# Dental applications of additive manufacturing


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# 1 Introduction (Arthur, Yara, Lucie, Michaela)

With already great influence on most industries, Additive Manufacturing, otherwise also widely referred to as 3D printing, is bound to set a new frontier in dental care. For this reason, by being highly detailed and customized, the technology is to be the game-changer in dentistry. All this is possible with this technology, which enables fabrications of everything from orthodontic devices right through dental implants to crowns with accuracies impossible with conventional means.

In this regard, among the few AM techniques used in dentistry, EBM is quite helpful for making solid metal parts-nearly as good as investment cast items-whereas SLA techniques of vat photopolymerization are the best for highly detailed resin models. In fact, all these methods have certain strengths, hence extending the current limits of what is possible with dental treatment.

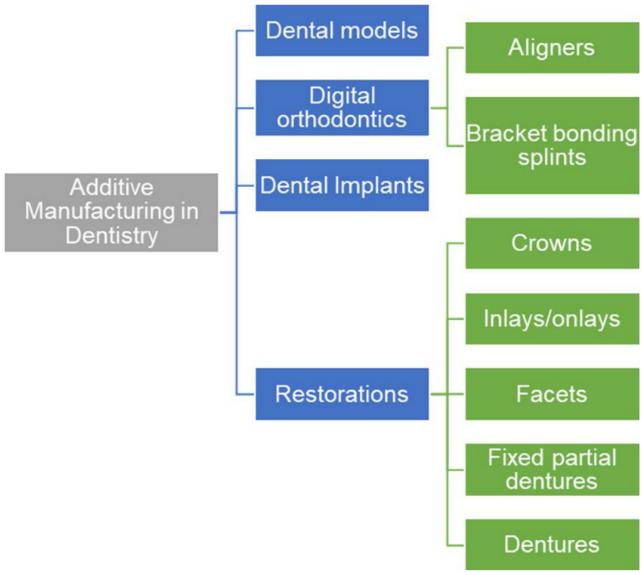


Figure 1.1: Applications of additive manufacturing in dentistry

## 1.1 Electron Beam Melting (EBM)

Electron Beam Melting (EBM) is an additive manufacturing technique that uses a high-energy electron beam to selectively melt metal powder layers, producing complex, high-strength metal parts. It is commonly used in medical and aerospace industries for creating dense, durable components with precise geometries.

## 1.2 Guided Bone Regeneration (GBR)

Guided Bone Regeneration (GBR) is a surgical technique in implant dentistry that involves the use of a barrier membrane to direct the growth of new bone in areas with insufficient bone volume. In additive manufacturing, custom titanium meshes are produced to fit patient-specific bone defects, supporting bone regeneration by providing a scaffold that optimizes bone growth and integration.

### 1.3 Material Jetting

Material jetting is a technique used to make 3D objects. This method builds the object layer by layer with the deposition of droplets of a photosensitive material that solidifies under ultraviolet light. The photosensitive material used is a thermoset photopolymer in liquid form.

An interesting use for material jetting is for multi material and multi color printing. This allows us to have different material properties in the same piece.

Figure 1.2: Head model made by material jetting with different colors and materials, credit Stratasys [5]

Other advantages of material jetting are very high accuracy (± 0.1 mm, one of the best for 3D printing technologies) and a smooth finish for the surface than other existing material printing technologies like FDM or SLA.

### 1.4 Selective Laser Sintering and Melting (SLS and SLM)

Selective Laser Sintering is a powder-bed additive manufacturing process, where a laser fuses a powder selectively, to build a piece layer by layer. SLS is used with ceramic, polymer or glass powders. To print metal parts, another process called Direct Metal Laser Sintering (DMLS) or Selective Laser Melting (SLM) is used. The energy source is also a laser, but the layer of powder is heated to its melting point, and higher enery is needed. Pieces are also made layer by layer, and cooling due to the high temperatures is often applied. In dentistry, ceramic parts can be made with SLS, and SLM is used to make chrome cobalt or titanium parts, as implants, bridges or surgical guides.

### 1.5 Vat Photopolymerization

Vat Photopolymerization, also called VPP, is an additive manufacturing technique category that creates 3D objects by using light to selectively cure liquid resin into solid layers. The resin is placed in a vat, and the light source can be above or below it; the process would be characterized as top down or bottom up respectively. This category of techniques is known for its high resolution and accuracy, leading to very intricate and detailed structures. It is increasingly being used across various industries, notably medicine and dentistry. There are two main VPP techniques: Stereolithography (SLA) and Digital Light Processing (DLP). [11]

### 1.5.1 Stereolithography (SLA)

Stereolithography (SLA) is a an additive manufacturing technique that uses a photopolymer resin to build 3D parts layer by layer. The photoresist molecules are selectively cured by a moving UV laser directed across the surface of the vat through galvanometric mirrors, solidifying the resin into the desired, possibly intricate, geometry. Each cured layer adheres to the previous one, and this new set of layers either moves upwards if it is a bottom up process or downwards if it is a top down process. This allows new, uncured resin to get closer to the surface and the process starts again for the next layer, until the 3D object is fully built. The precision of this technique is insured by the inhibitor, a chemical substance that prevents the UV-curing to diffuse to all the photoresist. [8]

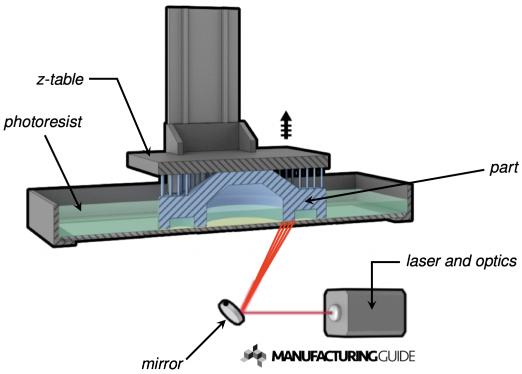


Figure 1.3: SLA Process - Bottom Up

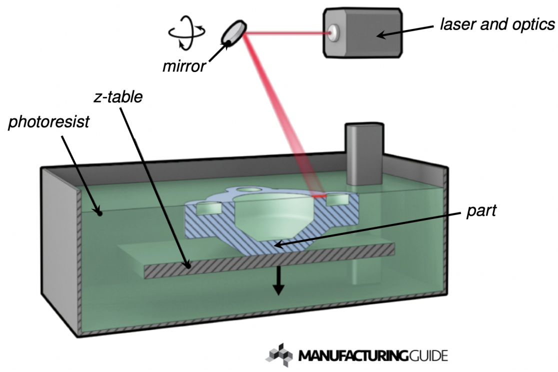


Figure 1.4: SLA Process - Top Down

### 1.5.2 Digital Light Processing (DLP)

Digital Light Processing (DLP) is an additive manufacturing technique that derives from SLA, but their consolidation tool and the intelligence transfer differ. DLP uses a UV flash as light source, and deflects it by a network of mirrors to selectively photopolymerize the resin. A Digital Micromirror Device (DMD) then transfers the wanted geometry into each layer by projecting light in specific, precise patterns. The DLP process, unlike SLA, cures entire layers at once, making this technique faster. This technique is only possible in a bottom up set-up; the cured layer moves upward to allow uncured resin to place itself at the surface, and the process is repeated until the object is fully constructed. [8]

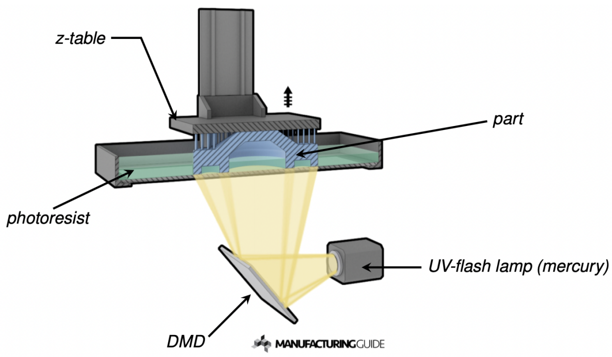


Figure 1.5: DLP Process

## 2 Dental models (Lucie Chêne)

Figure 2.1: Example of a dental model made by 3D resin printing [3]

In this section, the use and benefices of dental models made by additive manufacturing technologies for dental applications are presented. A representative picture of a dental model made by additive manufacturing is depicted in Figure 2.1.

Dental models are widely used in the dentistry industry. To know where to operate the patient or if there is enough room for moving a tooth, dentists help themselves with the use of dental models. It also allows them to plan and study the best strategies for the patient's treatment. Furthermore, the patient can see and understand what is planned and what will be done with a tangible model of his own mouth.

There are four main types of dental models to respond to different medical issues:

- Diagnostic Models
  Diagnostic models are used to determine the diagnostic of the patient's problem and to plan an adapted treatment.
- Working Models
  Working models are a representation of the patient's oral structure. They are useful in the restoration field like crown placement and bridge fabrication for example.
- Study Models
  Students use study models to practice their skills before working with real patients. It allows them to deepen their understanding of the theory and be more familiar with oral structure.
- Orthodontic Models
  In the orthodontic field, orthodontic models are a great tool for analyzing the tooth alignment of the patient and plan interventions such as braces and aligners. With orthodontic models, the orthodontist can see if there is enough space for moving a tooth, for example.

## 2.1 Wax-up


Figure 2.2: A wax-up model [18]

Wax-up are an essential step to model dental restorations. It allows the dentist to see if the treatment is adapted to a replica of the patient's mouth. It's usually used for restoration treatment like crowns, bridges or veneers. Furthermore, the patient can also see if the proposed prosthetics satisfy his desired aesthetic and meet his desire. So, the wax-up helps both the patient and the dentist in the decision-making process. Finally, the model can also serve as a guide for making the chosen prosthetic and try it in the patient's mouth replica before being placed permanently in the real patient's mouth. [18] In order to understand the benefits of the digital wax-up for dentures, we must first understand the challenges that the conventional methods face.

Wax-up are handmade by specialized technicians with wax based on a plaster model. To do a plaster model, the dentist takes the impression of the patient's teeth. This is done with a tray filled with a mixture of alginate powder and water.
Alginates are salts formed by combining alginic acid with various basic elements such as sodium, calcium, potassium or magnesium acid, a polysaccharide extracted from brown algae. Dental alginates are used in the form of a powder that is mixed with water to form a moldable material. The calcium sulphate is used as a reactor, the fluoride accelerates the setting and the sodium phosphate acts as a retarder. [13]

Once the dental plaster is made, the technician can make a replica with wax and insert the prosthetic in it. This way, the dentist can test the fit and appearance of the prosthetic.

Another important use of the wax-up is to create temporary restorations that match the planned final restorations. These allow patients to test the look and feel of the restorations before they are permanently installed.

The problem with this technique is that it is expensive, it is very difficult to make changes once the wax-up is finished, it is not very accurate and it depends on the skill of the technician. They are also quite fragile and can be deformed during handling.

## 2.2 Digital wax-up

The new field of digital wax-up is emerging and is gradually replacing traditional wax-ups. Digital wax-ups solve many of the problems encountered with traditional wax-ups. Digital wax-up can be done in different ways as shown in Figure 2.3.

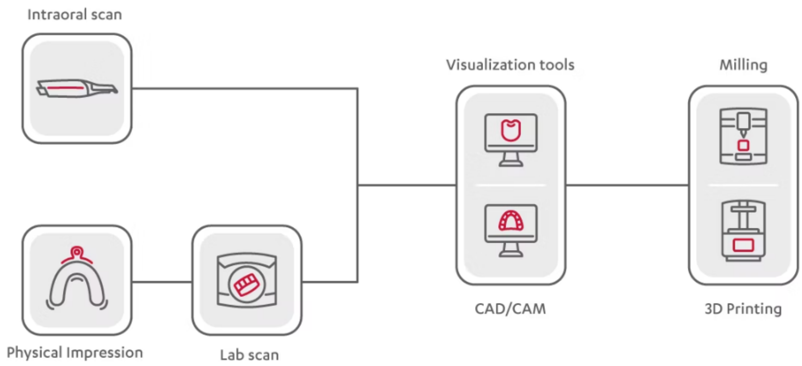


Figure 2.3: Digital wax-up processes [2]

To do the first step, the dentist can use a intraoral scan to obtain a 3D digital model of the patient's mouth as shown in Figure 2.4. If the dentist doesn't have an intraoral scan, the technique of physical impression and a plaster model can be done. The plaster is scanned with the use of a model scan afterward in order to have the 3D digital model.

The second step is modifying the digital model with CAD/CAM softwares.

Finally the model is printed and milled sometimes in order to have the correct edges for the patient. The process is more detailed in section 2.3. [2]

A major advantage of digital wax-ups is that the dentist simply scans the patient's mouth to obtain a 3D digital model of his or her teeth. It is faster and more comfortable for the patient, which may have a gag reflex during the dental impression. Furthermore, the CAD files can be easily sent to the different laboratories like for example between the dentist, the CAD designer and the ceramist. The risk of breaking a model or losing it during a transfer is gone. There is also no more time wasted sending models between laboratories.

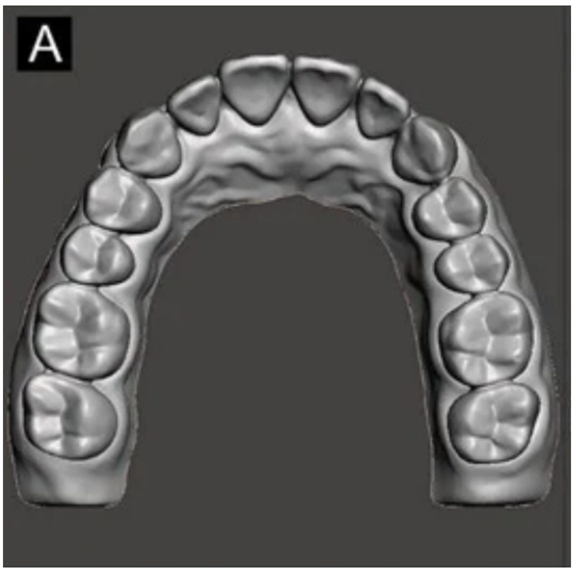


Figure 2.4: A 3D scan of a patient's mouth [38]

An another great advantage is that with CAD, the dentist can try different strategies and see how each step will occur. It is much easier to make changes and see different outcomes than with traditional wax-ups. Traditional wax-up being quite time consuming to make and therefore expensive. The possibility to have multiple wax-up to test was never offered.

Once the dentist is satisfied with the results, the digital model can be 3D printed. Then it is tested on the patient and if it fits perfectly the ceramist only need to replicate the model. Or if the model was made for a surgical procedure it is send to the surgeon and he can have a 3D physical model to see what the outcome need to be. [9]

However, there are still obstacles to the democratization of digital wax-ups. Dentists' habits have to change, and the specialists who make wax-up models by hand are protesting because they are going to lose their jobs. Only a small number of labs are equipped with the machines needed to scan the impressions made by dentists if they don't have a 3D scanner and print the CAD files. In addition, technicians need to be trained in computer-based design. Despite everything, the investment seems necessary because this technique is very promising in the world of dental models. It is faster, cheaper, more flexible and precise than the traditional wax-up.

## 2.3 Use of AM for dental models

Most of the times, the AM technologies used for dental models are based on polymers. There are no specific material properties required, we just need a fast, efficient and cost effective way to print the CAD model.

Vat-polymerization (VP) technologies are normally used for dental models. Actually, the printing of diagnostic cast is among the easiest applications done by VP technologies. The shape is simple to produce. There are no hollow parts and they are quite small and thick. The accuracy of the VP parts and milled parts were compared and were similar or higher for the VP ones [27].

No matter the choice of technique for printed dental model, there is the same procedure that need to be followed as explained in Table 2.1.

Steps to create a 3D printed dental model by using additive manufacturing.

| S. No | Step used | Description |
|---|---|---|
| 1 | Digital 3D model of the patient's mouth | • Digital models are created by 3D scanners in the form of cloud data with fast and accurate dimensions<br>• Used 3D scanner for precise scanning of patient mouth and teeth |
| 2 | Modification in design | • After scanning, it is essential to ensure that the dental model will fit perfectly by adjusting shape, size and position<br>• Easy modification in design is done through the use of different software and the associated AM technology |
| 3 | 3D printing | • Fabricate 3D solid object directly from the 3D digital file by the addition of materials layer by layer<br>• Dental implants are manufactured using different AM technologies according to the specification of printing material<br>• Post-processing is used to increase the physical property and strength of the implant<br>• Reliable for reconstruction of precise teeth and other tools used in dentistry<br>• It is cost effective as compared to the other manufacturing techniques and can well be used for training |

Table 2.1: Typical steps for 3D dental model procedure [22]

# 3 Digital orthodontics (Yara Sabbagha)

Orthodontics is a branch of dentistry focused on diagnosing, preventing, and treating dental and facial irregularities, notably malocclusions or misaligned teeth. Orthodontists mainly manage the positioning of teeth, jaws, and face structures to enhance functionality and aesthetics.

With further advancements in technology, the orthodontic industry is becoming more digital. Indeed, it is now common to use 3D imaging, digital scanners and modeling software instead of traditional manual impressions. It leads to higher-quality and more detailed and precise models and allows for more personalized treatments. It also enhances patient comfort, as it reduces the need for manual impressions and patient chair time.

One interesting advancement in orthodontics is additive manufacturing. Indeed, AM techniques like SLA and DLP allow for the manufacturing of highly customized and accurate orthodontic appliances such as brackets, aligners and surgical guides. These techniques are becoming more popular as they can produce small, complex, personalized items in low volumes in a fast way, while generating minimal waste, and increasing patient comfort. [24] [30] [21]

## 3.1 Additive Manufacturing for Orthodontic Aligners

Orthodontic aligners are becoming more common, replacing traditional braces. Indeed, they are able to treat malocclusions effectively, while maintaining oral hygiene, comfort and a discrete look. Additive manufacturing is behind the revolution of the design and production of clear aligners. AM processes are fast, efficient, and limit material waste, as they eliminate the need for intermediary dental models. They are also more precise and consistent, thouroughly matching the digital design. They are also customizable, most importantly in thickness, which helps exert specific forces and reach needed outcomes.

Figure 3.1: Picture of a transparent aligner.

### 3.1.1 Workflow of Clear Aligner Production

The production of clear aligners using AM techniques starts with a data acquisition of the patient's teeth. It is either done traditionally by performing a physical wax impression, used to create a plaster model, or by intraoral scanning. We then use this data to create 3D models of the patient's teeth, that are imported into a CAD software, specialized for orthodontic applications. Orthodontists use this software to design virtual aligners specific for the treatment of each individual patient, by segmenting teeth, planning tooth movements, and generating a sequence of aligners. The digital designs are later exported as STL files for the manufacturing step.

For the manufacturing step, it was traditionally done through thermoforming, or more specifically vacuum forming. It consists of a thermoplastic sheet molded over a 3D-printed orthodontic model. However, this method is not ideal as the heating involved can generate inconsistencies in thickness and mechanical properties (like surface hardness) of aligners, which can affect their performance. Another more modern process that eliminates these concerns is direct 3D printing. Through technologies such as SLA and DLP, photopolymer resins are used to build each aligner layer by layer, with customizable thickness and force application. After the manufacturing of aligners, post-processing steps, including UV curing and polishing, are followed. They make sure that the produced aligners have reached the necessary biocompatibility, transparency, strength, and other mechanical properties for the effective treatment of the patient.

You can see in the figure below the workflow of clear aligner production.

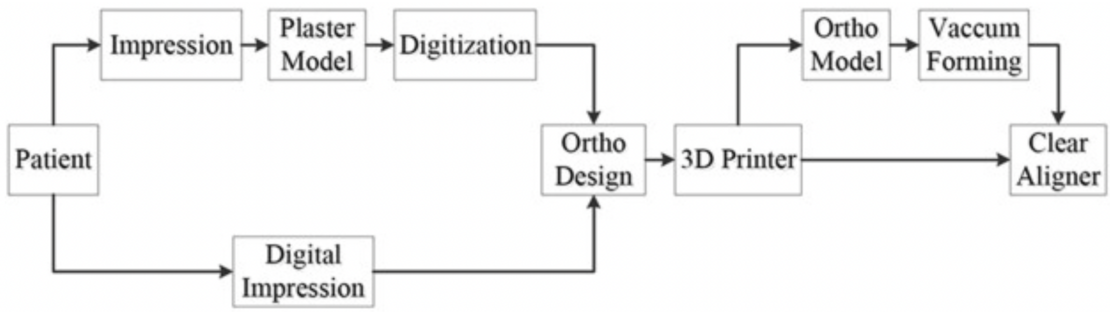


Figure 3.2: Workflow of clear aligner production.

### 3.1.2 Material Considerations

The material used for the additive manufacturing of clear aligners is important. Indeed, when aligners are produced by thermoforming, materials such as polyurethane and polyethuulene terephthalate glycol (PETG) are employed. Although these materials provide good flexibility and transparency, they are also likely to undergo changes in their properties due to the heat generation used to shape the material in the desired shape. It seems like their mechanical properties are also reduced in the intraoral environment, because of the body temperature, humidity and salivary enzyme. This can negatively impact the efficiency of aligners. As for the direct 3D printing process, it uses advanced biocompatible photopolymer resins such as Dental LT. These materials proved to be more flexible, dimensionally stable and stronger mechanically, as they can resist higher loads. However, further research about post-curing should be done in order to mitigate the risks of cytotoxicity of uncured resins, and ensure the safety of the patient as well as the effectiveness of the aligner. As of 2021, no material had been approved for the 3D printing of aligners. [33] [41] [30]

## 3.2 Additive Manufacturing for Orthodontic Brackets

In the last few years, additive manufacturing has transformed the production of orthodontic brackets. By using modern AM techniques and advanced digital tools, it is now possible to design and produce customized brackets depending on the anatomy of each individual patient. This improves torque control, alignment and efficiency, while increasing patient comfort. These techniques are also great choices for patients seeking discreet, aesthetic options.

### 3.2.1 Workflow of Customized Bracket Production

Personalized brackets are produced in several steps. First, orthodontists perform intraoral scanning using advanced scanners to capture accurate 3D digital impressions of the patient's dental arches. The digital scan is then treated using an orthodontic CAD software. The new software, Ubrackets, is specific for the design of customized orthodontic brackets. It allows the adjustment in bracket size, shape, and torque prescription based on the patient's needs, ensuring good placement and functionality. The brackets are later aligned on a virtual archwire and tested by placing them precisely on the digital model of the patient's teeth. Positioning keys and indirect bonding trays might also be created to help in the application of the brackets during bonding.

Once this design step is done, the digital 3D models are exported as STL files to proceed with the 3D impression. Depending on the material, resin or zirconia, the AM process will vary. Usually, SLA or DLP are used for a layer-by-layer production of resin-based brackets. After the printing step, isopropyl alcohol is used to wash the brackets and remove residual uncured resin from them. The brackets are then cured under UV light to enhance their mechanical properties like hardness and elasticity. For zirconia-based brackets, they are printed with a specific zirconia slurry 3D printer (like Zipro or AON). Slurry-based 3D printing consists of the layering of a liquid containing a high concentration of ceramic particles. After that, the printed brackets are sintered at high temperatures to fuse the zirconia particles in a dense, durable and precise ceramic structure. This zirconia-based process improves fracture resistance and hardness, making the brackets very robust. The zirconia brackets can also be colored in the teeth color of the patient by using color-matching coatings or translucent materials.


Figure 3.3: (a) Customized hybrid ceramic resin brackets with positioning keys for precise bonding. (b) Keys removed, and 0.012-inch Nitinol archwire inserted.

Figure 3.4: A patient bonded with unpainted zirconia brackets printed using a zirconia 3D printer. Brackets can be colored to match the patient's teeth.

### 3.2.2 Material Considerations

The material used for the 3D impression is important and critical in ensuring the performance and durability of the brackets. On one hand, resin-based brackets are lightweight, cost-effective and customizable in shapes and sizes based on the patient's anatomies and malocclusions. Studies showed that there is no difference between the permanent and temporary resins in terms of hardness, brittleness and modulus of elasticity. However, their hardness and durability are lower than those of zirconia-based brackets. Moreover, mechanical properties can be negatively impacted if the polymerization during curing is incomplete. On the other hand, zirconia-based brackets have better strength and wear resistance. However, their manufacturing process is more complex and expensive as the sintering step must be precise and needs additional time and costly equipment. [29] [30] [31]

# 4 Dental Implants (Arthur Lettermann)

Additive manufacturing has totally changed in dental implantology: precision for customization, intricate designs, smoothness in the workflow. Stereolithography (SLA), Digital Light Processing (DLP), Selective Laser Melting (SLM), and Electron Beam Melting (EBM) provide adequate means for highly individualized implant solutions, improving clinical outcomes. [22]

## 4.1 Additive Manufacturing Technologies in Dental Implants [7]

In dental implantology, SLA and DLP have become the most important AM techniques to fabricate customized surgical guides, fitting each particular anatomy of a patient. They provide precised pathways where the implant will go, making sure that the implant takes the pre-planned position inside the bone. This will reduce surgical errors and risks, hence enhance the success rate. (see Figure 4.1).

Figure 4.1: Surgical guide produced using SLA and DLP.

With SLM and EBM, it has become impossible to think about custom-made titanium meshes for guided bone regeneration without their use. These innovative techniques allow one, therefore, to produce with precision very intricate, patient-specific titanium frameworks perfectly matching the morphology of the bone defect. The flexibility of such AM processes allows adjustments to pore size, thickness, and shape according to needs, which are all very critical in enhancing optimal bone growth and soft tissue complications. Unlike traditional methods, by AM, it's possible to design and manufacture very complex meshes that can highly enhance the bone-healing and -integration outcomes in complicated GBR cases. (see Figure 4.2).

SLM and EBM are common methods in the manufacturing of models and frameworks of implants, as they ensure implants of strong, corrosion-resistant titanium. These AM frameworks are designed to deal with long-lasting demanding situations, fitting into the structure of the jaw in such a way that stability and functionality increase with time.(see Figure 4.3).

The AM technologies also make it possible to manufacture customized trays and implant casts for restorative procedures efficiently. Such trays and casts are being designed for the specific oral anatomy of the patient with the help of SLA and DLP, which later enables correct testing and fit-checks aimed at enhancing comfort and durability of the final restorations. Besides raising the level of accuracy, this approach contributes to sustainable practice because less material is wasted compared to traditional manufacturing.[20]

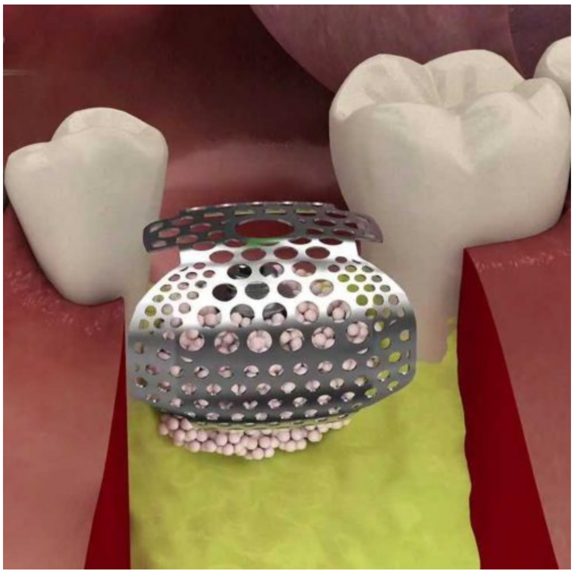

Figure 4.2: Custom titanium mesh for guided bone regeneration (GBR) produced using SLM and EBM.

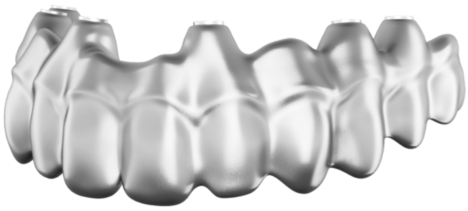

Figure 4.3: Implant framework fabricated using SLM and EBM for precise jaw fit.

### 4.2 Applications of AM in the Restoration Stage of Implant Therapy

Additive manufacturing technologies play a great role in the restoration phase of implant therapy in terms of precision and efficiency. Customized trays, fabricated through SLA and DLP, allow for a very precise impression of a patient's oral structure and thus provide room for the impression materials, and eventually the restorations, to be fitted with high accuracy. The high accuracy reduces the risk of any potential clinical error and simplifies the restoration process.

Another important use of AM in the restoration phase involves dental models. This is where clinicians, with the help of SLA or DLP, can create highly detailed replicas of the patient's oral anatomy, which are extremely important for test and adjustment purposes before the final placement of such implants. This helps the implants to feel comfortable and avoids adjustment afterward, thus improving patient satisfaction.

Moreover, the frameworks with SLM and EBM provide strong support for prosthetics. The contour of such frameworks, which fits a particular shape of the patient's jaw, was designed and optimized for the best stability and functionality. Because of the efficiency of AM, there is no wastage during the manufacturing process and hence it is economically friendly as well as environmentally friendly in implant restoration.[1]

### 4.3 Applications of AM in the Surgical Stage of Implant Therapy

During the surgical stage, the use of AM technologies in developing customized surgical guides and titanium meshes is particularly important, which will lead and support precise implant placement. SLA and DLP allow for highly accurate surgical guides, customized to the anatomy of each patient. These guides provide the potential for more precise positioning of implants, less invasion, and fewer complications, hence highly improving surgical outcomes and raising patient safety.

SLM and EBM are especially valued in the manufacturing of titanium meshes for GBR. AM allows this mesh to be fitted to the very contours of the bone defect, thus enhancing bone regeneration and encouraging integration. Such features as the possibility to change pore size and shape ensure optimal support for bone ingrowth and reduce soft tissue irritation, which is very important in complicated cases of GBR.[42]

The bottom line is that AM techniques smoothen the surgical workflow, hence making implant procedures more predictable and more precise. Patient-specific data utilization during AM in implant therapy enhances customization and preciseness of the whole treatment.

# 5 Applications of AM in restorative dentistry (Michaela Rosinska)

Restorative dentistry covers the interventions that repair or replace damaged teeth. It includes crowns, onlays, inlays, bridges and implants. A common operation is the filling of a hole after the treatment of a cavity. A composite filling is used for the smaller ones, but onlays and inlays are applied when the cavity is larger. Crowns are used for even larger cavities where all the tooth needs to be covered.


Figure 5.1: Difference between inlays, onlays and crowns [39]

Crowns are also used to repair broken teeth. There are several options to replace a missing or overly damaged tooth. A dental implant is a threaded post that is fixed in the jawbone during a surgery, and on which a dental restoration (the new tooth) can be attached. Dental bridges are also used. They are fixed on the neighboring teeth with crowns, with the new teeth in between them. Dental bridges replace 1 or more teeth, and can also be fixed with dental implants. Dentures for the replacement of one or more teeth are also used, and are placed directly on the gums without extensive surgery.[10]

Additive manufacturing is used for indirect restorations, where the restoration is made before the operation, and fixed with a special dental cement or on an implant. In direct restoration, the tooth is sculpted by the dentist directly in the mouth, and there is no manufacturing involved. That's why we will only develop the indirect restorative applications, where additive manufacturing is involved.

## 5.1 Advantages

At first sight, using additive manufacturing instead of subtractive manufacturing techniques has many advantages. It brings a high customization range, which is crucial in dentistry as each tooth is different. Accuracy can be enhanced with proper settings and an optimized process. The material cost is also smaller, as there is minimal waste compared to subtractive processes. Teeth being small pieces, this impact isn't significant, and will highly depend on the material that is used (gold teeth for example). [28]

Digitalization is common in dental clinics, and printing on the fly is the next step. Having printing equipment directly in clinics could allow a higher efficiency in the treatment of patients, with printed restorations, at least temporary, available quicker.

We will go through different types of restorations, to see if additive manufactured parts yield properties that are sufficient to be used in dentistry.

## 5.2 Crowns

As introduced in the beginning of this section crowns are commonly used in dentistry. As onlays and inlays are needed in the treatment of smaller cavities, manufacturing isn't always necessary and manual sculpting is often used. Depending on the material used for their fabrication, crowns can be temporary or definitive.

Today, the two main fabrication processes used for creating crowns are substractive technologies, mainly milling with CNC, but additive manufacturing with 3d printing is also used. Many studies are investigating the improvement of additive manufacturing techniques, and comparing them with classical milling. We will go through 3 of them, that shows the great potential and advantages of additive manufacturing techniques

Figure 5.2: Temporary crowns fabricated using Digital Light Processing (DLP) technology

The two techniques yield similar results, with precisions that are in the clinically accepted range. A first study compared metal-ceramics crowns made by conventional milling and various additive manufacturing techniques. It showed that the resistance for the milled crowns was slightly better, but the one manufactured by SLM were just behind. The difference isn't big enough to prevent the crowns made by additive manufacturing to be used in dentistry, and this for all the techniques (lost wax, selective laser sintering (SLS) and selective laser melting (SLM) ). [37]

Another study compared the fracture resistance of restorations made by milling and by direct light processing (DLP). As for the other processes used, the milling technique yielded better results. [25]

Other studies tried to improve the properties of 3d-printed ceramics crowns, and found that the combination of oxide stabilizers improve their performance, especially toughness and fatigue limit. Tests where made to simulate natural aging and use of the restorations during mastication, by putting them under cycles of thermal and mechanical stresses, in order to simulate the conditions in the mouth. [23]

## 5.3 Bridges

Bridges are restorations that replace one or more adjacent teeth, and are fixed on the remaining neighboring teeth with crowns, or on dental implants. The natural teeth on which the bridge is attached is called abutment.

Figure 5.3: Traditional dental bridge with prepared abutments [36]

As for crowns, dental bridges can be temporary to protect the teeth from further damages until the final bridge is produced. Permanent bridges are made in ceramics, most common being IPs EMAX and Zirconia, Porcelain fused metal, or metal, gold for example. They are typically made by lost wax casting or CAM (Computer-aided manufacturing).

In a research conducted in 2023, bridges made by alternative additive manufacturing methods were investigated. They tested Co-Cr bridges processed with conventional lost wax casting, casting with 3d printed models and SLM. As for the crowns, all the bridges passed load tests simulating chewing, and could be used clinically. [12]

## 5.4 Inlays and onlays

The idea behind the fabrication of inlays and onlays is similar as the one for crowns. A wax pattern of the restoration is made at first, then casting is applied to obtain the final part. To make the wax model, the commonly used techniques are milling and hand-made manufacturing. Using additive manufacturing was investigated and compared to conventional procedures in different studies.

As for bridges and crowns, the precision of both methods was measured to be comparable, and onlays made by additive manufacturing could be used. Another recent study came to the conclusion that the precision of onlays and inlays made by additive manufacturing had a better precision, and their use could be preferred. [6]

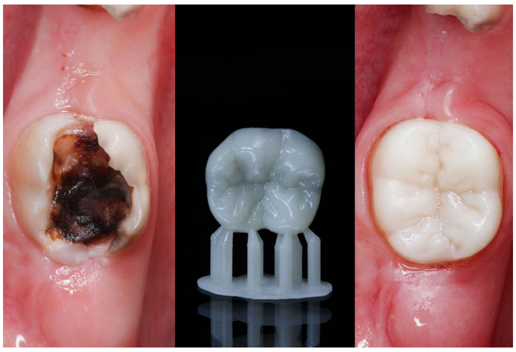

Figure 5.4: 3d printed onlay for cavity restoration [40]

# 6 Future development (Michaela and Yara)

## 6.1 Tissue regeneration

For all the restorations discussed above, the printed elements were only partially, or totally, replacing teeth. Smaller restorations are glued to existing teeth, but this technique cannot be used for soft tissues. SOft tissues are by definitions softer, and for their restorations new tissues must be used.

Advances in bioprinting technologies in the past 15 years revolutionized the fields of tissue engineering and regenerative medicine, including dentistry. Unlike for the restoration of teeth, the mechanical properties aren't the most important aspect that has to be considered. Indeed, when replacing soft tissues, the structure of the original tissue must be also matched, which is harder to mimic

Research was widely conducted to produce different dental tissues. Dental tissues can be divided in two categories based on their mechanical properties. The following where engineered for regenerative applications : [44]

| | **Tissue** | **Composition** | **Necessity of regenerative techniques** |
|---|---|---|---|
| **Hard Tissues** | Enamel | Hydroxyapatite, organic macromolecules | No cells in a mature tooth, lack of regeneration ability |
| | Dentin | Hydroxyapatite, protein matrix | Necessity of good cell adhesion, viability |
| | Alveolar bone | 60% inorganic (Ca), 25% organic, 15% water | Needed for implant restoration |
| **Soft Tissues** | Dental pulp | Cells, collagen, nerves, blood vessels | Pulp revascularisation wasn't succesful, stem cell-based regenerative therapy is developed |
| | Periodontal ligament | Collagen, proteoglycans | Bioprinted structure is closer to the structure of original ligaments |
| | Gingival | Cells, lipids | Overcome the lack of graft donors |

Table 6.1: Dental tissues composition and benefits from regenerative therapies

One clinical application of additive manufacturing in soft tissue reparation was a bioresorbable scaffold for a periodontal repair [34], that was produced by selective laser sintering (SLS).

Teeth are complex structures with both hard and soft tissues. With the development of regenerative techniques for the individual tissues, more complex systems could be processed in the future. Full teeth restoration is the next step where additive manufacturing, especially bioprinting, could be applied in the future.

## 6.2 4D Printing

4D printing is among the new innovative additive manufacturing technologies. It transforms the well-known 3D printing by adding to it the time dimension. This allows materials to constantly adapt their shape, size and structure over time, based on environmental stimuli. Implants, dentures and other orthodontic appliances produced with 4D printing increase comfort and improve functionality, through their adaptability and their customization based on each patient's case.

Below is a table comparing 3D and 4D printing characteristics.

| | 3D printing | 4D printing |
|---|---|---|
| Technique | Additive manufacturing technology with static materials | Additive manufacturing technology with smart materials |
| Dimensions | Three dimensions | Four dimensions (time is added) |
| Reaction to time and stimulus | Materials do not respond to time and stimulus | Smart materials transform after being subjected to external stimulus |
| Built process | Here, one layer is printed, and the next second layer is printed above the first layer | It is the same as 3D printing but with the additional advantage of using smart materials |
| Materials | Resins, ceramics, metals, polymers. | Smart, multi-materials |
| Flexibility | Stiff, firm, static materials are formed | Dynamic, flexible materials |
| Applications | Surgical guides, aligners, individual impression trays, splints, models, wax-up framework, crowns and bridges, implants, etc | Restorative materials, individual-specific implants, dentures, splints, local drug delivery systems, root canal filling materials, ridge-specific dentures, etc |

Figure 6.1: Table comparing the characteristics of 3D and 4D printing technologies.

The main advantage of 4D printing is its dynamic adaptability, which enhances the orthodontic appliances' functionalities and improves the outcome of the patient's treatment. For example, with 4D technology, when the alveolar ridge changes, the dentures manufactured automatically adjust as well. This results in good fit of the dentures thoughout the whole time. 4D printing technology also allows smart dental implants to change accordingly to oral dimensional changes. This improves the reliability of the appliance and limits the risk of complications such as microleakage. Furthermore, restorative materials such as polymers and shape-memory alloys are used in 4D printing processes. They provide superior mechanical properties such as elasticity, strength, durability and biocompatibility relatively to traditional materials. We call them "smart materials", as they can change dynamically based on the environment they are in. Moreover, 4D-printed scaffolds allow gum and bone tissues repair, and when combined with stem cells, they can even enable damaged tissues regeneration and the growth of natural teeth.

While additional research and clinical trials are definitely required to discover more about 4D printing technology, it is an area that has a big potential in redefining the dental industry and overcoming its current challenges. [32]

## 7 Conclusion (Lucie Chêne)

The presence of additive manufacturing (AM) is increasing in the dental field, leading to improved treatments. The advantages of using AM are greater precision, lower cost and faster production time than traditional techniques.

The combination of computer aided design (CAD), computer aided manufacturing (CAM) and AM allows to produce new and various dental devices in applications such as restoration, orthodontics and aesthetics. AM technologies are available to produce parts in polymers, metals or ceramics. However, the maturity of the different methods is not the same. Methods for polymers are more advanced than for ceramics, which are the best suited materials for dental parts. Therefore, research and tests are still needed and traditional methods will stay in place and be used in the next years alongside the new technologies.

Finally , the future 4D printing technology, incorporating intelligent stimuli-responsive materials, offers adaptive and sustainable solutions for dentistry. Although still limited by technical and regulatory challenges, this technology could enable a major advance in the development of personalized dental care through adaptive technology.

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