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Vat Photopolymerization Additive Technique for Dental Zirconia Fabrication: A Systematic Review

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Abstract

Background: The VAT photopolymerization process is a potential way to create complex and functional zirconia structures since it allows for the fabrication of components with outstanding surface polish and mechanical qualities. This technique involves layer-by-layer curing of liquid resin using a light source to produce the desired zirconia product. 3D-printed zirconia is created via VAT photopolymerization, which is a process whereby a light-sensitive liquid resin is allowed to solidify in a vat. This study aims to comprehensively analyze the theoretical and practical aspects of Vat photopolymerization additive manufacturing technologies utilized in creating dental zirconia. Methods: An electronic systematic review was performed on multiple databases (Google Scholar, PubMed, and Science Direct on this subject and in a manual search of the scholarly literature. The articles included in this review were selected after searching for and reading relevant published works from 2018 to 2024. A literature search for publications published until now was conducted using internet databases without regard to date. The review focuses on the advancements in this area, illustrating the evolution of dental zirconia fabrication techniques in additive manufacturing, focusing on vat photopolymerization approaches. Findings: Until recently, digital light processing and Stereolithography were the only methods for producing dental zirconia in Vat polymerization. The basic concept of this technology was the utilization of liquid resin oligomers or monomers that undergo polymerization when subjected to specific frequencies of light. By the technique of laser curing, Stereolithography constructs three-dimensional structures in layers. Digital light processing involves using a digital micro-mirror device to project ultraviolet light onto a surface, which is then reflected into a photopolymer vat. Due to how efficiently digital light processing works, it promises to be a 3D printing technique for ceramics production. Conclusions: Digital Light Processing is a faster and more accurate method for manufacturing complex components compared to Stereolithography. It can be used in top-down or bottom-up manufacturing, depending on the building's structure. Bottom-up systems require less slurry, making them more cost-effective. Top-down printers can produce larger pieces.

Introduction:

By using three-dimensional Computer-Aided Design modeling, the new technology of Additive Manufacturing makes it possible to create a variety of structures, from the most basic to the most complex. Modern manufacturing techniques have improved so that Computer-Aided Design (CAD) digital models may be used to automate the creation of customized 3D items from standard materials. This method is known as Additive Manufacturing (AM) [1-3]. The terms "Generative Process," "Rapid Prototyping," and "3D printing" are often employed synonymously with "Additive Process"[4]. It provides greater creative flexibility than conventional methods because it is a near-net form process that doesn't need a mold. Consequently, it has gained popularity for a wide range of uses, particularly in dentistry, where its intricate geometry and personalization make it ideal for patient use[5, 6]. Improving upon milling in terms of speed and cost can create precise prostheses with minimal material waste[7].

Specifically, seven categories of AM techniques have been classified by the ASTM, distinguished by the way through which the final components are formed: several processes, including Material Jetting, Binders Jetting, VAT photopolymerization, Powder Bed Fusion, Material Extrusion, Direct Energy Deposition, and Sheet Lamination[8]. According to ISO/ASTM standard 52900:2015(E), "an Additive Manufacturing process in which a liquid photopolymer in a vat is selectively cured by light-activated polymerization" describes Vat photopolymerization, a Lithography-based technique[9].

Due to its economical machinery price, superior surface quality, and exceptional accuracy, Vat photopolymerization (VPP) has become a particularly common 3D printing technique for ceramics. This process is a subset of additive light cure industrialization that also includes Stereolithography (SLA) and Digital Light Processing (DLP)[10]. The possible applications involve a variety of dental ceramics, such as polycrystalline ceramics[11], glass ceramics, and ceramic-based composite[12, 13]. The introduction of Additive Manufacturing (AM) in the 1980s brought in a new period of fast technological advancement, which revolutionized production while offering exciting novel engineering opportunities in many other industries [14].

After Charles W. Hull introduced Stereolithography (SLA) in 1986, the first 3D printer, researchers have come up with a plethora of innovative ways and approaches to achieve identical use[15]. The quick evolution of printing technology, new materials, and equipment causes 3D printing to fundamentally transform conventional methods of instruction and experimentation[16]. In 2009, the first zirconia dental prosthesis was manufactured using Direct Inkjet Printing technology[17]. Because of its extensive research and wide range of indications, zirconia has become the material of choice in restorative dentistry and oral implantology[18-21].

Vat photopolymerization (VPP) with the right thermal treatments, can attain microstructure and density levels that are on the same level as conventional manufacturing, according to the latest research[22]. Considering its mechanical characteristics, 3D-printed zirconia has proven to be exceptionally durable, and comparable in hardness and fracture toughness to conventional blocks constructed from similar powder composition [23, 24]. A comprehensive evaluation of AM zirconia is still missing, even though there has been an increasing amount of research devoted to the features of AM dental zirconia and its manufacturing techniques[25]. This paper provides an overview of the most recent findings concerning the manufacturing process of VPP dental zirconia.

Procedures and Materials

This paper intends to produce a comprehensive analysis of the principles and applications of Vat polymerization additive manufacturing especially as they are relevant to the production of dental zirconia. Google Scholar, PubMed, and Science Direct electronic databases were searched for VPP zirconia manufacturing techniques. Journal articles published between 2018 and 2024 meet the inclusion criteria. Results from this study have broad dental use. This review provided a summary of the terminology and features of these dental technologies for the 3D printing of zirconia-based materials that belong to the category of indirect approaches. Based on the technology's first component, it will focus on the most widely used techniques for dental applications. Figure (1) below is an explanation of the working principle of Vat polymerization, which incorporates Stereolithography SLA and Digital Light Processing DLP.

Vat photopolymerization VPP

Vat photopolymerization or Vat polymerization printing, the first 3D printing method, has gained a lot of excitement in the biomedical industry because of how fast it can make complex designs with exactitude. Virtual photopolymerization, in simple terms, involves the utilization of liquid resin oligomers or monomers that, when exposed to the light of a particular frequency, undergo polymerization[26]. It was classified into Stereolithography SLA, and Digital Light Processing DLP according to the light source employed on the printer [27].

In Lithography-based ceramic part manufacturing, a UV-curable slurry is created by dispersing fine ceramic powders into a liquid photopolymer, typically derived from acrylate or epoxy monomers that are used in SLA and DLP printers[28, 29]. Light energy, wavelength, printer speed, build platform positioning, slicer software, printing parameters, support structures, printing angulation, slurry color, object geometry, and post-processing procedures are the various processing parameters that determine the quality of a vat-polymerized printed object[30]. By the technique of laser curing, SLA builds three-dimensional objects layer by layer Figure (2-A). The strategy of DLP involves the surface projection of ultraviolet light Figure (2-B) into the vat of photopolymer by a digital micro-mirror device[31].

Using a CAD file as a design, a photopolymerizing liquid is cured in a vat using ultraviolet (UV light or a UV laser). Thin layers of oligomers/monomers (epoxy, acrylic, or methacrylic) in the liquid are crosslinked with photo-initiators atop or beneath a submerged platform, based on whether the process is top-down or bottom-up driven Figure (3). The platform is re-immersed in the excess resin after each layer is built to facilitate its spreading throughout the vat. Each layer of the finished product is built up in this way until they are all stacked and cured[32].

1. Stereolithography SLA

The first and most widely used 3D printing technology in dentistry is Stereolithography (SLA)[33]. The term "-graphy" comes from the Greek for "writing," which is reflected in the way the photocurable substance solidifies[34]. Laser polymerization and solidification of a UV-sensitive liquid monomer is the basis of SLA's multilayer framework[4].

Because the resin is cured spot-by-spot, it enables the creation of complex-shaped objects with excellent surface quality and dimensional precision[35]. The laser is typically redirected to a specified place using a non-fixed mirror galvanometer, rather than being focused directly onto the resin. An SLA printer can be either vertically mounted above the vat, directing the laser downwards into the resin, and the platform transfer from top to down, or horizontally mounted below the vat, directing the laser upwards into the resin and the platform transfer from bottom to top [36, 37].

There are various benefits to using a platform-bottom-up method as opposed to a platform-top-down one. The platform-bottom-up method avoids oxygen interference by light-curing at the bottom, in contrast to the second method, which involves direct contact with oxygen during the polymerization of the resin. Additionally, the laser is positioned near the base, which makes it safer for operators. Finally, the third advantage is that gravity allows for automatic resin refilling[4, 37].

2. Digital Light Processing DLP

Digital light processing or referred to as Direct light projection. The initial idea of Digital Light Projection (DLP) was presented by Nakamoto and Yamaguchi in 1996, utilizing physical masks. In 1997, Bertsch et al. expanded on it and enhanced it strongly by employing a Liquid Crystal Display (LCD) as the dynamic mask generator(28). Due to their reflectivity and competitive fill factor, Digital Micromirror Devices (DMDs) from Texas Instruments have been gradually displacing LCDs since 2001. This resulted in significant improvements in light display resolution and contrast(35). Due to its integrated projection and ultra-fast light switching, DLP 3D printing allows for considerably more with less time than the traditional SLA point-line-layer scanning technique. As for the second technique, DLP is a popular choice(30).

Using numerically controlled slicing data, this technology thoroughly cures the resin layer at a time using digital micro-mirror devices. In this case, for example, the incident light will be reflected in the right direction by the mirrors that regulate the orientation of the light pixels. Dark pixels' matching mirrors will be angled so that they block out any light that might be shining on them (38). In a digital screen, like a projector, each layer consists of pixels, which are like a collection of small rectangular bricks called Voxels. By adjusting the UV light's intensity, one can control how it affects the resin. Compared to SLA, DLP is more effective at producing bigger and more complex components quickly because of its accuracy and high feature resolution (down to a few micrometers)(37).

Concerning the building's configuration, DLP can manufacture parts in either a top-down or bottom-up method. The first method involves curing the object on an upside-down platform before dipping it into a thin layer of slurry that has been placed in the vat. The second method involves submerging the object totally in the liquid resin. A bottom-up manufacture is more cost-effective due to the reduced amount of slurry needed to create the desired component. Conversely, larger pieces can be produced using printers that use a top-down setup(36).

Discussion

Zirconia ceramics printed using 3D technology have great promise for use in dental restorations. Incorporating engineering and materials science is at the core of 3D printing technology. To make ceramics, researchers have created photopolymerizable ceramic suspensions, which have a highly concentrated resin mixed with ceramic powder. To obtain a uniform green structure, the liquid resin is first photopolymerized selectively. Later, it undergoes post-processing to remove the photosensitive resin, fuse ceramic particles, and produce a dense ceramic component(39).

As a result of the high level of interest in their uses, Vat photopolymerization technologies (SLA and DLP) have been recommended for the production of dense ceramic structures. Many factors influence the quality of printed samples: raw materials, printing parameters, de-binding, and sintering as well as the separating procedures(37). Unlike powder-based approaches that utilize unbound material, the building process does not include any structural support from the material. This is because this methodology utilizes liquid to create items. Adding support structures is often necessary in such situations(40).

A scanning light beam tracks photopolymerizable areas layer by layer in an SLA printer, which treats suspensions. Ten to one hundred twenty millimeters is the usual range for layer height. Instead of scanning each area with the laser one by one like in SLA, a projector in DLP can expose the entire layer at once using customized laser energy, curing every layer with a single shot of light. This reduces the time required for the illumination stage (40, 41).

The number of objects and the geometry of each layer do not affect the total production time. As a result of the pixel-based exposure in DLP, the resolution can be increased with certain systems(4). Due to its high productivity compared to SLA, DLP offers enormous potential as a ceramic fabrication 3D printing technique.

Conclusions

Advantages provided by additive manufacturing include greater flexibility in design, categorizing materials and their functions, mold-free fabrication, and economical manufacture with limited production; these aspects could cause additive manufacturing to bring upward the ceramics industries. Since every AM method has its own set of advantages and drawbacks, choosing one for usage depends upon the specific application's demands for ceramic material, ultimate density, surface polish, part size, etc. There is a close correlation between the AM process's ability to meet manufacturing performance requirements and each of these criteria. In comparison to SLA, DLP can manufacture bigger and more complex components at faster speeds while maintaining good accuracy and feature resolution (down to several micrometers)

Depending on the building's layout, DLP can manufacture parts in either a top-down or bottom-up fashion. Unlike in the second scenario, where the object is submerged in liquid resin, the first scenario involves curing it on an upside-down platform before submerging it in a thin layer of slurry that has been placed in the vat. Since less slurry is needed to create the desired component with a bottom-up system, it is more cost-effective. Conversely, larger pieces can be produced using printers that have a top-down arrangement. Compared to SLA printers, DLP printers are better for ceramic buildings.

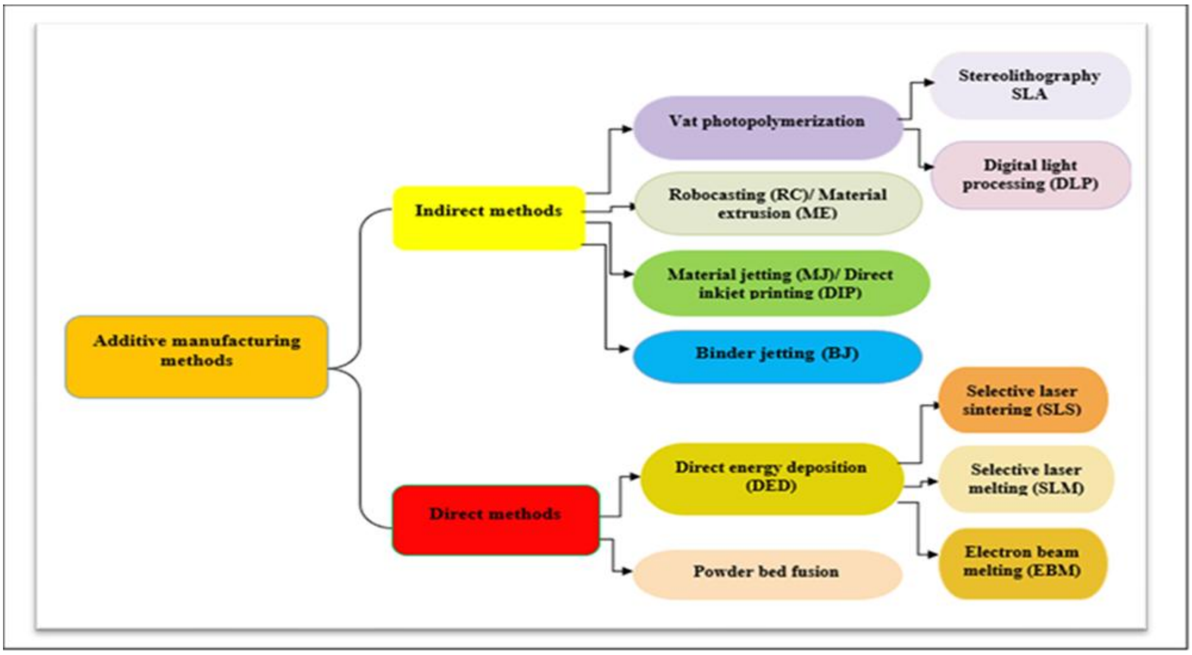

Figure 1: Schematic of the additive manufacturing methods, adopted from[36].

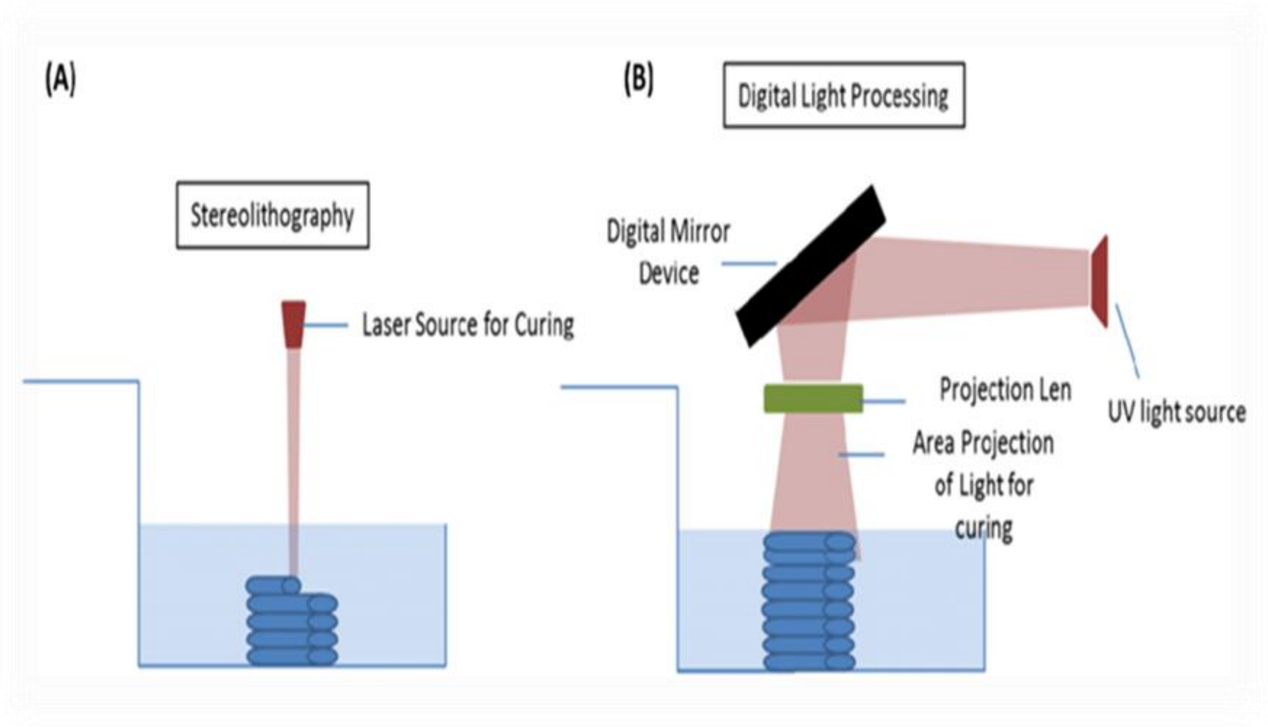

Figure 2: Vat photopolymerization, (A): Stereolithography SLA, (B): Digital light processing DLP[31].

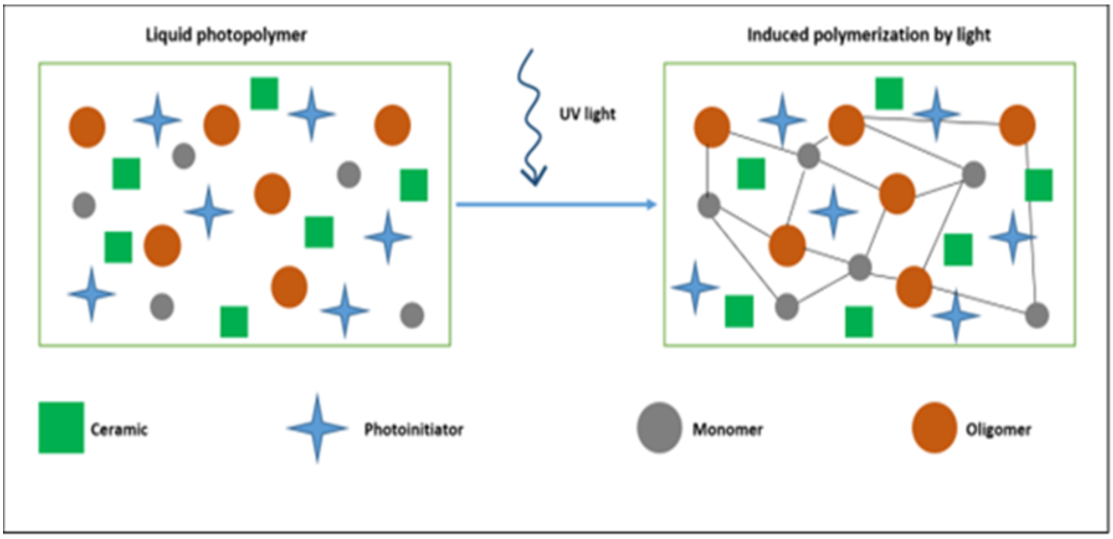

Figure 3: Graphical representation of polymerization [28]

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