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Effect of casting method on castability of titanium and dental alloys

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Titanium, once considered to be difficult to cast because of its relatively high melting point (1670 ± 50 °C) and strong chemical affinity, can now be acceptably cast using newly developed casting apparatus. The objectives of this study were to examine the castability of commercially pure (CP) titanium using an ultra high-speed centrifugal casting machine and a pressure difference-type casting unit and to compare the castability of titanium with that of conventional dental casting alloys. To determine castability, two types of patterns were used: a mesh pattern of 22 × 24 mm cut polyether thread sieve, and a saucer pattern (24 mm diameter) perforated to create four T-shaped ends. The casting equipment significantly affected the mold filling of both patterns ($p < 0.001$). The castability indices obtained from both patterns of CP titanium cast in the centrifugal casting machine were significantly ($p < 0.05$) better than the indices of the castings produced in the pressure-difference casting unit. The radiographs of the saucer pattern cast in the centrifugal casting machine showed some pores that were fewer and smaller in size than the pores found in castings made in the pressure-difference unit. When the ultra high-speed centrifugal casting machine was used with the manufacturer's recommended mold material, the castability of titanium was similar to that of gold alloy or Ni-Cr alloy cast by conventional means.

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1. Introduction

In the past decade, the use of biocompatible titanium dental prostheses has received increased attention because of the growing number of patients allergic to dental casting alloys [1, 2]. Unfortunately, titanium is an inherently difficult metal to cast, mainly due to its relatively high melting point (1,670 ± 50 °C), along with its active interaction with various gases, and the extreme reactions that occur between titanium and investment materials [3]. However, due to a worldwide effort, many of the technical problems associated with dental titanium casting have been solved.

Some problems frequently observed are incomplete casting and internal porosity [4]. The main factors leading to these defects are the casting force exerted on the molten metal [5, 6], temperature of the melt and mold [7, 8], the permeability of the investment [9], and the spruing configuration [10]. In some cases, these factors act independently but in other cases they combine to influence the results. To evaluate the completeness of casting, many investigators have tried various experimental methods with different kinds of patterns. Gehl and Payne [11] and Asgar [12] used a spiral-shaped wax pattern to study castability. Later, Asgar and Arfaei [13, 14] developed a saucer-shaped design that had both thick and thin sections as found in actual crown patterns. Meyer *et al.* [15] modified this design by making four perforations that created a T-shaped pattern at the thin outer section of the saucer-shaped design. In dental casting, the molten metal must change the direction of flow to reproduce thinner sections of castings with complicated configurations. This modified saucer pattern could only be filled by the molten metal flowing back toward the center of the saucer pattern. Mackert and Moffa [16] and Barreto *et al.* [17] employed a knife edge as a pattern to compare the castability of various alloys. Vincent *et al.* [18] utilized a wax cylinder and nylon lines of varying diameters. By using a simulated crown wax pattern, Brockhurst *et al.* [19] and Bessing [20] gave special attention to various dental alloys. A pattern design which is often used to test the castability of dental alloys is a square piece of polyester sieve cloth [21–25]. This method was believed to be sensitive to materials, temperature, techniques, or other variables affecting castability because of its thin thread sieve [25]. Many studies evaluating the castability of titanium have dealt

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with the quantity of internal porosity [5, 26, 27] or marginal deficiency of a simulated crown [28] and bridge [9, 29] as parameters for castability. A few researchers reported results of studies using the sieve cloth pattern. Tajima *et al.* [30] investigated the efficiency of the number of argon-gas purges on the castability of pure titanium cast into a mesh mold in a two-chamber pressure casting unit. Using both the mesh pattern and the plate pattern for which porosity was measured, Takahashi *et al.* [31] quantitatively clarified the relationship between casting methods and the castability of titanium. In this study, they found that the best results could be obtained from the centrifugal titanium casting machine, followed by the one-chamber pressure casting unit and then the two-chamber pressure casting unit. However, no control metals were used in that study. Although they didn't investigate castability *per se*, Watanabe *et al.* [32] performed a series of studies on the metal flow during casting, which has basic importance for the understanding of casting phenomena.

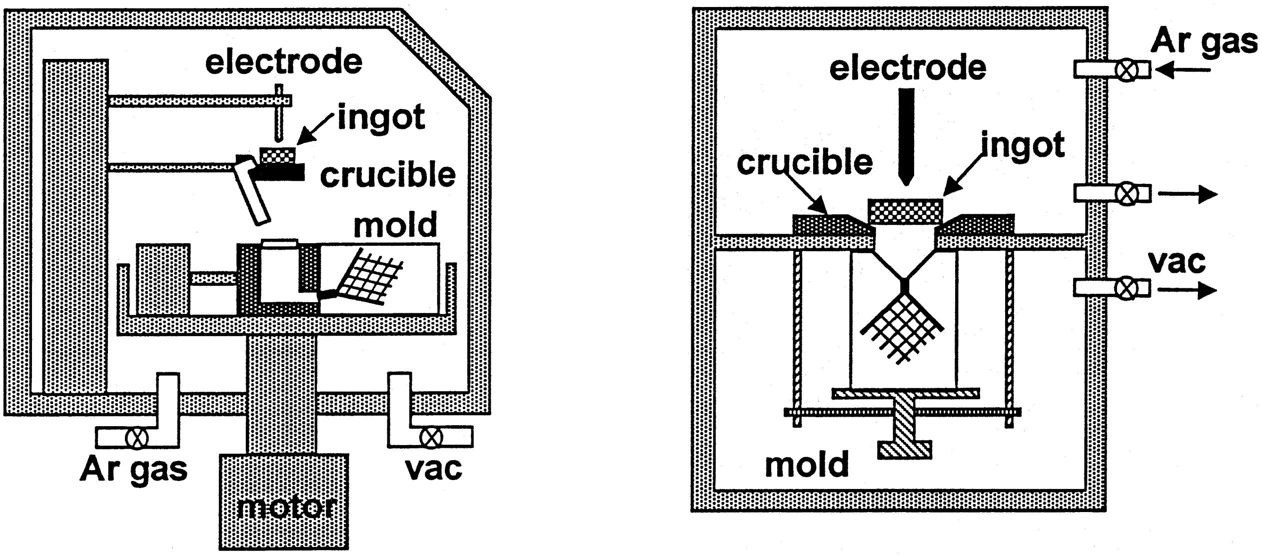
The objectives of the present study were to investigate the efficiency of casting methods (using either a centrifugal casting machine or a two-chamber pressure difference casting unit) on the castability of commercially pure (CP) titanium and to compare the castability of titanium with that of conventional dental casting alloys. In the present study, two types of patterns, a commonly used mesh pattern and Meyer's remodeled Asgar-Arfaei saucer-shaped pattern, were employed for evaluating castability.

2. Materials and methods

Three metals were used: a commercially pure titanium (CP-Ti) (ASTM Grade II, Titanium Industries, Grand Prairie, TX), a commercial ADA Type IV gold alloy (Au, 68%; Ag, 10%; Pt, 4.5%; Pd, 3%; Cu, 12.5%; other, 2%) (GP Type IV, Tokuriki Honten, Tokyo, Japan), and a Ni-Cr alloy (Ni, 60–76%; Cu, 12–21%; Mo, 4–14%; Ti, 4–6; Be, < 2%) (Talladium, Talladium, Inc., Valencia, CA).

Two types of casting equipment were employed to cast the CP titanium (Fig. 1). The first was a commercial centrifugal titanium casting machine (Ticast Super R, Selec, Inc., Japan) (Fig. 1a). When casting with this machine, a 30 gram CP-Ti piece (12 mm high and 30 mm in diameter) was placed on a graphite crucible positioned above the center of rotation of the turntable. A burn-out mold was placed close to the periphery of the turntable by weight-balancing it. The chamber was first evacuated to approximately 5×10^{-4} torr, and high purity argon gas (99.99% < 2 ppm O_2; Tri-gas, Dallas, TX) was introduced into the chamber until the pressure level was set at 200 torr (26.3 kPa). This procedure was repeated twice, which helped reduce the amount of residual air. The titanium ingot was then arc-melted (230 A, DC 45 V) over a period of 55 s. The crucible holding the molten titanium was then tilted toward the inlet located at the center of the turntable. Since the turntable began rotating 30 s after the arc had fired, the turntable had a designed full rotation speed of 3000 rpm when the molten metal was poured. According to the manufacturer, the turntable reaches 3000 rpm within 22 s of the initiation of rotation.

The other titanium casting unit used in this study was an experimental pressure difference-type casting unit built at the Scandinavian Institute of Dental Materials (NIOM) (described previously by Herø *et al.* [5]) and modified in our laboratory (Fig. 1b) [6]. It consists of an upper melting chamber and a lower mold chamber. After placing a piece of titanium (30 g) in the upper melting chamber, the upper chamber and the lower chamber (under which the mold was attached) were evacuated to a vacuum level of approximately 6×10^{-2} torr. Then high-purity argon gas (99.99% < 2 ppm O_2; Tri-gas, Dallas, TX) was introduced into the melting chamber until the



(a) **Ticast Super R**

(b) **Pressure-Difference Casting Unit**

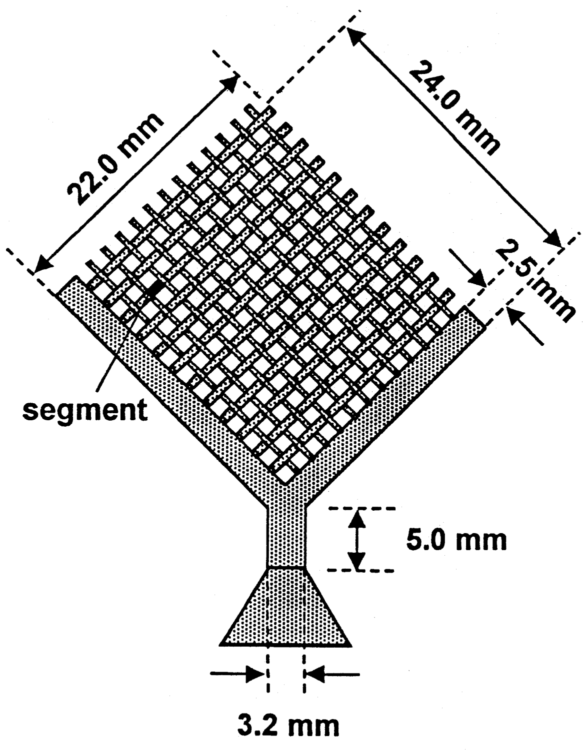
Figure 1 Two types of casting machines used in this study. (a) Ultra high-speed centrifugal titanium casting machine, Ticast Super R; (b) experimental two-chamber pressure-difference casting unit.

argon pressure difference between the two chambers became almost 150 torr (20.0 kPa). This pressure difference was chosen since our previous study [6] showed that the fewest casting defects were found under these conditions. The titanium was melted by an electric arc (200 A, DC 60 V) over a period of approximately 60 s, after which the molten titanium dropped by itself into the mold as a result of the argon gas pressure difference.

The Ni-Cr alloy and the Type IV gold alloy were cast conventionally using a broken-arm centrifugal casting machine (Kerr Centrifico casting machine; Kerr Manufacturing Co., Romulus, MI, USA) that was wound three complete turns. A propane gas/oxygen torch was used to melt the Ni-Cr alloy, whereas a propane gas/air torch was used to melt the Type IV gold alloy.

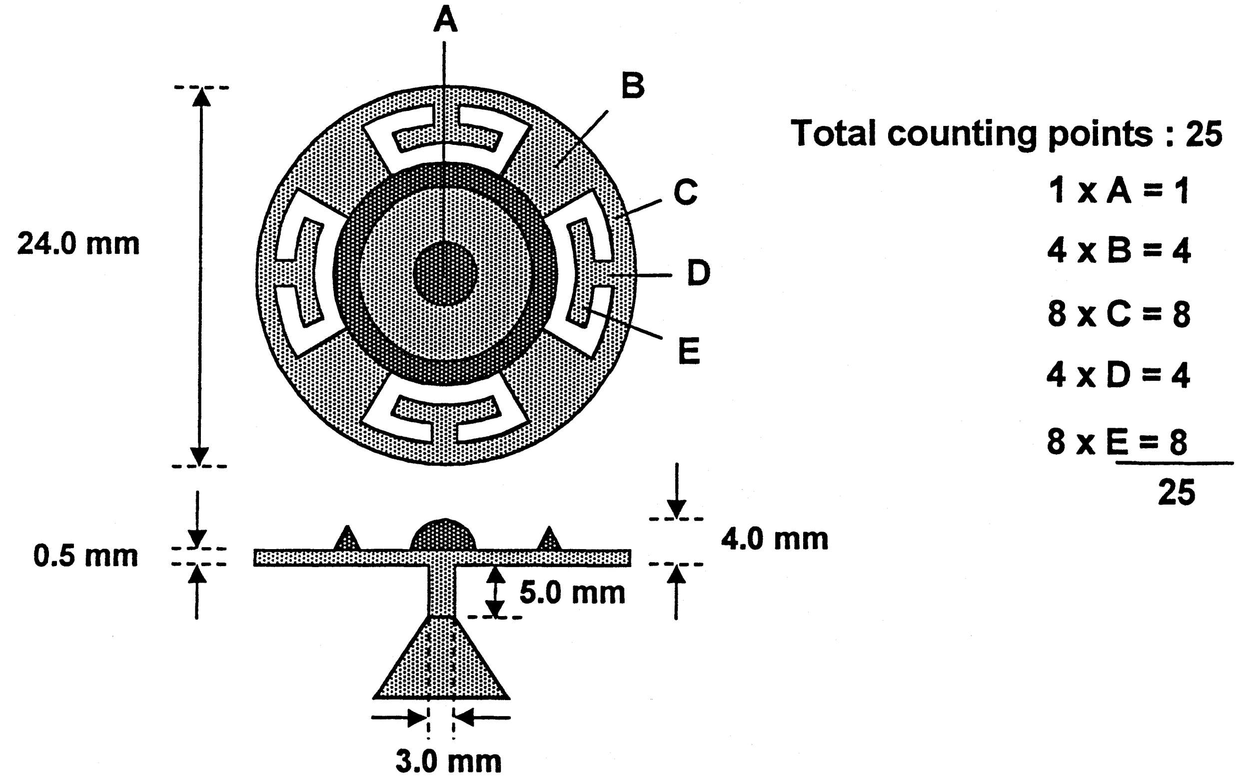
To determine castability, two types of patterns were used: a mesh pattern and a saucer pattern. The mesh pattern, similar to the configuration employed by Kaminski *et al.* [23], consisted of a 22 × 24 mm cut polyether thread sieve (Fig. 2). The diameter of the thread in the sieve was 0.5 mm. Each opening in the sieve measured 2.2 × 2.4 mm, making a total of 264 segments. The saucer pattern employed was a copy of the disc pattern originally developed by Asgar and Arfaei [13] and later modified by Meyer *et al.* [15] (Fig. 3). The disc was 24 mm in diameter with a thin outer section of 0.5 mm that was perforated to create four T-shaped patterns. The maximum thickness at the center of the convex portion of the pattern was 4.0 mm.

A total of twenty patterns were prepared for each type of pattern. Five patterns were then selected randomly from the twenty patterns of each type and subjected to molding for each casting condition: the two types of casting machines for CP-Ti, a gold alloy and a Ni-Cr alloy. The sprue of each pattern was attached perpendicularly to the sprue former and was invested in the mold ring using the investment materials (Figs 2 and 3). The distance between the top of the pattern and the top rim of the casting ring was set at approximately 10 mm to define the permeability of investment in the pressure-difference titanium casting unit. Magnesia-based investment materials were employed for CP-Ti: Selevest CB for the centrifugal titanium casting machine, as specified by the manufacturer (Selec Co., Japan) and Titavest C&B (J. Morita, Japan) for the pressure-difference casting unit, as was proven to be the best for the pressure difference casting unit [6]. Cristobalite investment (Cristobalite, Whip Mix, Louisville, KY) was used for the Type IV gold alloy, whereas a phosphate-bonded investment (Micro-Fine, Talladium, Inc., Valencia, CA) was used for the Ni-Cr alloy. The liquid/powder ratio and overall burn-out schedules for these investments followed the manufacturer's instructions. Since the metal was cast into cristobalite molds (for Type IV gold alloy) or Micro-Fine (for Ni-Cr alloy) immediately after removal from the burn-out furnace, the mold temperature at casting was considered to be close to the temperatures used to heat the molds: 650 °C for cristobalite and 980 °C for Micro-Fine. For the centrifugal titanium casting machine, the temperature of the Selevest CB mold (for CP titanium) at casting was believed to be approximately 200 °C since it usually took a few minutes for weight balancing after the mold heated



$$\text{Castability Index (CI)} = \frac{\text{Cast segments}}{264} \times 100\ (\%)$$

Figure 2 Configuration and castability evaluation of the mesh pattern.



$$\text{Castability Index (CI)} = \frac{\text{Counting points}}{25} \times 100\ (\%)$$

Figure 3 Configuration and castability evaluation of the saucer pattern.

at 350 °C was taken out of the furnace. The Titavest C&B mold was cast at room temperature (23 °C) as in our previous study [6]. When the molds were cast, each mold was placed so that it was oriented in the same direction in the holder of each casting machine. For the mesh pattern, the plane of the mesh sieve was parallel to the plane of rotation in the centrifugal casting machine, and it faced the front of the casting chamber in the pressure difference casting unit. For the saucer pattern, the line between the two diagonal T-shaped sections was parallel to the plane of rotation in the centrifugal casting machine, and it faced the front of the pressure difference casting unit. After completion of the mold preparation, the molds were cast according to the method described above.

After casting, the surfaces of the cast specimens were cleaned by alumina sandblasting, and ''castability indices'' to measure the mold filling were determined. For the mesh pattern, the number of successfully cast segments was expressed as a percentage of the total possible number of segments (264) (Fig. 2). For the saucer pattern, the castability index was determined according to Meyer's study [15] as the percentage of completely cast areas of the 25 selected areas (Fig. 3). The means and standard deviations of castability indices were statistically compared using an ANOVA followed by Scheffé's test at $\alpha = 0.05$.

The internal porosity of the cast titanium specimens (both cast mesh and saucer pieces) was examined radiographically using a conventional dental X-ray unit. This was performed on dental X-ray film (Kodak DF–50, Rochester, NY) at a target-film distance of 50 cm, a tube voltage of 70 kV, a tube current of 10 mA, and an exposure of $1/60 \times 36$ sec.

3. Results

Castability indices for casting the CP titanium using the two different patterns in both casting machines are summarized in Fig. 4. Fig. 4 also includes indices for the Type IV gold and the Ni-Cr alloy. It can be seen that the casting equipment significantly affected the mold filling of both patterns ($F = 97.99, p < 0.001$). The castability indices obtained from both patterns of CP titanium cast in the centrifugal casting machine were significantly ($p < 0.05$) greater than the indices for the castings produced in the pressure-difference casting unit. The castability indices obtained for the centrifugal titanium casting machine were not significantly ($p > 0.05$) different from those for the Ni-Cr alloy and the Type IV gold alloy. All the Ni-Cr alloy specimens exhibited a 100% castability index for both patterns. The values for the mesh patterns of the CP titanium cast in the pressure-difference casting unit were significantly lower (the mean $\approx$ 20%), compared to the values obtained in the ultra high-speed centrifugal casting machine.

Representative radiographs of both patterns cast in the pressure-difference casting unit and the centrifugal titanium casting machine are shown in Figs 5 and 6, respectively. There were much larger pores in both cast patterns made in the pressure-difference casting unit. The radiographs of the saucer pattern cast in the centrifugal titanium casting machine (Fig. 6) showed some pores

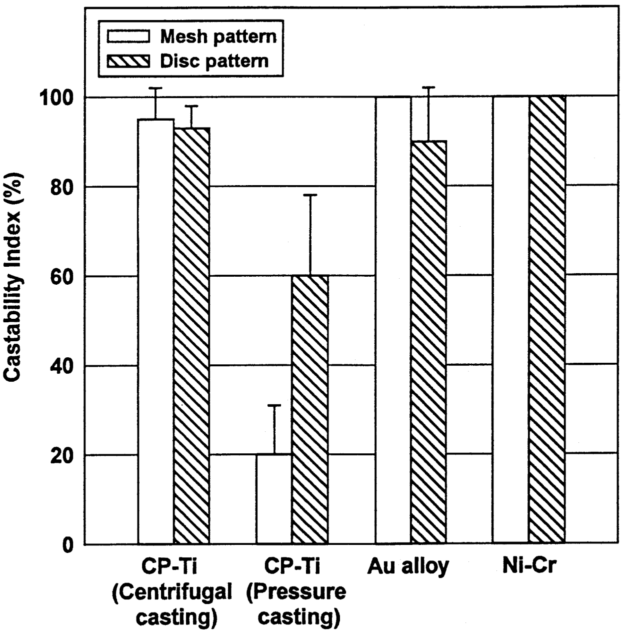


Figure 4 Castability indices with different casting conditions.

that were fewer and smaller in size than the pores found in castings made in the pressure-difference unit.

4. Discussion

The results of the castability indices (Fig. 4) and radiographic evidence (Figs 5 and 6) indicated that the centrifugal titanium casting machine produced a much sounder casting than did the two-chamber pressure difference casting unit. In general, castability is affected by two major factors: the intrinsic fluid properties of the molten metal and the casting conditions [33]. The latter include casting equipment, casting temperature, the mold temperature, the permeability of the investment material, the speed of the molten metal flow resulting from the casting force, the wettability of the mold components to molten metal, and the spruing configuration. These factors not only act independently to affect castability but they also act in combination to influence the results. One of the important factors that made a difference in the present results of the two casting methods appears to be the casting force exerted on the molten metal during casting. When one compares the difference in the forces exerted on the molten titanium in each of the casting units, it is not surprising that the castability of the centrifugal titanium casting machine is greater than that obtained for the pressure-difference casting unit. In the pressure-difference casting unit, the force exerted on the metal, F_P, is believed to be the sum of two forces, i.e., the force resulting from the pressure differences and the force exerted by gravity:

$$F_P = (P_1 - P_2)\mathrm{A} + mg \tag{1}$$

where $P_1 - P_2$ is the pressure difference (20.0 kPa) between the upper chamber and the cavity, A is the cross-section of the opening in the mold $(1.3 \times 10^{-4}\mathrm{m}^2)$, m is the total mass of molten metal $(2 \times 10^{-2}$ kg) poured into the mold, and g is the gravity of acceleration (9.81 m/s^2). The P_2 (cavity pressure) is not equal to the pressure of the lower chamber but equal to an intermediate value between the pressures of each chamber at the molten titanium drop; it then decreases quickly to the pressure of the lower chamber. This decreasing speed depends on the investment permeability, that is, the net amount of the

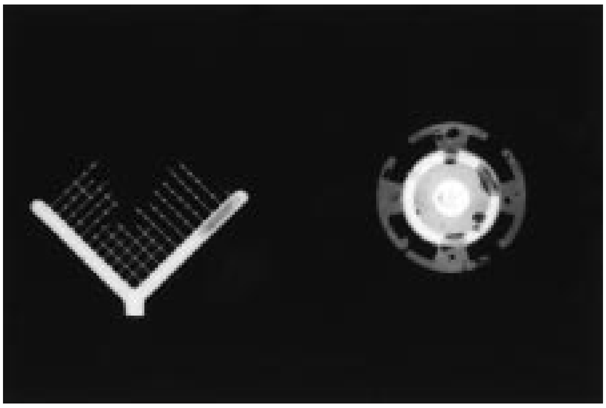


Figure 5 Radiographs of mesh and saucer patterns cast in the pressure-difference casting unit.

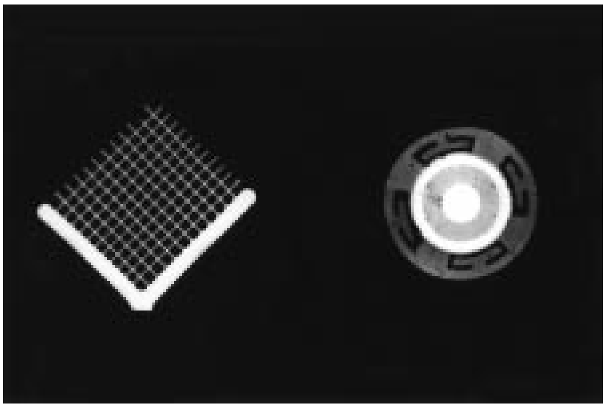


Figure 6 Radiographs of mesh and saucer patterns cast in the Ticast Super R.

casting force drastically changes with time. We cannot know the actual P_2 at the current stage of technology, but in order to compare this machine with the centrifugal casting machine, we used the half value of the pressure difference between both chambers. Thus, $(P_1 - P_2)A = 1.3\,\mathrm{N}$ and $mg = 0.2\,\mathrm{N}$, resulting in $F_P = 1.5\,\mathrm{N}$. By comparing F_P with the force of the free-falling $F_g(mg = 2 \times 10^{-2}\,\mathrm{kg} \times 9.8\,\mathrm{m/s^2} = 0.2\,\mathrm{N})$, $F_P/F_g \approx 7.5$. In the above calculation, the effect of the surface tension on the flow of the molten metal at the orifice was ignored.

On the other hand, in the centrifugal titanium casting machine, the force exerted by the centrifugal force F_c is given as:

$$F_c = m\omega^2 r \tag{2}$$

where m is the total mass of the molten metal $(2 \times 10^{-2}\,\mathrm{kg})$ poured into the mold, ω is the angular velocity based on 3000 rpm (314 rad/s), and r is the radius of the rotating arm ($5 \times 10^{-2}\,\mathrm{m}$ for the mesh pattern; $3.5 \times 10^{-2}\,\mathrm{m}$ for the saucer pattern). As a result, $F_c \approx 98.6\,\mathrm{N}$ for the mesh and 64.02 N for the disc. Thus, $F_c/F_g \approx 500$ for the mesh and 350 for the saucer. This means that when casting titanium, the centrifugal casting machine can exert approximately 40–60 times more force on the metal than the pressure-difference casting unit. A similar calculation of the force exerted on the molten metal in a conventional centrifugal casting machine, F_{cc}, with a rotation speed of 600 rpm (62.8 rad/s) used for casting Type IV gold alloy and Ni-Cr alloy yields $F = 17.8\,\mathrm{N}$. Thus $F_{cc}/F_g \approx 60$. It is interesting to know that this force is good enough and works well for the conventionally used dental casting alloys to produce sound castings. This casting force is approximately 10 times higher compared to that in the pressure-difference casting unit. Therefore, it is obvious that the main reason for better castability of titanium and conventional dental alloys in centrifugal casting machines is believed to be due to a much larger force acting on these molten metals.

It should be noted that in the above estimations of the forces exerted on the molten metal for centrifugal castings in titanium and in conventional dental casting alloys, the only force considered is the one generated by the centrifugal force. However, as pointed out more precisely by Watanabe [34], the total forces exerted on the molten metal during centrifugal casting include additional forces that should be evaluated for each casting condition.

In the present titanium centrifugal casting machine, the transverse force, F_{trans}, can be ignored since the casting turntable is already rotating at a constant speed as high as 3000 rpm before the molten metal starts to flow into the mold. Because the speed of the metal flow, which is needed to estimate Coriolis force, was not measured in the study, the Coriolis force unfortunately cannot be directly calculated. We can ignore this force in our case because the velocity of the titanium in the cavity is not expected to be very rapid due to the complicated cavity shape of the mesh pattern and modified disc.

In any case, from the examination of various forces exerted on the molten titanium in centrifugal and pressure-difference casting, it is obvious that the centrifugal casting machine yielded much greater total force than that produced in the pressure-difference casting unit. This may be the main reason why the castability of titanium was better in the centrifugal casting machine in this study. However, the difference in castability (particularly for the saucer pattern) is not as large as the difference in the force exerted on the metal for both machine types. This fact probably originates from the type of casting force; pressure is area force, and centrifugal force is body force. These two forces are essentially different in nature.

Another factor affecting castability is the mold temperature during casting. The mold temperatures used for titanium casting in this study were around 200 °C for the Ticast Super R and room temperature for the pressure-difference casting unit. These preheated mold temperatures for both casting units are very low when compared to the temperature of molten titanium (approximately 1700 °C). When the titanium that had just been melted at a high temperature flowed through the thin openings of the low-temperature mold, the molten metal adjacent to the mold wall immediately solidified and thus, most of the cavities were quickly filled, stopping further filling of the mold. In the present study, the castability of the mesh pattern was only 20% in the pressure-difference casting unit. On the other hand, the saucer pattern yielded better castability compared to the mesh pattern even when the pressure-difference casting unit was used. This is probably due to the thin diameter (0.5 mm) of the mesh thread. Note that the cavity cross section anywhere in the saucer pattern is thicker, except for the edges. When the Ticast Super R was used, the higher mold temperature (200 °C) compared to the room temperature mold slightly helped produce greater castability. The castability indices of titanium obtained in the present study are comparable with those of an earlier study (Takahashi *et al.*, [31]). In their experiment, three different commercial casting machines [two types (one chamber and two chambers) of pressure casting units and the same centrifugal casting machine used in this study, the Ticast Super R] and a phosphate-bonded investment were employed, and the castability of a mesh pattern with 0.4 mm-sized diameter sieve thread were evaluated. The castability index of the Ticast Super R in this study was a value (95%) similar to that in Takahashi's study [31]. However, the two-chamber pressure casting unit in their study [31] yielded worse castability (less than 10%) compared to the present experimental two-chamber casting unit. This is probably due to the difference in mesh patterns (greater thread diameter), permeability of investment material and the argon pressure force rendered to the molten titanium.

All the Ni-Cr alloy specimens cast into the molds that were preheated to 980 °C exhibited a 100% castability index for both patterns. This result was in agreement with findings on the castability of base metal alloys by Jarvis *et al.* [22]. Using a mesh pattern and a phosphate-bonded investment, they reported that the beryllium-containing Ni-Cr alloys showed 98–99% castability indices at the burn-out temperature of 760 °C and 100% at 870 and 980 °C, and that the manufacturer's recommended burn-out temperature (980 °C) should be used as a metal-mold equilibrium point. Hinman *et al.* [25] found that increasing the mold and casting temperature increased the castability values of the Ni-Cr alloys, but the optimal mold and casting temperature region was discerned for each alloy. The mold temperature used in this study should be suitable to obtain the best castability for the Ni-Cr alloy. On the other hand, the Type VI gold alloy cast into the mold at 650 °C did not attain 100% castability in the saucer pattern (90%), but reached 100% castability in the mesh pattern. Reagan and Kois [24] investigated the effect of burn-out temperature on the castability of Type III gold alloy cast into a mesh mold with 210 possible cast segments. They reported that increasing the burn-out temperature of the phosphate-bonded investments increased the number of cast segments (120–188 seg., 650 °C; 166–192 seg., 675 °C; and 202–210 seg., 700 °C). Although a cristobalite investment preheated to 650 °C was used to cast the Type IV gold alloy in this study, the results suggested that this mold temperature was optimal for casting the mesh pattern, but not the saucer pattern. If a higher mold temperature (around 700 °C) had been employed to cast the saucer pattern, a 100% castability index might have been obtained because the larger wall area of the mold in the disc pattern (compared to the wall area of the mesh pattern) promoted quick solidification of the molten metal, preventing further filling of the thin outer T-shaped sections of the mold.

The internal pores in the cast specimens observed by X-ray radiography (Figs 5 and 6) clearly revealed that the centrifugal casting machine produced better quality castings than did the pressure-difference unit: in the specimens cast by centrifugal force, the size of the pores was much smaller, and the pores were more evenly distributed. One of the reasons for this difference in porosity is that in the case of centrifugal casting, larger bubbles in the molten metal can escape quickly through the sprue due to the large centrifugal force. Porosity was observed mostly in the saucer pattern in either casting process. This was probably due to the spruing configuration of the saucer pattern in which the disc plane was placed perpendicular to the metal flow (sprue axis) The metal poured first hit the wall of the disc plane, and the severe disturbance that was created probably caused the incorporation of pores. The castability of titanium in the pressure-difference casting unit could be improved over the values obtained in the present study by changing the experimental conditions and materials.

In summary, when the ultra high-speed centrifugal casting machine was used with the manufacturer's recommended mold material, the castability of titanium was similar to the gold alloy or the Ni-Cr alloy cast by conventional means.

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