A BUSINESS CASE STUDY FOR COMPARING THE MANUFACTURING OF IMPLANT-SUPPORTED DENTURE FRAMES THROUGH DIRECT METAL LASER SINTERING TO CONVENTIONAL CASTING AND MACHINING PROCESSES

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ABSTRACT

Retaining dentures in edentulous patients is a common problem which can be overcome through the use of implant-supported denture frames. These frames are conventionally manufactured through the lost wax investment casting processes or through computer aided machining in cobalt chrome. Although Additive Manufacturing (AM) processes are now commonly used in the manufacturing of crowns and bridges in dentistry, the manufacturing of implant-supported denture frames is less common. This study aimed to investigate the feasibility of manufacturing these frames through AM from a business point of view compared to conventional casting and machining. A case study is presented where a full overdenture frame is designed and manufactured in Titanium-6Aluminium-4Vanadium (Ti-6Al-4V) alloy through the Direct Metal Laser Sintering (DMLS) process. This is compared to manufacturing the same frame in cobalt chrome through traditional processes in terms of manufacturing time and cost. Results from the study showed that it is more expensive and takes longer to produce overdenture frames through DMLS compared to conventional manufacturing techniques. Although costs and time can be reduced by producing a number of frames simultaneously on the DMLS machine's building platform, the manufacturing process is still not considered viable for overdenture frames from a business point of view.

Keywords
Implant-supported overdenture frames, Direct Metal Laser Sintering

1. INTRODUCTION

The face is the most recognizable feature of the human body, it embodies our social identity and is the most important means for our interpersonal communications. Any deviation of facial features from culturally acceptable standards of attractiveness can result in negative psychological implication such as low self-esteem. Negative changes in a person's facial appearance is often perceived as negative changes to the person and has a direct effect on how society perceives and judges them. Tooth loss leading to partial or complete endentulism is one of the major factors that may adversely affect a person at anatomic, esthetic and biomechanical levels. This may varyingly be perceived by the patient ranging from feelings of inconvenience to severe handicap [1].

Up to recent years, the accepted standard treatment for endentulism was complete dentures. Early success with this technique even resulted in partial dentitions being needlessly sacrificed since complete denture treatment was regarded as preferential. Subsequent experience with this technique however revealed the inability of this treatment to match the abilities of the natural dentition. For teeth to function properly in the trituration of food, they need to be adequately supported. This support is provided by the periodontium which provides a resilient suspensory apparatus between the teeth and the jaw bone. The periodontium is resistant to functional forces while also allowing the position of the teeth to change in response to stress. A secondary and similarly important function of the periodontium is sensory perception which indicates to the patient the amount of force applied to the dentition during mastication. The endentulous patient is deprived of this functionality of the periodontium [1].

The fundamental challenge in how endentulous patients are treated can be attributed to the ways that natural teeth and artificial replacements are supported. When the aveolar bone that contains the tooth sockets is made endentulous, the sockets get filled in with new bone and thus forming the residual aveolar ridges. These ridges form the foundations for dentures, a role for which they are ill suited because of their much smaller surface area compared to that of the preceding periodontal ligaments and the denture-supporting tissues. Masticatory forces using complete dentures are reported to be five to six times less compared to that of the natural dentition. Following on the removal of teeth the aveolar ridges are gradually resorbed by the body up to the point of their virtual disappearance. This has a direct effect on the positioning and stability of dentures [1].

The idea of attaching dental prostheses to the facial skeleton making use of implanted devices was considered as a means of overcoming the known disadvantages of removable dentures. This outcome however proved to be elusive with many unsuccessful attempts over several decades. The publication of pioneering research into the technique of osseointegration by Brånemark however changed the picture [2], [3]. For the first time alloplastic tooth roots could be safely located in the jaw bone. The Toronto Conference on Tissue Integrated Prostheses in 1982 introduced the concept of including a controlled interfacial osteogenesis between dental implant and host bone to the broader dental academic community. The merits of this technique was followed by an international research endorsement for the treatment of endentulous patients with implant-retained fixed or removable overdenture prostheses. Subsequent publications on implant prosthodontics proved this technique to be a valid treatment option [4], [5], [6].

2. IMPLANT-SUPPORTED OVERDENTURES

Implant-supported overdentures (Fig. 1 a-d) overcome many of the problems associated with traditional dentures. Functional and esthetic requirements using this technique are better met and maintained over time with variable residual ridge resorption no longer the dominant treatment concern.

a b c d

Fig. 1a-d Titanium implants, overdenture frame, removable overdentures and fixed overdentures [7].

Overdentures are supported by titanium screws (Fig. 1a) that are implanted into the mandible and maxilla. An overdenture frame is manufactured to fit precisely onto the abutments that are attached to the implants. The overdenture may be manufactured to be either removable or fixed. For removable overdentures clips are incorporated into the denture that attaches to the frame (Fig. 1c). Fixed overdentures on the other hand encloses the frame and are more permanently attached to the screw implants through small screws (Fig 1d) [8].

3. TECHNIQUES FOR MANUFACTURING DENTAL DEVICES

3.1 Lost-wax casting process

Dr. William H. Taggart introduced the loss-wax casting process to dentistry in the early 20th century for the manufacturing of crowns and bridges [9]. Since the advent of implant supported over-dentures, the frames to support the dentures have also been manufactured using this technique. The process starts out with the dentist taking an impression of the patient’s oral cavity with the implants already placed. A Polyvinyl siloxane impression material can for example be used for this purpose. A plaster model is cast from the impression and a mock-up of the frame is sculpted in wax (referred to as a wax-up) on the plaster model. Wax casting rods (or sprues) are attached to the wax model and this is invested into a ceramic slurry. Once cured the ceramic mould is placed in a high temperature furnace and the wax is completely burnt out to leave an accurate negative replica of the wax model. Chromium-cobalt alloy is melted and cast into the sprues to fill the mould. There are processes available to help force the molten alloy into the mould such as for example spin casting. Once the alloy has cooled, the mould is broken away, casting sprues removed and the surface of the frame finished by hand [10], [11].

3.2 Computer Assisted Design and Computer Assisted Machining

Duret and Preston [12] was the first to explore the use of Computer Assisted Design (CAD) with Computer Assisted Machining (CAM) in dentistry in the 1970s although early efforts were considered cumbersome. The work of Moermann [13] in the 1980s led to the development of the well accepted CEREC® system. As software, materials and equipment improved the dental chairside use of CAD/CAM became more commonplace. Nowadays, many dental practices have this equipment in-house allowing crowns for example to be manufactured and placed in the same day instead of having to wait for dental laboratories to manufacture such which may take several weeks [14], [15]. For the manufacturing of a dental frame such as for an overdenture, an intra-oral scan is taken of the patient with the implant already placed. Dedicated CAD software is then used to design the frame to fit precisely onto the abutments of the implants. As an alternative, a conventional impression can be taken of the oral cavity, a plaster model cast and wax-up of the frame can be sculpted. This wax-up can then be reverse engineered using a scanning device suitable for this purpose. The CAD design or scan data is next exported to a 5-axis CAM machine which mills the frame from a solid disc of cobalt chrome or titanium. Because of the subtractive nature of the technique a large portion of the feed-stock material ends up as shavings which cannot be reused. There is also a limited number of frames and other devices that can be machined from a single disc with the rest of the material going to waste.

3.3 Additive Manufacturing

The term Additive Manufacturing (AM) describes a number of processes where a part is fabricated through a layer-wise construction method. The required part is first designed in a Computer Aided Design (CAD) software package and then sliced in thin virtual slices using dedicated software. This so-called slice-file is sent to the AM machine where different melting or bonding techniques are used to bind consecutive thin layers of material in powder, solid or liquid form together. The primary advantage of AM is its ability to create almost any shape or geometric feature because of the free-form manufacturing process utilized. Another advantage is that only the material to make up the volume of the part is used instead of machining a great deal of material away from a block to produce a part such as with subtractive manufacturing [16]. The following AM processes are used in dentistry.

3.3.1 Stereolithography (SLA)

In Stereolithography (SLA) an ultraviolet laser is used to scan the first cross section of the part onto the machine's building platform which is positioned in a vat of photopolymer. A thin layer of photopolymer which is scraped across the surface by a recoating blade is selectively cured when exposed to the laser. The platform is lowered by one layer thickness into the vat of photopolymer, the layer scraped even and the next cross section is scanned by the laser. This process is repeated till the part is completed. The part is removed from the platform and unused photopolymer on the surface is cleaned with a solvent. SLA is routinely used to produce surgical guides for the placement of dental implants [17], [18], [19]. New photopolymer resins with properties similar to wax is also used to print patterns for the manufacturing of bridges and crowns through the lost wax casting process [20].

3.3.2 Polyjet printing

Similar to SLA, the polyjet process that was developed by Stratasys makes use of photopolymer that is cured by ultraviolet light. Instead of using a laser and vat of polymer, the polyjet process jets fine droplets of photopolymer by a printing head similar to an inkjet printer. Mounted on the printing head are two ultraviolet lamps that cures the droplets of photopolymer directly after deposition. The advantage of the polyjet process compared to SLA is much faster part production time. The polyjet process furthermore has the advantage that photopolymers with different properties can be jetted simultaneously resulting in composite parts [21]. Applications for polyjet technology in dentistry is surgical planning models, surgical guides for implant placement, orthodontic brackets and even try-in veneers [22].

3.3.3 Laser sintering

In the Laser Sintering (LS) process a thin layer of powder material is laid down on the machines building platform by means of a recoating device. A laser next scans the first cross-section of the part design onto the layer of powder thus melting the powder particles together. The building platform is lowered by one layer thickness and a next layer of powder is scraped across the platform. The second cross section of the slice-file is scanned by the laser again melting the powder particles together but also melting the layer to the previous layer. A wide variety of powder materials can be processed through this AM technique including polymers and metals [23]. LS of titanium and cobalt-chrome alloys is now commonly used in the direct manufacturing of dental crowns and bridges [24] and partial dental frameworks [25].

4. CASE STUDY – METHOD AND RESULTS

A 65 old female presented with severe periodontitis that required an implant-supported denture frame for the mandible. Impressions were taken of the oral cavity after four IA-LH-43 4.3mm implant screws from Southern Implants were placed. Screwed into the implant screws were MC-L-43 compact conical abutments. Plaster models of the maxilla and mandible were cast from the impressions and fixed to a dental frame. Incorporated into the models were abutments with identical positioning to that that were placed in the patient's mouth (Fig. 2a, b).

a b

Fig. 2 a-b Plaster models of maxilla and mandible fixed to a dental frame.

In this case study, traditional investment casting and CNC machining processes that has been proven and refined over decades for the manufacturing of overdenture frames are compared to the new AM process. Frames were manufactured using all three techniques and compared in terms of manufacturing cost and time.

4.1 Lost wax casting

Temporary cylinders were positioned and screw mounted to the abutments on the plaster model (Fig. 3a). To make up the shape of the frame, thin Perspex™ was cut to fit over the cylinders and held in place with wax (Fig. 3b). Casting sprues were attached to the frame (Fig. 3c) and the wax-up was removed from the model by removing the screws. The wax-up was invested in Deguvest® investment casting ceramic where after it was burnt out to form a casting shell. Cobalt-chrome alloy (Dentaurum Remanium® GM 800) was heated up to 980ºC (ramp-up 2 hours, dwell time 1 hour) in a furnace and cast into the casting shell at the same temperature using a spin casting process. The casting shell was removed and the completed frame hand finished and sand blasted (Fig. 3c, d).

a b c d

Fig.3 a-d Casting an overdenture frame

Table 1 and 2 indicate the time and cost respectively associated with manufacturing an overdenture frame through the investment casting process.

Table 1 Time to produce an overdenture frame through investment casting.

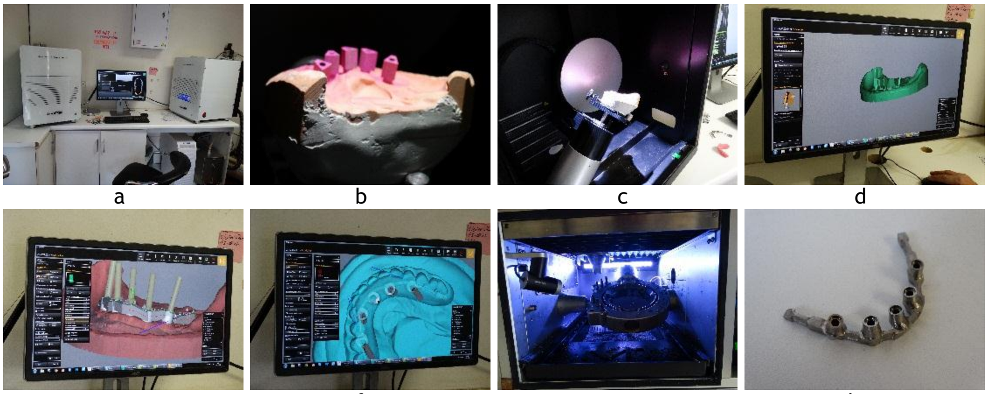
Process	Time
Wax-up	60 min
Invest	20 min
Cast	10 min
Devest and sandblast	30 min
Trim and polish	60 min
Total	3 h

Table 2 Cost to produce an overdenture frame through investment casting.

Process	Cost
Labour to produce wax-up (R500/60 min)	R 500 (60 min)
Labour to invest wax-up (R500/60 min)	R 117 (20 min)
Labour to cast (R500/60 min)	R 83 (10 min)
Labour to devest and sandblast (R500/60 min)	R 250 (30 min)
Labour to trim and polish (R500/60 min)	R 500 (60 min)
Cobalt-chrome alloy to cast frame	R 142
Investment casting material	R 200
Temporary cylinders	R 1600
Cost for casting (R500 standard rate)	R 500
Total	R 3892

4.2 Computer Assisted Design and Computer Assisted Machining

An overdenture frame was designed and manufactured using a Zirkonzahn® S600 ARTI scanner and M1 milling unit (Fig. 4a). In order to produce a frame using this equipment, the exact positions and angles of the abutments on the plaster model of the patient need to be determined. The Zirkonzahn® scanner system makes use of markers that are specific to the type of abutments used (Fig. 4b). The scanner recognizes the markers and indicates in the scan the exact geometry, position and angle of each abutment. The plaster model is mounted in the scanning unit and a precise scan is taken using the optical structured-light principal (Fig. 4c, d). The scan is exported into dedicated Zirkonzahn® Modellier software where the required dental feature is designed (Fig. 4e, f). Once completed the design file is exported to the milling unit and machining is performed in a cobalt-chrome alloy billet (Fig. 4g). Finally the supports that holds the frame to the billet is removed and the frame is finished by hand (Fig. 4h).



a b c d e f g h

Fig. 4 a-h Producing an overdenture frame through CAD/CAM

Table 3 and 4 indicate the time and cost respectively associated with manufacturing an overdenture frame through the CAD/CAM process.

Table 3 Time to produce an overdenture frame through CAD/CAM.

Process	**Time**
Scan	50 min
Design	120 min
Milling strategy planning	60 min
Setup in mill	10 min
Milling	300 min (5h)
Trim and polish	30 min
Total	9 h30

Table 4 Cost to produce an overdenture frame through CAD/CAM.

Process	**Cost**
Labour for scan (R500/60 min)	R417 (50 min)
Labour for Design (R500/60 min)	R1000 (120 min)
Labour for Milling strategy planning (R500/60 min)	R500 (60 min)
Labour for Setup in mill (R500/60 min)	R83 (10 min)
Cost of billet R3250	R 812 (¼ of billet used)
Cutting bits replacement	R1000
Milling of part (R500/60 min standard rate)	R 2 500 (300 min)
Scanning of part (R200/60 min standard rate)	R 167 (50 min)
Total	R 6 479

4.3 Additive manufacturing

Four TMC1 passive abutment titanium cylinders from Southern Implants were positioned onto the abutments on the plaster model and screwed into place. A dental frame was sculpted onto the cylinders using wax and afterwards the cylinders were cut flush with the top surface of the frame (Fig.5 a, b). Once done, the screws attaching the cylinders to the abutments were unscrewed and the wax-up of the frame removed. The wax-up as well as the impression of the mandible with abutments were next scanned using a Kreon ACE scanning arm with a Solano laser head (Fig. 5c). To prevent light reflection from the base cups of the metal cylinders which may affect the accuracy of the scan, the frame was sprayed a thin layer of grey primer.

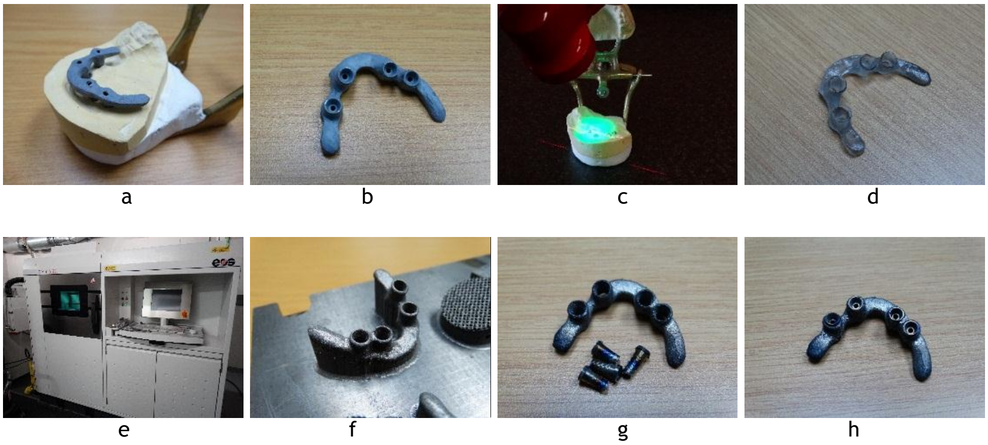


Fig. 5 a-h Producing an overdenture frame through AM

The scan data was imported into Geo-Magic software from Materialise and any imperfections in the scanned images corrected with the software's features. The data was exported as a Standard Triangulation Language (STL) file into 3-Matic software, also from Materialise. Upon closer inspection it was found that the resolution of the scans around the abutments on the plaster impression was insufficient. The exact dimensions of the abutments were obtained from Southern Implants and these features were corrected on the scanned image. The frame was designed such that the titanium cylinders fit loosely in the frame. Reason for this is that the AM process does not allow for the accuracy on the interfaces required between the abutments and frame. Any misalignment will cause tension between the frame and implant which will be detrimental to the patient in the long run. As a trial-run, the frame was first printed on an Objet Connex 350 in Vero Clear resin (Fig. 5d). (Printing a trial-run part will not be necessary for normal production and the cost and time required were not included in calculations). Inspection of the printed part showed that two of the supports were positioned close together with a narrow gap in between. Concerns were expressed that food particles may get lodged in this gap during mastication and it was decided to rather fill this gap. The necessary design changes were made, the design was sliced using RP Tools from Electro Optical Systems (EOS) and the slice file exported to the AM machine. The design was printed on an EOS EOSINT M280 Direct Metal Laser Sintering (DMLS) machine in Titanium-6Vanadium-4Aluminum alloy with a layer thickness of 30µm in an argon atmosphere (Fig. 5e). Once completed the part still attached to its titanium base was stress relieved in a furnace with a protective argon atmosphere at a temperature of 650ºC for three hours and left to furnace cool (Fig. 5f). The part was wire-cut from its base, support material removed and sent to the University of Cape Town where a heat treatment was performed under vacuum for one hour at 1000ºC. This is done to improve the mechanical properties of the frame to make it better suited for its intended application. Finally the frame was finished by hand. The four titanium cylinders were screwed to the abutments on the model and the frame cemented in place to prevent any tension between the implants and frame (Fig. 5 g,h). Table 5 and 6 indicate the time and cost respectively associated with manufacturing an overdenture frame through the AM process.

Table 5 Time to produce an overdenture frame through AM.

Process	Time
Wax-up	60 min
Scan	10 min
Reverse engineering with GeoMagics	50 min
Position frame in Magics	20 min
Set-up platform in machine	20 min
Laser sintering part	180 min
Perform stress relieving	600 min (10h)
Wire-cut and surface grind platform	60 min
Remove supports	60 min
Perform heat treatment	600 min (10h)
Cement cylinders	20 min
Total	28 h

Table 6 Cost to produce an overdenture frame through AM.

Process	Cost
Labour to produce wax-up (R500/60 min)	R 500 (60 min)
Labour for scan and reverse engineer with GeoMagics (R1250 standard rate/60 min)	R 1 250
Labour to position frame in Magics (R350/60 min)	R 117 (20 min)
Labour to set-up platform in machine (R 500 standard rate)	R 500
Laser sintering part, machine time and material (R1000/60 min)	R 3 000 (180 min)
Perform stress relieving (R500 standard rate)	R 500
Wire-cut and surface grind platform (R1750 standard rate/60 min)	R 1 750
Labour to remove supports (R500/60 min)	R 500 (60 min)
Perform heat treatment (standard rate)	R 2 000
Cost of titanium passive abutment cylinders (R2000 each)	R 8000 (four cylinders)
Labour to cement cylinders (R500/60 min)	R 117 (20 min)
Total	R 18 234

The costs and time to produce an overdenture frame through AM as described above is for producing a single unit. This can be reduced if more frames can be produced simultaneously on the DMLS machine's building platform. To demonstrate this, Tables 7 and 8 shows time and cost respectively to produce 10 frames simultaneously on the same platform through AM.

Table 7 Time to produce 10 overdenture frames simultaneously through AM.

Process	Time
Wax-up	600 min
Scan	100 min
Reverse engineering with GeoMagics	500 min
Position frame in Magics	200 min
Set-up platform in machine	20 min
Laser sintering part	240 min
Perform stress relieving	600 min (10h)
Wire-cut and surface grind platform	60 min
Remove supports	600 min
Perform heat treatment	600 min (10h)
Cement cylinders	200 min
Total	62 h / 10 = 6h20

Table 8 Cost to produce 10 overdenture frames simultaneously through AM.

Process	Cost
Labour to produce wax-up (R500/60 min)	R 5000 (600 min)
Labour for scan and reverse engineer with GeoMagics (R1250 standard rate/60 min)	R 12 500 (600 min)
Labour to position frame in Magics (R350/60 min)	R 1170 (200 min)
Labour to set-up platform in machine (R 500 standard rate)	R 500
Laser sintering part, machine time and material (R1000/60 min)	R 4 000 (240 min)
Perform stress relieving (R500 standard rate)	R 500
Wire-cut and surface grind platform (R1750 standard rate/60 min)	R 1 750
Labour to remove supports (R500/60 min)	R 5000 (600 min)
Perform heat treatment	R 2 000 (standard rate)
Cost of titanium passive abutment cylinders (R2000 each)	R 80 000 (forty cylinders)
Labour to cement cylinders (R500/60 min)	R 1170
Total	R 113 590 / 10 = R11 359

5. CONCLUSION AND DISCUSSION

In the current study, AM proved not to be a good solution to manufacture implant supported overdenture frames compared to conventional investment casting and CAD/CAM processes in terms of production cost and time as summarized in Tables 9 and 10 respectively. Although producing more frames on the same building platform reduces cost and time, the unit cost per frame is still significantly more compared to what can be achieved through conventional techniques.

Table 9 Cost comparison

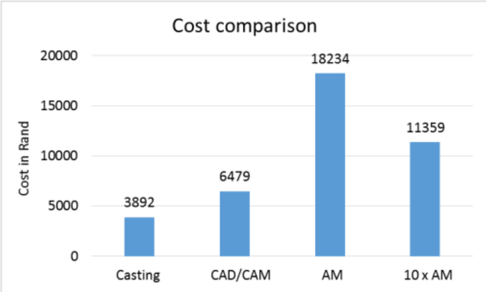
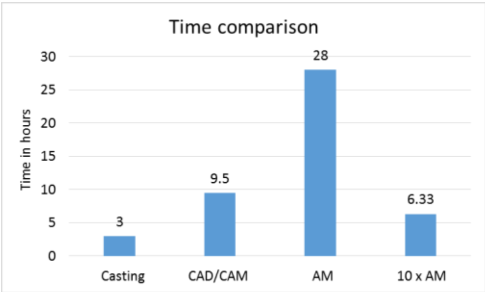


Table 10 Time comparison



A significant cost driver with producing overdenture frames through AM is the need to use passive abutment cylinders with the frames to compensate for misalignment. The AM process is not capable of delivering the precision required for the interfaces between the frame and abutments such as is possible through CNC machining. By eliminating these expensive cylinders the cost for a single frame can be reduced to as little as R3359 if 10 frames are manufactured simultaneously through AM. A possible solution to the problem may be to manufacture cylinders through conventional turning on a CNC lathe at much lower cost compared to what is available commercially. Another proposed solution to drive down cost in manufacturing overdenture frames is to combine the benefits of CAD/CAM and AM. The scanning and dedicated design software of a commercial system such as the Zirkonzahn® system can be used to design the frames. The parts can then be manufactured at a high production rate through DMLS which allows a number of parts to be manufactured simultaneously compared to CNC machining which allows for only one part at a time. To overcome the lack of accuracy of the DMLS process in critical areas such as interfaces with abutments, final machining of the DMLS parts can be performed in a CNC mill. Very accurate set-up of the part in the CNC machine will be required to make this possible and will form the basis of a future study for the authors.

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