EUROPEAN JOURNAL OF MATERIALS SCIENCE AND ENGINEERING
Volume 9, Issue 2, 2024: 151-172 | www.ejmse.ro | ISSN: 2537-4338

DOI: 10.36868/ejmse.2024.09.02.151

# A VERSATILE ADDITIVE MANUFACTURING INSTRUMENT: PHOTOPOLYMERIZATION-BASED 3D PRINTING AND CURRENT TRENDS FOR DENTISTRY AND ORTHODONTICS APPLICATIONS

Serkan SALMAZ[1,2], Çağın BOLAT[1,*]

[1] Samsun University, Faculty of Engineering and Natural Sciences, Ballıca Campus,
Mechanical Engineering Department, 55420, Samsun, Turkey
[2] Samulaş Incorparated Company, Samsun, Turkey

### Abstract

*The additive manufacturing route is a notably promising alternative option to obtain complex shaped parts, precise prototypes, and direct-usage system components for lots of independent sectors like medicine, dentistry, automotive, aviation, and construction. Compared to the conventional strategies, this methodology provides cleaner, healthier, and faster manufacturing opportunities for engineers and manufacturers. In this paper, actual applications of photopolymerization-oriented 3D printing in the field of dentistry are evaluated in light of the literature efforts, sectoral feedback, and additional original interpretations. Concordantly, the process backgrounds and printing materials were analyzed meticulously together with the evaluations of the physical and mechanical features of the dental components. When real implementations like models, surgical guides, aligners, temporary teeth, and implants are considered, it is seen that there is still a lot of room to be enlightened on this topic for a healthier future. In this context, this article aims to draw a broad perspective on the new interdisciplinary efforts and to emphasize the great potential of layer-by-layer production in the field of dentistry.*

**Keywords:** *additive manufacturing, photopolymerization, stereolithography, dental resin, dental implant*

## Introduction

Additive manufacturing, also known as layered manufacturing technology, encompasses a broad framework that includes various technologies and is a practical production method enabling the transformation of digitally designed objects into physical parts. This technology has the capability to convert digital designs into tangible objects using 3D printing methods. The fundamental principle of 3D printing is the opposite of subtractive manufacturing methods such as CNC milling and turning, which are based on computer-aided manufacturing processes. In subtractive manufacturing processes, a three-dimensional object is created by cutting and removing pieces from a material block, whereas in the 3D printing method, the designed three-dimensional object is obtained by the successive assembly of material layers [1]. Fig.1 shows the process from the conceptual stage of manufacturing with 3D printing to the acquisition of the final product.

The primary reasons for the preference of 3D printing technology include the elimination of additional production stages such as setting up production lines and mold design, and the ability to immediately incorporate the design into the manufacturing process. Another significant advantage of using this technology is that printers utilizing 3D printing methods enable cloud-

---

*Corresponding author: cagin.bolat@samsun.edu.tr

based production. As a result, incoming orders can be directly transmitted to the printer, allowing for rapid production without the need for any molds or assembly lines. This circumstance not only incorporates cloud technology but also includes technologies such as sensors, wireless communication, and robotic arms, contributing to the formation of Industry 4.0 [1]. Further, the models produced through three-dimensional printers have provided a low-cost alternative compared to traditional methods, saving on labor and time [2].

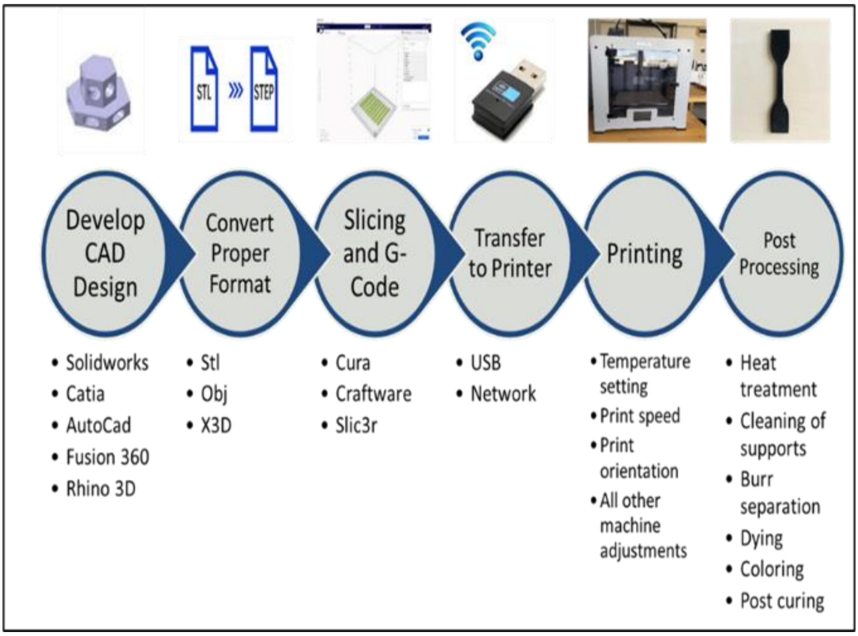

**Fig. 1.** Process steps for the additive manufacturing operations [1]

According to the ISO/ASTM 52900 standard, the definition of additive (layered) manufacturing is stated as follows: 'A process of joining materials layer by layer to produce parts from three-dimensional model data, in contrast to subtractive manufacturing and forming methods' [3]. According to the standard, the main additive manufacturing methods are divided into seven categories: Material extrusion, photopolymerization (Vat-polymerization), material jetting, sheet lamination, powder bed fusion, directed energy deposition, binder jetting [3]. If the most preferred versions are looked at, in material extrusion, thermoplastic materials are used with fused deposition modeling (FDM) technology. For photopolymerization, polymer and ceramic materials are utilized to activate stereolithography (SLA), digital light processing (DLP), and continuous digital light processing (CDLP) technologies. During the operations made through powder bed fusion, materials such as polymer, metal powder, and ceramic powder are used with selective laser sintering (SLS), direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM) technologies [4,5]. The commonly used additive manufacturing technologies are provided in Fig.2 according to the physical state of the consumed raw material [4,5].

Additive manufacturing, with its diverse array of methods, emerges today as a technology distinguished by its speed and practicality. Constantly evolving with new methods being added, it gains significant interest both in the industrial surroundings and academic institutions. Additive manufacturing technologies offer the capability to produce parts across a wide range of materials, spanning from hundreds of different types of plastics to dozens of metal powders. It is anticipated that in the future, the inevitability of increasing product diversity and application fields will force scientists to improve the novel printing ways more. With this perspective in mind, Fig.3 below presents the general usage distribution and the proportional allocation to relevant sectors.

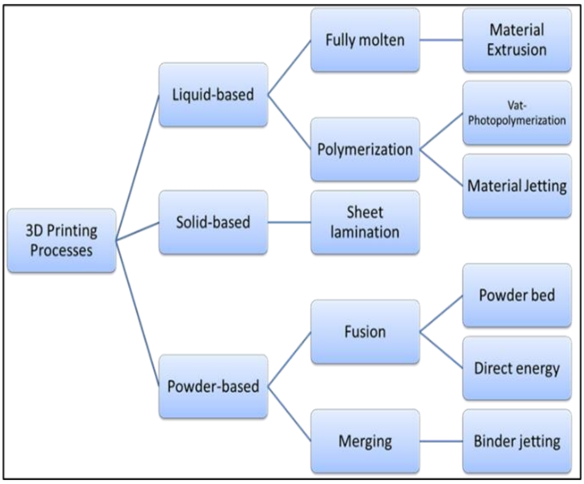

**Fig. 2.** Process classification dependion on the initial physical condition of the printed material

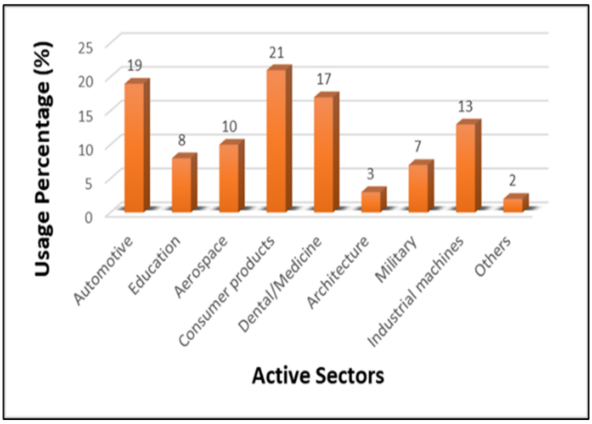

**Fig. 3.** Featured sectors for the additive manufacturing operations [6]

3D printing strategy has rapidly gained momentum, especially with advancements in the medical field and dentistry [7]. It is effectively used in both the design and production of both partial and full prosthetics [8]. Especially the utilization of 3D printing technology in the production of dental implants with complex morphology has enabled the successful creation of bone-like implants that cannot be produced solely with milling [9]. This technology, particularly enabling the production of implants with complex geometries, offers various advantages in dental applications. Implants can be manufactured to directly or indirectly replace defective or missing tissue. Additionally, dental applications such as crowns and bridges are also within the scope of printing technology as part of dental practice. In this context, the compatibility of the material with the tissue is of great importance, and selecting the appropriate material is a critical factor for a successful treatment outcome [10].

In dentistry area novel innovative layer-by-layer production offers a series of advantages over traditional methods. Herein, some of these advantages can be highlighted as follows [11].

- There is the possibility to produce products with complex structures tailored to individual needs, including

details such as irregularities and indentations, in three dimensions. A well-designed product can optimize costs without increasing complexity.

- It minimizes human errors in the manufacturing process and reduces the need for intervention due to fewer production stages.
- It offers the opportunity for rapid production by reducing both production and delivery times.
- It reduces energy consumption and material waste, lowering investment costs by eliminating the use of traditional production tools such as drills.
- It has a passive production process and does not require additional force for milling.
- It makes the production of large objects easier compared to traditional methods.
- It provides the possibility of detailed production based on digitized data (such as computer tomography (CT), magnetic resonance imaging (MRI)), and repeatability can be achieved at a lower cost.

According to data from the FDI World Dental Organization, nearly 2.3 billion people experienced health issues due to tooth decay in 2019. Approximately 20% of this number consisted of pediatric patients [12]. At this point, especially innovative processes in dentistry treatments, the qualified workforce of dental professionals, and new-generation supportive applications (such as 3D Printing) play a key role in the future healthy population rate. Fig.4 and Fig.5 provide a detailed perspective on predicting the global 3D printing market values focused on dentistry and the commercial future of the sector.

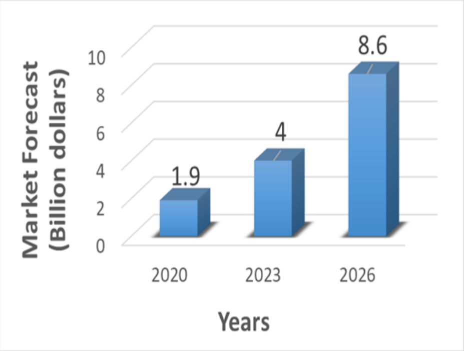

**Fig. 4.** Dental 3D printing market forecast [12]

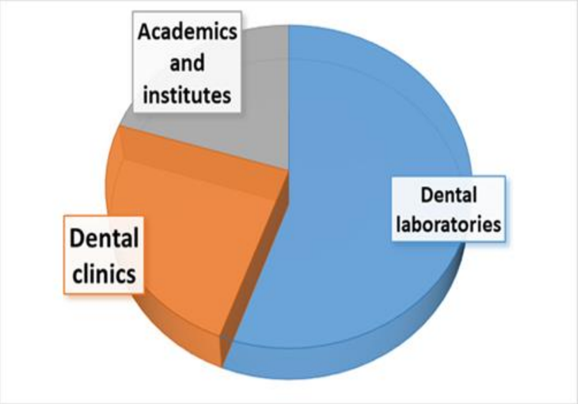

**Fig. 5.** Global dental 3D printing market according to real usage segments in 2023 [13]

## Photopolymerization process and technical background

This kind of polymerization-based methodology is the first example of additive manufacturing technology. The method utilizes a specific type of light (such as laser or LED light) to create one layer at a time inside a container containing light-processed photopolymer resin. As each layer is formed, the light passes through the surface of the liquid resin. Then, the platform is lowered onto another layer of resin, and this process is repeated [14]. The light source and exposure energy are the key factors that control the thickness of each layer [15]. Thanks to the ability of the photopolymerization, high-quality parts with resolutions of up to 10 µm can be obtained [16].

In general, to initiate the photopolymerization process, a light source emitting at specific wavelengths and a molecule containing a photosensitive initiator are required. These photosensitive initiators activate free radicals, allowing monomer molecules to combine and form cross-linked chains. Emerged chemical reaction sequence then continues, resulting in the accumulation of three-dimensional rigid polymer network with a layer thickness between 100 µm and 200 µm [17, 18]. The general reaction flow and the polymerization system on an epoxy example can be observed in Fig.6.

Over the past thirty years, 3D printing ways have been primarily tried to produce prototypes or models from polymeric or metallic materials. However, in recent years, the production of ceramic materials has been gaining increasing popularity [19]. Much of the recent research on ceramics produced using additive manufacturing technology focuses particularly on polymerization-based technologies [20, 21]. At this point, SLA stands out owing to its easy practicability and precision capacity. In this method, a highly ceramic-filled binder that hardens with light is used. To ensure the binder hardens with light, smaller ceramic particles with better light scattering properties are preferred [22].

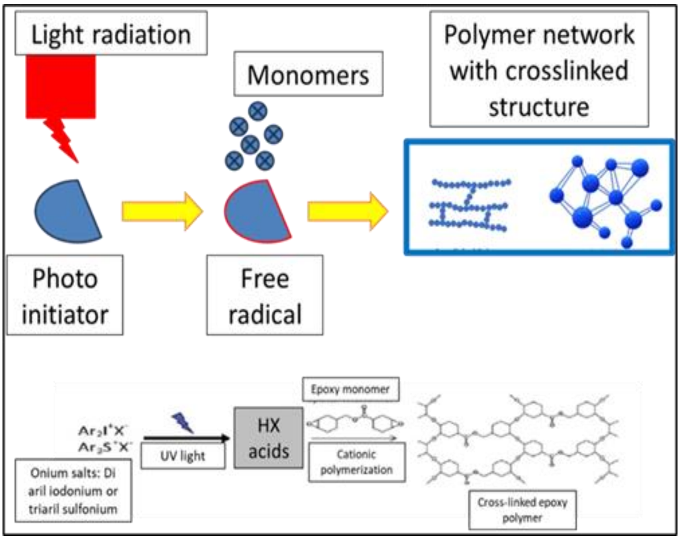

**Fig. 6.** Photopolymerization reaction process and a sample of epoxy [17, 18]

Personalization is of great importance in additive manufacturing. One of the fundamental advantages of this technology is the ability to form various products with specific features tailored to the individual needs of the patient. For example, various medical products such as diagnostic platforms, orthopedic and dental implants, drug manufacturing systems, medical devices, artificial tissues, and organs can be produced in a personalized manner [23, 24].

The earliest use of additive manufacturing technology for movable prosthetics dates back to 1994 when Maeda et al. produced prostheses using light-cured resin with the SLA method. Since then, various descriptions of different methods have been proposed to incorporate additive manufacturing technologies into the production of full prosthetics [25]. In another work, Bilgin et al. have produced single-piece full dentures containing nano-micro hybrid filler resin teeth using the DLP method [26]. Park et al. have stated that the fracture resistance of artificial teeth produced via SLA was sufficient compared to traditional temporary teeth [27]. Wu et al. have successfully cast skeleton models produced through SLA method compared to traditional methods [28]. Koh et al. compared the color stability of SLA-printed parts with different colorants to various prefabricated teeth and found no significant difference between them [29]. Xing et al. have produced complex zirconia ceramics with high dimensional accuracy using the SLA method and reported that these ceramics had mechanical properties (such as fracture toughness and hardness) close to those of zirconia produced by removal methods [30].

In specific to dentistry, functional properties such as wear, corrosion, and compressive strength are of great importance in examining resin-based interactions during the production process. In this context, a detailed evaluation of the photopolymerization properties of resins used in dentistry applications is important for determining both physical and mechanical properties. There is a necessity to thoroughly investigate the photopolymerization processes of dental resins in order to conduct advanced innovative studies. Fig. 7 schematizes current dental practice applications.

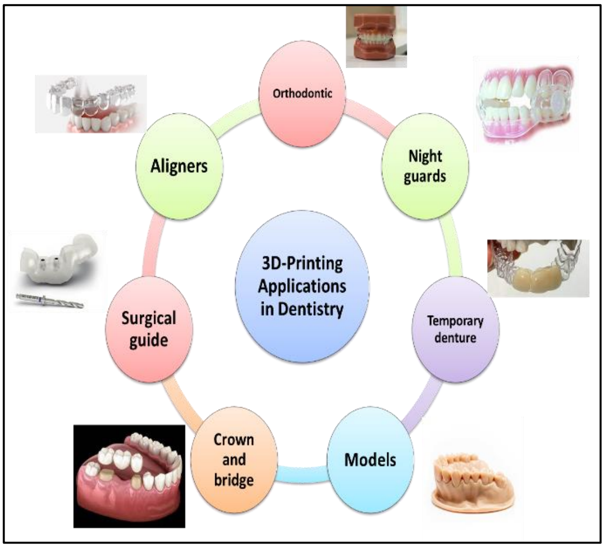

**Fig. 7.** Actual dentistry applications with 3D printing

## Photopolymerization-based printing techniques

In practice, vat-photopolymerization techniques consist of three types: SLA, DLP, and CDLP methods. As the general strategy, the DLP style manufacturing operates on almost the same principle as SLA. The fundamental difference between SLA and DLP is that in DLP, each layer is cured by ultraviolet light projected by a projector, whereas in SLA, light-sensitive resins are cured layer by layer using a laser source. Therefore, SLA is more precise and slower in the manufacturing process compared to DLP. With CDLP, part manufacturing is carried out on a similar principle to DLP, with the main difference being that during layer fabrication in CDLP, the manufacturing plate moves continuously upward in the Z direction. Once the first layer solidifies, it is lifted up from the resin vat, and the next layer to be built is solidified by the light emitted by the projector [31].

### Stereolithography (SLA)

The SLA technology is based on the principle of curing a liquid photopolymer resin layer at room temperature using a laser beam according to predefined geometric data. This curing process lies at the core of 3D printer technologies based on additive manufacturing logic. Each layer is designed using 3D slicing software based on pre-generated G-code data. The laser beam, guided by this data, scans the resin layer to carry out the curing process. Once the first layer is cured, the build platform moves up by one layer height, and a new resin layer is applied on top, repeating this process iteratively. Layers are added to each other until the entire object is produced. This method allows for obtaining detailed and complex, smooth 3D objects from liquid resin with no specific geometry. A schematic representation of the production process is shared in Figure 8 [32].

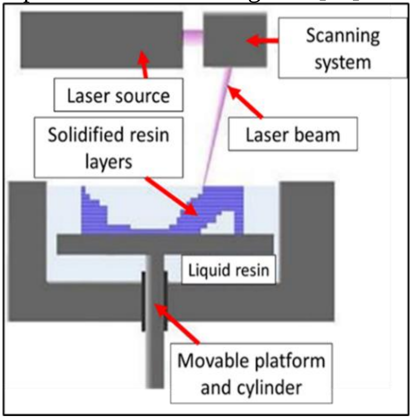

**Fig. 8.** Process schema of SLA methodology [33]

Like all other alternative applications, SLA-type 3D printers have some prominent advantages and disadvantages [34, 35, 36]. The capability of producing complex geometries with sharp accuracy can be considered a significant advantage of SLA printers. For the manufacturing of numerous products, the economical feature can be achieved by simultaneously using workshop-type multiple machines. Especially, it excels in terms of final product surface quality and does not require secondary surface treatments apart from cleaning. Additionally, considering the balance between increasing competition and speed in today's market, the daily production speed is high when scaled according to the design size. On the other hand, some drawbacks of this technique include the tendency of high stiffness parts to exhibit brittle behavior compared to their thermoplastic counterparts. Serial production is another complex issue, and integrating automation with SLA is laborious. Moreover, the necessity of the material being solely photo-polymer-based and the challenges such as post-production separation of support structures are prominent difficulties of this way.

### Digital Light Processing (DLP)

DLP-based 3D printing is another fabrication style that stands out with its rapid printing, excellent scalability, and easy-to-use operating conditions [37]. In this technique, a digital mirror mechanism consisting of independently positioned mirrors is used. A two-dimensional pixel pattern is projected onto a transparent plate to cure a layer of resin at once. The completion time of objects depends solely on the layer thickness, not on the dimensions in the x-y plane or the number of objects produced simultaneously. Therefore, a faster production process is achieved [38]. The schematic representation of the DLP method is shown in Fig.9.

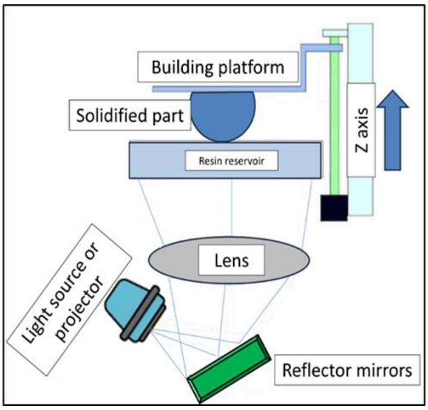

**Fig. 9.** Process schema of DLP methodology [40]

One of the most significant advantages of the DLP technique is high precision. On the other side, this high precision is typically guaranteed in small-scale production, making it a frequently preferred method, especially in the field of dentistry [39]. Thanks to the light creating two-dimensional pixels, this method is relatively faster, and the final products have a smooth surface quality. However, its basic handicaps include being limited to photo-polymerization-based materials and the need for post-production removal of support structures from the main body using chemical or mechanical methodologies.

## Continuous Digital Light Processing (CDLP)

Also known as continuous liquid interface production, CDLP is a novel additive manufacturing technology utilized to create high-resolution parts with high mechanical properties using oxygen-permeable lenses and programmable liquid resin. CDLP technology operates similarly to DLP technology, with the build platform continuously moving along the Z-axis, allowing parts to be completed more quickly. Continuous liquid interface production creates a "dead zone" (permanent liquid interface) where photopolymerization is inhibited between the window and the polymerizing section using a window that allows oxygen to pass below the UV projection plane. The schematic representation of the CDLP method is shown in Fig. 10.

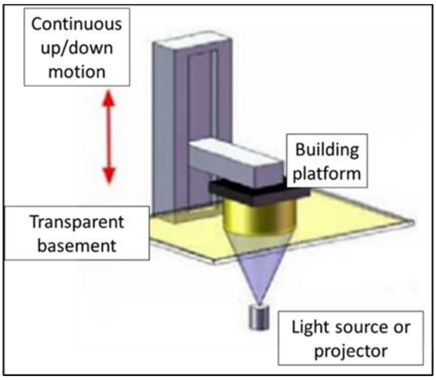

**Fig.10.** Process schema of CDLP methodology [42]

With CDLP technology, complex solid parts can be produced via a specially formularized resin at a print speed of over 100 mm per hour. This high printing speed allows 3D printing to move from being a process that takes hours to one that can be completed in minutes. CDLP also enables the consumption of various materials such as soft elastic materials, ceramics, and biological materials [41].

For CDLP type 3D printers, low-viscosity standard resins are generally preferred, allowing designs that provide a strong interlayer transition connection. Nevertheless, delamination-type defects may occur if the optimum manufacturing parameters are not adjusted or if exposure processes deviate from the resin manufacturer's recommendations [43, 44].

## Dentistry Outlook of the Polymerization

### Resin Types for Dentistry Applications

Additive-based fabrication options have successfully been applied in the dental sector since the beginning of the millennium, encompassing polymers, metals, and alloys. During this period, the laser sintering approach used in the processing of metal alloys in dentistry can be qualified as a serious advancement. Studies in this field have generally focused on the production of structures using materials such as chromium-cobalt, titanium, and nickel alloys [45]. Today, additive manufacturing technologies frequently utilize methods such as DLP, SLA, and PJ (Polyjetting), which are economically and technically viable for the production of polymers and plastic objects [46]. The biocompatibility, chemical stability, and performance stability of the material are critically important alongside production accuracy. Therefore, the chemical compositions of resins suitable for additive manufacturing technology must be specially tailored. The resin should flow easily between the printer's platform and the tank with the correct viscosity after each layer. The addition of fillers, pigments, and photo-initiator agent's not only affects the mechanical properties of the materials but also alters their accuracy. If the refractive index between the resin and the incorporated substances is not properly adjusted, laser light scatters, leading to a decrease in polymerization depth and consequently loss of accuracy in the produced object [47].

Depending on the evolving manufacturing options, ongoing development of polymeric resin formulations, and interdisciplinary knowledge transfer, the resin types selected in dentistry, biomedical, and medical education for vat-polymerization are provided in Fig. 11.

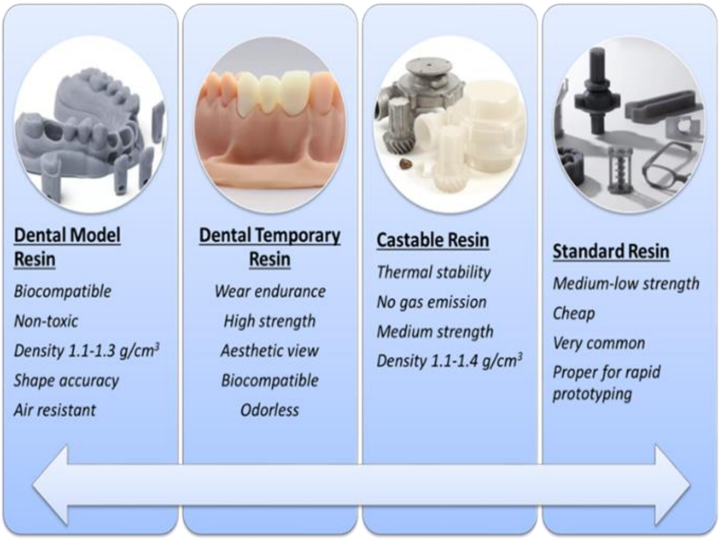

**Fig. 11.** Dentistry, biomedical and medicine oriented resin types [48, 49]

The widespread use of ceramic materials in dentistry is based on their specific advantages such as superior biocompatibility, chemical stability, appropriate mechanical properties, and high aesthetics. On the other side, the brittle nature of ceramics requires meticulous control during the manufacturing process to obtain products with suitable mechanical properties for dental restorations. Due to these characteristics, while polymer or metallic materials have generally been used in additive manufacturing for a long time, ceramics have only recently found their place among the materials in this technology. The processing methods of ceramic materials are quite complex and detailed [50]. Most recent research focusing on ceramics produced by additive manufacturing technology has largely centered on SLA-based methods in particular [51]. Micro-particle ceramic materials dispersed in polymeric resins can be individually obtained after the curing of the polymer followed by furnace sintering processes. For instance, Dehurtevent et al. found that alumina ceramics produced via SLA method with a layer thickness of 50 µm using acrylic resin exhibited acceptable similarity in physical and mechanical properties to those produced by abrasive manufacturing systems [52]. Liu et al pointed out that zirconia/alumina ceramics could be produced via the SLA method combined with powder sintering route [53].

## Dental implants

In recent years, alongside increasing aesthetic concerns, a healthy oral structure has been carefully considered by many individuals. At this point, implant treatment and aesthetic dentistry have reached a significant demand level for both a beautiful appearance and a comfortable oral structure. Integrating 3D printing technologies into dentistry is a useful method for rapidly producing durable implant materials. Considering the frequency of dental implant usage and the continuously increasing demand, there are patient and practitioner expectations from various perspectives. This situation can be overcome through the collaborative efforts of biomedical, mechanical, material, and manufacturing engineers, as well as medical and dental disciplines. Fig. 12 illustrates all the expected features from a surgical implant.

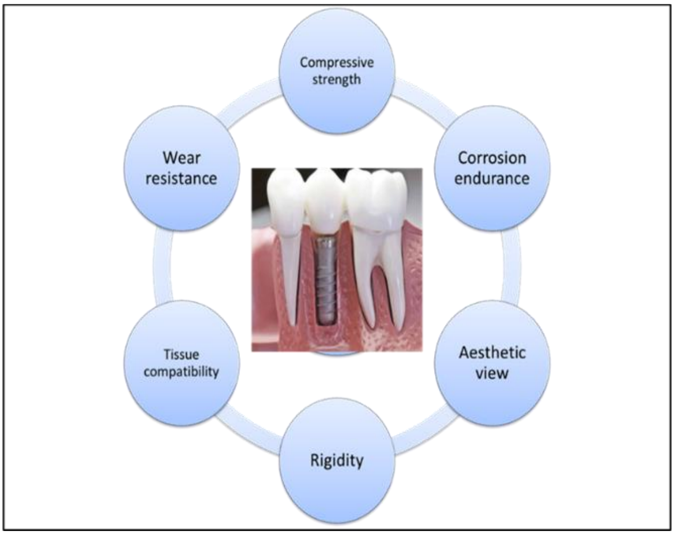

**Fig. 12.** Expectations from a dental implant

Chen et al. aimed to evaluate the mechanical and biomechanical performance of a new custom-made dental implant produced by selective laser melting technique through simulation and experimental studies. They have produced implants with high strength that can compete with fabricated implants, and reported that these implants have a granular surface [54]. In their study, they fabricated flat and threaded implants made of titanium material, as shown in Fig. 13.

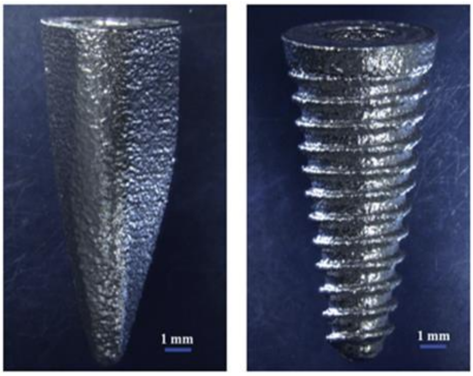

**Fig. 13.** Titanium implants made through SLM; plain (left) ve threaded (right) [54]

According to some similar studies, metallic implants produced with 3D printers have been reported to feature porous surfaces in various geometries [55, 56, 57]. Ramakrishnaiah et al. examined features such as surface roughness, surface chemical composition, and microstructure of the dental implant they produced using selective laser technology with Ti-6Al-4V material [57]. Hyzy et al. observed similar or increased roughness compared to surfaces produced by traditional methods [58]. Osman et al. reported that additively manufactured custom zirconia dental implants exhibited sufficient dimensional accuracy. They indicated that implants produced with this system demonstrated mechanical properties close to traditional methods in terms of bending resistance [59]. Fevzi et al. highlighted the advantages of shaping metal-based materials using additive manufacturing methods. Metal powders used in additive manufacturing, along with their properties and applications, are introduced within the biomedical field. 3D printed products are compared with those shaped using standard production methods, confirming their mechanical and physical properties [60]. In Fig. 14, the application of CoCrMo alloy and Ti64 material in dentistry using the DMLS method is illustrated.

**Fig. 14.** CoCrMo alloys (a) and Ti64 (b) for dental applications [60]

The development of additive manufacturing in the dental field has led to significant changes in dental practice. Unlike traditional manufacturing methods, it offers a faster and more costeffective production option. Rather than requiring multiple appointments for various dental treatments, patients can receive customized designs and a wide range of materials in a single session. These kinds of reasonable situations accelerate the advancement of layer-by-layer manufacturing method in the dental field.

## Orthodontics and digital orthodontics

Apart from the implants and models, additive manufacturing plays a significant role in the field of orthodontics, by providing opportunities for customization and reproduction. Concordantly, this technology facilitates the creation of precise, accurate, and reproducible dental models, particularly for orthodontic purposes [61]. Especially, there is a growing interest and use of 3D printing technologies in the manufacturing of aesthetic aligners, jaw alignment devices, and prototype prostheses, which serve as alternatives to wire treatments.

Digital orthodontic method is benefited to draw a treatment plan before orthodontic treatment. With 3D intraoral scanning, patient information is obtained digitally in a short time. Besides, digital screening provides great convenience and advantage as it does not require the use of large measuring spoons. By modeling with the measurements taken from the 3D scanner, the product needed for the patient is made ready for production. By way of orthodontic analysis and treatment planning, it is possible to analyze all the details of case analysis, simulation of orthodontic treatments, tooth extractions, interface abrasion and tooth movements. Completing the treatment on time, evaluating the treatment process in a virtual environment, customizing the treatment, positioning the brackets without errors, and previewing the stages of the treatment process can be done digitally. In digital dentistry, models are generated in a virtual environment with 3D scanning, making the treatment of people with a gag reflex easier, especially since large metal spoons are not used. The cone beam computed tomography image of a patient who was born without upper jaw and lateral incisor teeth is shown in Fig. 15.

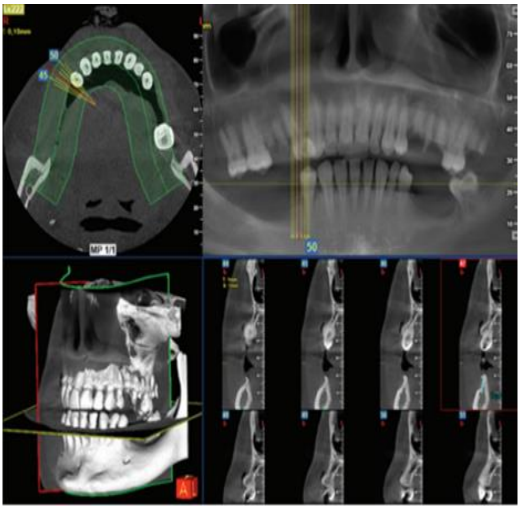

**Fig. 15.** A sample BT scan view for maxillofacial operations [62, 63]

In clinical practice, traditional computer-assisted approaches still prevail. Daniel et al. evaluated a concept based on flapless surgical technique, a treatment planning procedure relying on CT images, and fixed prosthesis reconstruction for immediate loading of the upper jaw, reporting the protocol to be successful [11]. Eufinger et al. examined CAD/CAM techniques for preoperative modeling of implants based on CT data and stated that the reconstruction of craniofacial bone defects with individual implants based on tomographic data is superior to traditional methods [64]. On the other hand, in another study emphasizing the competitive aspect of additive manufacturing, Revilla-Leon et al. analyzed the accuracy of implant analog positions in complete maxillary models made of plaster and polymers produced by additive manufacturing using a coordinate measuring machine and reported no significant difference between them [65].

## Surgical guides and models

Surgical guides prepared through additive manufacturing assist in the accurate positioning and angulation of implants. During the production of surgical guides, the regions where implants will be placed are determined in the planning phase, and centering guides for the initial drill path are established. Some sample guide models are shown in Fig. 16. The rapid and serial production of these guides enables quick examination and surgical operations. This situation highlights clinics familiar with innovative three-dimensional printing technologies compared to others.

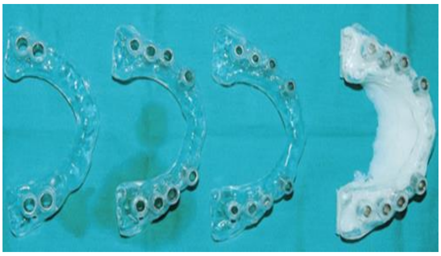

**Fig. 16.** Surgical guides with different size range [66]

Additive manufacturing also stands out as a technology used in medical modeling, enabling the production of anatomical study models. Through these models, it is possible to examine complex anatomy in detail and conduct preoperative surgical planning. These models can be used as references in diagnosis, preoperative planning, and during surgical procedures. In addition, additive manufacturing is increasingly being utilized not only in oral applications or intraoral procedures in dentistry but also in maxillofacial surgery [67, 68]. The stages of surgical guide and model production in dentistry are illustrated in Fig. 17. These stages can be listed as follows: obtaining cone-beam computed tomography images from the patient (Stage 1), saving the images obtained from cone-beam computed tomography in DICOM format (Stage 2), creating a three-dimensional design from the obtained DICOM files to obtain an STL format model (Stage 3), designing a three-dimensional bone implant on the obtained STL format model (Stage 4), printing the designed bone implant on a 3D printer (Stage 5), and applying the 3D-printed bone implant to the patient (Stage 6) [69, 70].

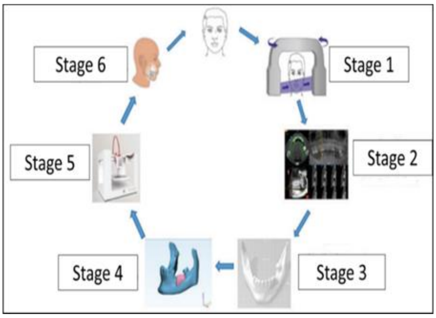

**Fig. 17.** 3D printing stages for the model and surgical guide production in dentistry

## Physical properties

Studies on the examination of physical properties have confirmed that products produced by additive manufacturing are not inferior to those produced by traditional methods. Especially considering that CAD/CAM-focused and traditional casting-based applications have a longer usage history, it can be said that 3D printing technologies are quite an attractive alternative both in terms of manufacturing speed and dimensional accuracy of produced dental prostheses, models, and implants. In the context of dental applications, some physical property outputs are important in terms of design, usage, performance, and aesthetics (Fig. 18).

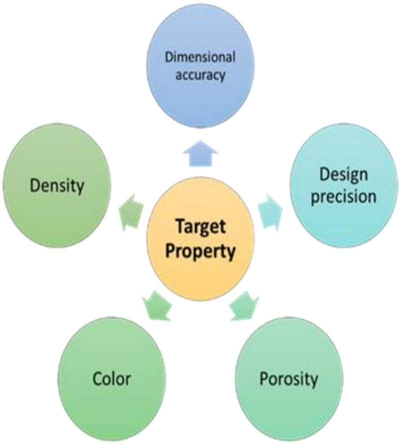

**Fig. 18.** Target physical properties in specific to dentistry

In recent years, both experimental and finite element-supported scientific studies have focused on personalized dental models and analyses specific to jaw structure and profile. Jeong et al. have stated in their study evaluating the dimensional accuracy of dental models produced by different methods (CAD/CAM-based milling and 3D printing) that additive manufacturing is more successful [71]. The detail depth and design sharpness created by additive manufacturing are illustrated in Fig. 19.

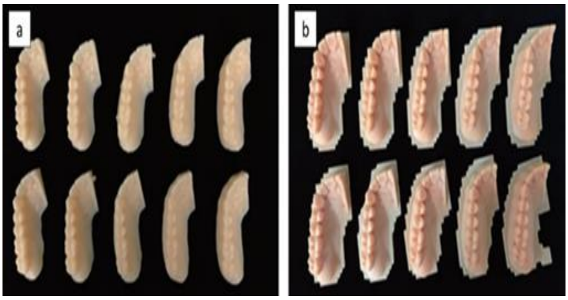

**Fig. 19.** Precision difference between milling (a) and 3D-printing (b) [71]

Regarding implant locations and positions, Revilla-Leon et al. reported no significant difference by analyzing the accuracy of implant analog positions in polymer models obtained through plaster and additive manufacturing [65]. Particularly, it has been observed that samples produced with DLP and multijet printing (MJP) technologies, with layer printing thicknesses ranging from 50 µm to 100 µm, provide the same performance as conventional plaster casting but in a much faster and more practical manner.

In material and mechanical engineering applications, especially considering the increasingly competitive industry landscape, the process of achieving high performance with low weight stands out. This phenomenon is also evident in dental implants produced with 3D printers, with titanium alloys being at the forefront. Many examples of dental implants, ranging from porous structures for tissue integration to standard solid structures, are being optimized for application-specific purposes on titanium alloys. Ghassemieh et al. have worked on the final sintering processes of titanium implants produced by the binder jetting method, showing that the central porosity and surface porosity values begin to decrease with sintering temperature [72]. Kim et al. have utilized the DMLS method to produce a group of dental implant products from Ti-6Al-4V powders, emphasizing that as the laser spacing increases, the number of pores observed in the microstructure also increases [73]. Ji et al. have reported that porous bone-like dental titanium produced with SLM exhibit pore sizes of 500 µm and are porous to varying degrees ranging from 48% to 84% [74]. Tsai et al. suggested that non-destructive testing methods can be used on zirconia ceramic dental prostheses produced with SLA (Fig.20) and potential internal structural defects can be detected using ultrasonic inspection [75].

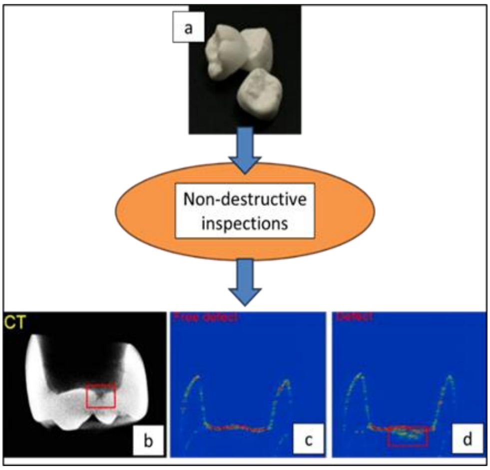

**Fig. 20.** Zirkonia printing for dentures: a) SLA printed samples, b) computer tomography views of defects; c) ultrasonic results of the samples without defects; d) ultrasonic results of the samples with defects [75]

## Mechanical behaviors

Mechanical properties of samples produced by the photopolymerization-based additive manufacturing technique have been investigated by various research groups, and some experimental findings have been revealed. Typically, the general focus has been on target properties such as tensile strength, elongation capability, elastic modulus, compressive strength, and flexural strength.

Looking at some reported studies, Li et al. worked on the effects of material printing orientation on the tensile-type mechanical behavior of printed samples. The authors identified a decrease in tensile strength with increasing sample building angle and explained this phenomenon with mechanical anisotropy [76]. In their study, Aktitiz et al. printed epoxy parts via a SLA device and applied UV secondary curing process at different durations to examine its effect on the mechanical and thermal properties of the polymer structures [77]. According to the findings, with increasing curing time, the impact strength of the epoxy samples showed a decreasing trend. Hossain et al. investigated the strain-dependent behavior of elastomeric polyurethane material attained by DLP process and studied viscoelastic structural behavior at low strain rates [78]. Miedzinska et al. conducted quasi-static and dynamic compression tests to investigate the strain rate dependency of various resin materials manufactured by SLA [79]. The researchers highlighted that polymer samples tended to become more brittle and break into smaller pieces with rising deformation rate. Reyes et al. produced biocompatible polymeric samples specific to dental applications using different additive manufacturing techniques and stated that samples created with SLA achieved a higher flexural modulus value in all printing directions [80]. Topsakal et al. investigated the effects of aging properties of biocompatible dental resins on mechanical properties [81]. The researchers noted that parts fabricated by DLP and SLA printers remained mechanically sound even after aging processes, capable of withstanding physiological forces. Simeon et al. compared the bending and wear behaviors of bite splints produced with DLP and SLA [82]. According to the obtained data, DLP-originated samples showed less statistical fluctuation in flexural strength and wear resistance results depending on the printing direction.

## Probable future works

Additive manufacturing holds significant future potential in both prosthetic and dental modeling, as recognized by relevant literature and professional organization reports. In this regard, from an academic perspective, there are some points that can be proposed as topics for future scientific research. Fig. 21 illustrates the proposed outlines for future studies.

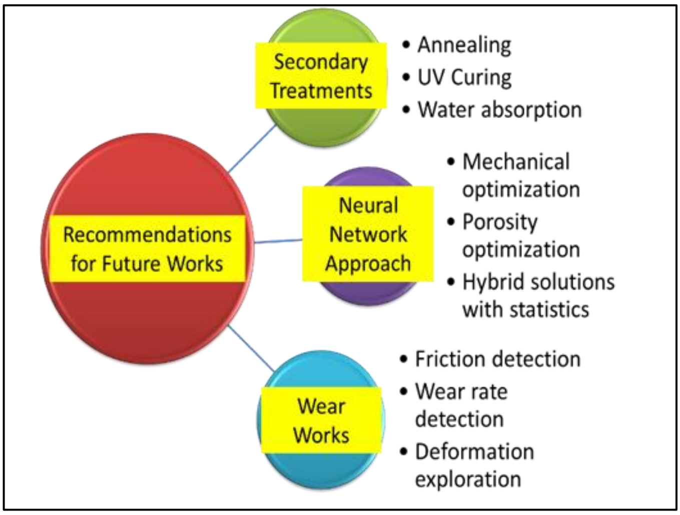

**Fig. 21.** Probable future work recommendation schema

When considering the implications of advancing technology and increasing competition in the healthcare sector, next-generation artificial intelligence-based optimization and prediction approaches may be beneficial in terms of mechanical performance, physical properties, and cost in dental applications. Here, interdisciplinary activities can be accelerated between dentistry, biomedical engineering, mechanical engineering, and software branches. Another issue is the matter of tribo-corrosion for artificial temporary teeth. The tribo-corrosion performance of such dental structures should be examined based on the oral fluids and the crushing activity performed by the teeth. Printing process variables can be taken as input variables, and the mechanism-based examination can be experimentally conducted for each process methodology. In this way, the wear performance of temporary dental structures and the nature of deformation can be explored.

The effects of secondary finishing processes (such as annealing, aging, light curing, and water absorption) on the tensile, compressive, flexural, and wear strengths can be investigated in both resin models and temporary dental structures after additive manufacturing. Particularly, the interactions of critical performance-oriented mechanisms, such as changes in crystallinity degree in polymeric materials and microstructural hardening in metallic materials, can be focused on. In metallic implants, bone-like designs and product-tissue compatibility are crucial. Therefore, achieving foam-like and porous structures with the lowest possible weight is determinant. In this regard, hybrid optimization techniques (Taguchi, response surface, Box-Benkhen combined with artificial intelligence-based deep learning) and finite element-based simulation programs can be blended together in a common framework for the determination of mechanical properties and product porosity.

## Conclusion

In recent years, researchers have conducted a series of studies aimed at further enhancing the functionality of parts produced using the SLA method, primarily due to its wide range of applications. Current trends indicate that model creation, prototyping, temporary dental treatments, orthodontic applications, and implant therapies are among the most active areas in dentistry, and the contribution of photopolymerization-based additive manufacturing in these areas is expected to continue in the coming years. With the potential of additive manufacturing to provide personalized and rapid treatment opportunities, it is anticipated that resin-based material formulations will diversify in the coming years. This will enable a targeted approach to functional properties such as compressive strength, rigidity, corrosion resistance, hardness, and wear resistance, which are critical in dentistry. Over the years, many valuable studies have shown a direct relationship between manufacturing process parameters and target output properties. In light of these findings, the importance of optimization techniques and interdisciplinary scientific research has once again been highlighted. In the rapidly changing and evolving industrial world, 3D printers have the power to bring together many different disciplines in the field of human health, which is a common field of study. This situation also holds high potential in dentistry and oral-maxillofacial surgery branches. On the other hand, in individual clinical applications, 3D printing processes are becoming faster and more economical in modeling, prototyping, and temporary dental applications compared to other traditional systems after the initial investment cost. This trend will increase the percentage share of additive manufacturing in the dental market in the future.

## References

[1] H.K. Sürmen, *Eklemeli imalat (3B baskı): teknolojileri ve uygulamaları*, **Uludağ Üniversitesi Mühendislik Fakültesi Dergisi, 24**, 2019, pp. 373-392.

[2] M. Kasparova, L. Grafova, P. Dvorak, T. Dostalova, A. Prochazka, and H. Eliasova, *Possibility of reconstruction of dental plaster cast from 3d digital study models*, **Biomedical Engineering Online, 12**, 2013.

[3] ISO/ASTM 52900, "Additive manufacturing — General principles — Fundamentals and vocabulary," International Standard Organisation, West Conshohocken, PA 19428-2959, USA, 2021.

[4] B. Ergene, Ç. Bolat, *An Experimental study on the role of manufacturing parameters on the dry sliding wear performance of additively manufactured PETG*, **International Polymer Processing, 37**, 2022, pp. 255-270.

[5] F. Calignano, D. Manfredi, E. P. Ambrosio, S. Biamino, M. Lombardi, E. Atzeni and P. Fino, *Overview on additive manufacturing technologies,* **Proceedings of the IEEE, 105**, 2017, pp. 593-612.

[6] A.D.K. Katta, "Analysis of PA6 Powder Ageing during the Selective Laser Sintering Process," Master Tezi, Aelen University, Germany, 2019.

[7] S.H. Saheb, J.V. Kumar, *A Comprehensive review on additive manufacturing applications*, **AIP Conference Proceedings, 2281**, 2020.

[8] A. Bhargav, V. Sanjairaj, V. Rosa, L. W. Feng, J.F. Yh, *Applications of additive manufacturing in dentistry*, **Journal of Biomedical Materials Research B: Applied Biomaterials, 106**, 2017, pp. 2058-2064.

[9] Ç. Bolat, A. Gökşenli, *Fabrication optimization of Al 7075/Expanded glass syntactic foam by cold chamber die casting*, **Archives of Foundry Engineering, 20**, 2020, pp. 112-118.

[10] M. Salmi, *Additive manufacturing processes in medical applications*, **Materials, 14**, 2020, pp. 191.

[11] S.D. Van, R. Glauser, U. Blombäck, M. Andersson, F. Schutyser, A. Pettersson, *A computed tomographic scan derived customized surgical template and fixed prosthesis for flapless surgery and immediate loading of implants in fully edentulous maxillae: A prospective multicenter study*, **Clinical Implant Dentistry and Related Research, 7**, 2005, pp. s111-s120.

[12] "What makes dental 3D printing the new normal in dentistry?" https://www.medicalplasticsnews.com/medical-plastics-industry-insights/medical-plastics-3d-printing-insights/what-makes-dental-3d-printing-the-new-normal-in-dentistry/, Accesed: 2 February 2024.

[13] "Dental 3D Printing Market Size, Share & Trends Report." https://www.grandviewresearch.com/industry-analysis/dental-3d-printing-market/, Accessed: 2 February 2024.

[14] H. Wu, Y. Cheng, W. Liu, R. He, M. Zhou, S. Wu, *Effect of the particle size and the debinding process on the density of alumina ceramics fabricated by 3d printing based on stereolithography*, **Ceramics International**, 2016, pp. 17290-17294.

[15] F.P. Melchels, J. Feijen and D. W. Grijpma, *A review on stereolithography and its applications in biomedical engineering*, **Biomaterials, 31**, 2010, pp. 6121-6130.

[16] X. Wang, M. Jiang, Z. Zhou, J. Gou, D. Hui, *3d printing of polymer matrix composites: A review and prospective*, **Composites Part B: Engineering, 110**, 2017, pp. 442-58, 2017.

[17] A. Endruweit, M.S. Johnson, A.C. Long, *Curing of composite components by ultraviolet radiation: A review*, **Polymer Composites, 27**, 2016, pp. 119-128.

[18] "Epoksi Reçinelerin Fotopolimerizasyon ile Kürlenmesi ve Kompozitlerde Kullanımı." https://www.turkchem.net/epoksi-recinelerin-fotopolimerizasyon-ile-kurlenmesi-ve-kompozitlerde-kullanimi.html/, Accessed: 1 February 2024.

[19] I. Buj-Corral, A. Tejo-Otero, *3D printing of bioinert oxide ceramics for medical applications*, **Journal of Functional Biomaterials, 13**, 2022, pp. 155.

[20] L. Yang, H. Miyanaji, Ceramic additive manufacturing: A review of current status and challenges, 28th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference, p. 652-679, Texas, USA, 2017.

[21] W. Zhou, D. Li, H. Wang, *A novel aqueous ceramic suspension for ceramic stereolithography*, **Rapid Prototyping Journal, 16**, 2010, pp. 29-35.

[22] N. Travitzky, A. Bonet, B. Dermeik, T. Fey, D.I. Filbert, L. Schlier, *Additive manufacturing of ceramic-based materials*, **Advanced Engineering Materials, 16**, 2014, pp. 729-754.

[23] H.N. Chia, B.M. Wu, *Recent advances in 3d printing of biomaterials*, **Journal of Biological Engineering, 9**, 2015, pp. 4.

[24] E. Sachlos, J. Czernuszka, *Making tissue engineering scaffolds work. Review: The application of solid freeform fabrication technology to the production of tissue engineering scaffolds*, **European Cells and Materials, 5**, 2003, pp. 29-40.

[25] Y. Maeda, M. Minoura, S. Tsutsumi, M. Okada, T.A. Nokubi, *CAD/CAM system for removable denture. Part I: Fabrication of complete dentures,* **International Journal of Prosthodontics, 7**, 1994, p. 17-21.

[26] M.S. Bilgin, A. Erdem, O.S. Aglarci, E. Dilber, *Fabricating complete dentures with CAD/CAM and RP technologies,* **Journal of Prosthodontics, 24**, 2015, pp. 576-579.

[27] J.H. Park, I.H. Cho, S.Y. Shin, Y. S. Choi, *The treatment of an edentulous patient with DENTCA™ CAD/CAM Denture,* **The Journal of Korean Academy of Prosthodontics, 53**, 2015, pp. 19-25.

[28] J. Wu, X. Wang, X. Zhao, C. Zhang, B. Gao, *A study on the fabrication method of removable partial denture framework by computer-aided design and rapid prototyping*, **Rapid Prototyping Journal, 18**, 2012, pp. 318-323.

[29] E.S. Koh, H.S. Cha, T.H. Kim. J.S. Ahn, J.H. Lee, *Color stability of three dimensional-printed denture teeth exposed to various colorants,* **The Journal of Korean Academy of Prosthodontics, 58**, 2020, pp. 1-6.

[30] H. Xing, B. Zou, S. Li, X. Fu, *Study on surface quality, precision and mechanical properties of 3D printed* $ZrO_2$ *ceramic components by laser scanning stereolithography,* **Ceramics International, 43**, 2017, pp. 16340-16347.

[31] W.A. Sarwar, J. Kang, H. Yoon, *Optimized zirconia 3D printing using digital light processing with continuous film supply and recyclable slurry system,* **Materials, 14**, 2021, pp. 3446.

[32] C. Chaput, T. Chartier, *Fabrication of ceramics by stereolithography*, **RTejournal-Forum für Rapid Technologie, 4.**

[33] W. Oropallo, L.A. Piegl, *Ten challenges in 3D printing,* **Engineering with Computers, 32**, 2016, pp. 135-148.

[34] A. Dawood, B.M. Marti, J.V. Sauret, A. Darwood, *3D printing in dentistry*, **British Dental Journal, 219**, 2015, pp. 521-529.

[35] E. George, P. Liacouras, F.J. Rybicki, D. Mitsouras, *Measuring and establishing the accuracy and reproducibility of 3D printed medical models,* **Radiographics, 37**, 2017, pp. 1424-1450.

[36] M. Javaid, A. Haleem, *Current status and applications of additive manufacturing in dentistry: A literature-based review,* **Journal of Oral Biology and Craniofacial Research, 9**, 2019, pp. 179-185.

[37] C. Schmidleithner, D.M. Kalaskar, Stereolithography, in: Cvetković, D, (ed.), 3D Printing, In Tech Open, p. 1-22, Londra, 2018.

[38] Z. Zhao, X. Tian, X. Song, *Engineering materials with light: Recent progress in digital light processing based 3D printing,* **Journal of Materials Chemistry C, 8**, 2020, pp. 13896-13917.

[39] Y. Lu, G. Mapili, G. Suhali, S. Chen, K. Roy, *A digital micro-mirror device-based system for the microfabrication of complex, spatially patterned tissue engineering scaffolds,* **Journal of Biomedical Materials Research Part A, 77A**, 2006, pp. 396-405.

[40] K.D. Agashe, A. Sachdeva, S.S. Chavan, *3D printing and advance material technology,* **International Journal of Grid and Distributed Computing, 13**, 2020, pp. 1899-1936.

[41] J.R. Tumblestone, D. Shirvanyants, N. Ermoshkin, R. Januszewicz, A.R. Johnson, D.V. Kelly, E.T. Samulski, *Continuous liquid interface production of 3D objects,* **Science, 347**, 2015, pp. 1349-1352.

[42] J. Wallace, *Validating continuous digital light processing (cDLP) additive manufacturing accuracy and tissue engineering utility of a dye-initiator package,* **Biofabrication, 6**, 2014, pp. 015003.

[43] D. Dean, J. Wallace, A. Siblani, M.O. Wang, K. Kim, A.G. Mikos, J.P. Fisher, *Continuous digital light processing (cDLP): Highly accurate additive manufacturing of tissue engineered bone scaffolds,* **Virtual and Physical Prototyping, 7**, 2012, pp. 13-24.

[44] Y. Shin, M.L. Becker, *Alternating ring-opening copolymerization of epoxides with saturated and unsaturated cylic anhydrides: Reduced viscosity poly(propylene fumarate) oligomers for use in cDLP 3D printing*, **Polymer Chemistry, 11**, 2020, pp. 3313-3321.

[45] W. Marcenes, N.J. Kassebaum, E. Bernabe, A. Flaxman, M. Naghavi, A. Lopez, *Global burden of oral conditions in 1990-2010: a systematic analysis*, **Journal of Dental Research, 92**, 2013, pp. 592-597.

[46] N.S. Gasner, R.S. Schure, *Necrotizing periodontal diseases*, 2020.

[47] R. Marcel, H. Reinhard, K. Andreas, *Accuracy of CAD/CAM-fabricated bite splints: milling vs 3D printing*, **Clinical Oral Investigations, 24**, 2020, pp. 4607-4615.

[48] K. Son, J. Lee, K. Lee, *Comparison of intaglio surface trueness of interim dental crowns fabricated with SLA 3D printing, DLP 3D Printing, and milling technologies*, **Healthcare, 9**, 2021, pp. 983.

[49] A.Z. Farkas, S. Galatanu, R. Nagib, *The Influence of printing layer thickness and orientation on the mechanical properties of DLP 3D-Printed dental resin*, **Polymers, 15**, 2023, pp. 1113.

[50] A. Zocca, P. Colombo, C.M. Gomes, J. Günster, *Additive manufacturing of ceramics: issues, potentialities, and opportunities*, **Journal of the American Ceramic Society, 98**, 2015, pp. 1983-2001.

[51] J.W. Halloran, *Ceramic stereolithography: additive manufacturing for ceramics by photopolymerization*, **Annual Review of Materials Research, 46**, 2016, pp. 19-40.

[52] M. Dehurtevent, L. Robberecht, J. C. Hornez, A. Thuault, E. Deveaux and P. Behin, *Stereolithography: A new method for processing dental ceramics by additive computer-aided manufacturing*, **Dental Materials, 33**, 2017, pp. 477-485, 2017.

[53] X. Liu, B. Zou, H. Xing, C. Huang, *The preparation of $ZrO_2$-$Al_2O_3$ composite ceramic by SLA-3D printing and sintering processing*, **Ceramics International, 46**, 2020, pp. 937-944.

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

[55] W. Peng, L. Xu, J. You, L. Fang, Q. Zhang, *Selective laser melting of titanium alloy enables osseointegration of porous multi-rooted implants in a rabbit model*, **Biomedical Engineering Online, 15**, 2016, pp. 85.

[56] A. Shaoki, J.Y. Xu, H. Sun, X.S. Chen, J. Ouyang, X.M. Zhuang, *Osseointegration of threedimensional designed titanium implants manufactured by selective laser melting*, **Biofabrication, 8**, 2016, pp. 045014.

[57] R. Ramakrishnaiah, A. Mohammad, D. Divakar, S. Kotha, S. Celur, M. Hashem, *Preliminary fabrication and characterization of electron beam melted ti–6al–4v customized dental implant*, **Saudi Journal of Biological Sciences, 24**, 2017, pp. 787-96.

[58] S.L. Hyzy, A. Cheng, D.J. Cohen, G. Yatzkaier, A.J. Whitehead, R.M. Clohessy, *Novel hydrophilic nanostructured microtexture on direct metal laser sintered ti–6al–4v surfaces enhances osteoblast response in vitro and osseointegration in a rabbit model*, **Journal of Biomedical Materials Research Part A, 104**, 2016, pp. 2086-2098.

[59] R.B. Osman, A.J. Veen, D. Huiberts, D. Wismeijer, N. Alharbi, *3d-printing zirconia implants; a dream or a reality? An in-vitro study evaluating the dimensional accuracy, surface topography and mechanical properties of printed zirconia implant and discs*, **Journal of the Mechanical Behavior of Biomedical Materials, 75**, 2017, pp. 521-528.

[60] E. Koç and F. Yılmaz, "Biyomedikal parçaların eklemeli imalatla (3D baskı) üretimi," 1. Ulusal Biyomedikal Cihaz Tasarımı ve Üretimi Sempozyumu, İstanbul, Türkiye, 14 Mayıs 2016.

[61] A. Hazeveld, J.J.H. Slater, Y. Ren, *Accuracy and reproducibility of dental replica models reconstructed by different rapid prototyping techniques*, **American Journal of Orthodontics and Dentofacial Orthodontics, 145**, 2014, pp. 108-115.

[62] A.C. Miracle, S.K. Mukherji, *Conebeam CT of the head and neck, part 2: Clinical applications*, **American Journal of Neuroradiology, 30**, 2009, pp. 1285-1292.

[63] A. Aditya, S. Lele, P. Aditya, *Current status of knowledge, attitude, and perspective of dental practitioners toward cone beam computed tomography: A survey*, **Journal of Oral and Maxillofacial Radiology, 3**, 2015, pp. 54.

[64] H. Eufinger, M. Wehmöller, E. Machtens, L. Heuser, A. Harders, D. Kruse, *Reconstruction of craniofacial bone defects with individual alloplastic implants based on cad/cam-manipulated ct-data*, **Journal of Cranio-Maxillofacial Surgery, 23**, 1995, pp. 175-181.

[65] L.M. Revilla, M.O. Gonzalez, L.J. Perez, R.J.L. Sanchez, M. Özcan, *Position accuracy of implant analogs on 3d printed polymer versus conventional dental stone casts measured using a coordinate measuring machine,* **Journal of Prosthodontics, 27**, 2018, pp. 560-67.

[66] J.L. Lozada, A. Garbacea, C.J. Goodacre, M.T. Kattadiyil, *Use of a digitally planned and fabricated mandibular complete denture for easy convension to an immediately loaded provisional fixed complete denture. Part 1. Planning and surgical phase*, **International Journal of Prosthodontics, 27**, 2014, pp. 417-421.

[67] D.M. Erickson, D. Chance, S. Schmitt, J. Mathts, *An opinion survey of reported benefits from the use of stereolithographic models*, **Journal of Oral and Maxillofacial Surgery, 57**, 1999, pp. 1040-1043.

[68] J. Xia, H. H. Ip, N. Samman, D. Wang, C.S. Kot, R.W. Yeung, *Computer-assisted three-dimensional surgical planning and simulation: 3d virtual osteotomy*, **International Journal of Oral and Maxillofacial Surgery, 29**, 2000, pp. 11-17.

[69] L. Frizziero, G.M. Santi, A. Liverani, F. Napolitano, P. Papaleo, E. Maredi, *Computer-aided surgical simulation for correcting complex limb deformities in children*, **Applied Sciences, 10**, 2020, pp. 5181.

[70] N. Yu, T. Nguyen, Y.D. Cho, N.M. Kavanagh, I. Ghassib, W.V. Giannobile, *Personalized scaffolding technologies for alveolar bone regenerative medicine*, **Orthodontics & Craniofacial Research, 22**, 2019, pp. 69-75.

[71] Y.G. Jeong, W.S. Lee, K.B. Lee, *Accuracy evaluation of dental models manufactured by CAD/CAM milling method and 3D printing method*, **Journal of Advance Prosthodontics, 10**, 2018, pp. 245-251.

[72] G. Gagg, E. Ghassemieh, F.E. Wiria, *Effects of sintering temperature on morphology and mechanical characteristics of 3D printed porous titanium used as dental implant*, **Materials Science and Engineering: C, 33**, 2013, pp. 3858-3864.

[73] J. Kim, M. Kim, J.C. Knowles, S. Choi, H. Kang, S. Park, H. Kim, J. Park, J. Lee, H. Lee, *Mechanophysical and biological properties of a 3-printed titanium alloy for dental applications*, **Dental Materials, 36**, 2020, pp. 945-958.

[74] J. Fangqiu, C. Zhang, X. Chen, *Structure optimization of porous dental implant based on 3D printing*, **IOP Conference Series: Materials Science and Engineering, 324**, 2018, pp. 012060.

[75] T.H. Tsai, N. Jeyaprakash, C.H. Yang, *Non-destructive evaluations of 3D printed ceramic teeth: Young's modulus and defect detections*, **Ceramics International, 46**, 2020, pp. 22987-22998.

[76] S. Li, S. Yuan, J. Zhu, C. Wang, J. Li, W. Zhang, *Additive manufacturing-driven design optimization: Building direction and structural topology*, **Additive Manufacturing, 36**, 2020, pp. 101406.

[77] İ. Aktitiz, K. Aydın, A. Topcu, *Stereolitografi (SLA) tekniği ile basılan 3 boyutlu polimer yapılarda ikincil kürleme süresinin mekanik özelliklere etkisi*, **Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, 35**, 2020, pp. 949-958.

[78] M. Hossain, R. Navaratne, D. Peric, *3D printed elastomeric polyurethane: Viscoelastic experimental characterizations and constitutive modelling with nonlinear viscosity functions*, **International Journal of Non-Linear Mechanics, 126**, 2020, pp. 1-12.

[79] D. Miedzinska, R. Gieleta, E. Małek, Experimental study of strength properties of SLA resins under low and high strain rates, **Mechanics of Materials, 141**, 2020, pp. 1-18.

[80] M. García Reyes, A. Bataller Torras, J.A. Cabrera Carrillo, J.M. Velasco García, J.J. Castillo Aguilar, *A study of tensile and bending properties of 3D-printed biocompatible materials used in dental appliances*, **Journal of Materials Science, 57**, 2022, pp. 2953–2968.

[81] K.G. Topsakal, M. Aksoy, G.S. Duran, *The Effect of aging on the mechanical properties of 3-dimensional printed biocompatible resin materials used in dental applications: An in vitro study*, **American Journal of Orthodontics and Dentofacial Orthopedics, 164**, 2023, pp. 441-469.

[82] P. Simeon, A. Unkovskiy, B.S. Sarmadi, R. Nicic, P.J. Koch, F. Beuer, F. Schmidt, *Wear resistance and flexural properties of low force SLA-and DLP-printed splint materials in different printing orientations: An in vitro study*, **Journal of the Mechanical Behavior of Biomedical Materials, 152**, 2024, pp. 106458.

*Received: March 21, 2024*
*Accepted: May 20, 2024*