Vickers hardness¹⁾ and the cutting force of the Ti-Cu alloys: (a) x component vs. Vickers hardness and (b) y component vs. Vickers hardness.

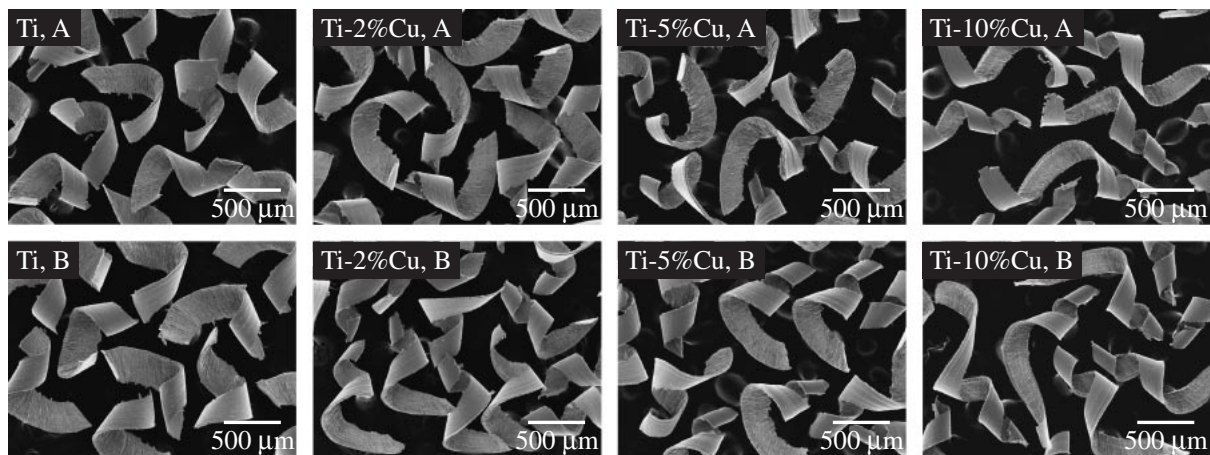


Fig. 4 Metal chips cut from the Ti-Cu alloys.

characteristics of intermetallic compounds Ti_2Ag and Ti_2Cu described in the literature^{3,4,14,15)} are summarized in Table 2. The hardness of Ti_2Cu is well above that of Ti_2Ag . In addition, as stated previously, the intermetallic compound precipitated at a lower concentration of the alloying element in the Ti-Cu alloys than in the Ti-Ag alloys. Hence, the adverse effect on the machinability by alloying titanium with copper in the present study can also be explained by the higher degree of hardness of Ti_2Cu than of Ti_2Ag , or the larger amounts of Ti_2Cu in Ti-5%Cu and Ti-10%Cu than of Ti_2Ag in Ti-20%Ag and Ti-30%Ag.

Despite the significantly better grindability of Ti-5%Cu and Ti-10%Cu than of titanium when ground at high speed in the previous study,²⁾ their machinability was worse under the present cutting conditions. Because grinding is a machining process of material removal by small and complex cutting edges of very hard abrasives and has a self-dressing action, it can be applied to hard materials. However, the grinding tools

Table 2 Characteristics of intermetallic compounds Ti_2Ag ^{3,14)} and Ti_2Cu .^{4,15)}

Intermetallic compound	Crystal structure	Temperature range of existence, °C	Microhardness, mean (SD)
Ti_2Ag (Ti-53.0%Ag)	Tetragonal	≤ 940	256 (20) ^a
Ti_2Cu (Ti-39.9%Cu)	Tetragonal	≤ 1005	451 (14) ^b

The microhardness values are given in a:¹⁴⁾ $kg\ mm^{-2}$ and b:¹⁵⁾ $daN\ mm^{-2}$.

tend to become clogged when a ductile material is ground, and, consequently, the grinding efficiency becomes low. The decrease in elongation through alloying with copper was effective in improving the grindability of titanium, exceeding the disadvantage caused by the increase in strength and hardness.²⁾ Therefore, we conclude that grinding is more suitable than cutting for processing Ti-Cu alloys.

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