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Additive manufacturing of dental polymers: An overview on processes, materials and applications

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Keywords: Additive manufacturing, Polymer, 3D printing

INTRODUCTION

Additive manufacturing (AM) processes are increasingly used in dentistry. There are a variety of AM processes and a variety of materials that can be used to build a computer aided design (CAD) object. The underlying process of AM is the joining of material layer by layer based on 3D data models (1-4). All AM processes are based on a process chain for the production of three-dimensional physical components, which can be divided into two levels: The virtual level consists of data acquisition and data processing, the real level of subsequent post-processing (5). Data acquisition can be carried out by several technologies. Computerized tomography (CT), magnetic resonance imaging (MRI), laser digitizing or cone beam computed tomography (CBCT) are commonly used (6). Data processing describes the process of the virtual design of the object via CAD software. Afterwards an STL file is produced which can be used with the printers software to modify building variables and parameters for the manufacturing process (6). Afterwards in the process of additive fabrication the building of the object takes place based on the STL file imported to the printer (6). According to the manufacturers recommendations a post-processing (e.g. cleaning, post-curing) of the object built is necessary depending on the printer used (6). Regardless of the method used, all additive technologies differ from subtractive methods by several aspects showed in Table 1 (1-3,6-18). Compared to materials such as ceramics and metals, the use of polymers in AM is still under development. There are several printers for AM of polymers for dental applications available on the market (6). They differ in the technology used as well as in the resolution, accuracy and repeatability. In terms of clinical usability, it depends on how accurately the processes can produce dental appliances. Here the distinction between the terms resolution, accuracy and repeatability plays an important role. Resolution is the finest or smallest feature of an object that the 3D printer can reproduce and that is specific to each technology and each printer (6). It should be defined in all three axes (x, y and z axes) in µm or dots per inch (DPI; measure of resolution). The z axis is usually corresponding to the layer thickness. Precision or repeatability is the ability of a 3D printer to produce objects with exactly the same 3D dimensions.

In the dental digital workflow, deviations can occur at any stage of the treatment and manufacturing process. In addition, the type of technology selected, the 3D printer used and the material used for the additive production of the desired object also determine the accuracy of fit later on. Not all printers that produce an object with the same technology have the same resolution options. In addition, there are material-specific differences (wavelength, power, exposure time, etc. required for the activation range). Post-processing also plays an important role in avoiding fitting inaccuracies. Among the factors that influence the accuracy of the object produced with AM are: laser speed, laser intensity, construction direction (13,16), number of layers (11,12,17), the software used (15), shrinkage processes (14,17), the amount of carrier...
### Table 1 Differences between additive technologies and subtractive methods

| Characteristics of additive processes |
|--------------------------------------|
| • layered, vertically directed construction of the object |
| • no material losses/unused material can be recycled and reused |
| • possibility to produce large objects (limitation: size of the construction chamber) |
| • passive production (no force required, e.g. for milling) |
| • detailed production based on digitalized data (calculation from CT, MRI data or by means of scanning processes) |
| • reproducibility |
| • production of customized, individual products of different consistency and material properties within a workpiece |

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**MATERIALS AND METHODS**

A literature search for processing polymers in dentistry using AM was carried out using pubmed, cochrane library, google scholar and medline search engines. In addition, the use of google search engine also included grey literature. Included were publications between 1980 and March 2018. The keywords used were: rapid prototyping OR 3D printing OR additive manufacturing AND dent*/prosthodontics/complete denture/denture/polymer*/dental polymer. In addition, a manual search was carried out in referenced books and papers.

**RESULTS**

**AM processes for processing dental polymers**

Four additive processes are mainly used for the processing of dental polymers. These are polymerization processes such as laser stereolithography (SLA), polymer jetting (MJ) and digital light processing (DLP). On the other hand, the process of material extrusion (ME) using fused deposition modeling (FDM) is common.

**Polymerization processes**

1. **Stereolithography (SLA)**

   The original SLA process, referred to as 3D printing, was invented by the American Charles “Chuck” Hall19,20. He described and patented the SLA procedure for 3D Systems as early as 198621. At about the same time, professor André developed another patent for the same technology in France22,23. The term SLA refers to the layerwise crosslinking (polymerization) of light-curing resins initiated by ultraviolet (UV) laser radiation (wavelength between 200–500 nm)24. The process is carried out from bottom to top by repeated flooding of the construction chamber with the monomer and selective polymerization by laser based on CAD data. The laser solidifies the respective layer and simultaneously connects it to the layer below it. Necessary support structures are built from the same material. In general, the process is characterized by high accuracy9,25,26, smooth surfaces and attention to detail27. The construction speed is to be regarded as low. However, it is advantageous that several objects can be produced simultaneously2. The degree of curing influences the resolution in the z-axis. Curing depends on the photoinitiator used, the type of laser used (wavelength, exposure time, strength, etc.) and added pigments or UV-absorbing substances28. The mechanical properties of the components produced are limited by the viscosity of the materials used28. However, the end products exhibit only low anisotropy and good strength properties28. Decisive for the further development in this area is the adaptation of the process for newly developed materials (polypropylene (PP), acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC)), especially with regard to the working time, expenditure for post-processing, required curing processes and ageing properties21. Another aim should be the production of multi-colored end products21. Currently, filled and unfilled epoxy and/or acrylic resins are available.

2. **Polymer jetting (material jetting; MJ)**

   MJ was developed back in 1994 by researchers at the Massachusetts Institute of Technology (MIT). In the process the material is applied to the construction platform with the aid of a piezoelectric multiple print heads. UV lamps, which move synchronously with the print head (x-y-direction) are used for the polymerization of liquid monomers24,29. By lowering the construction platform in the z-direction, the components are assembled from bottom to top. It is necessary to establish support structures generated simultaneously by a second set of nozzles. Due to the high output of the UV lamps, very thin layers can be produced (16–20 µm), resulting in a very high surface quality. Therefore, post-processing is no longer necessary29. A large amount of material is required due to the design principle with supporting structures. However, it is positive the supporting structures can be washed out without on the surface. Multi-colored materials can be used21,30. Furthermore, a large number of materials with different physical properties can be used simultaneously2,31. Where a high resolution is specific for this kind of processing2 with regard to the accuracy, there is a lack of data in the field of dental polymers.
3. Digital light processing (DLP)
DLP was invented by Larry Hornbeck (Texas Instruments) in 1987\textsuperscript{32}. Below the building chamber, directly under a glass plate, there is a DLP projector used for polymerization via UV radiation, which projects the contour of the component to be produced onto the building platform into the applied resin and simultaneously solidifies it according to the contour. The construction platform dips down into the liquid monomer from above. The penetration depth and the resulting distance to the glass bottom of the construction chamber correspond to the layer thickness. After the resin has solidified, the platform rises. Resin flows, supported by negative pressure, again onto the glass plate. The polymerization process is now repeated. A variety of photosensitive polymers with good biocompatibility are available for the described process\textsuperscript{5,29}.

\textit{Extrusion/fused layer modeling (FLM)}

In contrast to the processes described so far, FLM is characterized by the application of molten materials in paste form.

1. Fused deposition modeling (FDM)
A trademark registered by Stratasys (Stratasys Company, Eden Prairie, MN, USA) is known as FDM\textsuperscript{33}. The process was developed by S. Scott Crump in the late 1980s\textsuperscript{2}. The FDM already processes semi-finished products, extruding them layer by layer\textsuperscript{39}. Machines for FDM consist of a heated construction chamber and a heatable nozzle head, which is responsible for depositing the material in the x-y-direction. The layer thickness of the applied material is essentially determined by the cross-section of the nozzle head. Depending on the process, a layer thickness of 0.1 to 0.25 mm is possible. The construction platform is responsible for the three-dimensional construction (z-direction). The use of supporting structures is absolutely essential. The supporting structures are constructed simultaneously by a separate nozzle. In principle, simultaneous construction is possible using different materials or materials of different colors. The poorer mechanical properties of the end products result from anisotropic material behavior (characteristic layer deposition in different directions)\textsuperscript{21}. The range of materials available is wide. In addition to polymers such as ABS, PC-ABS and PC, thermoplastics, which must be processed at the highest temperatures, are also used (e.g. polypenlynsulfone (PPSF)). They are available as filaments with a diameter of 1.75±0.05 mm\textsuperscript{33}. Also available are poliyamide (PA), polystyrene (PS), polyetherimide (PEI) and polyoxymethylene (POM) as well as polyethylene (PE)\textsuperscript{40}. In addition materials of different colors are available. However, multi-colored components are currently not yet possible, as the cartridge cannot be changed with the material during the process. In the future, however, it is conceivable that this problem can also be solved by the simultaneous use of several nozzles. The surface quality immediately after manufacture is often insufficient (large layer thickness). Post processing is necessary. At the same time, however, the accuracy of the parts may be negatively affected by the post-processing. Research also focuses on the development of materials to improve the resulting thermal, electrical and magnetic properties\textsuperscript{21}.

Polymers for additive processes in dental technology
In the field of dentistry, the number of materials that can be used for AM of polymers is small compared to other areas. Table 2 gives an overview of available polymers for AM and their characteristics divided by the underlying chemical reaction.

Based on the chemical reaction, the following classes of polymers can be classified:

\textit{Polymerization}

1. Vinyl polymers
Vinyl Polymers, e.g. polyvinyl alcohol (PVAL) are often used as carrier structures. They are characterized by deterioration of mechanical properties at high humidity. Also they are water-soluble and biodegradable. Their production is cost-intensive.

2. Styrene polymers
Styrene polymers include polystyrene (PS) and acrylonitrile-butadiene-styrene (ABS).

PS is used for a wide range of applications and suitable for almost all processing methods. It is possible to use additives to modify properties. PS show a large dependence of the resulting characteristics on the type of processing. Processing is adjustable due to the temperature dependence of the melt viscosity. PS is characterized by a non-crystalline, amorphous state, stiffness, rigidity, brittleness. There is a tendency to stress cracking. PS shows a high dimensional stability, good workability and low water uptake. On the other hand, it has a limited chemical resistance to organic substances. PS is transparent with a brilliant surface and very good electrical and dielectric properties.

ABS results of a block co-polymerization of butadiene and styrene. Processing is possible as with thermoplastics. It is characterized by an easy postprocessing, high melting point (requires temperatures of 220°C) and a warp effect (upward curvature of first material layer). ABS is biodegradable. It has a higher impact strength and higher resistance to stress cracking compared to PS. Also a higher absorption capacity for deformation work can be observed. ABS is known for an increased breaking strength, a high mechanical strength, great rigidity, high hardness, scratch resistance and a good dimensional stability under heat, relatively low water absorption, high thermal shock, wet and chemical resistance. It is available in natural colors (yellowish opaque) and can be offered in different colors.

3. Acrylates
Acrylates are the polymers of acrylic acid or methacrylic acid and their esters.

PMMA is industrially usable since 1933. In dentistry it is used as a filling and replacement material. Its brittleness can be influenced by adding modified
Table 2  Overview of the applications of additive processes in dentistry and dental technology

| Application | Literature |
|-------------|------------|
| **Fused deposition modeling (FDM)** | Chen *et al.* 2016(1) |
| custom trays | Alghazzawi 2016(2); Solaberrieta *et al.* 2014(3) |
| prototype of complete dentures made of ABS or polycarbonate | Jimenez *et al.* 2015(4) |
| casts for the fabrication of orthodontic splints | Fuenmayor *et al.* 2018(5); Fina *et al.* 2018(6) |
| medical carrier substances/medicines | Wendel *et al.* 2008(7); Zein *et al.* 2002(8); Serra *et al.* 2013(9) |
| **Stereo-lithographie (SLA)** | Alghazzawi 2016(2) |
| orthodontic appliances | Maeda *et al.* 1994(10) |
| cast fabrication | Elomaa *et al.* 2011(11) |
| complete dentures | Yu *et al.* 2018(12) |
| biological frameworks (polycaprolactone) | Alharbi *et al.* 2016(13) |
| implant drilling guides | Cascón *et al.* 2019(14) |
| provisional crowns | Cascón *et al.* 2018(15) |
| esthetic diagnostic template | |
| custom tray | |
| **Digital light processing (DLP)** | Alghazzawi 2016(2) |
| cast fabrication | Alghazzawi 2016(2) |
| temporary restorations | Williams *et al.* 2004(16) |
| frameworks for removable dentures | Revilla-León *et al.* 2017(17) |
| custom trays | Bilgin *et al.* 2015(18) |
| production of artificial teeth for complete dentures | Revilla-León *et al.* 2019(19) |
| silicone index for provisional try-in | |
| **Polymer jetting/material jetting (MJ)** | Inokoshi *et al.* 2012(20) |
| prototype of complete denture for try-in | Alghazzawi 2016(2); Kanazawa *et al.* 2018(21) |
| custom trays | Alghazzawi 2016(2); Jimenez *et al.* 2015(22) |
| cast fabrication | Werz *et al.* 2018(23); Fernandes *et al.* 2018(24); Kim *et al.* 2019(25) |
| simulation models in surgery | Alghazzawi 2016(2) |
| implant drilling guides | Alghazzawi 2016(2); Bibb *et al.* 2006(26,27) |
| models for frameworks, crowns, bridges, inlays, onlays, veneers, model casting frameworks | Silva *et al.* 2007(28); Marga *et al.* 2012(29); Hockaday *et al.* 2012(30); Athirasala *et al.* 2018(31); Yu *et al.* 2017(32); Park *et al.* 2018(33); Panayotov *et al.* 2016(34) |
| tissue regeneration | |
| dental implants, abutments | Wendel *et al.* 2008(35) |
| dental prosthesis base for digitally manufactured complete dentures | |
| biodegradable implants with medical active ingredients (e.g. antibiotics) bioresorbable bio-composites and bio-ceramics | |
| production of artificial teeth for complete dentures | Bilgin *et al.* 2015(36) |

polyacrylic esters or elastomers and can be converted into increased impact strength by co-polymers. Acrylonitrile additive increases initial chemical resistance. A residual monomer content (2–6%) is typical. PMMA is characterized by a high hardness, stiffness and strength, low moisture and water absorption. The surface is polishable, scratch-resistant with a high-gloss.

PMMA shows a water-bright transparency. A color addition is possible. PMMA has a high dimensional stability in heat and resistance to chemical influences and weathering. It is well known for good processing and repair possibilities. It is sterilizable (not steam sterilizable, high water absorption from 100°C).

**Polycondensates**

1. Polyesters

Polyesters are saturated, linear or thermoplastic condensates.

Polycarbonate (PC)—known since 1956—is synthesized of bisphenol A and phosgene. They are linear, thermoplastic polyesters of carbonic acid with aliphatic or aromatic di-hydroxy compounds. PC is frequently used in the field of medical technology(35,36). Its properties can be modified by adding additives. At the moment PC can be used as a medical device (scope ISO 10993-1) for temporary contact with tissues, blood or other body fluids for up to 30 days. PC is characterized by a mostly amorphous (requires good toughness) state.
The degree of crystallization is less than 5%. It shows a high strength, hardness and toughness, low water uptake. PC is transparent and translucent\(^\text{35,36}\). There are limitations in the number of available colors and pigments due to the desired and technically necessary resistance to high temperatures. PC has a good heat deflection temperature, a good dimensional stability due to low shrinkage, a high electrical insulating capacity/good dielectric strength as well as a resistance to high-energy radiation. PC also shows a low water absorption capacity, easy workability and high notch sensitivity. A thermo- and photo-oxidative damage may lead to a yellowing of the material. Functional additives (e.g. phosphites, phosphines, 2-hydroxybenzophenones) can be used to counteract this effect. PC can be used in medicine due to its biocompatibility. Although it has no resistance to continuous exposure to hot water but against alcohol, water, fats, oils, milk, fruit juices, diluted acids and alkalies\(^\text{35}\).

2. Polyamides (PA)
PA is industrially produced since 1936. A great variety of PA is known and modifications are possible. Therefore, it is suitable for many technical applications. PA is characterized by a high strength, rigidity and hardness. It shows a dimensional stability under the influence of heat and very good electrical insulating properties. A high damping capacity and a high resistance to solvents, fuels and lubricants as well as a high wear resistance can be observed. PAs are biocompatible. There mechanical properties depend on the moisture content of the workpiece. The color depends on its structure: aromatic PAs have a water-bright transparency, aliphatic PAs are semi-crystalline/opaque.

Polyamide 11/12 is an aliphatic PA. (monomer of PA 11: aminoundecanoic acid; monomer of PA 12: laurinlactam). The use of functional, filling and reinforcing additives is well known. The material is softer and the melting temperature lower. The slower the material cools down during processing, the higher is its crystallinity (high degree of crystallization corresponds to low water absorption, improved mechanical properties and abrasion resistance). PA 12 is suitable for SLS\(^\text{21}\). Both show a low water absorption (PA 12<PA 11) and dimensional stability compared to other PA. PA 11 is characterized by a lower hardness and stiffness. PA 12 shows a higher resistance to stress corrosion. PA 12 shows a low melting temperature/thermal conductivity, large interval between melting and crystallization temperature, low viscosity and high surface tension.

Thermo-plastic polyamide elastomers combine a good processability of thermoplastics with the properties of elastomers. Flexible PA 12 is characterized by a high flexibility, low-temperature impact strength and a semi-crystalline structure. Its hardness, modulus of elasticity and strength is reduced compared to classic PA 12. Also it shows an improved resistance to hot water and hydrolysis, a deterioration of resistance to chemical agents and a reduction of the melting range and dimensional stability in heat. Flexible PA 11 has a low density, high flexibility and flexural fatigue strength as well as a high impact strength and resilience with low hysteresis. It is chemically resistant. Flexible PA 11 is physiologically harmless and healthy\(^\text{35}\).

Nylon/PA 66 were made industrially usable by Wallace H. Carothers in 1937. Its monomers are hexamethylenediamine and adipic acid. It is an aliphatic PA. By the use of additives, fillers and reinforcing materials a modification of properties can be reached\(^\text{35}\).

Nylon/PA 66 were characterized by high hardness, stiffness, abrasion resistance, low water absorption and dimensional stability under the influence of heat. PA 66 has a characteristic structure with carbonamide groups arranged opposite each other so that each functional group reaches a high melting temperature (255°C).

3. Polyether-ketones
Polyether-etherketone (PEEK) was developed by the Du Pont company in 1979. It is a high-performance polymer and belongs to the thermoplastics.

It is easy to apply without additives\(^\text{36}\) and can be used for multiple applications\(^\text{35}\). Structural changes can improve biomechanical and biological properties\(^\text{35}\). Unfilled PEEK materials or PEEK-composites show a different melt index and molecular weight\(^\text{35}\) which can be modified by the integration of nanoparticles (e.g. SiO\(_2\), Al\(_2\)O\(_3\) etc.). PEEK materials with modified bioactive surfaces are versatility and can be used in implantology, facial and cranial reconstructions or as dental prostheses\(^\text{35}\). The future material development should be linked to the further development of 3D printing processes\(^\text{35}\). PEEK has a glass transition temperature of 143°C, a melting temperature of 334°C and reaches a crystallization maximum of 48%\(^\text{35}\). PEEK is characterized by a lower glass and melting point, a high tensile and bending strength, impact strength and alternating strength. The Young’s modulus of 3–4 GPa is near the one of human bone (7–30 GPa)\(^\text{39}\). It is dimensionally stable at heat and shows good sliding and wear behavior. A resistance in the human body is known\(^\text{35}\). PEEK has a high resistance to chemicals, radiation and hydrolysis (except sulphuric acid)\(^\text{45}\) and a high in-vitro biocompatibility (non-cytotoxicity)\(^\text{35}\). Its natural radiolucent makes it compatible with MRI examinations\(^\text{42,43}\). PEEK can be modified to PEE-LT 1 by addition of various bioactive substances (e.g. hydroxyapatite, tricalcium phosphate)\(^\text{37}\). Carbon-reinforced PEEK (CFR-PEEK) shows an increased modulus of elasticity and improved breaking strength, with decreasing elasticity. Glass fiber reinforced PEEK (GFR-PEEK) has an E-module near cortical bone.

Polyadducts
Epoxy resin (also: epoxy or ethoxylin resin; EP) was developed by Company De Trey, Zurich in 1938. It is available for a variety of possible manufacturing processes. Currently EP is produced almost completely from the reaction of bisphenol A (from phenol and acetone) and epichlorohydrin (from propylene and chlorine). The polycondensates of thermoplastic EP are
linear and high molecular, characterized by one or more terminal, reactive epoxy or hydroxyl groups. EP shows low shrinkage and a low tendency to stress cracking. It is curing by air drying. Due to the lack of separation of reaction products there can only be found a few microporosities which results in a good ageing behavior. EP is also characterized by a high tensile or dynamic strength and a high dimensional stability at heat and heat resistance. It is categorized non-toxic and harmless to health.

**Natural polymers/bio-polymers**

Polylactide (also polylactic acid, PLA) is aliphatic polyesters produced by polycondensation of lactic acid or polyglycolic acid. The melting temperature of PLA of 160 to 220°C makes it possible to dispense with heatable printing plates during the processing. PLA is also called biopolymers (degradable polymers based on renewable raw materials). PLA is a semi-crystalline thermoplastic material with a high resistance to grease, alcohol and moisture. Depending on modification it is rigid or flexible. It could appear transparent, but is colorable and has a glossy surface.

**Further developments in the field of dental polymers**

In the area of AM of polymers, new and further developments of materials are currently taking place due to the increasing demand. In material development, biocompatibility and the possibility of using materials not only temporarily under oral conditions seem to be of primary importance. Especially for the production of dental prostheses there is a lack of suitable dental polymers, which can remain in the mouth for a long time (currently no material is suitable for intraoral use for longer than 12 months). At the moment, only a small number of additive manufactured polymers, approved for interim dental applications, are available. They can be divided into two groups based on their chemical composition (monomethacrylates or acrylic resin; dimethacrylates and urethane dimethacrylate (polymerisation induced by light))

Often specifications of the provisional AM polymers are not provided by the manufacturers. It is therefore necessary to compare these materials with conventional materials used for dental applications.

In addition, possible materials must be processable using AM technology and at the same time—the physical properties required for the end product—can be integrated. Mechanical properties such as flexural strength, hardness, impact strength and color stability are important regarding the usage of provisional dental restorations for a longer period of time.

An example of the further development of materials has been described by Rimell and Marquis. They developed an ultra-high molecular weight polyethylene for the production of dental workpieces by selective laser sintering. However, the material showed high shrinkage and porosity. They concluded that other starting materials (higher-density powders) would be necessary for successful use in order to achieve better final results.

Hart et al. describe the development of biocompatible supramolecular polymers (PCL) and their composites for use in regenerative medicine. They point out that by changing the initial polymer with a terminal benzyl group, the best printing results in terms of resolution were achieved. Further modifications using hybridization with silicate particles completed the test series. All designed polymers met the ISO 10993-5 and 10993-12 standards for cytotoxicity and biocompatibility.

Suwanprateeb described the use of a mixture of the natural products starch, cellulose, gelatine and maltodextrin. This mixture was added using AM (Z400, Z Corporation). Subsequently, a polymer consisting of triethylene glycol dimethacrylate (TEGDMA), bis-GMA and urethane dimethacrylate (UDMA) was infiltrated and photopolymerized. The modulus of elasticity and the flexural strength of the natural starting materials have been increased. First in-vitro tests showed no toxicity. Linan et al. developed three biocompatible polymers (PMMA-60, PMMA-70, PMMA-56) for use in human medicine in a pilot study. The polymers produced had improved properties compared to conventional PMMA. They concluded that in this way ideal PMMAs adapted to the intended use can be produced in the future. The toxicity of the described polymers was tested both in vitro and in vivo (cell tests, animal experiments). The development of an antimicrobial, printable polymer was described by Yue et al.: For this purpose, positively charged monomers with terminal alkyl chains, which are decisive for the antibacterial effect, are co-polymerized with conventional dental polymers. The printed objects had almost identical mechanical properties as objects produced without the addition of antimicrobial monomers. The antimicrobial effect is based on contact inhibition of the bacteria and not on the release of an antimicrobial agent. Steinhaus et al. investigated the 3DP with PMMA as powder and a liquid binder consisting of 2-hydroxyethyl methacrylate (HEMA) and phenylethylene (styrene). It was shown that the styrene concentration has a decisive influence on the polymerization reaction. It reduces thermal stress and enables stress reduction in the material. The age of the binder material also significantly influences the polymerization process.

In addition to the further development of polymers, the improvement of photoinitiators also leads to an increase in the polymerization process and its speed, in turn, to an improvement in the material properties in end products in dentistry. Lee et al. describe the beneficial use of the photoinitiator 4,4’-bis(N,N-diethylamino) benzophenone (DEABP) in combination with a camphor quinone amine.

**Applications of additive processes in dentistry and dental technology**

Additive processes for processing polymers in dental technology and dentistry are already used in many different ways (Table 2, Fig. 1).

There is a variety of materials available for AM printers for dental applications. In regard to dental
polymers further development and improvement in terms of material development, biocompatibility and the possibility of using materials not only as temporarily but as definitive reconstructions under oral conditions is needed to implement this material in the daily dental digital workflow. Also mechanically more stable materials where less or no post-processing is needed are required. Therefore applications in dentistry using AM are at the moment limited to study models, custom trays, surgical guides, maxillo-facial prostheses, orthodontic appliances and mock-ups.

**DISCUSSION**

The greatest challenge currently lies in developing suitable materials for production using additive processes\(^3\). Important parameters of suitable dental polymers are viscosity and high speed in the polymerization process. The viscosity should not be too high or too low for processing. It is also disturbing to accelerate polymerization by adding high concentrations of photoinitiators at the expense of high residual monomer concentrations in the end product\(^2\).

It can be assumed that digital dentistry and the associated additive and subtractive manufacturing processes will increasingly find their way into clinical practice\(^5\). The use of this technology makes diagnosis easier and faster. Digital technologies also promote patient education and communication\(^5\). According to Prithviraj et al., the advantages of additive methods (reduction of waste products, reuse of materials, enabling mass production in a shorter time, etc.) will replace subtractive methods in the future. It is to be expected that manufacturing processes that allow the integration of dental prostheses on the same day will also expand into other areas of dental prosthetics (e.g. fixed and removable restorations, full dentures)\(^5\). The fields of application of additive procedures in dentistry and dental technology are not only in the clinical field. Thus, cost-effective and individually printed models can also be used in the area of training and further education of dentists and surgeons\(^5\). The use of additive procedures in dentistry and dental technology is on the advance. In order to be able to use these methods in a targeted manner, however, further development work is required —both in the area of hardware and software\(^5\) and, above all, in the area of material development and testing. The integration of additive procedures within medicine and dentistry is also proving to be difficult because interdisciplinary knowledge from the fields of medicine and engineering is necessary for implementation\(^5\).

In the field of additive procedures in dental technology, the use of ceramics and above all metals is now common. Currently, the demand and use of additive processes —especially in the field of polymers— is low. However, further growth can and should be expected\(^5\).
The additive processing of polymers requires further research both in the field of applied processes and techniques and in the field of processable materials. Additive polymers can be predicted to be of great importance with regard to their fields of application²⁸. The importance of AM in dentistry and dental technology should not be underestimated: These processes allow individually manufactured, personalized end products to be manufactured economically in small quantities²⁹. The current rapid development in the field of AM in dentistry and dental technology is certainly also based on the high affinity in dentistry for the processing of light- and UV-curing polymers. The photopolymerization process is particularly attractive for use in the field of dentistry. This enables good resolutions and resulting smooth surface structures to be achieved without the need for additional processing steps in the form of post-processing. Furthermore, factors such as a short construction time, geometric variety of the end products and good strength in the direction of the z-axis (due to the layered construction method) are characteristic²⁸ and advantageous. The additive processes of FDM, 3DP and selective mask sintering can be regarded as promising processes for the future, not least because of their fast processing speed²¹. Currently, series production with the aid of additive processes is limited by the relatively long construction times. A solution for this problem could be the enlargement of the construction chambers²¹. Overall, it can be assumed that from the time when the advantages of additive methods exceed their limitations, the demand for the use of the methods will increase²¹. For this, however, higher requirements must be achieved, especially in the area of medical devices²⁸. The material development represents a decisive process for the utilization of the procedures: The use of several materials simultaneously and the improvement of dimensional accuracy are of decisive importance²¹. Due to the high sensitivity of the currently available materials with regard to the conditions in the manufacturing process, the same material, if used in different systems, can lead to different end results²⁹. Due to the multitude of materials and processes available, it is necessary to define standards²⁹. Regarding the terminology used in AM, guidelines (ASTM Standard F2792-12a) have already been established by the ASTM International Committee F42²⁸. The National Institute for Standards and Technology developed a test series for AM procedures⁶⁰.

The future will show whether AM processes have the potential for a third industrial revolution and whether polymers—if they can be improved for their use—can be part of this process²⁸.

**CONCLUSION**

AM technologies currently have a promising future due to their potential for applications in dentistry and dental prosthetics. However, complete, systematic, digital workflows would be helpful for the clinical implementation. Especially in regard to dental polymers further development and improvement is needed to implement this material in the daily dental digital workflow. At the moment only limited applications are known. The needs of dentists and dental technicians pose new challenges for AM technologies and materials which can be used in dentistry. Depending on the application, mechanical stability, eliminating post processing procedures and free monomers are potential needs for further implementation of clinical dental applications in additive technologies.

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