The present study was undertaken to evaluate the clinical applicability of cast CP titanium crowns fabricated with sintered molds. To this end, the dimensional changes and accuracy of fit of cast CP titanium crowns, manufactured under varying mold firing temperatures, were examined. Molds were fired at 7 temperatures.

The outer height of the crown and outer width of the occlusal surface decreased under all sets of firing conditions. The outer width of the cervical part tended to increase at firing temperatures of 1,200, 1,300 and 1,400°C. The inner widths of the occlusal surface and cervical part tended to increase under all sets of firing conditions. In the analysis of the fit of crowns, floating (gained latitude) was observed under all sets of conditions. However, the amount of floating was significantly smaller when the firing temperature was 1,200, 1,300 or 1,400°C than when it was 800, 900, 1,000 or 1,100°C.

Key words: Titanium, Investment, Cast

INTRODUCTION

Commercial pure titanium (CP titanium) has come to be regarded as a promising material for dental prosthetic devices because of its excellent bioaffinity, anti-corrosive resistance and mechanical properties. Since prosthetic devices are often complex in shape, various techniques are used for their fabrication. At present, the “lost wax” technique is regarded as the best method. When CP titanium is used to fabricate molded devices, however, its high melting point and the fact that it is highly active at high temperatures make it difficult to obtain high-quality results.

We have conducted various studies on the application of investment materials (phosphates) for CP titanium casting. In these studies, we manufactured cast CP titanium products using sintered molds and examined the surface properties and features of the reactive layers of these products. The results suggested that the reactive layers of the cast titanium products had better properties than those of titanium products manufactured by other methods. The tone of the CP titanium cast crown appeared metallic in color, particular to titanium.

The present study was undertaken to evaluate the clinical applicability of cast CP titanium crowns fabricated with sintered molds. Thus, the dimensional changes and accuracy of fit of cast CP titanium crowns, manufactured under varying mold
sintering temperatures, were examined.

MATERIALS AND METHODS

Materials
1. Metal
The metal used in this study was CP titanium, (JIS Class 2, Nippon Stainless Co., Ltd., Tokyo, Japan).

2. Investment material
The investment material used was the commercially available phosphate-bonded investment material (T-INVEST C&B, Powder Lot No. 9910271, Lipuid Lot No. 080981, Taisei Shika Kogyo Ltd., Osaka, Japan), which can endure temperatures up to 1,500°C. A special mixing liquid was used, and mixed following the manufacture’s instruction regarding the liquid powder ratio and mixing method.

Table 1 shows the X-ray diffraction profiles of this investment material. Table 2 shows the physical properties of the material as stated by the manufacturer. Table 3 shows the compressive strength of this material at varying firing temperatures.

Fabrication of cast CP titanium crowns
1. Preparation of metal dies and wax pattern
For this experiment, metal dies were modeled after the morphology of an abutment tooth prepared to receive a full cast crown. The axial plane of the abutment tooth

<table>
<thead>
<tr>
<th>Refractory</th>
<th>SiO₂, ZrO₂, Al₂TiO₅</th>
<th>Binder</th>
<th>MgO, NH₂H₂PO₄</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Mixing ratio (L/P)</th>
<th>Setting time (min)</th>
<th>Setting expansion (%)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13</td>
<td>10.4</td>
<td>0.66</td>
<td>15.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperatures (°C)</th>
<th>Compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>800</td>
<td>3.7 (2.8)</td>
</tr>
<tr>
<td>900</td>
<td>4.2 (1.2)</td>
</tr>
<tr>
<td>1,000</td>
<td>6.3 (2.6)</td>
</tr>
<tr>
<td>1,100</td>
<td>25.4 (3.0)</td>
</tr>
<tr>
<td>1,200</td>
<td>27.6 (4.2)</td>
</tr>
<tr>
<td>1,300</td>
<td>29.0 (4.8)</td>
</tr>
<tr>
<td>1,400</td>
<td>35.5 (4.9)</td>
</tr>
</tbody>
</table>

( ) : S.D.
was tapered 1/20. The tooth neck (cervical part) was designed as a 1.0 mm wide shoulder type. The occlusal plane was designed to be 1.5 mm thick. The shoulder was designed as a detachable ring, 1.0 mm wide and 3.0 mm high (Fig. 1). A reference line was engraved, necessary for positioning the die and the wax, pattern and to measure the dimensions of the cast crown (as described later).

A wax pattern was then modeled by softening and pressure welding, using wax for casting (Green Inlay Wax, GC Corp., Tokyo, Japan). After being retained on the die for 2 hr under 1.5 MPa oil pressure, the mold was removed from the die. When removing the wax pattern from the die, the reference line engraved on the die was imprinted on the corresponding location of the wax pattern, to be used for subsequent measurements of the wax pattern and cast crowns.

2. Investing
Investing was performed using a ring lined internally with 1 mm thick kaowool. A hollow sprue tube, 2.0 mm in diameter, was placed in the center of the occlusal surface, so that the wax pattern would be centered within the ring (Casting Ring No.2, GC Corp., Tokyo, Japan).

3. Firing
The molds were fired at 7 temperatures (800, 900, 1,000, 1,100, 1,200, 1,300 and 1,400°C). The ring was removed from the hardened mold and fired in an electric furnace equipped with an automatic temperature controller (Chugai-NABER Electric Furnace, Chugai Engineering Co., Ltd., Osaka, Japan). For firing at 800°C, firing was performed according to the schedule recommended by the manufacturer. For firing at other temperatures, the temperature was elevated to the target level at a heat rate of 100°C/hr, the target temperature was maintained for an hour, and then the mold was allowed to cool to room temperature.

4. Casting
CP titanium (16 g) was cast with a vacuum pressure caster (AUTOCAST HC-III, GC Corp., Tokyo, Japan) under 7 atm at room temperature. The removal of investment
on the as cast crown were carried out using an Evans carving knife.

**Measurements**

1. The thermal and residual expansion of the investment material

Thermal expansion was measured with a differential high temperature thermal expansion meter (Motoyama Mfg., Ltd., Osaka, Japan). The expansion of the material was measured as it was heated at a rate of 5 °C/min to each of the 7 target temperatures. After the target temperature was maintained for 5 min, the investment material was allowed to cool within the furnace to 100°C, when the residual expansion was measured. The measurement of thermal expansion was based on Fudemoto’s measuring method.

2. Dimensional changes in cast CP titanium crowns

Fig. 2 shows the points of the cast CP titanium crown at which the measurements were taken. Horizontally, the outer width of the occlusal surface (Oo-Oo'), the inner width of the occlusal surface (Oi-Oi'), the outer width of the cervical part (Co-Co') and the inner width of the cervical part (Ci-Ci') were measured. Vertically, the outer height of the crown (Oo-Co) was measured. Each of these parameters was measured four times. The average of the 4 measurements was adopted as the value of each parameter. Six cast crowns were prepared under each set of firing conditions. Percent changes in dimensions of the cast CP titanium crowns from each of the molds were calculated relative to the dimensions of the mold.

3. Fit of cast CP titanium crowns

After the mold was fabricated, the shoulder ring of the cervical part of the die was removed. Subsequently, the mold was returned onto the die, and the space from the upper part of the die base to the cervical part of the mold was measured, in the direction parallel to the tooth axis (original space). The same space was also measured in the cast CP titanium crown and was compared with the original space, and the difference between them was calculated as an indicator of fit (Fig. 3). Eight cast crowns were prepared under each set of firing conditions.

Dimensional changes and fit were measured by observing the sample under a universal tool microscope with 1/1,000 mm precision (Topcon TUM200, Tokyo)
RESULTS

Thermal and residual expansion of the investment material
Fig. 4 shows the expansion curve for each set of firing conditions. Under each of the 7 sets of firing conditions, maximal expansion was about 1.5% which was recorded when the temperature was 600°C. As the temperature rose from 600 to 1,000°C, no marked change in expansion was observed. When the temperature exceeded 1,000°C, expansion decreased. When the temperature rose over 1,200°C, expansion increased again.

The residual expansion, as measured after cooling to 100°C, was 0.82% at a firing temperature of 800°C, 0.70% at 900°C, 0.71% at 1,000°C, 0.70% at 1,100°C, 0.43% at 1,200°C, 0.71% at 1,300°C and 0.88% at 1,400°C. Thus, the residual expansion was highest when the firing temperature had been 1,400°C.

Dimensional changes of cast CP titanium crowns
Figures 5 through 9 show the percent dimensional changes at each site of measurement. The vertical axis of the graphs indicate the percent dimensional changes (+ means expansion and - means contraction of the cast crown relative to the original size). The horizontal axis indicates the firing temperature.

The outer width of the occlusal surface tended to decrease under all sets of firing conditions. The shrinkage was 0.82% when the firing temperature had been 800°C, 0.46% at 900°C, 1.00% at 1,000°C, 1.22% at 1,100°C, 0.89% at 1,200°C, 0.77% at 1,300 °C and 0.45% at 1,400°C.

Kogakusha, Tokyo, Japan) at a magnification of x30. Records were taken using a digital linear scale counter (Mitutoyo Mfg., Ltd., Kawasaki, Japan). In addition, the microscope and scale counter were connected. The significance of the differences was tested by one-way layout analysis of variance.
Fig. 4 Thermal expansion and cooling shrinkage curve of used investment.
The inner width of the occlusal surface tended to increase under all sets of firing conditions. The magnitude of expansion was 0.39% at a firing temperature of 800°C, 0.57% at 900°C, 0.77% at 1,000°C, 0.57% at 1,100°C, 1.07% at 1,200°C, 1.51% at 1,300°C and 2.15% at 1,400°C.

The outer width of the cervical part decreased at temperatures of 800°C (0.16%), 1,000°C (0.31%) and 1,100°C (0.34%) and increased at temperatures of 900°C (0.08%), 1,200°C (0.18%), 1,300°C (0.30%) and 1,400°C (0.96%).

The inner width of the cervical part remained almost unchanged at temperatures of 1,000 and 1,100°C, but it increased at the other temperatures (0.19%, 0.16%, 0.55%, 0.56% and 1.35% at 800, 900, 1,200, 1,300 and 1,400°C, respectively).

The outer height of the crown tended to decrease under all sets of firing
conditions. It decreased by 0.81% at a firing temperature of 800°C, 0.36% at 900°C, 0.86% at 1,000°C, 1.31% at 1,100°C, 0.77% at 1,200°C, 0.73% at 1,300°C and 0.11% at 1,400°C. At each measuring site significant differences were recognized at 1% risk between 1,100°C and 1,200°C.

**Fit of cast CP titanium crowns**
Fig. 10 shows the findings concerning the fit of the crowns. The magnitude of the discrepancy was 0.63 mm at a firing temperature of 800°C, 0.52 mm at 900°C, 0.54 mm at 1,000°C, 0.44 mm at 1,100°C, 0.18 mm at 1,200°C, 0.17 mm at 1,300°C and 0.16 mm at 1,400°C. The difference in this parameter between the temperature range 800-1,100°C and the range 1,200-1,400°C was statistically significant (P<0.01).

**DISCUSSION**

**Thermal and residual expansion of the investment material**
The investment material tested underwent similar expansion under all sets of firing conditions. As shown in Fig. 4, the expansion rate decreased as the firing temperature was elevated from 1,000 to 1,200°C. This is probably attributable to a decrease in volume that occurs during the course of sintering of the investment materials. This finding is consistent with our previous observation that at firing temperatures over about 1,100°C, contraction occurred due to sintering of Al₂TiO₅ (a component of the investment material). The fact that expansion occurred again after the temperature was elevated over 1,200°C suggests that sintering was approximately completed at that temperature and expansive compounds were formed.

The difference between the expansion recorded upon reaching the target temperature and the residual expansion rate recorded after cooling to 100°C was greatest (0.74%) when the target temperature was 900°C, and it was 0.66%, 0.70%, 0.64% and
0.68% at target temperatures of 800, 1,000, 1,100 and 1,200°C, respectively. Thus, this difference did not vary greatly as the target temperature was elevated between 800 and 1,200°C. The difference was smaller at target temperatures of 1,300°C (0.52%) and 1,400°C (0.43%). Thus, the shrinkage recorded at temperatures 1,300 and 1,400°C was not as great as those seen in the temperature range between 800 and 1,200°C. This is probably because the compound formed within the investment material by sintering at 1,300 or 1,400°C hardly shrunk during cooling, and, therefore, inhibited the shrinkage of the investment material during the cooling process4).

Dimensional changes and fit
The inner widths of the occlusal surface and the cervical part tended to increase under all sets of firing conditions, and they increased more as the firing temperature became higher. The inner width of the cast crowns was affected by the presence of the core material within the cavity of the mold. That is, the strength of the investment material serving as the core suppressed shrinkage of the metal during casting. As shown in Table 3, the compressive strength of the investment material increased as the firing temperature rose. This finding is consistent with the result that the inner width of the occlusal surface increased as the mold firing temperature rose, while it contradicts the finding that the increase in the inner width of the occlusal surface at a mold firing temperature of 1,100°C was smaller than that at 1,000°C (a temperature at which the compressive strength was lower).

We further analyzed the results in order to explain this contradiction. Metals like titanium, which has a high melting point (1,670°C), respond differently to casting than conventional gold alloys or gold-silver-palladium alloys. Since the molten titanium used for casting has a very high temperature, the investment material is re-heated by the inflow of the molten titanium, which is probably the cause of the expansion seen when the investment material is fired at high temperatures. The influence of re-heating by the molten metal appears to be particularly great on the occlusal surface of the mold’s core. The mold cavity is surrounded by the molten metal and is in contact with the investment material (located in the outer area of the mold’s cavity) only at the tooth cervical area. The expansion curve of the investment material tested shows that the expansion decreased at a temperature of about 1,100°C, probably due to sintering of the mold, and that the expansion was resumed at temperatures over 1,200°C (i.e. after approximate completion of sintering). This suggests that when high-temperature molten titanium is cast, the compound formed as a result of completion of mold sintering at 1,200, 1,300 or 1,400°C is re-heated for a short period of time and is, thus, likely to expand greatly. Concerning the findings that the value was higher on the occlusal surface than at the tooth cervical area, it is suggested that the occlusal surface of the core was most heated by the inflow of molten metal and was affected more greatly by re-heating than was the cervical part, because the sprue tube was located at the center of the occlusal surface.

When changes in external dimensions were analyzed, the outer width of the occlusal surface and the outer height tended to decrease, and this tendency was
similar among different sets of firing conditions. The outer width of the cervical part decreased slightly at firing temperatures of 800, 1,000 and 1,100°C but tended to increase at temperatures of 1,200, 1,300 and 1,400°C. The changes in the outer width appear to be associated with residual expansion of the mold after firing, the compressive strength and the amount of cast-induced shrinkage of titanium. The finding that the outer width was smaller at temperatures of 1,000 and 1,100°C than at other temperatures is probably attributable to the instability of the mold at these temperatures, similar to the results for the inner width.

When the lateral cervical part was compared with the occlusal surface, the latter had shrunk significantly, resulting in a deformation (broadening toward the end). Considering that investment was conducted using a ring lined with kaowool in this study, this deformation may be attributed to resistance of the mold to expansion of the investment material9,10).

As shown in Fig. 1, a metal die was prepared, also taking into account excessive expansion of the cast crown, and this die was used to measure fit. We analyzed the space between the upper part of the die base after removal of the shoulder ring and the cervical part of the mold, and examined the changes in this parameter after returning the cast crown into the die. This analysis revealed that the cast CP titanium crowns fabricated under all sets of conditions had gained latitude (floating). However, the amount of floating was significantly smaller when the firing temperature was 1,200°C, 1,300°C or 1,400°C than when it was 800°C (the temperature recommended by the manufacturer), 900°C, 1,000°C or 1,100°C. This indicates that the use of sintered molds can improve the fit of cast crowns. Although the inner width increased under all conditions, floating was always observed. In general, the fit of cast crowns may be affected by their surface roughness in addition to expansion of the investment material and compressive strength of the mold. We previously reported that the surface roughness did not differ between products fired at 1,100°C and those fired at 1,200°C. It appears, therefore, unlikely that surface roughness affected the fit in the present study4). Considering that the outer height decreased, formation of a space in the cervical part may be the cause of floating. This, however, needs to be further studied before we can make any definite conclusion.

CONCLUSIONS

The present study was undertaken to evaluate the clinical applicability of cast CP titanium crowns fabricated with sintered molds. To this end, the dimensional changes and accuracy of fit of cast CP titanium crowns, manufactured under varying mold sintering temperatures, were examined. The following results were obtained.

1. The residual expansion of the mold was maximal when fired at 1,400°C.
2. The outer height decreased under all sets of firing conditions. The decrease was greatest when the firing temperature was 1,400°C.
3. The outer width of the occlusal surface decreased under all sets of firing conditions, while the outer width of the cervical part tended to increase at firing
temperatures of 1,200, 1,300 and 1,400°C.

4. The inner widths of the occlusal surface and cervical part tended to increase under all sets of firing conditions. The increase became greater as the firing temperature was elevated. It was greater on the occlusal surface than on the cervical part.

5. In the analysis of the fit of crowns, floating (gained latitude) was observed under all sets of conditions. However, the amount of floating was significantly smaller when the firing temperature was 1,200, 1,300 or 1,400°C than when it was 800, 900, 1,000 or 1,100°C.

Poor fit and a reactive layer have been the greatest problems hampering the clinical application of cast CP titanium crowns. The results of this study suggest that cast CP titanium crowns with clinically acceptable levels of fit can be fabricated using sintered molds of phosphate-bonded investment.

REFERENCES


