

Digital manufacturing of biocompatible metal frameworks for complex dental prostheses by means of SLS/SLM

J.-P. Kruth, B. Vandenbroucke, J. Van Vaerenbergh

Division PMA, Department of Mechanical Engineering, Katholieke Universiteit Leuven, Belgium

I. Naert

School for Dentistry, Oral Pathology and Maxillofacial Surgery, Department of Prosthetic Dentistry, Katholieke Universiteit Leuven, Belgium

ABSTRACT: In recent years, digitizing and automation have gained an important place in the manufacturing of medical products. However, many dental parts are still being produced by manual and inefficient conventional methods. This paper presents a fully digital and fast procedure for the design and manufacturing of implant-supported frameworks for complex dental prostheses by means of Selective Laser Sintering (SLS) or Selective Laser Melting (SLM). Offering a digital solution to the dental profession implies a real challenge because patient and dentist set high requirements on quality, material and precision. During this study, frameworks were manufactured by SLS/SLM of stainless steel, Ti6Al4V and a dental CoCr-alloy. The accuracy of the final framework has been analyzed by studying the error accumulation of the successive steps in the proposed procedure. SLS/SLM allows an efficient and customized production of the complex biocompatible frameworks without lengthy manual pre- or post-processing and with a medically acceptable accuracy corresponding to the precision of a conventionally fabricated framework.

1 INTRODUCTION

Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) are layer-wise material addition techniques that allow generating complex 3D parts by selectively consolidating successive layers of powder material on top of each other, using thermal energy supplied by a focused and computer controlled laser beam [6, 8, 10]. Different binding mechanisms can be responsible for the consolidation of the powder: Solid State Sintering, Liquid Phase Sintering, Partial Melting or Full Melting [3]. The competitive advantages of SLS/SLM are geometrical freedom and material flexibility.

Over the last decade SLS/SLM processes have gained a wide acceptance as Rapid Prototyping (RP) techniques. Recently, a shift to Rapid Manufacturing (RM) has come up because of technical improvements of layer manufacturing processes [2, 6]. SLS/SLM techniques are no longer exclusively used for prototyping and the possibility to process all kind of metals yields opportunities to manufacture real functional parts. Medical and dental applications could take advantage of this evolution by using SLS/SLM not only for plastic devices like visual anatomical models or one-time surgical guides, but also for functional implants or prostheses with long-term consistency made from a biocompatible metal. Dental applications are very suitable for processing by means of RM due to their complex geometry, low

volume and strong individualization. The manufacturing of multiple unique parts in a single production run enables mass customization. Moreover, computer controlled production corresponds to the global trend of digitizing the fabrication of medical and dental parts.

This paper presents a fully digital solution for the design and manufacturing of implant-supported biometal frameworks for complex dental prostheses (Fig. 1) [9]. The intended framework (2) is the metal base structure of the prosthesis (1). It is supported by oral implants (4) placed in the jawbone (5) or by remaining teeth. Such framework is fixed to the jaw by screws retaining it on the implants or by luting it on the remaining teeth. The framework supports the artificial teeth (3) which are attached on the support surfaces on top of the framework.

The framework is made from a titanium or CoCr (cobalt chromium)-alloy because these metals combine good mechanical and biocompatible properties. The framework is patient specific and has to meet strict requirements of accuracy to minimize the risk of mechanical or biological failures of the prosthetic system. To distribute forces evenly and to avoid high stresses in the jawbone causing the oral implants to loose and to diminish the risk for colonization of bacteria resulting in infection and eventually bone loss, a good passive fit at the prosthesis-implant or prosthesis-tooth junction and severe fit criteria below 40 μm are necessary [1, 12].

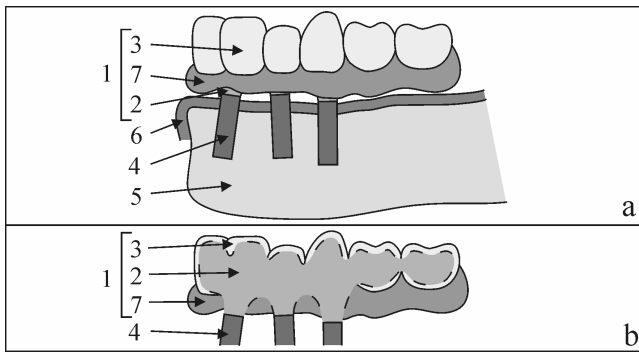


Figure 1: Scheme of implant-supported prosthesis: (a) drawing of lower jaw with implant-supported prosthesis (b) transparent view of prosthesis; 1. prosthesis, 2. framework, 3. teeth, 4. oral implants, 5. jawbone, 6. soft tissue, 7. artificial gums.

The proposed digital procedure for the design and manufacturing of dental frameworks replaces the conventional system based on a manual design by ‘clay’ modeling and a production by lost wax casting or milling. Although these methods lead to high precision, they are time consuming and inefficient. The lost wax method is a lengthy and labor-intensive process and comprises many manual steps: fabricating, embedding and burning out the wax pattern, metal casting and post-processing. By digitizing the manually designed ‘clay’ model and using CAM-instructions, the frameworks can be produced by CNC-milling. However, this milling process is also time consuming because of the complex tool path calculations and because of the manual finishing needed to obtain the required shape of the framework. Moreover, most of the expensive material is wasted and spatial restrictions limit the production of complex shapes.

Figure 2 shows the different steps of the conventional and digital method for producing a framework. After installing the oral implants into the jawbone of the patient, a plaster work model with implant replicas is made representing the position of the implants. Upon this work model a tooth arrangement is shaped from which the patient validates the aesthetics. This tooth arrangement will look the same as the final prosthesis but the internal metal framework is still absent. The developed digital procedure consists of three main steps: the digital geometry capture of implant positions and tooth arrangement, the digital design of the framework and the computer-driven production of the framework by means of SLS or SLM. The complex shape of the framework can be fabricated without the need for manual intervention and with less pre- or post-processing. SLS/SLM allows an efficient and customized production of the complex framework for different materials. Remaining unprocessed powder can be reused. The prosthesis is finished by gluing or pressing the teeth upon the support surfaces of the framework and finally installed in the mouth of the patient.

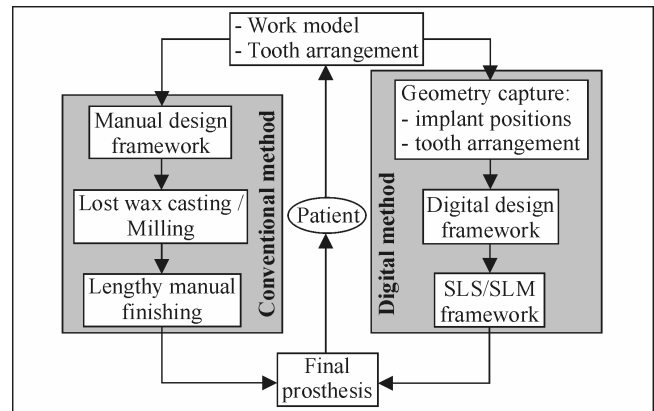


Figure 2: Global scheme of the conventional and digital method to manufacture a dental framework.

The following presents the fully digital procedure to design and manufacture dental frameworks and investigates if this procedure, including SLS/SLM, fulfills the strict requirements of quality, accuracy and material.

2 PROCEDURE

The possibility and repeatability of manufacturing dental frameworks by means of SLS/SLM have been proved in a preliminary research where neither the complex design of the framework, nor the production in a biocompatible metal have been dealt with [5]. The following procedure explains the different steps to digitally design and manufacture complex dental frameworks with high precision in a biocompatible metal.

2.1 Geometry capture

The first step of the digital procedure is the measurement of the twofold input geometry: firstly the position of the implant replicas in the plaster work model, corresponding with the position of the implants in the jawbone of the patient, and secondly the tooth arrangement, approved by the patient.

The position and inclination of each implant vary depending on the presence of qualitative and quantitative surrounding bone and the anatomical location of nerves and blood vessels. The measurement of the position of the implants has to be very accurate with regard to the final fit between framework and implants. Due to the complexity of the upper part of the implants, mechanical or optical techniques have difficulties to measure directly the position of the implants. Therefore the use of registration elements is preferred. Figure 3a shows cylindrical registration elements mounted upon the implant replicas of the work model. An optical scan of the mounted registration elements leads to an accurate point cloud (Fig. 3b).



Figure 3: Measurement of position of implants: (a) registration elements mounted upon implant replicas of work model, (b) point cloud of scanned elements, (c) fit of top plane and cylinder surface on identified points of a registration element.

Using numerical algorithms the position and the inclination of each registration element are computed by fitting a top plane and cylinder surface on the identified points of each element (Fig. 3c). Based on these data and the well-known dimensions of the registration elements, the position and inclination of each implant can be calculated, providing sufficient information to design the lower part of the framework which fits on the implants.

The precision of digitizing the tooth arrangement is not very critical, in contrast to the position of the implants, because no major effect is stated with regard to possible biological or mechanical failures. Teeth used for the tooth arrangement have a standard shape and thus the measured point cloud (Fig. 4a) only has to indicate the relative positions of the teeth. Because the data of the implant positions will be combined with the tooth arrangement data, both measurements are mathematically matched with the work model as reference object.

2.2 Digital design of the framework

The second step of the procedure is the digital and automated design of the framework based on the computed position of the implants and the captured geometry of the tooth arrangement. This digital design replaces the conventional manual design, requiring a lot of experience of the dental technician who builds up the framework in a wax material. Based on the many manual actions of the technician, several design rules are defined and put in a certain sequence to determine the design strategy. This strategy is implemented in a software module by translating the design rules to computer tools. An important issue during the design step is the manipulation of the complex dataflow. The different and large data files of the complex medical shape have to be filtered and combined to one geometrical model in a fast and convenient way without any mistakes.

The design process starts with the modeling of the tooth arrangement. Based on the scan (Fig. 4a) a digital 3D teeth model (Fig. 4b) is designed by fixing measurement errors like gaps, scatter and inverted normals of the surfaces. Each artificial tooth of the final prosthesis needs a support surface on top of the framework, obtained by an offset of the real tooth

surface (Fig. 1b). The different teeth can be identified by means of a curvature analysis (Fig. 4c). Each separate tooth surface, obtained by cutting the 3D teeth model, is incomplete because the side surfaces are missing (Fig. 4d). These side surfaces are needed to compute the offset of the total tooth surfaces. Therefore each incomplete tooth surface is matched with a full point cloud of the corresponding standard tooth (Fig. 4e). By scanning all standard teeth once, a digital library of standard tooth surfaces is available. The support surfaces of the framework are then computed by a defined offset of the completed tooth surfaces (Fig. 4f), depending on the tooth material (acrylic, composite or porcelain).

Using the mathematical match calculated in the previous step, the position and inclination of the implants are transferred to the design environment. Conical fitting structures are designed according to these data (Fig. 4g) and connected to the support surfaces of the teeth (Fig. 4h). Finally, the digital design of the framework is finished by adding detail features like screw holes and fillets (Fig. 4i).

2.3 Production by means of SLS/SLM

The third step of the digital procedure is the production of the framework by means of an SLS or SLM technique. These Rapid Manufacturing processes use a computer controlled laser beam for scanning successive layers of powder material to create the 3D framework. Based on the slicing of the digital design from the previous step, scanning patterns of each layer are computed automatically.

2.3.1 Binding mechanisms

For the consolidation of the powder, two different binding mechanisms are used depending on the material. Other mechanisms are possible, but not considered in this study [3].

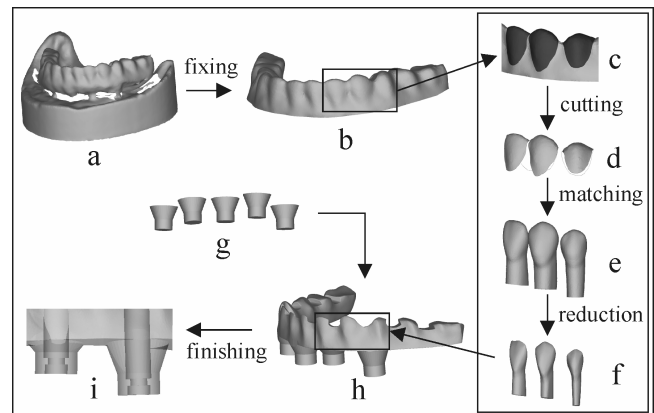


Figure 4: Digital design strategy: (a) scan of tooth arrangement, (b) 3D digital teeth model, (c) identified tooth surfaces, (d) incomplete tooth surfaces, (e) completed tooth surfaces, (f) support surfaces of framework, (g) fitting structures, (h) connection of support surfaces and fitting structures, (i) finished framework.

The first mechanism is a kind of Liquid Phase Sintering where the polymer coating of steel powder grains is liquefied by the laser beam and acts as a binder for the structural stainless steel grains. This technology needs an additional furnace cycle, in which the polymer is burnt out and the green part is further sintered and infiltrated with e.g. bronze to reach high density. The second used mechanism is Full Melting of a biocompatible metal like Ti6Al4V or a dental CoCr-alloy. Near full density is reached within one step by melting the metal powder completely by the laser beam, thus avoiding lengthy post-processing steps.

2.3.2 Process parameters

SLS/SLM is a complex thermo-physical process and the determination of parameters is very important to reach high precision. Table 1 divides the many process parameters into four groups: material, laser, scan and environmental parameters. The optimal parameter setting can be found by a combination of empirical research and numerical simulations.

Due to the contraction of molten material that solidifies and cools down and due to high thermal gradients during SLS/SLM processes, distortions like curling or delamination can appear [7,11]. An optimal scan strategy and appropriate energy density can avoid these harmful effects. The energy density is an absolute process parameter for a certain material powder. This parameter represents the energy supplied by the laser beam to a volumetric unit of powder material and combines some important laser and scan parameters:

$$E_{density} = \frac{P_{laser}}{v_{scan} \cdot s_{hatching} \cdot t_{layer}} \quad (1)$$

where $E_{density}$ = energy density, P_{laser} = laser power, v_{scan} = scan speed, $s_{hatching}$ = hatching space, t_{layer} = layer thickness. A few loops of benchmark tests can help to reach optimal parameters. For example, offset and scaling values, used to compensate for dimensional changes due to the laser beam spot size, are optimized iteratively based on dimensional analyses of produced benchmark parts [4].

Table 1: Process parameters of SLS/SLM, divided into material, laser, scan and environmental parameters.

Material	Laser	Scan	Environm.
composition	mode*	scan speed*	preheating*
powder density	wave length	hatching space*	pressure*
morphology	power*	layer thickness*	gas type*
diameter of grains	frequency*	scan strategy*	O ₂ level*
distribution	pulse width*	scan sectors*	
thermal properties	offset*	pulse distance*	
flow properties	spot size	scaling factors*	

* Studied parameters to reach high precision (material parameters and some laser parameters are not varied due to machine dependency).

2.3.3 Production strategy

Before the production of the framework can be started, some geometrical decisions have to be taken with regard to the position of the framework within the build volume of the SLS/SLM machine. Firstly, the framework is positioned upside down to guarantee well finished fitting planes and secondly, the framework is tilted to reduce the stair effect and the volume of eventual support structures.

Top surfaces of a part manufactured by SLS/SLM have a relatively low roughness and high accuracy. Bottom or overhanging surfaces are not finished well since the laser beam penetrates deeply into the powder bed. The fitting planes of the framework which make the connection with the implants need to be very accurate. Therefore the framework is positioned upside down to guarantee an accurate finish of the fitting planes (Fig. 8d).

Due to the layer-wise production of SLS/SLM a stair effect appears on the inclined fitting planes of the framework (Fig. 5a). Gaps arise between the framework and the implants, leading to local inaccuracies (Fig. 5b). Since the sloping angles of the various fitting planes differ, only one plane can be positioned horizontally and thus the stair effect can not be avoided completely. Yet the gap size can be reduced by decreasing the layer thickness or by increasing the sloping angle.

The layer thickness is difficult to change because its value depends on the powder grain size. A possible, but in this study not tested solution to decrease the layer thickness is a combined process: firstly, the layer is scanned with the usual layer thickness and secondly, this layer is partially taken away by laser erosion.

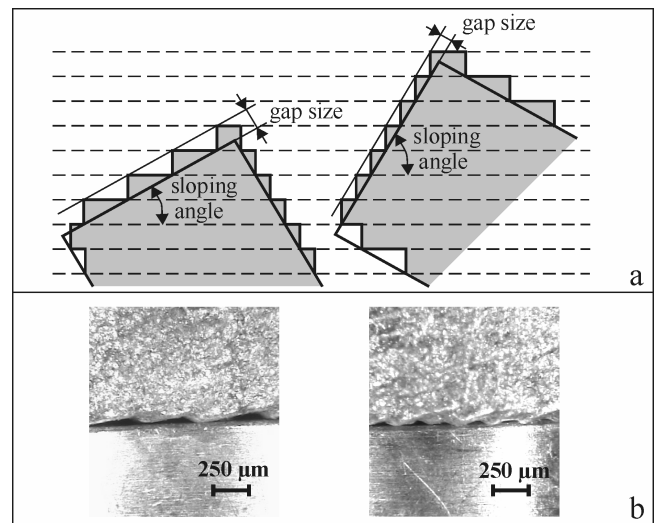


Figure 5: The stair effect due to the layer-wise production of SLS/SLM: (a) Small sloping angle leads to few stairs with large gap size (left), large sloping angle leads to many stairs with small gap size (right); (b) Gaps between fitting plane of framework and implant: sloping angle of 7.5° leads to few large gaps of 40 μm (left), sloping angle of 15° leads to many small gaps of 12 μm (right).

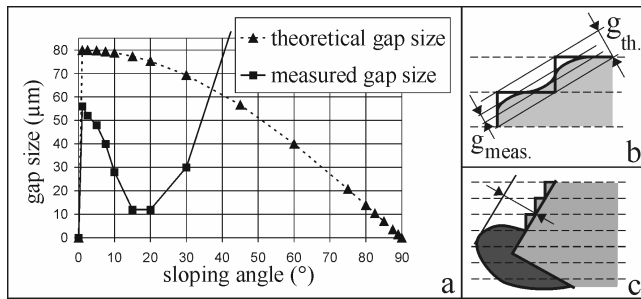


Figure 6: (a) Theoretical and measured gap sizes related to sloping angle (b) Rounded edges of the stairs reduce the gap size (c) Inaccurately built bottom surfaces increase the gap size.

Theoretically, the gap size due to the stair effect decreases proportionally with the cosine of the sloping angle. When the fitting plane is steeper, more stairs appear but the gaps are smaller (Fig. 5). This property is experimentally studied by producing stainless steel cylinders with a different sloping angle and by measuring the gap size. Figure 6a shows that the measured gap size decreases with increasing sloping angle up to 15-20°. The gaps are smaller than the theoretical size due to the rounded edges of the stairs (Fig. 6b: $g_{meas.} < g_{th.}$). For higher sloping angles the total gap size increases, in spite of the decreasing stair effect, because appearing bottom surfaces are not finished accurately (Fig. 6c). Consequently, an optimal sloping angle, depending on process and material, minimizes the gap size.

Because the inclinations of the different implants do not vary more than 10 degrees for an average patient, all fitting planes can be positioned around the optimal sloping angle by tilting the framework in the build volume. Full melting processes (SLM) need support structures for overhanging surfaces. When calculating the tilt angle of the framework to minimize the gap size of all fitting planes, the need for support structures has to be taken into account. When the inclination of one implant differs much from the others, the tilt operation doesn't succeed in reducing the gap size between the framework and that implant. Therefore, some extra material is designed upon the fitting plane of the framework and during a simple post-process, this extra material is removed by a tool (Fig. 7). A well known reference object defines the border condition of this removal process so that the final fitting plane is on the right position and without any stairs.

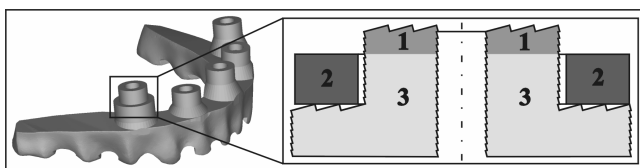


Figure 7: During a simple post-process, the extra material (1) is removed by a tool to avoid the stair effect on the fitting structure (3). A ring (2) is the reference object and its top surface defines the border condition for the tool path.

3 RESULTS AND DISCUSSION

The proposed digital procedure has been applied to fabricate frameworks in stainless steel, Ti6Al4V and a dental CoCr-alloy (Fig. 8). The energy density, introduced by equation 1, amounts to 1 J/mm^3 for liquid phase sintering of polymer coated stainless steel and to 100 J/mm^3 for full melting of Ti or CoCr-alloys. Good geometrical and mechanical properties are reached with densities over 97%.

In dental literature, there is a growing consensus that the final gap size between framework and implant should not exceed $40 \mu\text{m}$ to avoid failures of the prosthetic system. Therefore, the accuracy of a stainless steel framework is analyzed by studying the gap size accumulation of the different steps of the procedure. The impression of the jaw of the patient, needed to fabricate the work model, implies a small deviation on the position of the implants, but is neglected in this study. A first error is caused by the geometry capturing system, including the precision and mounting of the registration elements and the accuracy and resolution of the measurement equipment. The production of the framework by SLS leads to the most important errors. The stair effect is inherent to the layer-wise manufacturing but can be reduced by tilting the framework in the build volume. The SLS process accuracy, limited by deformations due to thermal stresses and dimensional errors, can be increased by using optimal parameters. The infiltration process, needed for Liquid Phase Sintering, is responsible for a last deformation error because the complex framework is difficult to support during the furnace cycle.

The total gap size between framework and implant is divided into three errors which can be quantified by different experiments: firstly the combined gap due to the measurement system and the SLS process accuracy, secondly the stair effect and finally the infiltration deformation. This error accumulation is studied for three differently produced frameworks.

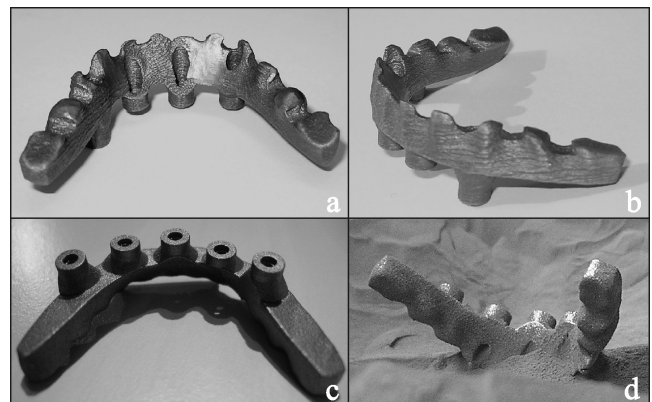


Figure 8: Produced frameworks by SLS/SLM from stainless steel (a, b) and from Ti6Al4V (c, d). Figure d shows the framework emerging from the powder.

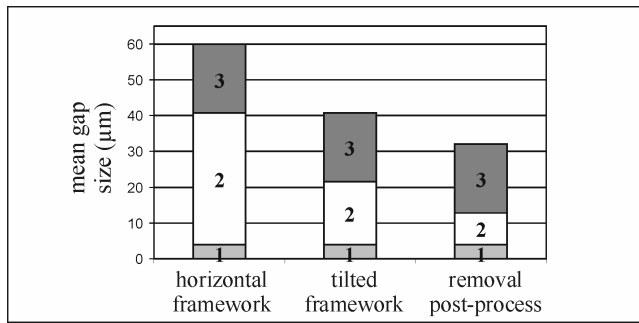


Figure 9: Mean gap size accumulation: 1. gap size due to measurement system and SLS/SLM process accuracy, 2. stair effect, 3. infiltration deformation.

Framework 1 is positioned horizontally in the build volume, framework 2 is tilted to position all fitting planes around the optimal sloping angle and framework 3 is built horizontally and subjected to the removal post-process. Figure 9 shows the gap size accumulation for these frameworks, averaged for the different implant positions.

The first error amounts to 4 µm and proves that the measurement method is very accurate and that the frameworks are produced with optimal process parameters. The stair effect of the first framework is very high (37 µm) due to the low sloping angles of the fitting planes. This gap size is reduced with 50% (to 18 µm) by tilting the second framework in the build volume. The third framework has no stairs but the error is not completely removed (9 µm) because the post-process was applied with a manual tool. The infiltration deformation (19 µm) can not be reduced due to lack of process control during the furnace cycle, but is absent when Full Melting is used as binding mechanism (SLM). The total mean gap size of framework 2 amounts to 41 µm and for framework 3 to 32 µm and would be reduced to about 22 and 13 µm for SLM. The analysis of the gap size accumulation proves that the developed procedure, including the SLS or SLM process, allows an accurate production of the framework.

4 CONCLUSIONS

The proposed procedure provides an efficient and fast method to digitally design and manufacture biocompatible metal frameworks for complex dental prostheses. Based on the computed position of the implants and the captured geometry of the tooth arrangement, the framework is designed by implementing specific design rules. Frameworks are produced with good mechanical and geometrical properties by means of SLS/SLM of stainless steel, Ti6Al4V and a dental CoCr-alloy. SLS/SLM allows an efficient and customized production of the complex framework without lengthy manual pre- or post-processing. Optimal process parameters and an appropriate production strategy guarantee an

accurate fit between the framework and the implants, needed to avoid mechanical or biological failures of the prosthetic system. Analysis of the fitting gaps demonstrates a medically acceptable accuracy.

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