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Additive Manufacturing in Dentistry - A Contemporary Review

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Abstract: ***Introduction:*** ***Nowadays the additive technologies have become an integral part of every industry all over the world, including healthcare and dentistry, as they have been developing with unusual speed. In order to be resolved key issues many new technological approaches were developed.*** ***Methods:*** ***Key publications in English from past two decades are surveyed.*** ***Results:*** ***The additive processes allow layered fabrication of complex objects. Technologies such as: Vat polymerization, Powder bed fusion, Material extrusion, Binder jetting, Material jetting can be used in dentistry for fabrication of custom implants, apnea appliances, occlusal splints, surgical guides, complete dentures, crowns, bridges, RPD frameworks, or their prototypes. Other types as Direct energy deposition and Sheet lamination are not directed to the medical or dental branches at present.*** ***Conclusion:*** ***The additive manufacturing is developing incredibly fast and today it is used in almost every stage of the production process in dentistry, often than ever. During the past few years the process of 3D printing has become more accurate, fast and accessible, but there is still need to be optimized.***

Keywords: prosthetic dentistry, dental materials, 3D printing, review, dentistry, additive manufacturing

1. Introduction

Nowadays the digital technologies have become an integral part of every industry all over the world, including healthcare and dentistry. [1] Actually, the CAD/CAM technology is not a brand-new process, as they are involved in 1970s, but the development of the information technology and the lack of materials with specific properties delay their use and progress by two or three decades. First the subtractive manufacturing takes its place in dentistry, but the slow process, the limitation for an intricate detail fabrication, the huge amount of the waste material and last but not least the expensive machines and consumables significantly reduced its use in contemporary dental practice. [8, 13, 26, 37] It is gradually replaced by the additive manufacturing that resolves most of the mentioned issues. [16, 26] During the past ten years the additive technologies have been developing with unusual speed. At the same the machines evolve from a huge industrial type with a price around a couple of hundred thousand euros into desktop small devices with a hundred times lower price. This forces the new material development as well as the machines are constantly upgraded for better results to be achieved. [2, 11, 12, 18, 20, 38, 51, 61] Today the more the digital technologies develop, the more essential part of the dentistry they become. [4, 6, 7, 8, 24, 25, 31, 50, 54, 55, 67]

2. Aim

The aim of the current review is to systemize the information about the additive manufacturing in dentistry and to make a critical review of some issues according to the extremely fast development of these processes.

3. Additive manufacturing

Additive manufacturing is defined by the International Organization for Standardization (ISO) and American Society for Testing and Materials (ASTM) as: Process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies. [23]

As it belongs to a CAD/CAM (Computed Aided Design / Computer Aided Manufacturing) technologies, the additive manufacturing involves three main stages of the production process: 1) data acquisition, 2) data processing and 3) manufacturing. [45, 48, 60] The first step is collecting information about the object that will be 3D printed. The data can be acquired by a range of sources such as: intra-oral scanners, laboratory scanners, CBCT, MRI, etc. [3, 19, 28, 33, 41, 42, 53] Currently all the available technologies suitable for data acquisition have an extremely high resolution so that the digital image of the oral cavity or juts desired tissues or structures are very detailed. [52] The scanning devices acquire 2D data for a 3D object, which is combined into a raw 3D point cloud, which contains information about surface configuration, but also artefacts such as noise, reflections, unwanted structures. [46] Therefore, all the unnecessary information is automatically filtered by the scanning device software, keeping the essential one. This process is followed by surface reconstruction and modelling process (texture mapping) in order a digital 3D model with fundamental characteristics of the real object to be achieved. Then the 3D image is suitable to be imported into a CAD software, which allows the achieved image to be manipulated. The process is followed by a preparing process for printing that contains importation of the 3D object in a specific software for 3D printing, setting up the printing options such as: determination of the layer thickness, supporting structures, material, etc. Finally, the designed object can be fabricated by additive manufacturing process. [1, 48, 49]

According to the ISO and ASTM the additive process can be divided into seven different categories as follows [23]:

- Vat polymerization
- Powder bed fusion
- Material jetting

- Binder jetting
- Material extrusion
- Direct energy deposition
- Sheet lamination

4. Vat Polymerization

It is defined as an additive manufacturing process in which liquid polymer in a vat is selectively cured by light-activated polymerization. This type of process contains a group of methods that differs to each other by the integrated light source or just the device structure.

The Stereolithography (SLA) is the first described method for 3D printing, invented by Charles Hull in 1984. This method is based on layer-by-layer laser light-curing of a solid object in a vat full of liquid polymer until the whole object is fabricated. [79, 86] An UV laser source emits a vat full of photosensitive resin-based material by tracing a single layer of the built object (in x, y axis). Once the illuminated area is cured, the building platform moves down (along the z axis) and the next layer is cured. This process repeats for every layer until the whole object is 3D printed. [27, 80, 85, 90] **Figure 1.** This method allows precise manufacturing of objects with smooth surface and measurements that correspond to the digital pattern. [84] The low printing speed can be point out as the main disadvantage. The complete process may take from a few minutes to more than a day depending on the number, size and complexity of the printing objects. Therefore, this method is suitable for producing of just a few objects with small sizes. It is usually used for fabrication of working and diagnostic models, custom trays, surgical guides, orthodontic aligners, splint and occlusal guards, gingival mask, implant models, temporary crowns, complete dentures, denture frameworks or fixed partial denture prototypes etc. [14, 15, 17, 30, 39, 40, 57, 81, 8]

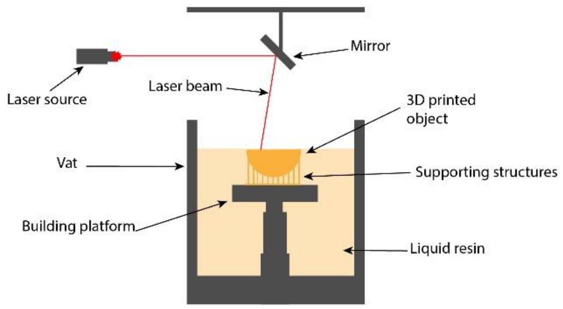

Figure 1: A schematic illustration of SLA 3D printing process

A modification of the classical SLA technology is the Inverted SLA. The major difference is that the laser emits through the vat bottom and the object is bult upside down as the building platform rises after each layer polymerization and dips again in the vat for the subsequent layer. **Figure 2**. This technology allows the volume of the printed object to exceed the amount of the liquid material, which reduces the expenses and makes the apparatus much smaller. The major issue with this technology is that the cured layer sticks to the vat bottom and when the building platform rises the object can be deformed. As a result, a new modification was developed during last few year, called Low Force SLA. The process is the same as the inverted SLA, but the tank (vat) bottom is made of flexible material that generates lower forces when the object is detached. [27, 47]

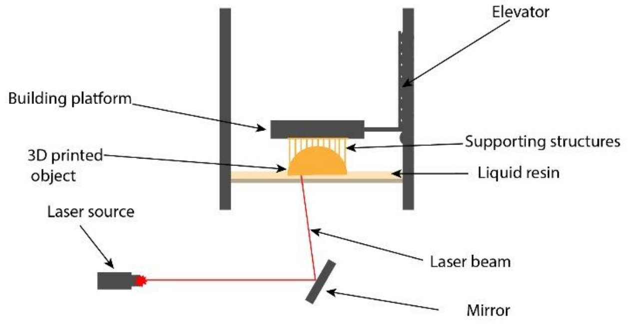

Figure 2: A schematic illustration of Inverted SLA 3D printing process

Digital light processing (DLP) is invented by Larry Hornbeck in 1987. It is based on DLP light source (arc lamp or LED) that emits in UV range, while exposes a vat filled up with light-curing resin. **Figure 3.** One of the major differences between SLA and DLP is the printing speed. [83] The digital projector exposes and curing a whole layer at once by projecting an image of the whole layer, rather than to draw the layer voxel by voxel. [29, 71] The major issue here is the great surface roughness of the printed objects which is result of the digital projector which emits in square shaped pixels and creates voxels with same parameters. [72, 75] At the same time the DLP is also faster and cheaper method than the SLA, as it allows reduction of the raw material consumption and faster processing. The technology characterizes with the same variety in its application as the SLA. [34]

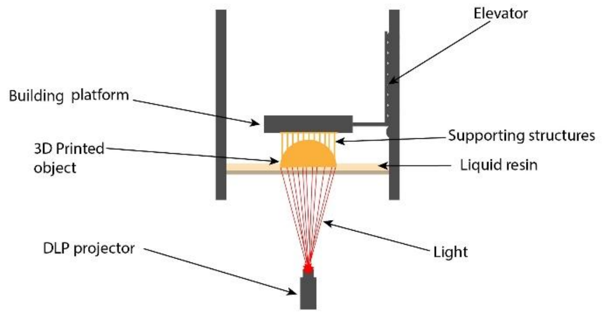

Figure 3: A schematic illustration of DLP 3D printing process.

A modification of DLP technology is the continuous digital light manufacturing (CDLM). It utilizes the ability of the oxygen to inhibit the curing process as increasing its concentration just between the building platform and polymerizing layer. This prevents the layer to stick to the vat bottom. At the same time the building platform continuously lifts vertically rather than to stop between different layers. As a result, this technology allows a faster way of production with less distortion of the object. [74]

Masked stereolithography (MSLA) is technology which is a very similar to the DLP. The major difference between the two processes is that the MSLA technology adopts LCD

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display as an emitting device rather than a digital projector. The vat is situated above the display and only a thin layer of fluorinated ethylene propylene (FEP) plastic foil separates them. The display illuminates only the desired configuration of the current layer as curing the resin above. **Figure 4.** The same issues with the surface roughness are also presented as to the DLP technology. Therefore, the producers try to overcome this with a variety of tricks such as incorporating anti-aliasing option in their devices or even integration of displays with higher resolution or just selective depth of emission along the z axis. Another major issue with the MSLA technology is the short life of the LCD display - just a couple of years. The benefits and application of the MSLA are the same as the described to the DLP process. [9]

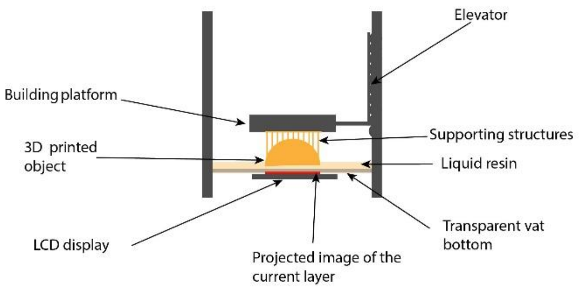

Figure 4: A schematic illustration of MSLA 3D printing process

The common post-processing procedure includes alcohol rinsing for remnants removal, post-curing process and removal of the supports. [76, 78, 87, 88]

5. Powder Bed Fusion

It is an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. The first developed technology of powder bed fusion is the SLS process, which is introduced in 1987 by Carl Deckard. The 3D printing method adopts the same principle as SLA, except that the raw material is in powdered solid state. The technology utilizes a vat filled up with powdered material (ceramics, polymer, metal, alloy), a building platform, situated in the vat and a heigh intensity laser. [89] The process starts with illuminating and heating the upper layer of the powder by tracing it with the laser, as a result the particles are selectively sintered creating a solid layer. After the layer is done, the building platform lowers, then some new raw material is delivered by a special roller and the process repeats from the beginning for every subsequent layer till the complete object production. **Figure 5.** As it mentioned the laser heats the powdered material bellow the melting temperature, as a result only the surface of the particles starts melting causing them to fuse, a process known as a sintering. It is remarkable that the SLS doesn't require supporting structures when the object is bult, the rest of unsintered powder acts as support. However, when the apparatus prints structures of metal or alloy additional supports are necessary and the printer creates such a structures to prevent distortion. The technology is used for direct fabrication (rapid manufacturing process) of all-ceramic restorations, partial denture frameworks, acrylic provisional restorations. [21, 39, 62]

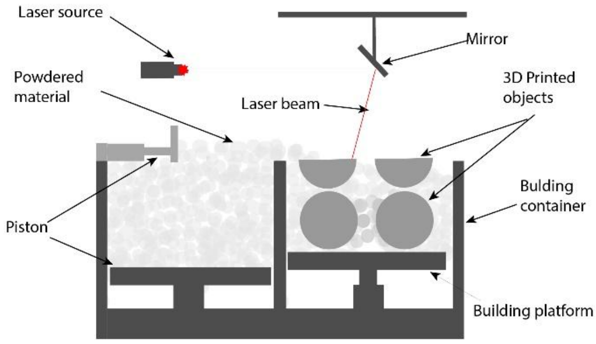

Figure 5: A schematic illustration SLS 3D printing process

In 1995 a very similar process called SLM was developed. The SLM devices are built and work on the same principle as SLS ones. Unlike the SLS, SLM technology prints the objects layer by layer but the particles of the material for every layer are fully melted and fused to the previous one. [65] **Figure 6.** This results in objects with a homogenous and very solid structure. [36] The supporting structures for this process are also mandatory as a prevention of distortion. The SLM process is used for partial denture frameworks, coping fabrication, custom implant abutments etc. [10, 22, 43, 59, 63, 66]

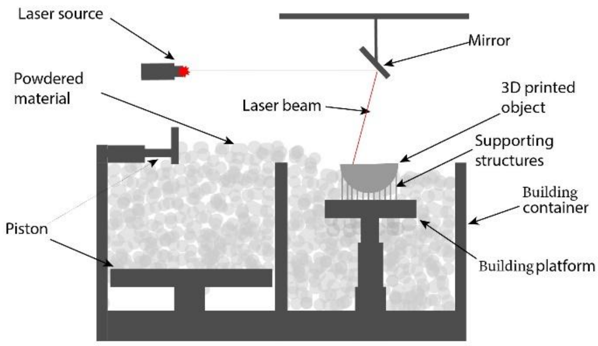

Figure 6: A schematic illustration of SLM 3D printing process

Some producers describe technologies as Direct Metal Laser Sintering (DMLS), or "Direkt Metall Laser Schmelzen", or also Direct Metal Laser Melting (DMLM) that are based on SLS 3D printing process and own all of its characteristics, advantages and disadvantages. [68, 69, 91] There are authors who define that DMLS refers to an alloy sintering, as the SLM uses only base metals for the build process. This state is not so clear as the company SLM Solutions® which integrates the SLM technology in its devices and suggests a variety of alloys for the printing process. The things become more and more confusing when the ISO/ASTM 52900:2015 is examined. According to the standard, term "sintering" is historical term and misnomer in context of 3D printing, as the laser sintering involves full or partial melting. [1, 23, 60, 98]

Electron beam melting (EBM) is a technology similar to the SLM, that manufactures objects by melting alloys or metal powder layer upon layer with an electron beam in a vacuum and high temperature (e.g. 1000 °C). The electron beam is a result of tungsten filament heating and the emitted electrons have higher energy than the laser. [92] This allows the powder particles to be melted without vaporization, as the vacuum and high temperature inside the building tank allow creation of pure structures without residual stress. This technology is used for fabrication of prosthetic implants, dental restorations, also is applied in orthopedics and maxillofacial surgery for construction of customized implants. The process is time consuming and relatively expensive. [56] Usually, the post processing includes supporting structure or single particles removal a stress releasing heating and burning.

Multi Jet Fusion (MJF) is developed by Hewlett Packard technology that allows the digital prototype to be divided into voxels. During the preparation of the digital prototype and during the build procedure, every voxel could be controlled by individually setting characteristics such as color, translucency, surface texture, mechanical properties or electroconductivity etc. The process starts with delivery of material, over the building platform. It is followed by a selective application of fusing agent, then a heat is applied to fuse the agent and the material. All these procedures are repeated until the desired object is built. The process is defined to make possible creation of object that the other 3D printer cannot build, but currently is focused on the industrial use and only a couple of synthetic thermoplastic polymers are available for utilization. [93, 94, 95]

Another process that can be associated with the powder bed fusion is the selective absorption fusion (SAF) technology. It uses a special fluid that is infrared-sensitive to fuse the particles of powdered polymer. The process starts with a thin layer of powder delivery, then a special printheads selectively jets the fluid in the desired areas. After that the layer is exposed to infrared radiation to fuse it and the process restarts from the beginning, until the complete object is finished. The method is defined as a cost-efficient, and relatively accurate. The technology is not applicable to dentistry so far. [99.100, 101]

6. Material Jetting (MJ)

It is an additive manufacturing process in which droplets of build material are selectively deposed. Material jetting technology, also known as inkjet printing technology, is method of 3D printing that is very similar to 2D inkjet printing and is based on direct delivery of the build material drop by drop through a special nozzle directly to the building platform. The material can be an aqueous solution of coloring agent, solutions of ceramics or metal nano particles, polymers and even cell solution for tissue and organ printing. [102] In order to be created a 3D object, every single layer should be transferred to a solid state, this can be achieved by drying, UV light, heat exposure or just a chemical reaction. Usually, this technology uses a water-soluble material for the supporting structures or a wax that is melted-away during the post processing procedure. The Material jetting technology is used for fabrication of occlusal splints, drill guides, models for thermoforming. Due to poor accuracy the technology doesn't find application in dental restorations, where a higher precision is required. [60] **Figure 7.**

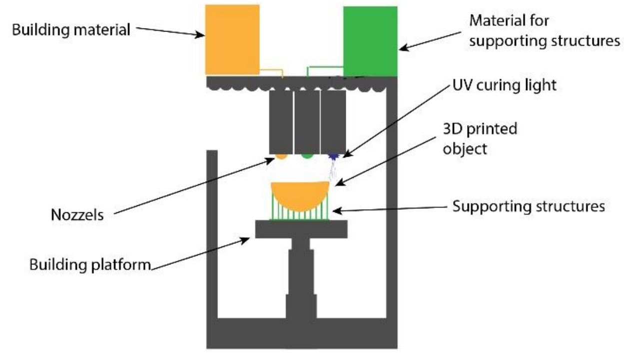

Figure 7: A schematic illustration of MJ 3D printing process

The contemporary devices that integrate inkjet printing usually have two, three or more nozzles with an option to build objects by deposing all the loaded types of raw materials at the same time. In this context an object can be created with different physical (mechanical, optical) characteristics in different areas. For example, a toothbrush with stiff handle and elastic fibers, or an occlusal splint with resilient internal and stiff outer surface can be produced at once.

During the past few years due to the development of nanomaterials and nanotechnologies a type of inkjet printing called Nano particle jetting (NPJ) was introduced. This technology uses dispersed ceramic or metal nanoparticles in aqueous solution that is deposed over the building platform, while heat is applied. After evaporation of the water the residue of the nanoparticles form a single layer of the printed object. The same procedure is repeated for every single layer until the 3D object is finished. Finally, the produced object is sintered to ensure high material density. This technology is on its way to be integrated in dentistry. [103]

7. Binder Jetting (BJ)

The technology is defined as an additive manufacturing process in which a liquid bonding agent is selectively deposed to join powder materials. [77] **Figure 8.** A huge variety of material are developed for this such as: polyamides, PMMA, alloys with various composition, ceramic, hybrid materials (ceramic-metal composites), metal composites, gypsum, calcium polyphosphate etc. This method allows creation of porous objects, as some of them have to be impregnated in order to improve the mechanical properties during the post processing. Another approach is the burning out the bonding agent and the final sintering of the printed object. [32, 64]

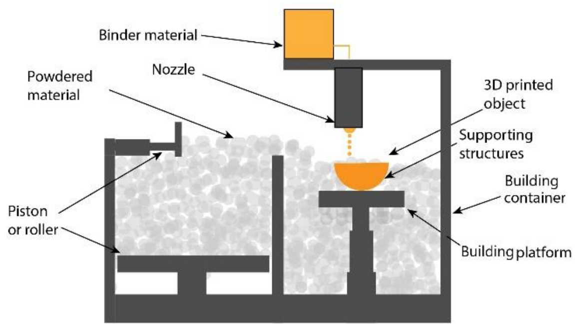

Figure 8: A schematic illustration of BJ 3D printing process

8. Material Extrusion

It is an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice. There are several technologies that are incorporated in this group, but they always refer to an extrusion of a thermoplastic material through a nozzle. The raw material can be stored in reservoirs (the process is called fused deposition modelling "FDM") or a just a wire of a raw material (fused filament fabrication "FFF") is extruded through a heated nozzle.

Fused Deposition Modeling is one of the most common 3D printing technologies. It is developed by Scott Crump in 1989. The object is created by extruding a small but enough portions of raw material to finish a single layer, which hardens almost immediately. Then the nozzle moves in vertical direction and starts creating the next layer. At the same time another nozzle is responsible for the supporting structures creation. **Figure 9.** The main advantage of this technology is the ability to create objects with good mechanical properties, which are relatively cheap. This method also allows 3D printing using multiple materials and creation of objects with various structures and properties. [60]

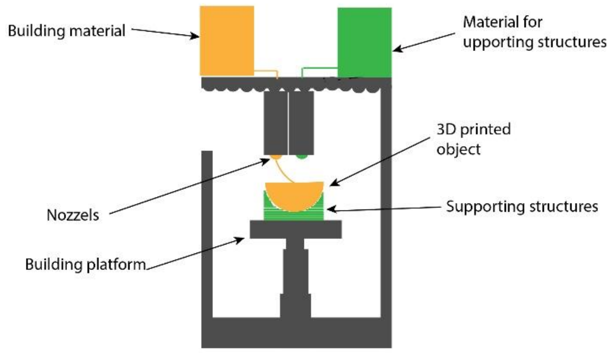

Figure 9: A schematic illustration FDM 3D printing process

There are wide range of materials with various physical properties that are associated with this technology such as: acrylonitrile butadiene styrene polymer (ABS), polycarbonates, polycaprolactone, waxes and different type of water-soluble material that are suitable for supporting structures that can be washed out after the end of the printing process. [35]

FDM is also integrated in tissue engineering where the wide range of available materials such as ceramic pastes (used for porous bone scaffolds), polyether ether ketone (PEEK), polycaprolactone (used for bone regeneration, cartilage regeneration, drug release and hybrid scaffolds), biocompatible silicone (used for soft implants), agar, gelatin, collagen (used in organ printing) and etc. [5, 35, 39, 58] The technology also allows creation of porous structures with microstructural patterns that allow cell invasion and proliferation. The lower accuracy and anisotropy of the printed object are the main reason this technology to have limited use for fine object production in dentistry.

9. Direct Energy Deposition

It's an additive manufacturing process which uses focused thermal energy to fuse materials by melting them as they are being deposed. This group of technologies contains variety of methods that differentiate form each other only in type the raw material (powder or wire) and the energetic source (laser, electron beam or plasma arc).

Laser Engineering Net Shape (LENS) is a technology that is based on powdered material deposition over the building platform, followed by subsequent laser melting in argon environment. **Figure 10.** In this order the object is bult layer upon layer of the available material: titanium, stainless steel, Nickel Based Super Alloys (Inconel), Cobalt, Tungsten etc. The technology is applied in aerospace or for production of medical implants. [96]

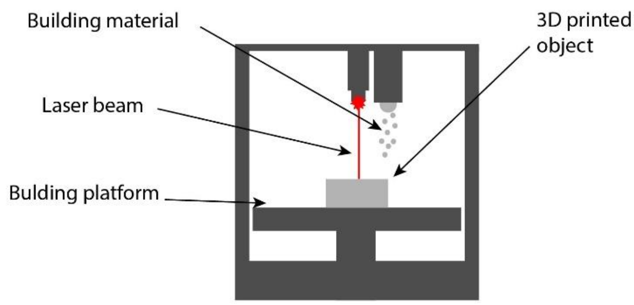

Figure 10: A schematic illustration of LENS 3D printing process

Electron Beam Additive Manufacture (EBAM) is another process which is similar to the LENS, except that it utilizes wired raw material and an electron beam as an energetic source. Another difference is that the process is accomplished in a vacuum environment. Currently all these technologies are applied predominantly for industrial purposes. [97]

10. Sheet Lamination

It is an additive manufacturing process in which sheets of material are bonded to form a part. Laminated Object Manufacturing (LOM) is technology that refers to adhesive coated paper or sheets which are heated and pressed to each other by creating a 3D object. Afterward the desired form of the part is milled. In this context the technology combines a subtractive and additive method of fabrication. The method is not suitable for intricate structures, but it is cheap and is very useful for the art and prototypes fabrication. [44, 70]

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11. Discussion

Before a decade many authors share their opinion that the future of dentistry is in the digital approach. Actually, this obvious progress has become more and more common during the years, as today it is significant part of the daily practice. At the same time branches as the additive manufacturing develops with a stunning speed. The available machines, technologies and suggested materials are revised permanently, as they are upgraded almost every year. As a result the consumers may get confused when choose the appropriate technology for their career field, due to permanent innovations and the lack of commonly used classification of the production processes, including suggested applications and corresponding materials.

The contemporary 3D printers operate in very similar range of accuracy, regardless of the technology that they are based on. Many of them are available to reach similar or even better accuracy compared to the conventional production technologies. Although the satisfying precision there is still a lot to be improved. Most of the suggested machines work not so fast, as the 3D printing process takes from a couple of hours to a day, even if the fabricated objects are relatively small. In addition, the post-processing procedures also have to be modified or just reduced as much as possible in order to optimize the whole production process. Nowadays most of the technologies require more than an hour for the post-processing procedure, which additionally slow the process down. Another issue is the lack of great variety of materials for the 3D printing process and even if they are multiplied day by day, there is still a lot to be done.

Additive manufacturing is still an expensive undertaking. Most of the printers cost around a couple of hundred thousand dollars, which is a numerous investment for the small industries. Although almost all the companies offer desktop versions of their 3D printers, which should be cheaper, the initial investment still remains as a serious obstacle for some businesses.

12. Conclusion

Additive manufacturing develops incredibly fast, while it becomes an essential part of the production process for more and more industries. Nowadays 3D printing technologies become more and more widely used in dentistry as they allow to be successfully integrated in almost every stage of the production process. Although during the past few years the process of 3D printing becomes more accurate, fast and accessible, they still need to be optimized.

References

[1] Ahmad I, Al-Harbi F. 3D Printing in Dentistry 2019/2020. Quintessence Publishing; 2019

[2] Al-Harbi N, Osman R, Wismeijer D. Effects of build direction of the mechanical properties 3D printed complete coverage interim dental restorations. Journal of Prosthetic Dentistry. 2016:115:760-767

[3] Alwala AM, Arvind UD, Malyala SK, Vasamsetty P. Customization of patient specific distraction device using additive manufacturing technology. Materials Today:. Proc. 5 (2) (2018) 4134–4137.

[4] Anderson J, Wealleans J, Ray J. Endodontic applications of 3D printing, International Endodontic Journal.2018;51(9):1005–1018

[5] Asa'ad F, Pagni G, Pilipchuk SP, Giannì AB, Giannobile WV, Rasperini G. 3D-printed scaffolds and biomaterials: review of alveolar bone augmentation and periodontal regeneration applications. International Journal of Dentistry.2016;4:1-15

[6] Beuer F, Schweiger J, Edelhoff D. Digital dentistry: an overview of recent development for CAD/CAM generated restorations. British Dental Journal. 2008;204:505-511

[7] Bilgin MS, Baytaroğlu EN, Erdem A, Diber E. A review of computer-aided design/computer-aided manufacture techniques for removable denture fabrication. European Journal of Dentistry.2016;10:286-291

[8] Bogue R. 3D printing: the dawn of new era in manufacturing? Assembly Automation.2013;4:307-311

[9] Cha HS, Park JM, Kim TH, Lee JH. Wear resistance of 3D-printed denture tooth resin opposing zirconia and metal antagonists. Journal of Prosthetic Dentistry 2020;124(3):387-394

[10] Chen J, Zhang Z, Chen X, Zhang C, Zhang G, Xu Z. Design and manufacture of customized dental implants by using reverse engineering and selective laser melting technology. Journal of Prosthetic Dentistry. 2014; 112:1088-1095

[11] Chen S, Yang J, Jia YG, Lu B, Ren L. A study of 3D-Printable reinforced composite resin: PMMA modified with silver nanoparticles loaded cellulose nanocrystal. Materials.2018;11

[12] Chia HN, Wu BM. Recent advances in 3D printing of biomaterials. Journal of Biological Engineering. 2015;9:4

[13] Christensen GJ. Impressions are changing: deciding on conventional, digital or digital plus in-office milling. Journal of American Dental Association. 2009;140(10):1301–1304

[14] Chung YJ, Park JM, Kim TH, Ahn JS, Cha HS, Lee JH. 3D Printing of Resin Material for Denture Artificial Teeth: Chipping and Indirect Tensile Fracture Resistance. Materials 2018;11

[15] Clark WA, Duqum I, Kowalski BJ. The digitally replicated denture technique: a case report. Journal of Esthetic Restorative Dentistry.2019;31:20–25

[16] Dawood A, Marti B, Sauret-Jackson V, Darwood A. 3D Printing in dentistry. British Dental Journal. 2015;219:521-529

[17] Della Bona A, Cantelli V, Britto VT, Collares KF, Stansbury JW. 3D printing restorative materials using a stereolithographic technique: a systematic review. Dental Materials. 2021;37(2):336-350

[18] George E, Liacouras P, Rybicki F, Mitsouras D. Measuring and Establishing the Accuracy and Reproducibility of 3D Printed Medical Models. RadioGraphics.2017;1424:1450

[19] Georgieva I, Peev S. CBCT-Assessment of Morphological Characteristics of the Alveolar Bone in

the Aesthetic Zone. International Journal of Science and Research.2016;5(2): 2085-2089
[20] Goodacre BJ, Goodacre CJ, Baba NZ, Kattadiyil MT. Comparison of denture base adaptation between CAD-CAM and conventional fabrication techniques. Journal of Prosthetic Dentistry. 2016;116:249-256
[21] Gueche YA, Sanchez-Ballester NM, Cailleaux S, Bataille B, Soulairol I. Selective Laser Sintering (SLS), a New Chapter in the Production of Solid Oral Forms (SOFs) by 3D Printing. Pharmaceutics. 2021;13(8):1212
[22] Hong JK, Kim SK, Heo SJ, Koak JY. Mechanical Properties and Metal-Ceramic Bond Strength of Co-Cr Alloy Manufactured by Selective Laser Melting. Materials 2020;13(5745):1-15
[23] ISO/ASTM 52900:2015(E)
[24] Javaid M, Haleem A. Current status and applications of additive manufacturing in dentistry: A literature-based review. Journal of Oral Biology and Carniofacial Research.2019;9:179-185
[25] Jawahar A, Maragathavalli G. Applications of 3D printing in dentistry–a review, Journal of Pharmaceutical Science and Research. 2019;11(5):1670–1675
[26] Kalberer N, Mehl A, Schimmel M, Müller F, Srinivasan M. CAD-CAM milled versus rapidly prototyped (3D-printed) complete dentures: an in vitro evaluation of trueness. Journal of Prosthetic Dentistry.2019;121:637–643.
[27] Katsarov S, Penchev P. Laboratory assessment of the accuracy of two different resins designed for 3D printing for cast metal frameworks and suprastructures. Clinical Oral Implants Research.2020;31:112-112
[28] Katsarov S. Contemporary assessment of the accuracy of merging DICOM and STL files for the purpose of guided implant placement. Clinical Oral Implants Research.2020;31:282-282
[29] Kim DY, Lee GY. Evaluation of dimension stability according to UV-C ultrasonic cleaning of full arch artificial teeth made with DLP printer for photopolymerization. Journal of Technologic Dentistry.2021;43(3):84-92
[30] Lee S, Hong SJ, Paek J, Pae A, Kwon KR, Noh K. Comparing accuracy of denture bases fabricated by injection molding, CAD/CAM milling, and rapid prototyping method. Journal of Advanced Prosthodontic.2019;11:55–64
[31] Lee SJ, Kim E. Minimizing the extra-oral time in autogeneous tooth transplantation: use of computer-aided rapid prototyping (CARP) as a duplicate model tooth, Restorative Dentistry and Endodontics. 2012;37(3):136–141
[32] Li M, Wei X, Pei Z, Ma C. Binder jetting additive manufacturing: observations of compaction-induced powder bed surface defects. Manufacturing Letters.2021;28:50-53
[33] Lin WS, Harris BT, Morton D. Use of CBCT Imaging, Open-Source Modeling Software, and Desktop Stereolithography 3D Printing to Duplicate a Removable Dental Prosthesis-A Proof of Concept. Compendium of Continuing Education in Dentistry.2017;38:5–8.
[34] Lin WS, Harris BT, Pellerito J, Morton D. Fabrication of an interim complete removable dental prosthesis with an in-office digital light processing three-dimensional printer: a proof-of-concept technique. Journal of Prosthetic Dentistry.2018;120:331–334
[35] Malyala SK, Kumar YR, Alwala AM, Vasamsetty P, Benefits of additive manufacturing medical model in orbital floor reconstruction surgery: a case study. Journal of Surgery.2017;13(2):77-79
[36] Mangano F, Chambrone L, Van Noort R, Miller C, Hatton P, Mangano C. Direct metal laser sintering titanium dental implants: a review of the current literature. International Journal of Biomaterials.2014;(461534):1-11
[37] Miyazaki T, Hotta Y. CAD/CAM systems available for the fabrication of crown and bridge restorations. Aust Dent J. 2011;56:97-106
[38] Molinero-Mourelle P, Canals S, Gómez-Polo M, Solá-Ruiz MF, J. Highsmith J, A. Viñuela AC, et al. Polylactic acid as a material for three-dimensional printing of provisional restorations, International Journal of Prosthodontics.2018; 31(4):349-350
[39] Msallem B, Sharma N, ShuaiShuai C, Halbeisen F, Zeilhofer H, Thieringer F. Evaluation of the Dimensional Accuracy of 3D Printed Anatomical Mandibular Models Using FFF, SLA, SLS, MJ and BJ Printing Tehcnology. Journal of Clinical Medicine.2020;9:817
[40] Nayar S, Bhuminathan S, Bhat WM. Rapid prototyping and stereolithography in dentistry. Journal of Pharmacy and BioAllied Sciences. 2015;7:216-219
[41] Nedelcu RG, Person AS, Scanning accuracy and precision in 4 intraoral scanners: an in vitro comparison based on 3-dimetional analysis. Journal of Prosthetic Dentistry. 2014;112:1461-1471
[42] Nickenig HJ, Wichmann M, Hamel J, Schlegel KA, Eitner S. Evaluation of the difference in accuracy between implant placement by virtual planning data and surgical guide templates versus the conventional free-hand method–a combined in vivo–in vitro technique using cone-beam CT (Part II), Journal of Cranio-Maxillofacial Surgery.2010;38(7):488–493
[43] Örtorp A, Jönsson D, Mouhsen A, Vult von Steyern P. The fit of cobalt - chromium three-unit fixed dental prostheses fabricated with four different techniques: a comparative in vitro study. Dental Materials.2011;27:356-63
[44] Park J, Tari Mi, Hahn, H. Characterization of the laminated object manufacturing (LOM) process. Rapid Prototyping Journal.2000; 6:36-50
[45] Patel N. Integrating three-dimensional digital technologies for comprehensive implant dentistry. Journal of American Dental Association. 2010;1(141):20S–24S.
[46] Patzelt SB, Vonau S, Stampf S, Att W. Assessing the feasibility and accuracy of digitizing edentulous jaws. Journal of American Dental Association.2013;144(8):914–920
[47] Penchev P, Katsarov S. Digital casting cone and sprue fabrication for 3D printed patterns designed for casting dental alloys. 2020; 2:1256-1263
[48] Rekow E. Digital dentistry: The new state of the art- is it disruptive or destructive? Dental Material.2019

[49] Rudoph H, Luthardt RG, Walter MH. Computer aided analysis of the influence of digitizing and surfacing on the accuracy in dental CAD/CAM technology. Computers in Biology and Medicine. 2007;37:579-587
[50] Sabeva E, Peev S. Assessment of Primary Stability of Four Different Implant Designs Inserted into 3D-printed Simulation Models of Lower Jaw. International Journal of Science and Research.2016;5(9):818-821
[51] Schweiger J, Edelhoff D, Güth JF. 3D Printing in Digital Prosthetic Dentistry: An Overview of Recent Developments in Additive Manufacturing. Journal of Clinical Medicine. 2021;10, 2010
[52] Seelbach, P., Brueckel, C. & Wöstmann, B. Accuracy of digital and conventional impression techniques and workflow. Clinical Oral Investigations. 2013;17:1759–1764.
[53] Spector L. Computer-aided dental implant planning, Dental Clinics of North America.2008;52(4):761–775
[54] Stavropoulos P, Foteinopoulos P. Modelling of additive manufacturing processes: a review and classification, Manufacturing Review.2018; 5 (2):1-26
[55] Takeda Y, Lau J, Nouh H, Hirayama H. A 3D printing replication technique for fabricating digital dentures. Journal of Prosthetic Dentistry.2020;124(3):251-256
[56] Tamayo JA, Riascos M, Vargas CA, Baena LM. Additive manufacturing of Ti6Al4V alloy via electron beam melting for the development of implants for the biomedical industry. Heliyon.2021;7(5):1-26
[57] Totu EE, Nechifor AC, Nechifor G, Aboul-Enein HY, Cristache CM. Poly (methylmethacrylate) with TiO(2) nanoparticles inclusion for stereolitographic complete denture manufacturing - the future in dental care for elderly edentulous patients? Journal of Dentistry.2017;59:68–77
[58] Trenfield SJ, Awad A, Goyanes A, Gaisford S, Basit AW. 3D printing pharmaceuticals: drug development to frontline care. Trends in Pharmacological Sciences.2018;39(5):440–451
[59] Ucer Y, Akova T, Akyil MS, Branylay WA. Internal fit evaluation of crowns prepared used a new dental crown fabrication technique: laser sintering Co-Cr crowns. Journal of Prosthetic Dentistry. 2009;102:253-259
[60] van Noort R. The future of dental devices is digital. Dental Materials.2012; 28:3-12
[61] Vasamsetty P, Tejaswini, Pss T, Kukkala D, Singamshetty M, Gajula S. 3D printing in dentistry – Exploring the new horizons. Materials Today: Proceedings.2020;26(2):838-841
[62] Wilkes J, Hagedorn Y-C, Ocylok S, Meiners W, Wissenbach K. Rapid manufacturing of ceramic parts by selective laser melting. Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials IV. 2010;31
[63] Wu L, Zhu H, Gai X, Wang Y. Evaluation of the mechanical properties and porcelain bond strength of cobalt-chromium dental alloy fabricated by selective laser melting. Journal of Prosthetic Dentistry. 2013;3(1):51-55
[64] Xiong Y, Quian C, Sun J. Fabrication of porous titanium implants by three-dimensional printing and sintering at different temperatures. Dental Materials Journal. 2012;31:815-820
[65] Yadroitsev I, Thivillon L, Bertrand P, Smurov I. Strategy of manufacturing components with designed internal structure by selective laser melting of metallic powder. Applied Surface Science. 2007;254:980-983
[66] Yun CS, Hanawa T, Hong MH, Min BK, Kwon TY. Biocompatibility of Ni–Cr alloys, with the same composition, prepared by two new digital manufacturing techniques. Materials Letters. 2021;305 (130761)
[67] Zaharia C, Gabor AG, Gavrilovici A, Stan A, Idorasi L et al. Digital dentistry – 3D printing applications. Journal of Interdisciplinary Medicine. 2017;2:50-53
[68] 3Dsourced [Internet]. Direct Metal Laser Sintering: Everything to Know About DMLS 3D Printing. Available from: https://www.3dsourced.com/guides/direct-metal-laser-sintering-dmls/
[69] all3dp.com [Internet]. What Is DMLS? Available from: https://all3dp.com/2/direct-metal-laser-sintering-dmls-simply-explained/
[70] CleanGreen3D [Internet]. How Paper-based 3D Printing Works. Available from: https://cleangreen3d.com/wp-content/uploads/2020/11/how-paper-3d-printing-works-v01.pdf
[71] EnvisionTEC [Internet] 3D Printing 101: Stay Flat and Parallel. [updated 2017 March; cited 2021 Oct]. Available from: https://envisiontec.com/wp-content/uploads/2017/03/3D-Printing-101-Stay-Flat-and-Parallel-03132017.pdf
[72] EnvisionTEC [Internet] Advanced DLP for Superior 3D Printing [updated 2017 Apr; cited 2021 Oct]. Available form: https://envisiontec.com/wp-content/uploads/2017/04/Why-EnvisionTEC-DLP-3D-Printing-is-Better-rebranded.pdf
[73] EnvisionTEC [Internet] The Ultimate Guide to 3D Printing Thermosets for Manufacturing and Production. [updated 2017 Apr; cited 2021 Oct]. Available from: https://envisiontec.com/wp-content/uploads/2017/04/3sp-white-paper-2017-the-ultimate-guide-to-3d-printing-for-manufacturing-and-production.pdf
[74] EnvisionTEC [Internet] The Ultimate Guide to High-Speed 3D Printing with Continuous Technology [updated 2020 Aug; cited 2021 Oct]. Available from: https://envisiontec.com/wp-content/uploads/2018/02/cDLM-white-paper-08052020.pdf
[75] EnvisionTEC [Internet] Understanding 3D Printer Accuracy: Cutting Through the Smoke and Mirrors. [updated 2017 Aug 24; cited 2021 Oct]. Available from: https://envisiontec.com/wp-content/uploads/2017/08/Accuracy-versus-Resolution-0824172.pdf
[76] EnvisionTEC [Internet]. Technical Guide Post Processing: Clear Materials. [updated 2018 Apr; cited 2021 Oct]. Available from: https://envisiontec.com/wp-content/uploads/2018/04/TS-OPI-Clear_Material_Processing-V04-FN-EN.pdf
[77] ExOne [Internet]. What is Binder Jetting? Available from: https://www.exone.com/en-US/Resources/case-studies/what-is-binder-jetting

[78] Formlabs [Internet] Zguris, Z. Formlabs White Paper: How Mechanical Propeties of Stereolythography 3D Prints are affevted by UV Curing. Available from: https://3d.formlabs.com/rs/060-UIG-504/images/How-Mechanical-Properties-of-SLA-3D-Prints-Are-Affected-by-UV-Curing.pdf?mkt_tok=MDYwLVVJRy01MDQAAAF_9QTCfOurammoQg8kif3fHma43BbM1_d7AslYQbukx7hWTVrVJDRfGfmsf4JzUbsb6qIA7J7IMtlsaZ-d3X670R30juwit3fLQebYqbctJPY

[79] Formlabs [Internet]. 3D Printing Technology Comparison: FDM vs. SLA vs. SLS. Available from: https://formlabs.com/blog/fdm-vs-sla-vs-sls-how-to-choose-the-right-3d-printing-technology/

[80] Formlabs [Internet]. Demystifying 3D Printer Specifications. Available from: https://formlabs.com/blog/demystifying-3d-printer-specifications/

[81] Formlabs [Internet]. Introduction to Casting for 3D Printed Jewelry Patterns [updated 2021 Jan; cited 2021 Oct]. Available from: https://media.formlabs.com/m/5df7ee4477cb6ea8/original/-ENUS-Introduction-to-Casting-for-3D-PrintedJewelry-Patterns.pdf

[82] Formlabs [Internet]. Introduction to Casting with Formlabs Resins. [updated 2019 Jul; cited 2021 Jan]. Available from: https://support.formlabs.com/s/article/Introduction-to-Casting-with-Formlabs-Resins?language=en_US

[83] Formlabs [Internet]. SLA vs. DLP: Guide to Resin 3D Printers. [updated 2020; cited 2021 Oct] Available from: https://formlabs.com/blog/resin-3d-printer-comparison-sla-vs-dlp/

[84] Formlabs [Internet]. Understanding Accuracy, Precision, and Tolerance in 3D Printing. Available from: https://formlabs.com/blog/understanding-accuracy-precision-tolerance-in-3d-printing/

[85] Formlabs [Internet]. Validating Isotropy in SLA 3D Printing. [updated 2020 Aug; cited 2021 Aug]. Available from: https://3d.formlabs.com/rs/060-UIG-504/images/formlabs_validating-isotropy-in-sla.pdf?mkt_tok=MDYwLVVJRy01MDQAAAF_9SAhbYW9_2RlN_3RvYFEwSlvIvLKP8Zf2p2mOKNsng-msea1M83Pn6c9Ez9D0K8aBtuyJWvBlIepo9SfNM-g7CBqm0tyMlVDJhssHIxbGjo

[86] Formlabs White Paper [Internet] Intro to Stereolithography 3D printing. [updated 2019 May; cited 2021 October]. Available from://3d.formlabs.com/rs/060-UIG-504/images/Formlabs-3D-Printing-Intoduction-to-SLA.pdf?mkt_tok=MDYwLVVJRy01MDQAAAF_9KxtwUZA9fb2FLC2xVj2wl5Ahao41_00l11gp6zEveNrVnXrDXWDXme5J7FuXJYN7Stq2GSvb3kPgZHgY4HqE86cdp3zRHhD2EuHsSN8eJw

[87] Formlabs. [Internet]. An Introduction to Post-Curing SLA 3D Prints. Available from: https://formlabs.com/blog/introduction-post-curing-sla-3d-prints/

[88] Formlabs. [Internet]. Guide to Post-Processing and Finishing SLA 3D Prints. Available from: https://formlabs.com/blog/post-processing-and-finishing-sla-prints/

[89] Formlabs. [Internet]. Guide to Selective LaserSintering (SLS) 3D Printing [updated 2021 Jan; cited 2021 Oct] Available from: https://3d.formlabs.com/rs/060-UIG-504/images/WP-EN-Guide-to-Selective-Laser-Sintering-SLS-3D-Printing.pdf?mkt_tok=MDYwLVVJRy01MDQAAAF_9Ro65EQQLzatZaX7qLMi4XrmgCEhybd0NZyIM8d3WH1LzsUPZD1UWD_uv-kr29Egz8T1I9OM1rZCvuRgQWD51cqFzkUudtakXwCPRkHBaZ7mTA

[90] Fromlabs. [Internet]. What Does Resolution Mean in 3D Printing? Available from: https://formlabs.com/blog/3d-printer-resolution-meaning/

[91] GE Additive [Internet]. How Direct Metal Laser Melting (DMLM) Works. Available from: https://www.ge.com/additive/additive-manufacturing/information/direct-metal-laser-melting-technology

[92] GE Additive [Internet]. Inside Electron Beam Melting. Available from: https://go.additive.ge.com/rs/706-JIU-273/images/GE%20Additive_EBM_White%20paper_FINAL.pdf

[93] HP [Internet]. HP Multi Jet Fusion technology [updated 2018 March, cited 2021 Oct]. Available from: https://images.marketingcontent.ext.hp.com/Web/HPMartech/%7B95dccb4d-3ade-4a53-bb5f-64a813e3b83e%7D_4AA5-5472ENW_Hires_(WO_CM).pdf?d_site=704062726&d_creative=3099&d_campaign=&d_dpuuid=15033994&elqTrackId=723b3bb6fa7e41bc9f1f48de7c47eccb&elq=8ba169415339479e9cb48b3bba52208a&elqaid=3099&elqat=1&elqCampaignId=

[94] HP [Internet]. MJF Handbook. Available from: https://reinvent.hp.com/us-en-3dprint-mjfhandbook

[95] HP Development Company, L.P., © Copyright 2016-2018 [updated 2018 March; cited 2021 Oct]. HP Milti Jet Fushion Technology. Available from: https://images.marketingcontent.ext.hp.com/Web/HPMartech/%7B95dccb4d-3ade-4a53-bb5f-64a813e3b83e%7D_4AA5-5472ENW_Hires_(WO_CM).pdf?d_site=704062726&d_creative=3099&d_campaign=&d_dpuuid=15033994&elqTrackId=723b3bb6fa7e41bc9f1f48de7c47eccb&elq=7865aa21b21541a79af94fdefd23a118&elqaid=3099&elqat=1&elqCampaignId=

[96] Optomec [Internet]. LENS Directed Energy Deposition (DED) 3D Printed Metal Technology. Available from: https://optomec.com/3d-printed-metals/lens-technology/

[97] Sciaky [Internet]. Benefits of Wire vs. Powder Metal 3D Printing. Available from: https://www.sciaky.com/additive-manufacturing/wire-vs-powder

[98] Stratasys [Internet]. DMLM vs. DMLS – What's the Difference? Available from: https://www.stratasysdirect.com/technologies/direct-metal-laser-sintering/dmlm-vs-dmls?resources=183bc4cb-a9a5-45a0-a291-aa5cc115a931

[99] Stratasys [Internet]. Origin One: accuracy, repeatability, and isotropy. Available from: https://www.stratasys.com/explore/whitepaper/origin-

one-accuracy?returnUrl=%2Fexplore%3FPage%3D1%26Phrase%3D%26ResourceTypes%3D%257B460BE7D2-8558-48CB-9AF8-C21F926E875D%257D

[100] Stratasys [Internet]. The Complete Guide to 3D Printing Plastic Parts with Selective Absorption Fusion (SAF™). Available from: https://www.stratasysdirect.com/technologies/saf#what-is-saf

[101] Stratasys [Internet]. Transforming dentistry. Available from: https://www.stratasys.com/explore/whitepaper/transforming-dentistry?returnUrl=%2Fexplore%3FPage%3D1%26Phrase%3D%26ResourceTypes%3D%257B460BE7D2-8558-48CB-9AF8-C21F926E875D%257D

[102] Guo Y, Liu Y, Liu J, Zhao J, Zhang H, Zhang Z. Shape memory epoxy composites with high mechanical performance manufactured by multi-material direct ink writing. Composites Part A: Applied Science and Manufacturing. 2020;135

[103] Xjet [Internet]. NanoParticle Jetting™ (NPJ). Available from: https://www.xjet3d.com/technology/