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Porosity and mould filling of titanium castings

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A vacuum/Ar pressure casting machine was used to study porosity and mould filling of cast bridges of Ti. Two series of experiments were carried out: (1) The melting and the mould chamber were separated by a thin Ti foil until penetrated by the Ti melt. The mould chamber including the mould cavity was evacuated. (2) No separating Ti foil was applied. The pressure in the mould chamber was then controlled by diffusion of Ar through the investment. The moulds were made of two investments with different gas permeability. A standardized wax pattern for a five-unit bridge was used. Mould filling was evaluated by visual inspection and by measuring the missing lengths of the margins of the crowns. The porosity was studied by x-ray radiography and density measurements. In the first series mould filling was satisfactory in all cases, while the porosity was substantial for high Ar pressures. Without a Ti foil (second series) all castings contained little porosity, but the mould filling was adequate only for the high permeability investment. The experiments show that porosity can be avoided by maintaining small pressure differences between the melting chamber and the mould cavity. Adequate mould filling is promoted by minimal back pressures from trapped Ar gas in the mould.

1. Introduction

Cast crowns, bridges and inlays of Ti have attracted increased and widespread interest during recent years. This is mainly due to the well-documented biocompatibility of the metal in combination with a much lower price than for noble metal alloys. Due to the extreme reactivity of Ti to elements like O, N and C, and its high melting point, special casting machines and investments with stable oxides have to be employed. Nevertheless, problems concerning porosity and mould filling have been reported [1–3].

The aim of the present work was to study factors affecting mould filling and porosity for an Ar-arc, vacuum/Ar pressure type casting machine.

2. Materials and methods

The casting machine employed has been described previously [4], and a schematic drawing is shown in Fig. 1. The principles of this machine are similar to those of the machines employed by Ida [1] and Waterstrat and Giuseppetti [5]. A 40 g Ti ingot is melted by an Ar arc in a Cu crucible (scull melting) with a central hole 13 mm in diameter in an upper chamber. The investment mould is located in a lower chamber. A standardized cast pattern consisted of a five-unit bridge with one cylindrical crown (6 mm in diameter) on each side and three prefabricated wax pontics in the middle. A casting with spruing is shown in Fig. 2. Both chambers are initially evacuated to a pressure of 13 Pa prior to the introduction of Ar gas into the melting chamber. The Ar pressure in both chambers was monitored during the casting process. The steel ring of the mould was pressed tight against the separating steel floor between the two chambers with a ring of silicone rubber as a seal.

Two series of experiments were carried out: with a

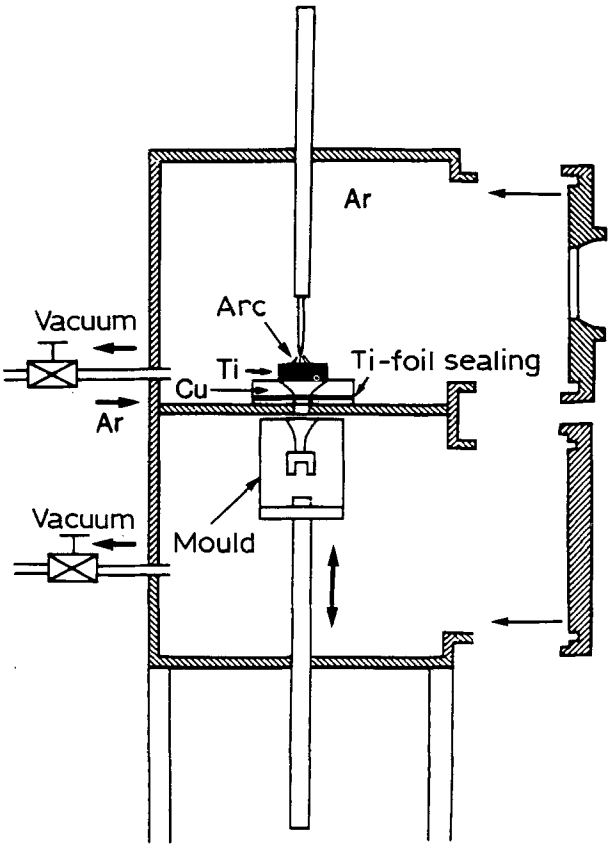

Figure 1 Schematic drawing of the casting machine employed.

thin, 25 μm thick separating Ti foil between the two chambers (series 1); and without such a foil (series 2). The experimental details are given in Tables I and II, respectively. Three parallel runs were made for each set of experimental procedure.

2.1. Series 1

The Ti foil prevents the Ar gas from flowing into the evacuated mould until the foil is penetrated by the Ti melt falling through the central hole in the Cu crucible. Subsequently, the melt is pushed into the mould cavity by the Ar pressure in the melting chamber. Five vents from the cavity to the bottom of the mould were applied in the two first sets of experimental procedures (6.6×10^3 and 5.3×10^4 Pa Ar pressure, Table I). In the third experimental procedure no vents were used, along with an Ar pressure of 6.6×10^3 Pa. The investment used in these three experimental procedures was a conventional phosphate bonded investment based on quartz (Bellavest T, BEGO, Germany) with a coating of ZrO_2 on the wax model to reduce reactions with the Ti melt. The details of the coating procedure have been described previously [6]. The conditions for the fourth experimental procedure (Table I) were similar to those for the third, except for the investment (Titavest CB, Morita, Japan). This investment is based on Al_2O_3 and MgO without SiO_2, according to information from the manufacturer.

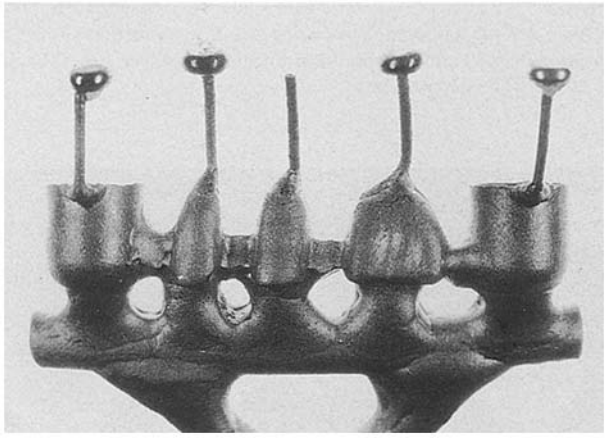

Figure 2 A completely filled five-unit bridge, displaying the standardized pattern with spruing and vents. Experimental procedure 1 was employed. A similar and completely filled casting was achieved with experimental procedure 6 without vents and separating Ti foil.

2.2. Series 2

Without a separating Ti foil the mould cavity is filled prior to melting with Ar gas at the same pressure as in the melting chamber. No vents from the mould cavity to the mould chamber should be used in this case in order to keep the Ar pressure in the mould chamber as low as possible. When the melt flows into the mould cavity, the captured Ar gas therefore has to escape through the investment to the mould chamber. In this series the same two investments with different porosity, (and thus gas permeability) as in series 1, were employed. The Ar pressure in the melting chamber was 5.3×10^4 and 8.0×10^4 Pa, respectively. These two

TABLE I. Series 1: conditions and results using separating Ti foil

Experimental procedure number	Major experimental parameter	Investment[a]	Ar[b] (Pa)	Vents	Porosity	Density Bridge + sprue ($g\ cm^{-3}$) $\bar{X}$	s.d.	Filling
1	Ar-pressure	1	6.6×10^3	5	Some	3.98	0.37	Good
2			5.3×10^4	5	Subst.	3.84	0.27	
3	No venting	1	6.6×10^3	None	A few in the sprues	4.23	0.26	Incomplete
4	Investment permeability	2	6.6×10^3	None	A few in the sprues	4.45	0.06	Good

[a]Investments: 1 = Bellavest T + ZrO_2 coating, 2 = Titavest CB
[b]Melting chamber

TABLE 2. Series 2: conditions and results using no separating Ti foil and no vents.

Experimental procedure number	Major experimental parameter	Investment[a]	Ar pressure Melting chamber (Pa)	Ar pressure Mould chamber (Pa)	Porosity	Density bridge + sprue ($g\ cm^{-3}$) X	s.d.	Filling
5	Investment permeability	1	5.3×10^4	130	None	4.45	0.04	Incomplete
6		2	8×10^4	2×10^4	None	4.47	0.09	Good

[a]Investments: 1 = Bellavest T + ZrO_2 coating, 2 = Titavest CB

conditions will be referred to as experimental procedures number 5 and 6 (Table II).

Both investments were fired according to the manufacturer's instructions and cooled to room temperature before the moulds were inserted in the casting machine.

The overall mould filling was evaluated by visual inspection of the casting. The filling of the margins of the cylindrical crowns with a sharp angle of 30° was measured by recording the degree of deficiency in reproducing the full length of the margin. The measurements were made by an indirect method using a dental impression material [7]. Four sections of each impression of the circular margins were measured. The investment applied for these measurements was Titavest CB with and without the use of a separating Ti foil, experimental procedures 4 and 6, respectively.

Internal porosity was recorded by means of x-ray radiography. The density was measured by pycnometry. Open pores in cut sections will be filled with water and thus reduce the volume of displaced water, i.e. recorded volume of the casting. On the basis of the radiographs the volume of open pores in each casting was, therefore, added to the volume of the casting determined by pycnometry.

3. Results

The visually observed mould filling and the recorded density/porosity are summarized in Table I (series 1) and Table II (series 2). The open pores in the cut sections caused only minor corrections to the densities measured by pycnometry.

3.1. Series 1

The detrimental effect of increasing Ar pressure on porosity in series 1 in the presence of vents is illustrated by the x-ray radiographs in Figs 3 and 4 for 6.6×10^3 and 5.3×10^4 Pa (experimental procedures 1 and 2, Table I). The corresponding differences in density are shown in Table I. Mould filling was good in both cases, as illustrated in Fig. 2 for experimental procedure 1. Without vents (experimental procedure 3) the porosity was still low for 6.6×10^3 Pa Ar pressure, while the mould filling in this case was inadequate for the phosphate bonded and quartz based investment, as illustrated in Fig. 5. For the investment based on Al_2O_3 and MgO, however, mould filling was good (experimental procedure 4) with an appearance similar to the casting shown in Fig. 2.

3.2. Series 2 (no separating foil)

The porosity in the castings was low using both investments. The mould filling, however, was satisfactory only for Titavest CB (experimental procedure 6, Table II). The appearance of these castings was similar to that shown in Fig. 2, except for the vents which were deleted in series 2. The castings obtained with Bellavest T (experimental procedure 5) were incomplete and similar to those shown in Fig. 5. The Ar pressure in the mould chamber during casting was recorded and found to be 130 and 2.0×10^4 Pa for Bellavest T and Titavest CB, respectively.

The average lengths of the missing part of the cast

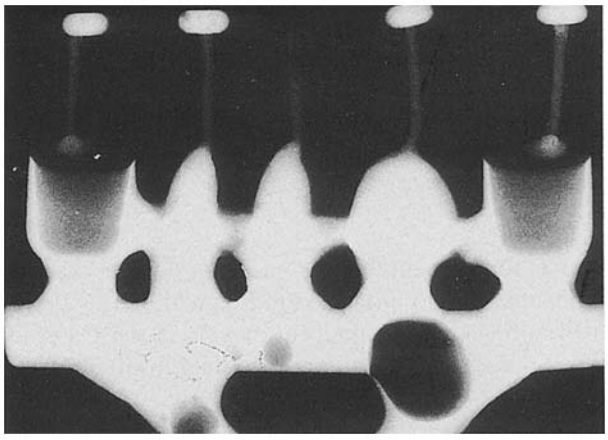

Figure 3 X-ray radiograph of casting displaying little porosity (separating foil of Ti, five vents). Experimental procedure 1 in Table I, 6.665×10^3 Pa Ar pressure.

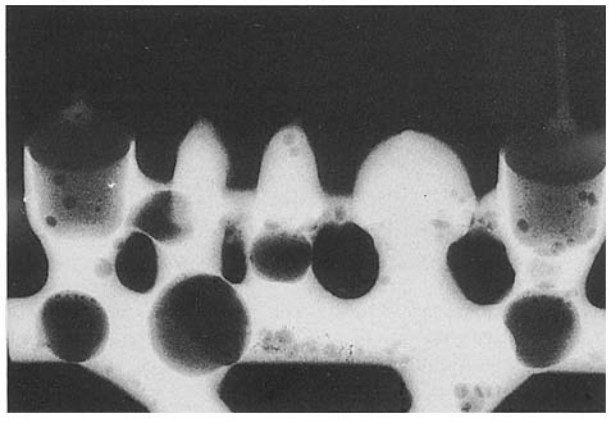

Figure 4 X-ray radiograph of casting displaying increasing porosity with increased Ar pressure (separating foil of Ti, five vents). Experimental procedure 2 in Table I, 5.33×10^4 Pa Ar pressure.

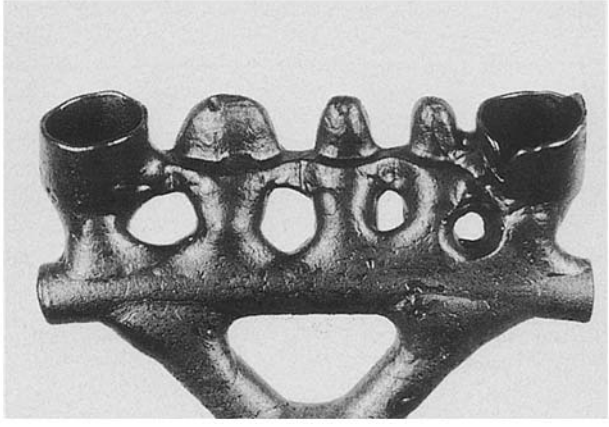

Figure 5 Photograph of a poorly filled mould cavity in the absence of vents (separating foil of Ti, 6.665×10^3 Pa Ar pressure, investment with a low gas permeability). Experimental procedure 3 in Table I was employed. A similar and even more inadequate mould filling was recorded for experimental procedure 5 in Table II (no Ti foil, 5.33×10^4 Pa Ar pressure, investment with low gas permeability).

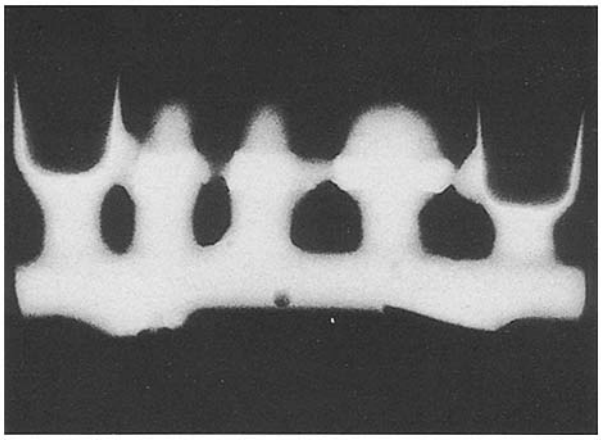

Figure 6 X-ray radiograph of a casting obtained with experimental procedure 6 in Table II (no Ti foil, investment with high gas permeability). The photograph indicates adequate mould filling and displays a casting almost free from porosity.

crowns were 127 μm (s.d. 44 μm) and 123 μm (s.d. 44 μm) with and without a separating Ti foil for Titavest CB. The surface quality of all castings was adequate with little or no oxidation for both investments (a ZrO_2 coating was applied for Bellavest T).

4. Discussion

4.1. Porosity

It has been shown that internal porosity may be a problem, even if the mould appears to be completely filled by visual inspection. A substantial increase in porosity was observed when the Ar pressure was changed from 6.6×10^3 to 5.3×10^4 Pa, in combination with the use of a separating Ti foil and vents. This indicates that Ar gas under these circumstances tends to follow the molten Ti into the mould and becomes trapped in the casting because of rapid solidification. The higher the Ar pressure, the more gas is likely to enter the evacuated mould cavity. On the other hand, an Ar gas pressure of 8.0×10^4 Pa without the presence of a separating Ti foil and no vents caused almost no porosity for the investment based on Al_2O_3 and MgO. The reason is most likely a smoother metal flow with less occluded Ar gas in this case because of a lower underpressure in the mould cavity caused only by the removal of gas through the investment to the evacuated mould chamber. This assumption is in line with the work by Watanabe *et al.* [8] who found lamininar flow to cause less porosity than turbulent flow in titanium castings. The higher Ar pressure detected (2×10^4 Pa) in the mould chamber during casting in series 2 for this investment compared with that for the quartz investment (130 Pa) indicates a substantial difference in permeability (Table II).

4.2. Mould filling

Inadequate mould filling, as observed by visual inspection, occurred in two cases:

1. By using a separating Ti foil in combination with the absence of vents as well as a low permeability and quartz based investment (experimental procedure 3). However, the use of either vents (experimental procedure 1) or an investment with a higher permeability (experimental procedure 4) eliminated the mould filling problem.
2. By removing the separating Ti foil along with the use of an investment having a low permeability (experimental procedure 5) Vents connecting the mould chamber with the mould cavity should only be used in the presence of a Ti foil. Otherwise, there is a risk that there will be no difference in gas pressure between the two chambers prior to casting.

The margins were filled quite well and to the same level as found for gold alloys using centrifugal casting with Ar gas protection [10]. No difference was observed on this point between castings produced with or without a separating Ti foil.

The dimensional fit has previously been found to be good [6] and since the surface quality of the castings was always satisfactory, adequate bridges with at least five units can be made by selecting suitable casting procedures.

5. Conclusions

1. Low internal porosity is obtained by producing a smooth metal flow with little Ar gas following the metal into the mould cavity.
2. Inadequate mould filling is usually due to poor escape possibilities for the gases trapped in the mould which produces high back pressures.

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