Numerical simulation of the casting process of titanium removable partial denture frameworks

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The objective of this work was to study the filling incompleteness and porosity defects in titanium removal partial denture frameworks by means of numerical simulation. Two frameworks, one for lower jaw and one for upper jaw, were chosen according to dentists' recommendation to be simulated. Geometry of the frameworks were laser-digitized and converted into a simulation software (MAGMASOFT). Both mold filling and solidification of the castings with different sprue designs (e.g. tree, ball, and runner-bar) were numerically calculated. The shrinkage porosity was quantitatively predicted by a feeding criterion, the potential filling defect and gas pore sensitivity were estimated based on the filling and solidification results. A satisfactory sprue design with process parameters was finally recommended for real casting trials (four replica for each frameworks). All the frameworks were successfully cast. Through X-ray radiographic inspections it was found that all the castings were acceptably sound except for only one case in which gas bubbles were detected in the grasp region of the frame. It is concluded that numerical simulation aids to achieve understanding of the casting process and defect formation in titanium frameworks, hence to minimize the risk of producing defect casting by improving the sprue design and process parameters.

1. Introduction

Due to the world wide effort, many technical problems associated with titanium dental castings have been solved. The remaining special concerns for partial denture frameworks were filling incompleteness and the internal porosity. The experimental studies on castability (filling incompleteness and porosity) of titanium dental castings indicated that centrifugal casting system produced sounder and more complete castings than pressure difference casting unit [1–3]. Other factors influencing the castability, e.g. mold preheating [4], mold materials [5–6], permeability of the mold materials [7–8], etc., were also well recognized and brought under control. However, the influence of the sprue design was not so evident because it is very sensitive to particular casting geometry [7–10]. A very recent experimental study stated that the ball-sprue produced the most complete castings for removal partial denture titanium frameworks among the sprue systems (tree, ball, and circular) investigated, but no significant difference regarding to porosity [11].

In previous studies numerical simulation method was used by the authors to investigate the porosity and gas pores in titanium dental castings [4, 12]. It was successfully applied to ''visualize'' the mold filling and solidification sequence and to optimize the sprue design for titanium crowns and bridges [12]. The objectives of this work was to extend this method

1. to simulate the mold filling and solidification in removal partial denture frameworks;
2. to achieve understanding of the potential filling incompleteness defect and porosity;
3. to optimize the sprue design and process parameters for the framework castings.

2. Materials and methods

Two partial denture frameworks, one for lower and one for upper jaw, were chosen as masterpieces according to dentists' recommendation. The criteria to choose these master frameworks were that they represented the typical clinical cases, and they were prone to the filling incompleteness and porosity defects.

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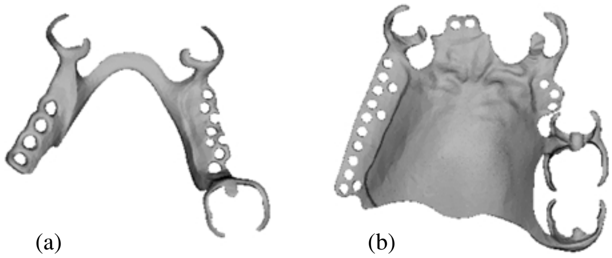

Figure 1 CAD models of the laser digitized partial denture frameworks. (a) Lower jaw; (b) Upper jaw.

2.1. Numerical simulation

The outer contour of the frameworks were laser digitized from the masterpieces in the principle of light-section-triangulation on a commercial system (Mine 70, Micromeasure GmbH, Linden, Germany). This system was suitable for dental or high precision medical prostheses and had a maximum envelope of $100 \times 100 \times 60\,mm^3$ and measurement accuracy of $50\,\mu m$. A complete framework was digitized from many views. Thousands of points (the point cloud) were digitized in each view. Using a matching function, the point clouds from different views were merged together to form the contour of the framework. The point clouds were further processed and converted into a CAD model in STL format (Fig. 1), which was required by the numerical simulation software and widely used by many rapid prototyping systems.

A casting simulation software, MAGMASOFT (MAGMA Gießereitechnologie GmbH, Aachen, Germany), was used to simulate the mold filling and solidification by solving the Navier-Stokes (fluid flow) and Fourier (heat transfer) equations numerically. Potential filling defect regions were estimated based on the coupled fluid flow and heat transfer calculations during mold filling. When a region was isolated by solidified metal during filling, or filling path was blocked by the premature solidification, the program gave a warning ''solidification during filling'', indicating the filling incompleteness defect. Shrinkage porosity was predicted by a built-in ''feeding criterion'' function. During solidification, the criterion function automatically recorded the solidification shrinkage and feeding efficiency for each element. Gas pore tendency was evaluated according to a hypothesis of gas entrapping and escaping: ''the large temperature deference between the melt and the mold creates rapid cooling and thereby shortens the time for gases to escape''. Details of the numerical model, the initial and boundary conditions, the thermal physical properties for the simulation were previously described [4, 13].

Three types of sprue designs were constructed, the configurations after FDM (finite difference) meshment and the geometrical parameters were shown in Fig. 2. The tree sprue and the ball sprue were traditionally used for base-metal alloys [14] and late introduced for titanium [11]. The framework was placed in the position about vertical to the axis of the funnel (pouring basin). The sprues, leading the melt to different directions, were attached to the relatively thick sections of the cast parts. The spruing positions of ball sprue were slightly modified based on the simulation results of tree sprue. In the third design a runner bar was used to distribute the melt through ingates into the framework, which was tilted 45° angle to the axis of the funnel.

2.2. Experimental casting trials

Different from the traditional waxing process for framework, the physical object of the framework was directly created by means of the rapid prototyping (RP) technique. The CAD model (in STL format) of the framework was read into the RP machine: ModelMaker II 3D Plotting System (Sanders Prototype, Inc., Wilton, USA). An inkjet printed fine wax-like drops (Paraffin: Materialise NW, Leuven, Belgium), layer on top of layer, hence to build up the pattern. The objects with fine details of 0.1 mm were able to be built on this system. These objects served as normal wax patterns, being melt and burnt out in de-waxing and firing process. According to the simulation recommended parameters, the sprue systems were prepared and glued to the RP wax patterns, then following the normal investment casting procedure, the titanium frameworks were cast on a centrifugal casting machine (Titancast, Linn High-Therm, Eschenfelden, Germany).

Commercial pure titanium (~ 0.5 wt% Fe, ~ 0.4 wt% O, ~ 0.08 wt% C, ~ 0.05 wt% N, ~ 0.015 wt% H, $0.1 \sim 0.4$ wt% residual impurities, balance Ti) (Grade 4; Timet Ger. GmbH, Duesseldorf, Germany) was used. The mold was made of SiO_2 based investment (Gilvest T, Guilini Chemie, Ludwigshafen, Germany) with a layer (1 mm) of ZrO_2 face coat (Dynazirkon C, Dynamit Nobel, Troisdorf, Germany). The pouring temperature was 1700 °C, liquidus and solidus temperatures were 1668 and 1660 °C, and mold preheating was 500 °C. Details of the casting process was given in literature [4, 13].

All finished castings were examined by X-ray radiography for the internal porosity, and the filling incompleteness defects were inspected by naked eye.

3. Results

The simulated filling sequences of the lower jaw framework with the tree sprue were shown in Fig. 3. In the early stage of filling, the melt was equally distributed among the four separate sprues, which leaded the melt into different sections of the framework (Fig. 3(a)). At 0.167 s when the whole mold cavity was 95% filled, however, one (upper right) of the grasps was still not filled (Fig. 3(d)). The temperature of the front melt reaching the grasp was calculated 1663 °C. Although it was still above the liquidus, the cold melt (partially solidified) likely blocked the filling path, causing incompleteness defect. At the end of filling, ''solidification during filling'' was reported by the program. The solidification result was shown in Fig. 4(a), the solidification time at different point was read from the color scale: the dark region started to solidify and the light areas indicated the potential ''hot spots'', i.e. the last regions to solidify. The shrinkage porosity was quantitatively predicted by a feeding criterion, and an ''X-ray'' function of MAGMASOFT post-processor was used to display the porosity regions. The arrow-pointed

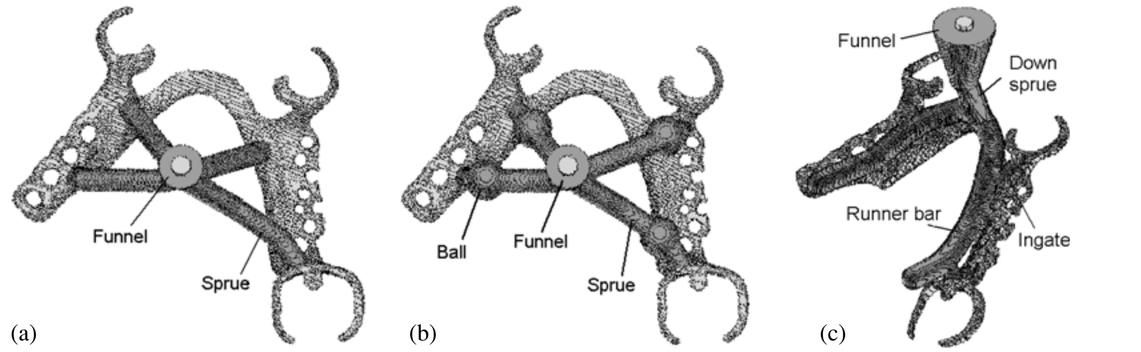

Figure 2 Configurations and geometrical parameters of the sprue designs. (a) Tree sprue: sprue ($\times$ 4): $\varnothing$ 3.25 mm; (b) ball sprue: sprue ($\times$ 4): $\varnothing$ 3.25 mm; ball ($\times$ 4): $\varnothing$ 6 mm, 2–3 mm away from the framework; (c) runner bar sprue: down sprue ($\times$ 1): $\varnothing$ 3 mm; runner bar ($\times$ 1): $\varnothing$ 4 mm; ingate ($\times$ 6): $\varnothing$ 3 mm, length $\sim$ 3 mm.

dark regions were lower than 80 $\sim$ 90% fed, it meant that more than 10 $\sim$ 20% of solidification shrinkage could not be fed and would leave in the ''hot spot'' regions as porosity. The predicted shrinkage porosity were all located in the sprues and the pouring funnel (Fig. 4(b)).

The filling result with ball sprue, at 0.191 s when the whole mold cavity was 95% filled, was shown in Fig. 5. The grasps were safely filled. Compared to the tree sprue design, one of the sprue (upper right) was slightly moved towards the grasp, hence the filling result was improved. However, another difficult-to-fill region (arrow) was identified. The program did not give any warning of ''solidification during filling'', but the arrow pointed thin-walled mesh area (Fig. 5), where the coldest melt met at the very late stage of filling, presented the most critical region where filling incompleteness defect might occur. Solidification and feeding calculations did not show any problem. As expected, the predicted shrinkage porosities were confined in the balls.

Very satisfied filling result was obtained with the runner bar sprue (Fig. 6). At 0.245 s when the whole mold cavity was 95% filled, all the grasp regions were nearly full. The whole cast part was filled without warning of ''solidification during filling''. Solidification and feeding calculations showed shrinkage porosity in the casting part. This runner bar sprue design was recommended for real casting trials.

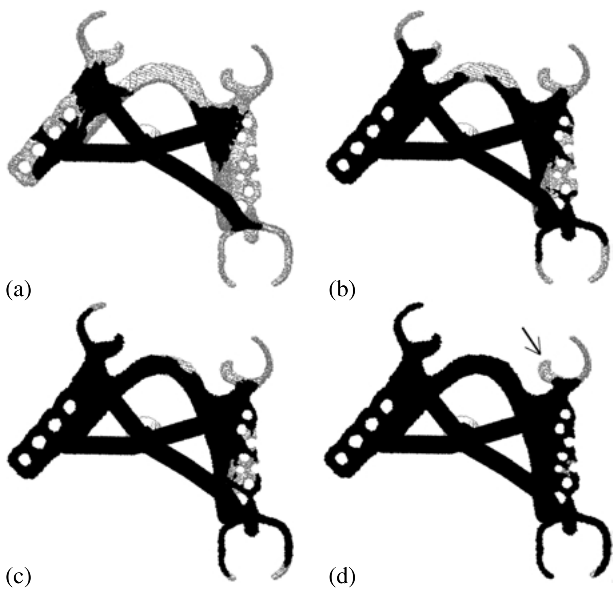

Figure 3 Filling sequence of the lower jaw framework with tree sprue. (a) 50% filled at 0.102 s; (b) 80% filled at 0.145 s; (c) 90% filled at 0.16 s; (d) 95% filled at 0.167 s.

Four titanium replica of the lower jaw framework were cast by using the computer created wax (rapid prototyping) patterns. No filling incompleteness defect was found (Fig. 7(a)). Each casting endured X-ray inspection, all the parts were found acceptably sound except one part in which intolerant gas bubbles at the grasp region were detected, as shown in Fig. 7(b) (arrow).

Similar simulations were carried out on the upper jaw framework. The runner bar sprue worked same well for the upper jaw framework. Filling sequences were shown in Fig. 8. At 0.375 s when the whole mold cavity was 95% filled, all the thin walled sections, especially in the grasp regions, were nearly full. No ''solidification during filling'' was warned. Both the solidification and feeding calculations demonstrated that the framework was well fed. Real casting trials (four replica) were also made, no filling defect was found and X-ray radiographs showed sound cast parts.

4. Discussions

4.1. Mold filling

Efforts were made to understand the fluid flow and mold filling in titanium dental castings, and to study the influence of different casting systems and their filling behaviors on the castability [3, 15, 16], but direct experimental observation was not possible because the whole filling process of dental casting was carried out in very short time (0.2 $\sim$ 0.4 s). Numerical simulation offered a new opportunity to ''visualize'' the details of the mold filling. During mold filling both fluid flow and heat transfer were coupled. Filling incompleteness defect occurred when the premature solidification blocked the filling channel and prevented the melt from filling the blocked regions. The most important filling related parameters, e.g. filling sequence, velocity, temperature distribution and solidification isotherm, were available through numerical calculation.

As an example, Fig. 3 shows the filling sequence of the lower jaw framework casting, which demonstrated that the first tree sprue design (four sprues used) did not satisfy the filling requirement. The upper right grasp was prone to be the most difficult-to-fill region. Based on the

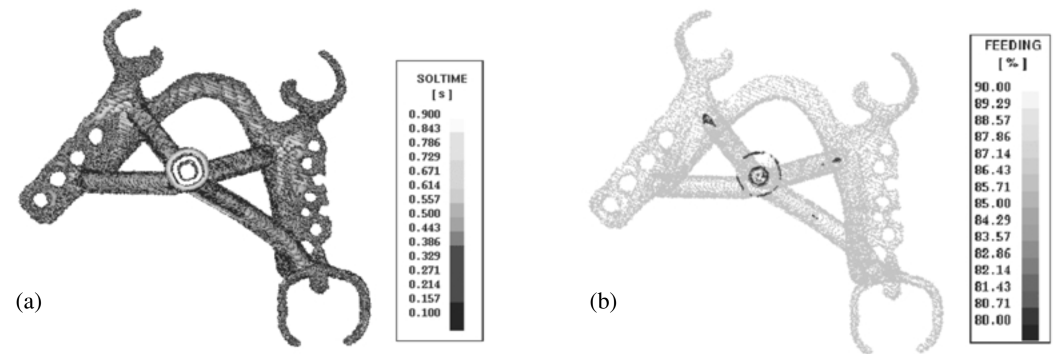

Figure 4 Solidification and shrinkage porosity (arrows pointed) prediction by feeding criterion in the lower jaw framework with tree sprue.

coupled heat transfer and fluid flow simulation the program gave a ''solidification during simulation'' warning. It indicated that the front melt solidified during filling, and blocked the filling path at the grasp regions. The upper right sprue was attached too far from the grasp (Fig. 2(a)), and the melt took the long journey to reach the grasp, suffering significant heat loss. This simulation result aids to achieve an understanding of the formation of the filling incompleteness defect caused by premature solidification during filling, and hence to get an idea to improve the sprue design and casting parameters and minimize the risk of producing this defect.

Up until now it was still difficult to predict the filling defect quantitatively. In the filling simulation the melt was treated as Newton flow. The rheologic property (kinematic viscosity) of the melt above the liquidus (1668 °C) was experimentally determined ($1.01 \times 10^{-6}\,m^2/s$), an infinitely large value was given for the temperature blow solidus (1660 °C). The apparent kinematic viscosity in the solidification range (mush zone) was assumed to be a piece-wise linear function of the temperature. This method was considered to be a reasonable approach for qualitative investigation of the filling problem. It was successfully applied for large engineering castings [17] and also tried for titanium dental crown and bridge castings [12–13]. For quantitative prediction of this filling incompleteness defect the apparent temperature dependent rheologic property of the particular alloy in the solidification range must be precisely determined.

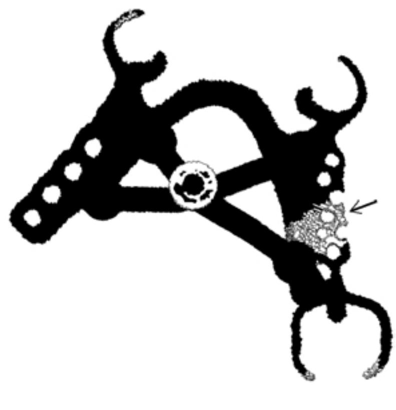

Figure 5 Filling result of the lower jaw framework with ball sprue. 95% filled at time 0.191 s.

4.2. Porosity

There are two different porosity in the titanium dental castings: shrinkage and gas pores. The shrinkage porosity, caused by solidification blocking the feeding path, was quantitatively predictable by a feeding criterion. It was previously evaluated that the computer-predicted shrinkage porosity ($\leq 90\%$ fed region) coincided well with the experimentally observed results [4, 12, 13]. Numerical prediction by using this criterion did not show any feeding difficulty for the framework castings. All the sprue designs in Fig. 3 satisfied the feeding criterion, no any $\leq 90\%$ fed region in the framework was detected. The reason is that the most sections of the frame are quite thin, the sprues are normally connected to the thick-walled sections. Directional solidification (Fig. 4(a)) from the grasps or mesh areas to the thick-walled regions, finally toward the sprues was obtained. This kind of directional solidification is in favor of directional feeding. Among the three sprue systems studied in this paper the tree sprue was found to be more risky. Porosities in the sprues were predicted quite near to the sprue-frame junctions (Fig. 4(b)). As shown in Fig. 4(a), the predicted hot spots were actually located at the sprue-frame junctions. Any mishandling of the sprue (geometrical parameter and positioning) would cause the porosity regions to move to the framework.

Gas pore is more difficult to control than shrinkage porosity. Previous numerical studies on gas pores in titanium dental casting stated that no matter where the gas came from (entrapping of the protection cover gas during filling, or metallurgical reactions in the melt or between the melt and the mold), the gas bubbles could escape out of the cast part when the solidification time was properly long and a favorite directional solidification sequence was achieved [4]. Directional solidification sequence favored not only avoiding shrinkage but also the control of the gas pores. The sprue designs in Fig. 2 followed the directional solidification role. However, many framework castings have one or more, larger or smaller plate areas. If the plate castings (including frame castings) are filled horizontally, as shown in Fig. 2(a) and 2(b), the liquid metal runs over the plate and drive the enclosed protection gas in a random manner (Fig. 3). Even venting is sometimes applied, enclosed gas pores are not easily predictable due to the random filling manner. Such problems can be avoided more effectively by tilting the plate area of the casting so that it fills in a controllable manner [18]. That is the reason why the final design makes the framework being tilted 45° to the pouring direction (the axis of the funnel). Repeated casting trials demonstrated that high successful (pore free) rate for the framework castings was obtained with this design. Only one case of gas pores was detected out of eight real casting trials. Carefully studying the special case, it was found that the gas pores at the grasp region were likely caused by mis-positioning of the ingate. The ingate near the defective grasp was attached a little too far from the grasp. The grasp solidified very quickly, the entrapped gas did not have enough time to move to the ingate and escape out of the cast part through the ingate.

Figure 6 Filling result of lower jaw framework with runner bar sprue. 95% filled at time 0.245 s.

4.3. Sprue design

Experimental investigations [11] show no significant difference between different sprue designs regarding to porosity. Numerical simulations did show similar results regarding to shrinkage porosity. All the sprues studied in this paper (tree, ball, and runner bar) satisfied feeding criterion, and no shrinkage porosity would occur in the frameworks. However, in respect to the gas pores, the runner bar sprue together with the tilted (45°) framework tended to produce the best result.

The mold filling simulations also indicated that the runner bar sprue was the best. Logical filling sequence was achieved, and lower possibility to create incomplete filling defect. The first melt stream, often dirty and cold, was carried to both ends of the runner bar. The late come melt, hot and clean, was distributed among the ingates and filled into the cast parts. From technical view, the runner bar sprue system is easy to be handled. Only one runner bar is necessary, it can be shaped according to particular casting geometry, ingates can be attached to the runner bar with great freedom. For example, six ingates were used for the lower jaw (Fig. 2(c)) and seven ingates for the upper jaw (Fig. 8).

Comparing Fig. 5 with Fig. 3, the ball sprue seemed to produce better filling result than the tree sprue. The filling incompleteness defect in the upper right grasp region in the tree sprue system was avoided by using the ball sprue. The ball themselves, as additional melt reservoirs, were intentionally added for improving the feeding efficiency, nothing to do with filling. The improvement was actually made through the re-positioning of the sprues. The sprue-framework junction was moved a little near to the upper right grasp.

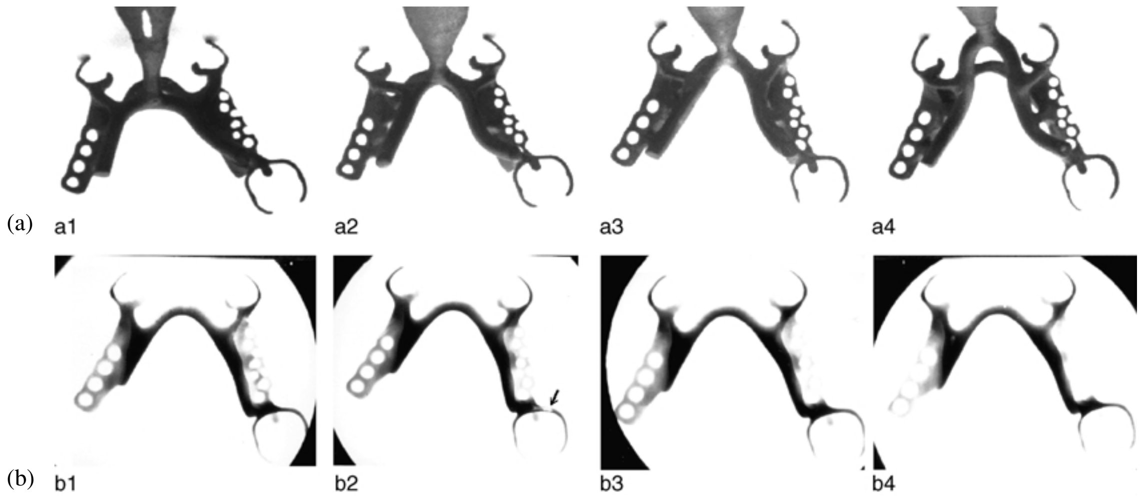

Figure 7 Experimental castings and X-ray radio photographs. All castings were sound except one part in which gas pores (arrow) were detected. (a) Castings, (b) X-ray.

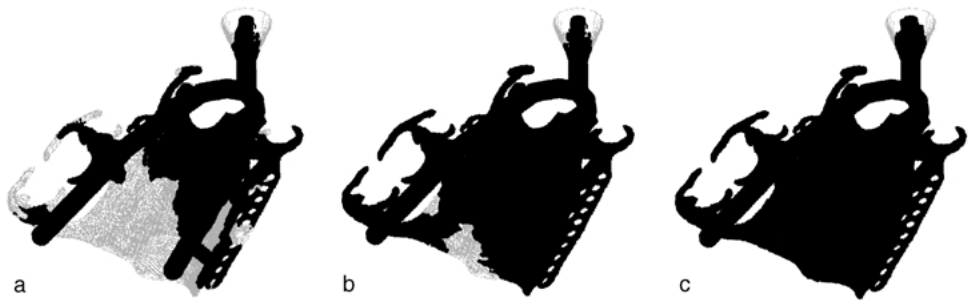

Figure 8 Filling sequence of the upper jaw framework with runner bar sprue. (a) 80% filled at 0.248 s, (b) 90% filled at 0.339 s, (c) 95% filled at 0.375 s.

Acknowledgment

This research is supported by the ''Interdisciplinary center for Clinical Research in Biomaterials and Tissue-Material-Interaction in Implants'' (BIOMAT project No. 15). Special thanks are given to Mr. A. Peseschgsadeh for his work in performing the experiments.

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Received 28 November 2000
and accepted 19 July 2001