Grindability of Dental Magnetic Alloys

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In this study, the grindability of cast magnetic alloys (Fe-Pt-Nb magnetic alloy and magnetic stainless steel) was evaluated and compared with that of conventional dental casting alloys (Ag-Pd-Au alloy, Type 4 gold alloy, and cobalt-chromium alloy). Grindability was evaluated in terms of grinding rate (i.e., volume of metal removed per minute) and grinding ratio (i.e., volume ratio of metal removed compared to wheel material lost). Solution treated Fe-Pt-Nb magnetic alloy had a significantly higher grinding rate than the aged one at a grinding speed of 750-1500 m • min-1. At 500 m • min-1, there were no significant differences in grinding rate between solution treated and aged Fe-Pt-Nb magnetic alloys. At a lower speed of 500 m • min-1 or 750 m • min-1, it was found that the grinding rates of aged Fe-Pt-Nb magnetic alloy and stainless steel were higher than those of conventional casting alloys.

Key words: Grindability, Fe-Pt-Nb magnetic alloy, Magnetic stainless steel

INTRODUCTION

Removable bridges, such as conus crowns, have merits of keeping the gingival healthier than fixed prostheses and retaining denture more firmly than plate dentures1,2). However, the conus crown has not been widely used in dental clinics because it is difficult to adjust and maintain its retentive force3,4). Removable prostheses equipped with dental magnetic attachments have been developed to solve this problem5-9).

These prostheses are composed of outer and inner crowns. A permanent magnet is generally fixed to the outer crown by adhesive cement after casting the crown to avoid heating of the magnet. Unlike conus crowns, the retentive force of magnetic attachments is barely affected by wear. However, ready-made magnetic attachments are too large to be used in prostheses for vital teeth. Long-term durability of the cement used to fix the magnet to the outer crown is also a concern.

New prosthetic appliances composed of outer and inner crowns, each made of Fe-39.5mol%Pt-0.75mol%Nb magnetic alloy and magnetic stainless steel, have been developed10-14). The Fe-Pt-Nb magnet has high energy product almost equivalent to that of Sm-Co magnet15-18), and excellent corrosion resistance14,19). Kanno et al. showed the possibility of dental casting Fe-Pt magnetic alloys10,12,13). However, there remains a problem: the magnetic properties of Fe-Pt-Nb magnetic alloy are very sensitive to the thermal history of a casting process.

Good grindability is desirable in magnetic alloys for clinical use. Furthermore, if magnetic alloys could be readily machined by a dental CAD/CAM system, it would be possible to avoid problems related to melting the material, which are inevitable when casting. In this study, the grindability of cast Fe-Pt-Nb magnetic alloy and magnetic stainless steel was evaluated and compared with that of conventional dental casting alloys. The hardness of these alloys was also measured, and its relationship to grindability was examined.

MATERIALS AND METHODS

Alloys tested

Magnetic alloys and conventional dental casting alloys used in this study are shown in Table 1. The Fe-Pt-Nb magnetic alloy (Fe-Pt-Nb) was made by melting platinum (99.99%; Tanaka Kikinzoku Kogyo K.K., Tokyo, Japan), electrolytic iron (>99.993%; Toho Zinc Co. Ltd., Tokyo, Japan), and niobium (>99.3%;Mitsui Mining and Smelting Co. Ltd., Tokyo, Japan) in an argon arc melting furnace (TAM-4S, Tachibanariko Co. Ltd., Sendai, Japan). Wrought SUS447J1 (Fe-30%Cr-2Mo, Shomac, Showa Denko K.K., Tokyo, Japan), electrolytic iron (>99.993%; Toho Zinc Co. Ltd., Tokyo, Japan), and niobium (>99.3%;Mitsui Mining and Smelting Co. Ltd., Tokyo, Japan) was used as the magnetic stainless steel. After the chamber was evacuated to 5 mPa, high-purity argon gas (>99.999%; Nipponsanso Co., Tokyo, Japan) was introduced until the pressure reached 50 kPa for the melting atmosphere. Wrought SUS447J1 (Fe-30%Cr-2Mo, Shomac, Showa Denko K.K., Tokyo, Japan) was used as the magnetic stainless steel used for inner crowns, as in previous studies20,21).

Three conventional dental casting alloys were used in this study: silver-palladium-gold alloy (Castwell, GC, Tokyo, Japan), Type 4 gold alloy (PGA2, Ishifuku Co. Ltd., Tokyo, Japan), and cobalt-chromium alloy (Vitalium2000, Dentsply Austenal,
These alloys have been clinically used for a long time. Therefore, it is worthwhile to compare the grindability of magnetic alloys with that of conventional dental casting alloys.

Preparation of specimens
Wax patterns (3.5 mm × 8.5 mm × 25.5 mm) were invested. An alumina-magnesia based investment for titanium (Titavest CB, Morita Co. Ltd., Tokyo, Japan) and a phosphate-bonded investment (UniVest Non-Precious, Shofu Inc., Kyoto, Japan) were used for casting Fe-Pt-Nb magnetic alloy and cobalt-chromium alloy respectively. The molds for Fe-Pt-Nb magnetic alloy were heated from room temperature to 900°C at a heating rate of 15°C min⁻¹. After 50 minutes holding period, they were cooled down to 600°C in the furnace. The molds for cobalt-chromium alloy were heated from room temperature to 800°C at a heating rate of 15°C min⁻¹ with a 30 minutes holding period. Both Fe-Pt-Nb magnetic alloy and cobalt-chromium alloy were cast into the molds using a high frequency induction melting vacuum and a pressure casting machine (Argoncaster T, Shofu Inc.). After casting, the molds were bench-cooled.

Three kinds of Fe-Pt-Nb magnetic alloy specimens (as cast (AC), solution treated (ST), and age treated (AT)) were prepared. Cast Fe-Pt-Nb magnetic alloys were solution treated at 1325°C for 30 minutes and age treated at 650°C for five hours.

A cristobalite investment (Cristobalite P, Shofu Inc.) was used for casting Ag-Pd-Au alloy and Type 4 gold alloy. The molds were heated from room temperature to 700°C at a heating rate of 15°C min⁻¹ and held for 30 minutes. These two alloys were cast into molds using a pressure casting machine (Caspac, Dentronics Co. Ltd., Tokyo, Japan).

All surfaces of each casting alloy were ground with silicon carbide abrasive paper down to 1000 grit to remove the oxide layer, thereby producing specimens which measured 3 mm × 8 mm × 25 mm. A magnetic stainless steel bar (5 mm in diameter) was cut by diamond saw (Isomet, Buehler, IL, USA) and ground into 3 mm thick and 8 mm long specimens.

Hardness test
For each specimen, Vickers hardness of a polished cross-section was measured using a microhardness tester (HM-102, Akashi, Tokyo, Japan) with a 1.961 N load and 30-second dwell time. Three specimens were used for each metal. Measurements were made at three randomly chosen locations on each specimen.

Grinding test
An experimental grinding test apparatus equipped with an electric dental handpiece (Micromotor LM-1, GC, Tokyo, Japan) was used, as in previous studies. Carborundum (SiC) wheels (#4, 15.8 mm in diameter, Shofu Inc.) were used as grinding tools. A new wheel was applied for each test, and the diameter of each new wheel measured (CD-15CP, Mitutoyo Co. Ltd., Kanagawa, Japan) before and after grinding. The 3.0 mm cross-section of the specimens was ground at one of the five circumferential speeds - 500, 750, 1000, 1250, or 1500 m·min⁻¹ - at 0.98 N. Specimen and wheel were enclosed during grinding, and metal chips were collected in a glass beaker.

Grindability was evaluated in terms of grinding rate and grinding ratio. Grinding rate was the volume of metal removed per minute, and represented the ease of metal removal. Grinding ratio was the volume ratio of metal removed compared to the wheel material lost - which was calculated from diameter loss, and was a convenient measure of wheel life. The volume of metal removed during one minute of grinding was calculated from the density (previously measured using the Archimedes’ principle) and weight loss of the specimen. Three specimens were used to evaluate the grindability of each metal, and the test was performed twice for each specimen at each grinding speed. The ground surfaces of the metals and the wheel surfaces were observed using a scanning electron microscope (SEM) (S570, Hitachi, Tokyo, Japan).

Statistical analysis
Results were analyzed using one-way ANOVA and Tukey’s test at a significance level of \( p = 0.05 \) (n = 6).
RESULTS

Hardness of the alloys

Fig. 1 shows the Vickers hardness values. Fe-Pt-Nb (AT) showed the highest hardness value of 485 among the alloys tested. Although the hardness of Fe-Pt-Nb (AC) was a little lower than that of Fe-Pt-Nb (AT), the difference was not significant. The hardness of SUS was the lowest (212) among the alloys tested and almost the same as that of Ag-Pd-Au. The hardness of both Fe-Pt-Nb (AC) and (AT) was significantly higher than that of the other alloys. The hardness of Fe-Pt-Nb (ST) was almost half of that of Fe-Pt-Nb (AT), and was lower than that of Co-Cr but a little higher than that of Ag-Pd-Au and SUS.

Grinding rates of the alloys

Fig. 2 shows the grinding rates of the alloys tested. At a lower speed of 500 m·min−1 or 750 m·min−1, the grinding rate of SUS was significantly higher than those of the other alloys. The descending order of grinding rate in Fe-Pt-Nb was Fe-Pt-Nb (ST), Fe-
Pt-Nb (AC), and Fe-Pt-Nb (AT) at almost all speeds. The grinding rate of Fe-Pt-Nb (ST) was significantly higher than that of Fe-Pt-Nb (AT) at all speeds. However, the grinding rate of Fe-Pt-Nb (AT) was significantly higher than that of Co-Cr at 500 m·min⁻¹.

Although the grinding rate of SUS at 1000 m·min⁻¹ and 1250 m·min⁻¹ decreased to half of those at 500 and 750 m·min⁻¹, it was still the highest of all the alloys. On the other hand, the grinding rate of Fe-Pt-Nb (AT) was significantly the lowest among all alloys at 1250 m·min⁻¹ and 1500 m·min⁻¹.

The grinding rates showed a tendency to increase with grinding speed except for those of Fe-Pt-Nb
(AT) and SUS. In the case of Fe-Pt-Nb (AC) and (ST), there were significant differences in grinding rate at 500 m·min⁻¹ and 1500 m·min⁻¹. On the other hand, the grinding rate of Fe-Pt-Nb (AT) decreased with increase of grinding speed above 1250 m·min⁻¹. In the case of SUS, the grinding rates at 500 and 750 m·min⁻¹ were significantly higher than those at 1000, 1250 and 1500 m·min⁻¹. For Ag-Pd-Au, Au-Pt, and Co-Cr, the grinding rate increased with increase in grinding speed, but the grinding rates were different in each case.

**Grinding ratios of the alloys**

Fig. 3 shows the grinding ratios of the alloys tested.
The grinding ratios of Fe-Pt-Nb (AC) and (AT) were 0.75-1.8, and there were no significant differences for all grinding speeds. The grinding ratios of Fe-Pt-Nb (ST) were 2.8-3.4 without significant difference in all grinding speeds. However, the grinding ratios of Fe-Pt-Nb (ST) were significantly higher than those of Fe-Pt-Nb (AC) and (AT), or SUS. SUS indicated higher grinding ratios at 500 and 750 m·min⁻¹ than those at 1000 m·min⁻¹ or more. The grinding ratios of other alloys were 0.6-1.9 except that of Au-Pt at 1250 m·min⁻¹, and there were few instances of significant difference among the grinding ratios.

Ground surfaces and wheel surfaces
Fig. 4 shows the SEM images of the ground surfaces. The ground surface of Fe-Pt-Nb (ST) indicated an obvious grinding burn at the highest speed of 1500 m·min⁻¹. The ground surface of SUS indicated that there were many adhesions of ground chips compared with the other alloys. As for Co-Cr, its grinding marks looked shallower than those of the other alloys. There was a tendency for the chips to become longer as the grinding speed increased. Differences in the appearance of ground chips were not clear among the alloys.

The surfaces of wheels after grinding are shown in Fig. 5. The wheel tended to become clogged at higher speeds. The wheel of SUS was more clogged than that of the other alloys.

DISCUSSION
In order to use Fe-Pt-Nb magnetic alloy as a permanent magnet, it must be subject to solution heat treatment followed by aging. After aging, the Fe-Pt-Nb magnetic alloy can be magnetized. According to previous studies13,14, aging at 650 °C for five hours after 30 minutes of solution treatment at 1325 °C rendered the Fe-Pt-Nb magnetic alloy the best magnetic properties as a permanent magnet. However, the mechanical properties of Fe-Pt-Nb magnetic alloy were affected by heat treatment. The hardness of Fe-Pt-Nb magnetic alloy decreased after solution heat treatment, but increased after aging. Since the machinability of a material is often affected by its mechanical properties26, the grindability of Fe-Pt-Nb magnetic alloys with different heat treatments was examined in the present study.

Grindability of Fe-Pt-Nb magnetic alloy
Among the three Fe-Pt-Nb magnetic alloys subject to different heat treatments, the solution treated alloy had the highest grinding rate at all grinding speeds. Likewise, the grinding ratio of solution treated Fe-Pt-Nb magnetic alloy was more than two or three times higher than that of as cast or aged Fe-Pt-Nb magnetic alloy. The aged alloy had the lowest grinding rate at all speeds except for 500 m·min⁻¹. At low grinding speed, the grinding rate of aged Fe-Pt-Nb magnetic alloy was equal to or higher than that of Ag-Pd-Au alloy, Type 4 gold alloy and cobalt-chromium alloy. Therefore, it can be said that aged Fe-Pt-Nb magnetic alloy can be ground as easily as the conventional dental casting alloys.

Grindability of magnetic stainless steel
The grinding rate of magnetic stainless steel at 500 and 750 m·min⁻¹ was more than 2.5 times higher than that of solution treated Fe-Pt-Nb magnetic alloy. However, the grinding ratio of magnetic stainless steel was only half of that of solution treated Fe-Pt-Nb magnetic alloy. This signified that wear of wheel was higher when stainless steel was ground. Both the grinding rate and grinding ratio of magnetic stainless steel decreased at higher grinding speeds. Apparently, the grindability of magnetic stainless steel became lower at high grinding speed.

Relationship between hardness and grindability
The Vickers hardness of solution treated Fe-Pt-Nb magnetic alloy was almost half of that of as cast and aged Fe-Pt-Nb magnetic alloys. The hardness of magnetic stainless steel was lower than that of solution treated Fe-Pt-Nb magnetic alloy. It is known that high hardness can be a reason for poor machinability of a material25. The Vickers hardness test used in the present study was an indentation hardness test where a pyramidal diamond indenter was used30. Hardness value was determined by the dimension of the indentation made by a constant force applied upon the indenter. Therefore, it can be hypothesized that the depth of cut becomes deep when a material has low indentation hardness and ground at a constant force. Therefore, it was thought that the alloys — which had the same or similar composition — exhibited higher grinding rate as hardness decreased. This result corresponded to a previous study which reported on the grindability of carbon steel and chromium-molybdenum steel with different hardness values27.

Ground surface
There were no marked differences in the appearance of ground surface among the three Fe-Pt-Nb magnetic alloys with different heat treatments when ground at 500 m·min⁻¹. At 1500 m·min⁻¹, the ground surface of solution treated Fe-Pt-Nb magnetic alloy showed a remarkable grinding burn (discoloration caused by oxidation). This suggested that the grinding temperature of solution treated Fe-Pt-Nb magnetic alloy was very high30. However, there were no pronounced differences in the appearance of wheel surface after the grinding test between solution treated Fe-Pt-Nb magnetic alloy and the other alloys.
Table 2 Elongation and tensile strength of the alloys.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Heat treatment</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe-Pt-Nb</td>
<td>Age hardened</td>
<td>571-758</td>
<td>1</td>
</tr>
<tr>
<td>SUS</td>
<td>As cast</td>
<td>539</td>
<td>32</td>
</tr>
<tr>
<td>Ag-Pd-Au</td>
<td>Softened</td>
<td>500</td>
<td>28</td>
</tr>
<tr>
<td>Ag-Pd-Au</td>
<td>Hardened</td>
<td>804</td>
<td>3</td>
</tr>
<tr>
<td>Au-Pt</td>
<td>Softened</td>
<td>495</td>
<td>20</td>
</tr>
<tr>
<td>Au-Pt</td>
<td>Hardened</td>
<td>789</td>
<td>14</td>
</tr>
<tr>
<td>Co-Cr</td>
<td>As cast</td>
<td>855</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Data for Fe-Pt-Nb were cited from references 19 and 29; data for the other alloys came from manufacturers’ specification sheets.

The tensile strength and elongation of aged Fe-Pt-Nb magnetic alloy were 571-758 MPa and 1% respectively (Table 2)\(^{29}\). The elongation of solution treated Fe-Pt-Nb magnetic alloy was not reported in any previous study. However, judging from its lower hardness, it was probable that solution treated Fe-Pt-Nb magnetic alloy had higher ductility. It was considered that the ejection of ground chips became worse and adhesion became more frequent because of the increase in local friction heat\(^{30}\). As a result, grinding burn occurred.

Adhesion of grinding chips on the ground surface was observed even at low grinding speed when magnetic stainless steel was ground. Clogging of the wheel was also observed more frequently compared to the other alloys. It was considered that magnetic stainless steel had lower tensile strength and higher ductility than the Fe-Pt-Nb magnetic alloys or conventional dental casting alloys examined in this study\(^{30}\). Stainless steel is generally considered to be a difficult-to-cut material. The high grinding resistance and high grinding temperature of stainless steel are due to its ductility, work hardenability, and low thermal conductivity\(^{30}\). These characteristics seemed to be also true for the magnetic stainless steel in the present study. In fact, a remarkable grinding burn was observed when magnetic stainless steel was ground. Through SEM observation, much adhesion and clogging of ground chips were found on the surface of ground metal and the wheel respectively. Use of coolant is therefore necessary to lower the grinding temperature when grinding magnetic stainless steel.

**Manufacturing process of Fe-Pt-Nb magnetic alloy prostheses**

Solution treated Fe-Pt-Nb magnetic alloy had the best grindability when ground at high speed. Therefore, the grinding process of Fe-Pt-Nb magnetic alloy prostheses, such as occlusal adjustment, could be done most easily after solution treatment. However, it should be taken into consideration that deformation of the prosthesis may occur by aging.

Many advantages can be obtained if magnetic alloys could be machined by a dental CAD/CAM system. The biggest advantage of machining magnetic alloys over casting is that the former process would barely affect the thermal history of the alloys. Cutting – instead of grinding – is commonly applied in dental CAD/CAM systems\(^{30,31}\). A grindability evaluation would give an indication of a material’s machinability (ease of cutting), since cutting and grinding have essentially similar mechanism in a microscopic scale\(^{31}\). However it must be noted that silicon carbide bur for grinding acquires the property of self-sharpening, while carbide bur for cutting could not acquire it.

Maximum cutting speeds (circumferential speeds) of commercial dental CAD/CAM systems are generally lower than the grinding speeds employed in this study. This is because the diameter of dental cutting tools is smaller than that of grinding tools\(^{35-37}\). Therefore, grindability at the lowest grinding speed will be a good guide to the machinability of magnetic alloys in this study. Titanium is machinable by dental CAD/CAM systems\(^{35-40}\). The grinding rate of aged Fe-Pt-Nb magnetic alloy was significantly lower than that of titanium at 500 m·min\(^{-1}\), although there were no significant differences in grinding ratio\(^{22}\). This would mean that it may take a longer time to machine aged Fe-Pt-Nb magnetic alloy than titanium. On the other hand, the grinding rate and ratio of magnetic stainless steel were higher than those of titanium at 500 m·min\(^{-1}\)\(^{22}\). Thus, magnetic stainless steel may have a potential as a dental machining material, although cutting test is still required to determine its machinability.

**CONCLUSION**

1. Solution treated Fe-Pt-Nb magnetic alloy had significantly higher grinding ratio than the aged one at grinding speeds of 750-1500 m·min\(^{-1}\).
2. There were no significant differences in grinding rate between solution treated and aged Fe-Pt-Nb magnetic alloys at 500 m·min\(^{-1}\). However, the grinding rate of aged Fe-Pt-Nb magnetic alloy was significantly lower at higher grinding speeds.
3. Grinding rate of magnetic stainless steel was more than 2.5 times higher than that of solution
treated Fe-Pt-Nb magnetic alloy at 500 and 750 m·min⁻¹. It was found that the grinding rates of aged Fe-Pt-Nb magnetic alloy and stainless steel were higher than those of conventional casting alloys at lower speed.

REFERENCES

34-43.