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3D Printing in Dentistry—State of the Art

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Clinical Relevance

3D printing has been found to exhibit properties and performance comparable or superior to those of traditional manufacturing processes. Additive manufacturing has the potential to overcome the disadvantages of the subtractive production method.

SUMMARY

Three-dimensional (3D) printing is a rapidly developing technology that has gained widespread acceptance in dentistry. Compared to conventional (lost-wax technique) and subtractive computer numeric controlled methods, 3D printing offers process engineering advantages. Materials such as plastics, metals, and ceramics can be manufactured using various techniques. 3D printing was introduced over three decades ago. Today, it is experiencing rapid development due to the expiration of many patents and is often described as the key technology of the next industrial revolution. The transition to its clinical application in dentistry is highly dependent on the available materials, which must not only provide the required accuracy but also the necessary biological and physical properties. The aim of this work is to provide an up-to-date overview of the different printing techniques: stereolithography, digital light processing, photopolymer jetting, material jetting, binder jetting, selective laser sintering, selective laser melting, and fused filament fabrication. Additionally, particular attention is paid to the materials used in dentistry and their clinical application.

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INTRODUCTION

The application of computer-aided design (CAD) and computer-aided manufacturing (CAM) in dentistry has progressed strongly over the past few decades. It has led to the development of new classes of materials and to the digitization and automation of various work processes. Until recently, in dentistry, the CAM process was synonymous with the subtractive manufacturing process.

In this process, an object is created out of a blank by milling, grinding, drilling, turning, or polishing using specific tools. From a procedural and ecological point of view, subtractive production has the disadvantage in that the surface resolution is limited by the smallest tool radius. The material loss by computer numeric controlled milling can reach 90%.[1] In addition, the subtractive technique also has a limitation with regard to the number of objects it can produce per machining operation, and it is not capable of reproducing more complex geometries. Furthermore, the tools used show signs of wear after repeated use, which can lead to cracks in the objects produced.

Alternative ways of producing CAD files are the additive manufacturing processes. All additive manufacturing processes have in common that on the basis of 3D design data, the physical object is built up by the sequential application of thin layers of material. In addition to the term "additive process," the synonyms "generative process," "rapid prototyping," and "3D printing" are often used. With the development of the first CAD programs, the first experiments in the 3D printing sector were carried out from 1980 on. The inventor of the 3D printer, Chuck Hull, took his place in history in 1986 with his patent application for stereolithographic printing. Shortly thereafter, a number of alternative processes were developed.

Legally protected patents on the various additive processes led to high costs and prevented the new technologies from spreading rapidly. With the expiration of important patents a few years ago, commercial and industrial use and further development of the additive processes started at even lower costs.

In contrast to subtractive methods, additive processes can save material and produce more complex geometries. As a result, this manufacturing method is a suitable solution in the dental field. From a process engineering point of view, the additive process has the potential to overcome the disadvantages of the subtractive production method.[2-4]

The basis for 3D printing is a complete description of the surface in a 3D CAD file. The object must be self-contained (watertight) and is usually available in the STL (Stereolithography, Standard Transformation Language, Surface Tessellation Language, or Standard Triangulation Language) file format of the standard interface. The STL format contains the description of the surface of 3D bodies with the help of triangulation (tessellation). Each triangular facet is characterized by its three corner points and the corresponding surface normal of the triangle. Curved surfaces are approximated by polyhedra. Increasing the number of polyhedra minimizes the secant error and describes the object surface with a higher resolution (Figure 1). The STL files can be stored as ASCII files with human-readable source code and much fewer data than binary machine code. Before printing, the CAM software cuts the STL file into multiple horizontal layers (xy plane) (slicing). The different slices contain the path information (xy coordinates). The result of slicing is the so-called G code, which contains the machine command for the printer. Thinner film thicknesses are associated with smoother objects but also with a longer printing time. The resolution of the printer is determined by its layer thickness, namely, the z-axis, which represents the vertical accuracy and is one of the essential technical features of any 3D printer. Staircase-shaped gradations of the object are characteristic of additively produced surfaces. They occur most distinctly on planes with low inclination and represent only an approximation of the actual object surface.

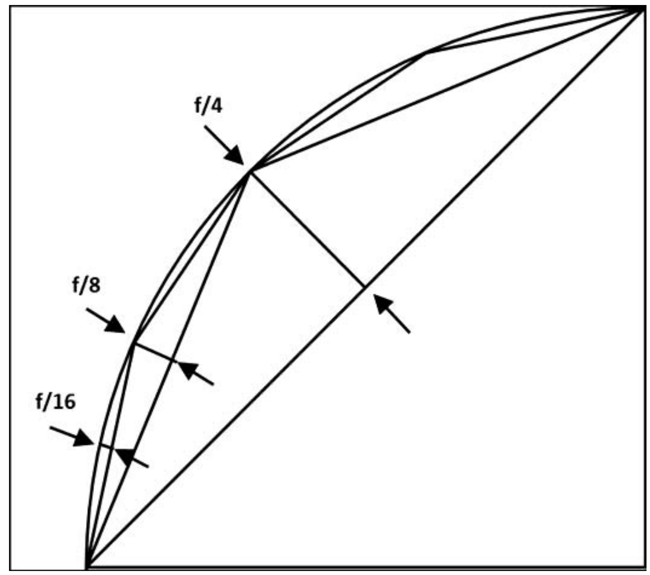
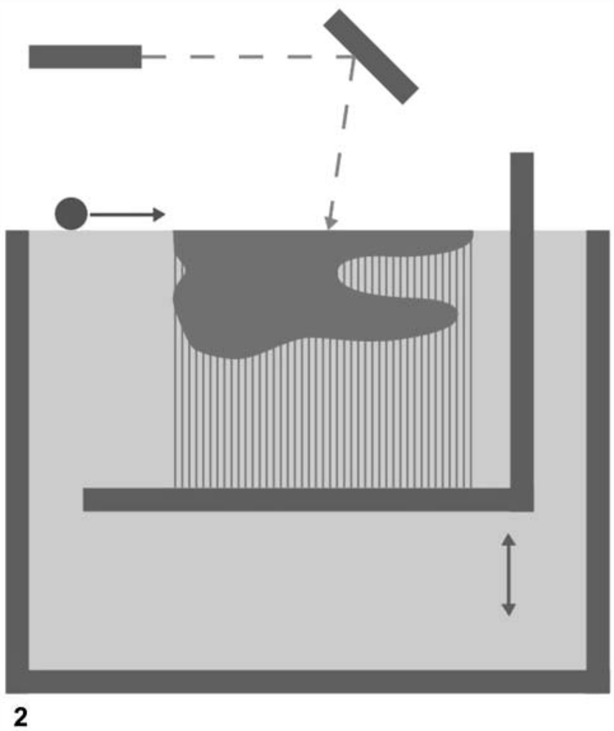


Figure 1. *Secant error when approaching a circle by 4 (f/4), 8 (f/8), or 16 line sections (f/16).*

The contributions of this technology to general medicine, which began in the 1990s with the production of 3D models, improvements in diagnosis and operation planning, and reduction in surgical risks,[5-9] is now being expanded to many areas of dentistry. In the following, the various additive processes and their use in the dental field are presented.

Stereolithography and Digital Light Processing

Stereolithography (SLA) is the oldest and most commonly used method of 3D printing in dentistry. This technique can be subdivided according to the build platform motion and laser movement. The principle of SLA is based on the layered structure of



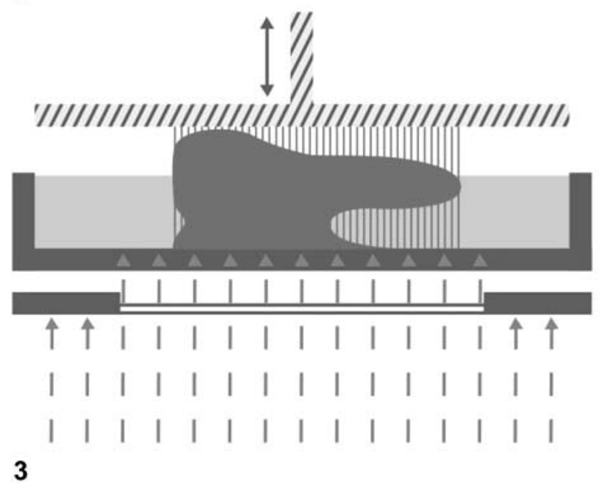


Figure 2. *Stereolithography.*

Figure 3. *Digital light processing.*

an object made of a UV-sensitive liquid monomer, which is polymerized and solidified by a laser.

In the top-down approach, the platform can be lowered vertically and is immersed in a reservoir with liquid monomer near the bottom of the reservoir. A layer of monomer can spread between the platform and the bottom. This monomer layer is exposed to a laser that scans from the bottom of the reservoir. The exposure of the monomer activates the polymerization reaction, which stops locally due to the solidification and limited movement of the free monomers. After each exposure cycle, the build platform is lifted to ensure that the resin flows into the gap between the platform and reservoir. In contrast, the bottom-up approach utilizes a laser that scans from the top of the reservoir. The movable build platform is covered with a thin film of resin and is localized in the resin reservoir (Figure 2). After scanning the first layer with a laser, the build platform moves down, and a roller applies a new layer of uncured resin. The cycle is repeated for each layer until the object is built up. There are many advantages of the top-down approach, so most of the currently available SLA printers operate by this technique. First, the integration of the laser reduces the potential risk to the operator. Second, by curing the resin in the depth of the reservoir, inhibition of the polymerization reaction by oxygen can be prevented. Third, the resin is refilled automatically, and, fourth, the printed layers have a smooth surface due to the contact of the building platform with the bottom of the reservoir.[10]

In addition to the activation of the monomer by a scanning laser in the SLA process, a projection-based SLA technique named digital light processing (DLP) is the second technique that is commonly used (Figure 3). DLP technology contains a microsystem with a rectangular mirror arrangement called a digital micromirror device. The angle of the micromirrors can be individually adjusted, and each one usually has two stable end states. The micromirrors, which act as light switches, project the light from the source as individual pixels onto the projection surface. The resolution of the projected image corresponds to the number of mirrors. The advantage of DLP technology in comparison to the SLA technique is that every layer can be cured with a single shot of laser exposure by producing patterned laser light rather than scanning each area one after the other with the laser. This advantage makes the construction time independent of the respective layer geometry or the number of objects. The resolution can be higher, depending on the system, due to the pixel-based exposure in the DLP method, but neither of the two techniques can be attributed a fundamental superiority over the other. In principle, the printing process in the SLA and DLP techniques can be divided into three discontinuous steps: light exposure, platform moving, and resin refilling, each of which is separate from the other, with no real printing taking place in the last two. A new technology invented by Tumbleston and others,[11] called continuous liquid interface production (CLIP), addressed this concern, allowing a part to be printed continuously and speeding up the building process. The technology can be combined with SLA or DLP in the bottom-up building approach and takes advantage of the inhibition of radical polymerization by oxygen. An oxygen-permeable membrane is attached to the top layer of the reservoir and is permeable to both UV light and oxygen. Normally, the last printed layer adheres to the surface of the reservoir and causes high peel forces when the building platform is lifted. With CLIP technology, the oxygen-permeable membrane avoids polymerization and adhesion of the bottom layer, which is called the "dead zone." This dead zone is fundamental for continuous printing, as it ensures that a fresh layer of resin is always present below the printed part. The thickness of the dead zone can be controlled by oxygen flux. As a result, the build platform motion can be continuous, and the speed of printing increases. However, CLIP technology also has some disadvantages. First, filled resins can lead to uncontrolled scattering of light at the particles in the dead zone whereby the intensity of the actual laser light reaching the resin may not be enough, potentially compromising print quality. Second, resins differ in their affinity to oxygen, which leads to varying thickness of the dead zones. Thus, the dead zone thickness and oxygen penetration rate are further variables that should be included in the printing settings.[10]

Typically, layer thicknesses between 25 and 100 μm can be converted.[12] A lower layer thickness leads to high-resolution object surfaces but is not conducive to a fast production time. Layer thicknesses of 5 μm along the xy-axis and 10 μm along the z-axis can already be achieved using micro-SLA methods.[13] The layer thickness is influenced by the amount of photoinitiators, the irradiation conditions (wavelength, power, and exposure time), and the temperature of the monomer and absorbent ingredients, such as the pigments. Since most monomers are acrylate based and cannot be activated directly by irradiation, photoinitiators are necessary. Photoinitiators can be classified into two major categories according to the mechanism of free radical generation: α-cleavage and H-abstraction initiators.

α-Cleavage photoinitiators are unimolecular radical generators. During the absorption of UV light, a specific bond within the initiator structure is homolytically cleaved. Both newly produced compounds contain a free radical. Each α-cleavage photo initiator requires UV irradiation within a specific range. Photoinitiators used frequently in dentistry include hydroxyacetophenone, benzoin, benzoin ethers, and phosphine oxides, such as TPO and BAPO.[14-16]

H-abstraction forms the second category of photo initiators. This type of initiator requires a coinitiator, usually an alcohol or amine. Benzophenone is a representative H-abstraction photoinitiator that is commonly used. By absorbing UV irradiation, the photoinitiator enters an excited electron state and abstracts an electron or hydrogen from the coinitiator. The donor molecule then reacts with a monomer to initiate polymerization.[10] Due to the initially short exposure time in 3D printing, 3-5 wt% of photoinitiators are added to the monomers.[12] The initiators should be matched to the light source and have a high molar absorption capacity to achieve high polymerization efficiency and a low curing depth.[12] Depending on the printer, the wavelength of the laser is set at 385 or 405 nm, with new printers tending to use 385 nm. If a 405-nm laser is employed, more initiator is required than that needed for a 385-nm laser due to the absorption spectra of TPO and BAPO. Since the complementary color of the absorbed blue light is yellow, the resins, which are designed for 405 nm, often have an undesirable yellowish tinge. Therefore, for the consumer, it is important to check whether the selected resin can be used with the printer and to ensure that the corresponding printing parameters are stored. By using a pulsed near-infrared laser in combination with two photon initiators, layers up to 300 nm below the light diffraction limit can be generated. However, this approach to the SLA method has thus far been limited to 3D microlabeling.[17-19] By contrast, the iron oxides used as pigments in conventional composites cannot be used in 3D printing resins because of their density, which causes sedimentation to occur. Manufacturers therefore use organic pigments; however, these pigments have the disadvantage of being less stable in the long term than inorganic pigments.

The monomers used for SLA and DLP printers should have a low to moderate viscosity. In SLA-printed structures, brittleness is often observed due to the inhomogeneous cross-linked network resulting from the uneven diffusion of unreacted monomers/oligomers in the vitrification stage or the fast reaction rate in the gelation stage. The most commonly used monomers are methacrylate, epoxy, and functionalized vinyl ether resins. The mechanical properties are limited by the increase in viscosity of the monomers. If fillers are added to increase the mechanical properties (eg, temporary materials or models), then the polarity of the resins, which is also an important factor, is affected. To achieve a uniform dispersion of fillers, a polarity similar to that of the monomers is advantageous. Therefore, surface modification is often used to adjust the filler-resin polarity.[10] If the viscosity is increased by increasing the content of fillers, gravity will no longer be capable of producing a smooth surface. To ensure a homogeneous dispersion of the fillers, manufacturers advise different mixture methods, such as shaking, stirring, or special roller/tilting stirring devices.

The incorporation of fillers also has considerable effects on the printing accuracy, as the light scattering of the material changes due to the addition of these agents. The accuracy depends significantly on the curing depth, which is described by the Beer-Lambert law:[20]

$$z_p = \delta_p \ln \frac{t_p}{T_c}$$

where z_p is the penetration depth in the z direction, t_p is the time it takes to reach the critical dose for polymerization at depth z_p, T_c is the time it takes to reach the critical dose for curing at depth z_0, and δ_p is the characteristic penetration depth, which is also expressed as $\delta_p = 1/\alpha$:

$$\alpha = \frac{4\pi k}{\lambda}$$

where λ is the wavelength of the laser and k is the extinction coefficient.

The extinction coefficient k depends on the intrinsic properties of the resin, which includes the loading of fillers, the surface of the fillers, and the refractive index of both the fillers and the resin. If there is a mismatch in refractive index between the fillers and the resin, the laser light is scattered significantly, resulting in a reduced polymerization depth. This effect can result in the previous layer not connecting to the next layer and the scattered light curing more resin around the laser beam, resulting in a reduced resolution.[10]

In addition to the layer thickness, the orientation of the objects on the building panel is another variable that can influence the printing result with regard to accuracy and mechanical properties like bending strength.[21] Recent research projects developed slant beam rotation scanning, where a laser can rotate and cure the resin from different angles. In a study of printed total dentures, Alharbi and others[22] found an angle of 135° to the building platform to be the most accurate. Vertically printed temporary materials showed significantly higher compressive strength than horizontally printed materials.[23]

To fix the object to the building platform, support structures are printed with both techniques. The support structures, which are in the form of small columns, also prevent overhanging structures from sinking, which would occur due to a change in density during polymerization. After printing, postprocessing follows. This step includes the removal of excess resin with isopropanol, postpolymerization, and reduction of the residual monomer content using light polymerization boxes and separation of the support structures. Postprocessing can vary greatly depending on the manufacturer. For example, UV-, LED-, or flash-based polymerization devices can be used.

SLA and DLP technology are still limited in the processing of several materials in one construction process. A realization of property gradients is therefore not yet possible. Furthermore, the layer-by-layer technique seems to prevent SLA/DLP-printed objects from achieving the mechanical properties of their monolithic counterparts. Additionally, the object is determined by the "stair-stepping" effect caused by the printer's capability to fabricate only straight layers.

While there are many companies that purchase and relabel printing resins from original equipment manufacturers, an example of the actual number of manufacturers is limited (Table 1). SLA and DLP technology is the most advanced 3D printing technology in dentistry. As a result, a large number of application areas are available. 3D-printed tooth models are widely implemented. In a study by Patzelt and others,[24] the superiority of 3D-printed models (dental casts) over milled models could be observed. Hazefeld and others[25] compared three printing technologies (DLP, photopolymer jetting, and binder jetting) and conventional production with regard to the accuracy of the models. However, they could not determine any superiority of a particular method. 3D-printed patient models are based on scanned surfaces or radiological volume data sets and can be helpful to the dentist for planning. However, they are also very popular in teaching and further education.[26]

The use of printed drilling templates to transfer virtual implant planning into reality has become firmly integrated as a standard fabrication method within navigated implantology and is superior to other procedures, such as milling.[27-31] In total prosthetics, patient-specific prosthetic teeth have already been successfully printed using DLP technology.[32,33] Furthermore, there is the possibility of printing long-term temporaries with a release of up to 48 months as well as occlusal splints and orthodontic appliances.

Photopolymer Jetting and Material Jetting

In the photopolymer jetting and material jetting processes, the object is built up in layers by a print head with several linear nozzles (Figure 4). The principle is comparable largely to that of a conventional inkjet printer. Instead of ink drops, a liquid photomonomer is used for photopolymer jetting, and wax is used for material jetting. Subsequently, either the monomer is cured in layers by UV light or the wax solidifies thermally on the building platform. Following the same pattern as the other printing processes, the construction platform lowers by one Z gradation after each layer, and the next layer can be applied. This process allows several print heads to work simultaneously. As a result, objects with different materials, colors, and property gradients are possible.[34] The monomers can contain silica nanofillers, which increase the viscosity and improve the controlled application and the mechanical properties of the finished object.[35]

To print overhangs on objects, support material is required in the same way as for the other procedures. The support either is made of a lower melting wax or, conventionally, consists of columns of the actual building material. If wax is used as a support material, it can be melted out by heat in postprocessing.[36] This is called the "hands-free" method and is particularly suitable for sensitive objects. The surface quality of the objects as well as the print resolution is very high in the photopolymer jetting and material jetting processes and does not require any surface finishing with layer thicknesses of less than 20 μm.[12] Similar to SLA and DLP, the photopolymer is vulnerable to sunlight and heat, and the material can creep over time. For printing, photopolymer jetting and material jetting are the most expansive technologies.

Models with high surface quality can be produced using photopolymer jetting and material jetting processes. Braian and others[37] reported in a comparative study in which four photopolymer jetting printers were compared with respect to two model configurations (inlay and bridge), and the accuracy of the models was <100 μm. Another study confirmed a significantly better fit of interim crowns in the proximal, marginal, and internal areas than ground or directly fabricated PMMA interim crowns

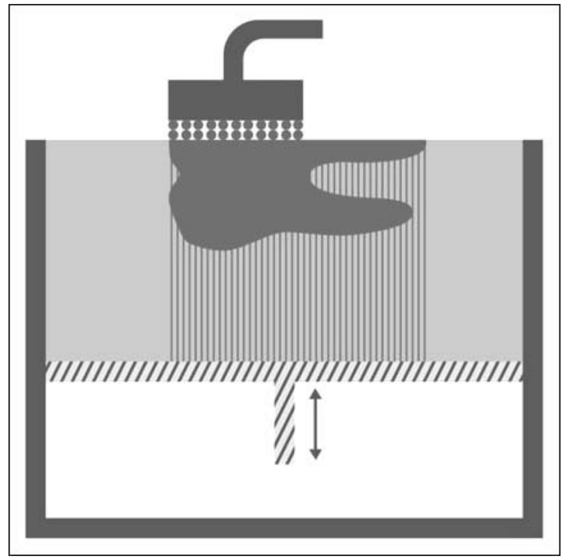


Figure 4. *Photopolymer jetting and material jetting.*

using overimpressions.[38] Metal crowns that were milled conventionally using the lost-wax method and produced using material jetting were also examined. A higher accuracy with regard to the marginal and internal fit of the metal crowns that were made from the printed wax crowns was determined.[39]

Another area of application for the jetting process is the production of prosthetic teeth and implant drilling templates.

Binder Jetting

A variation of the photopolymer jetting process is to apply an adhesive to a powdery substrate using pressure nozzles (Figure 5). After each layer, the building platform descends, and a fresh layer of powder at the level of a Z layer is applied by a blade. Additional support structures are not necessary, as the printed object is completely enclosed by a supporting substrate. If metal and glass powders are used, the object can then be subjected to a sintering process in which the adhesive is burned out. Due to the large adhesive content, the resulting objects exhibit high sinter shrinkage and subsequent porosity and must be subsequently infiltrated. By using several print heads, objects with different colors can be created. Due to the complicated geometries in dentistry, the binder jetting process using powder/adhesive is limited mostly to surgical planning models.

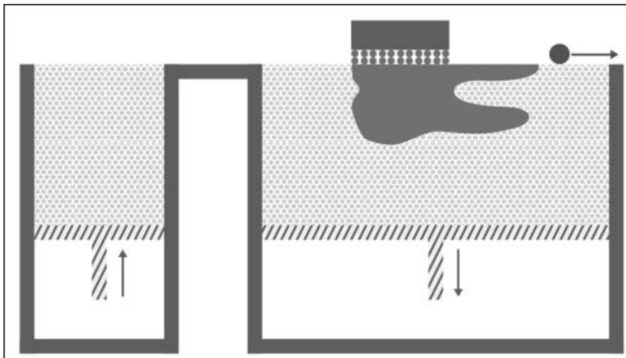
Selective Laser Sintering and Laser Melting

All powdery materials that can be sintered or melted by laser radiation and solidify after cooling can

Table 1: *Overview of Most Common Manufacturers of Stereolithographic and Digital Light Processing Materials*

	Drilling Template	Splint	Orthodontic	Temporary
Deltamed (Friedberg, Germany)	3Delta Guide			3Delta Temp
Detax (Ettlingen, Germany)	Freeprint Ortho Freeprint Splint	Freeprint Ortho Freeprint Splint	Freeprint Ortho	Freeprint Temp
DMG (Hamburg Germany)	Luxaprint Ortho	Luxaprint Ortho Plus	Luxaprint Ortho Plus	
Dreve (Unna, Germany)	FotoDent Guide	FotoDent Splint		
Nextdent (Soesterberg, Netherlands)	NextDent SG	NextDent Ortho Clear, NextDent Ortho Rigid	NextDent Ortho IBT	NextDent MFH, NextDent C&B
Keystone, (Burlington, VT, USA)	KeyGuide	KeySplint Hard, KeySplint Soft		
VOCO (Cuxhaven, Germany)	V Print SG	V Print Ortho		

generally be used for the selective laser sintering or laser melting process. The material spectrum ranges from plastics and metallic materials to ceramic materials. In dentistry, these methods are used mainly for metallic materials.



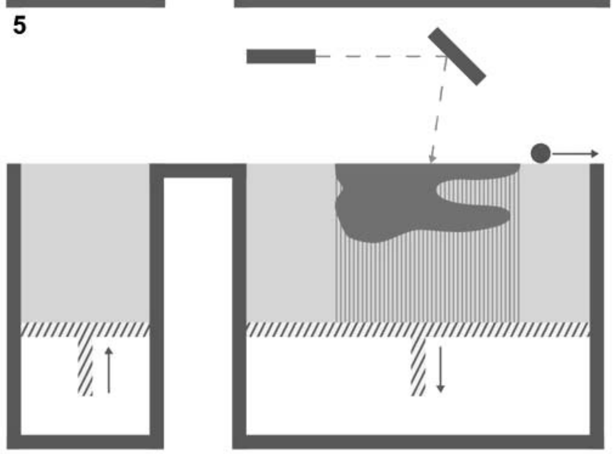


Figure 5. *Binder jetting.*

Figure 6. *Selective laser sintering and laser melting.*

The powder-filled tank is first preheated close to the melting point of the material and above the temperature required for recrystallization during the cooling cycle. Due to the preheating of the powder, the laser requires less energy to fuse or sinter the individual powder particles together, thus avoiding large thermal differences that can otherwise lead to distortion of the objects. High-power CO_2 lasers locally melt or sinter the powder particles two-dimensionally before the installation space is reduced by one-layer thickness after each cycle and a new thin powder layer is applied to the previous layer by a blade (Figure 6). Due to the lack of compression of the particles in the tank, the particle size, shape, and density, as well as the thermal behavior, are decisive factors in the selection of materials. Spherical particles have a lower rolling resistance than irregular particles and can be packed more tightly. Particles that are too small cause processing difficulties due to excessive cohesion or electrostatic repulsion forces.[12] Factors such as the preheating temperature of the powder bed[40] also have an effect on the density of the powder particles.

Because the object is completely enclosed by nonmelted powder, no additional support structure is theoretically required. In practice, however, they have proven their worth, as these structures dissipate heat, reduce internal stress, and decrease distortion of the work piece.[41,42] Since the support structures must be removed in postprocessing, the work piece should be aligned before printing in such a way that the support structures do not lie in the area of the fitting surfaces of the work pieces (eg, partial dentures).[41]

Table 1: *Overview of Most Common Manufacturers of Stereolithographic and Digital Light Processing Materials (ext.)*

Model	Castable	Tray	Denture Base	Gingiva Mask	Others
3Delta Model, 3Delta Model Ortho	3Delta Cast, 3Delta Cast P				
Freeprint model T, Freeprint Model	Freeprint Cast	Freeprint Tray			
Luxaprint Model	Luxaprint Cast	Luxaprint Tray			
FotoDent Model, FotoDent Model2, FotoDent Setup	FotoDent Cast	FotoDent Tray	FotoDent Denture	FotoDent Gingiva	
NextDent Model 2.0, NextDent Model Ortho	NextDent Cast	NextDent Tray	NextDent Denture 3+	NextDent Gingiva Mask	NextDent Try-In
KeyModel, KeyOrthoModel	KeyCast			KeyMask	
V Print Model					V Education

The terms "laser sintering" and "laser melting" are interpreted inconsistently. The two processes are further divided into several subcategories, some of which represent the brand names of certain companies (eg, direct metal laser sintering or laser CUSING). However, the basic printer construction principle is the same. Selective laser sintering is defined as sintering the individual layers of an object, which means that a laser fuses the individual material particles on the surface. Thus, only a partial melting process occurs.

In selective laser melting, however, the material powder is locally melted directly at the processing point. If an electron beam is used instead of a laser, the process is called electron beam melting. It is advantageous to carry out both processes under inert gas. The process is used on a range of metals, alloys, and plastics in dentistry for the fabrication of frameworks, crowns, model casting bases, and models. The most common metals used are Cr-Co and titanium. To achieve a high resolution in the vertical direction with metals, lasers with a power of more than 100 W, a beam diameter of 0.2-0.4 μm, and a resulting layer thickness of 30 μm are used.[42] Printed model casting bases are now comparable with traditionally produced bases.[41] Optimized processes lead to a material density of 99.98% for titanium, but the resulting products have a rough surface because of the size of the powder particles and require finishing.[42]

Metal-free materials include polyamides (Pa6, Pa12, PA10, Pa11, P12, and nylon), polystyrenes, polycarbonates, acrylonitrile-butadiene-styrene, and polyether ether ketone (PEEK), which are increasing in use in dentistry. Since most commercial SLS printers reach a maximum operating temperature of approximately 200°C, they do not allow printing of high-performance polymers such as PEEK, which require temperatures of up to 345°C.[43] Moreover, the current high costs of machines that can print polymers such as PEEK make them inaccessible to the majority of users. Furthermore, the high processing temperatures limit the potential recycling of the non-fused PEEK powder, which increases the production effort and costs. Polyamides are processed with a layer thicknesses of 100 μm and polymer particles of 30-90 μm at a laser power of 20-50 W. The layer thickness along the Z axis thus consists of an average of two to four particles.[12] Initial tests have already been carried out with PMMA printing, but the printing resolution and mechanical properties are still too low for commercial use in dentistry.[44]

Fused Filament Fabrication

The melt layer process was developed over 20 years ago by the founder of Stratasys (Edina, MN, USA) and protected by the trade name "fused deposition modeling." The processes called fused deposition modeling and the nonpatented term "fused filament fabrication" (FFF) work according to the principle of strand extrusion (Figure 7). Thermoplastic materials, such as polylactides, acrylonitrile-butadiene-styrene, and waxes, are supplied as semifinished products in various strand thicknesses to the extruder, where they are melted in the hot end and applied to the building board through a die at the respective xy-coordinate. Heated construction chambers can be used to minimize heat distortion in cases of uneven cooling. After completion of a one-layer plane, the construction panel is lowered onto the z-axis, and the next layer is started. Due to the reduced bonding of

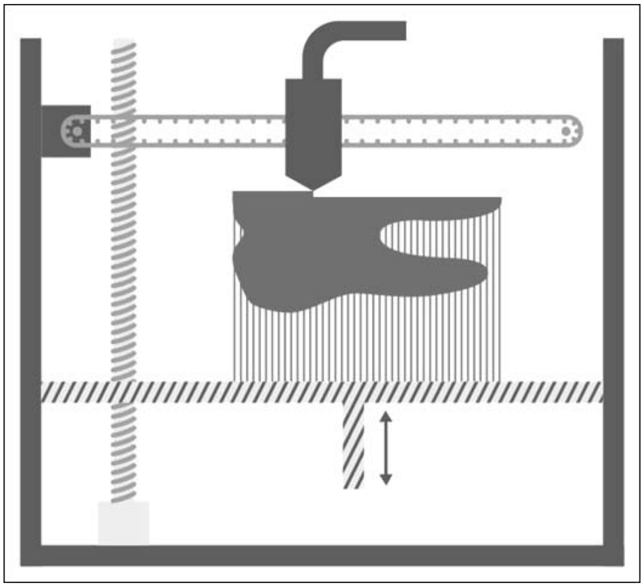


Figure 7. *Fused filament fabrication.*

the individual layers in FFF compared to the SLS and SLA processes, objects with increased anisotropy are created. This results in direction-dependent material properties, thus requiring special attention to be paid to the alignment of the objects before the printing process. If support structures are needed, they can be built up with the same material and then removed or produced from a water-soluble wax using a dual extruder. The surface of the objects is usually more stepped than with other methods due to the layer thicknesses of 200 μm.

The advantage of FFF is its cost efficiency and the lack of restrictions on materials. In general, all materials that can be extruded could be used. In terms of process technology, FFF shows potential superiority over other processes since objects with different material gradients can be produced with several extruders. At present, however, its use in the dental field is very limited. In addition to foam models, individual impression trays have been produced.[45]

Table 2: *Overview of 3D Printing Techniques and Their Most Important Features*

	SLA/DLP	**PJ/MJ**	**BJ**	**SLS/SLM**	**FFF**
Additive manufacturing process	Photopolymerization	Material jetting	Jetting	Powder bed fusion	Material extrusion
Material	Photopolymer resin	Photopolymer resin	Material in powder consistency (metal, ceramic, plastic)	Material in powder consistency (Co-Cr, titanium, PEEK, polyamides)	Thermoplastic filament (PLA, ABS, TPU, ASA)
Average layer thickness (μm)	25-100	16	50-100	30-100	178 or 254
Average xy resolution (μm)	30-150	42	60-100	200	200-400
Acquisition costs	$-$$	$$$	$$	$$$$	$
Application in dentistry	Model, castable, surgical guide, splint, tray, temporary restauration, gingiva mask, denture	Model, castable, surgical guide	Model	Crowns, implants, partial dentures	Model
Multicolor	No	Yes	Yes	no	Yes
Support structure needed	Yes	Yes	No	no	Yes
Strength	Smooth surface, fine details, most materials	Smoothest surface, fine details, multicolor	Low cost, multicolor, large build volumes, fast build, no support structure	High detail, objects with high density and mechanical properties, no support structure	Low cost, multicolor
Weakness	Only photopolymers, relative brittle materials, vulnerable to sunlight and heat	Only photopolymers, relatively brittle materials, high costs for photopolymer printing, vulnerable to sunlight and heat	Low mechanical properties, low details	Highest cost, special CAD software required, rough surface	Brittle materials, rough surface and low details, anisotropic mechanical properties

Abbreviations: SLA, stereolithography; DLP, digital light processing; PJ, photopolymer jetting; MJ, material jetting; BJ, binder jetting; SLS, selective laser sintering; SLM, selective laser melting; FFF, fused filament fabrication; PLA, polylactides; ABS, acrylonitrile-butadiene-styrene; TPU, Thermoplastic Polyurethane; ASA, Acrylonitrile Styrene Acrylate; CAD, computer-aided design.

CONCLUSIONS

This article intended to provide a practical and scientific overview of the nature, application, advantages, and disadvantages of the different additive procedures in dentistry (Table 2). Various additive processes are on a par with or superior to established manufacturing processes and already offer considerable advantages. Due to the elimination of production restrictions, it is possible to produce dental work on an industrial level, economically and with increased complexity on-site. As an integral part of Industrialization 4.0, we are currently experiencing the beginnings of the additive age. At present, promising processes are developing in parallel with each other; which of these processes will ultimately prevail is still unknown.

Future developments in dentistry must aim at optimizing surface quality and increasing process reliability and property gradients within the materials at lower costs and with shorter production times.

Conflict of Interest

The authors of this article certify that they have no proprietary, financial, or other personal interest of any nature or kind in any product, service, and/or company that is presented in this article.

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