Journal of Science and Engineering Applications

Contents are available at https://jsea.iujournals.com

Vat Photopolymerization Additive Manufacturing: Processes, Materials, and Applications

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ARTICLE INFORMATION

Received date: 02-06-2026
Revised date: 11-07-2026
Accepted date: 20-07-2026

Keywords

Vat Photopolymerization; Additive Manufacturing; Photocurable Resins; Stereolithography (SLA); Digital Light Processing(DLP).

ABSTRACT

Vat photopolymerization (VPP) is a promising additive manufacturing technology for producing high-resolution components with complex geometries and functional integration. Although previous reviews have examined printing techniques, resin formulations, and applications, an integrated understanding of material–process–property interdependencies remains limited. This review establishes a comprehensive framework linking these factors and critically examines stereolithography (SLA), digital light processing (DLP), LCD-based masked stereolithography (LCD/mSLA), and continuous liquid interface production (CLIP). Recent developments in polymeric resins, ceramic-filled systems, hydrogels, dental materials, sustainable formulations, and multifunctional composites are evaluated regarding printability, curing behavior, mechanical performance, and application requirements. Key parameters, including resin chemistry, filler incorporation, light penetration, exposure conditions, layer formation, post-curing, and environmental effects, are discussed. Furthermore, challenges involving material compatibility, curing uniformity, standardization, multi-material fabrication, scalability, and sustainability are highlighted. Finally, future research directions in intelligent process monitoring, advanced resin design, industrial-scale production, and practical implementation are identified to support reliable, high-performance VPP manufacturing systems.

1. Introduction

Additive Manufacturing (AM) has grown from a rapid-prototyping technique to a manufacturing system with a wide range of applications that can manufacture complex, customized, and functional components directly from digital models. Unlike subtractive manufacturing, AM is a process that builds up objects by adding material layer by layer, creating more freedom for geometric design, minimized material waste, and superior feasibility for specific, lightweight and multifunctional structures [1]. The seven most common AM technologies are categorized in accordance with the established process-based classification which includes material extrusion, powder bed fusion, directed energy Vat photopolymerization is a technique which selectively cures the liquid photo-curable resin using ultraviolet or visible light and makes 3D objects [4], [5].

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This allows for high resolution, fine surface quality and ability to make geometrically complex structures which are not readily achievable with many of the extrusion or powder-based processes [6].

But geometrical accuracy is not enough to control the performance of VPP-printed components. It depends on the interaction among resin chemistry, photoinitiator efficiency, optical penetration, exposure dose, layer thickness, oxygen inhibition, shrinkage behavior and the post-curing conditions[7]. This implies that VPP is not just a printing process anymore but a complete photo-chemical production process in which the process steps, the formulation of materials and properties are strongly interconnected [8], [9].

The most common VPP techniques are stereolithography (SLA), digital light processing (DLP), masked stereolithography or LCD-based printing, and continuous liquid interface production (CLIP) [10]. The main difference between SLA, DLP and LCD systems is that the former uses laser-based point or line scanning to cure a section of the cross-sectional pattern, while the DLP and LCD uses the projected or masked light to cure patterned areas or entire layers [11]. Continuous printing methods, such as CLIP, further adapt the layer-by-layer fabrication process by controlling oxygen inhibition near the optical window, thus allowing for more continuous fabrication of parts. These methods share the same basic photopolymerization chemistry, but vary significantly in terms of exposure strategy, print speeds, achievable resolution, resin compatibility, and process-induced defects [3], [12], [13].

Experimental research conducted recently has shown the sensitivity of part performance of VPP to processing and post-processing conditions [14]. A research study published in 2024 demonstrated that the tensile stress, elastic modulus and hardness of LCD-based VPP were significantly impacted by the resin chosen as well as the location on the build-platform and orientation of the layers [3]. The other experimental setup conducted on the mSLA-printed components showed that the mechanical properties of compression and flexure depended on both the thickness of the layers and the number of hours of post-curing; both printing and post-treatment parameters need to be optimized to obtain the desirable mechanical properties [15], [16]. The results indicate that further research on the VPP process should not only focus on the printing accuracy but also on the relationship of the process – structure – property of the printed photopolymer [17].

Another key research area in today's VPP is material development [18]. The materials used for printing are now mostly polymer based and incorporate acrylate and methacrylate resins which have shorter curing times and good printability, however printed photopolymer materials still have polymerization shrinkage, poor toughness, sensitivity to ageing, and low long-term durability [19], [20]. To address these challenges, in recent years studies have concentrated on ceramic-filled resins, hydrogel formulations, multi-material systems, dental resins, and functional composites [21], [22]. The use of controlled resin temperatures during VPP process, for instance, has been reported to improve the mechanical properties of dental acrylate resins, and soft-tissue scaffolds with controlled swelling behavior and controlled resolution can be fabricated using a hydrogel-based VPP process [23], [24], [25].

There are, however, a number of problems which limit the applicability of VPP in the field of industrial and biomedical applications. These include limited material window, resin toxicity problems, anisotropy, incomplete or non-uniform curing, post curing variability, dimensional instability, high fill material complexity and scalable multi-material printing challenges[26], [27]. It was also found in the recent reviews over multi-material VPP that there are still significant challenges to overcome such as switching the material, vat contamination, and integration of printing processes [25], [28].

Several review papers have discussed VPP technologies, materials or applications; however, these aspects are often treated separately and do not fully address how their interactions collectively influence the final performance of printed components. Establishing a reliable application of VPP fabricated structures in practical manufacturing relies on the interplay between the resin chemistry, optical behavior, process parameters, curing kinetics, post-processing conditions and application-specific requirements. Thus, the primary research gap addressed in this review is the lack of an integrated understanding of the process–material–property relationship in VPP systems. This review provides a critical framework linking photopolymer formulation, light – material interaction, printing strategies, post-processing effects, and the resulting mechanical, biological and functional properties of printed structures. In addition, the problems which still remain in the VPP, such as the integration of multi-materials, development of sustainable resins, process monitoring, process standardization and the transfer from laboratory research to industrial manufacturing are discussed critically. Consequently, the aim of this review is to critically and systematically discuss the processes, materials, and applications of vat photopolymerization additive manufacturing. Recent developments in SLA, DLP, LCD/mSLA and CLIP-based systems are reviewed, emphasizing the interdependency of the photocurable resin design, printing parameters, post-curing conditions and the resulting mechanical, biological and functional properties. This review also critically discusses current challenges and future opportunities toward the development of reliable, high- performance and industrially scalable VPP-based AM systems.

2.Overview of Additive Manufacturing Technologies

There are various process families of additive manufacturing techniques that are distinguished by their feedstock form, energy used, bonding process,

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and part properties. The process can be classified into seven major processes; they are: material extrusion, powder bed fusion, directed energy deposition, binder jetting, material jetting, sheet lamination and vat photopolymerization [1]. These are not covered in this review as independent technologies but as an enabling tool to communicate the importance of VPP as an alternative means for the manufacturing of high resolution polymer, composite, ceramic, dental, biomedical and micro-scale manufacturing[22], [29], [30].

Materials are extruded through a nozzle and deposited in layers to produce parts by a process called material extrusion. It is widely used as the material is inexpensive, and equipment is easy to build and can be used in thermoplastics and filled filaments[31]. However, layer interfaces and anisotropic mechanical properties often hinder printability of the parts, and relatively poor surface quality[32]. VPP is more suitable to achieve fine features, smooth surfaces and higher geometrical precision, in comparison with the material extrusion technology.

Powder bed fusion is a process in which particles of powder are selectively fused by the thermal energy. It particularly applies to metallic, polymeric and ceramic components of relatively high mechanical properties and complex shape[1]. But there are disadvantages to powder bed fusion, such as powder handling, thermal gradients, residual stresses, surface roughness and the time-consuming post-processing[33]. However, VPP is quite different since it is not melting/sintering of powder but rather polymerization initiated by light, and thus is more appropriate for precision polymeric and resin based systems [34].

Directed energy deposition processes are those that melt and deposit material with a focused beam of thermal energy, which is usually a laser, electron beam or plasma arc [35], [36]. The benefit of this process is that it can be applied to large metallic parts, to repairs or coatings, but the resolution and surface quality is generally less than VPP [37], [38]. Therefore, DED technology is more appropriate for large scale metallic repair and structural deposition, whereas, VPP is more appropriate method for fine detail and high resolution fabrication [34], [39].

Binder jetting is a method which selectively deposits a liquid binder onto a powder bed [40], [41]. A further cure, sinter or infiltration is typically necessary to provide the green body with final strength [42]. While productive and scalable in certain materials, particularly metals, ceramics and sand molds, post processing is a critical factor in achieving the final performance. VPP, on the other hand, cures the build material by means of photopolymerization during printing, but it is still common practice to follow it up with post-curing to achieve optimized conversion, mechanical properties and dimensional stability [4], [7], [24].

In material jetting, droplets of build material (typically a photopolymer) are deposited on a platform which are then cured or cooled to turn them into solid [43], [44]. It can now create parts with smooth, multi-colored and multi-material, but the number of useful, mechanically strong materials are limited [45], [46]. It shares some characteristics with VPP, such as the fact that it could utilize photocurable materials, but the method for delivering materials is not the same: material jetting adds droplets, whereas VPP cures specific areas of a vat of resin.

Sheet lamination is the process of bonding sheets of material and cutting them to the desired geometry [47], [48]. It may work for certain paper, polymer, composite or metal-laminate products, but it is not ideal for complex internal channels or highly complex micro scale structures [25], [49]. Consequently, sheet lamination is not often used as a direct competitor to VPP in high-resolution photopolymer or biomedical manufacturing [50].

The technique of this review, known as Vat photopolymerization, achieves this by controlling light exposure of a liquid photocurable resin [4], [34]. It is most notable for its high resolution, a smooth surface finish and ability to work with ever evolving resin systems [51], [52]. Recent advancements in VPP include multi-material printing, use of ceramic-filled resins, hydrogel scaffolds, dental materials, functional composites, and mechanoluminescent structures. The developments indicate that VPP is no longer used for visual prototypes, but is more and more investigated as a platform for functional and application specific parts [23], [53].

Table 1. Summary of the seven additive manufacturing categories

AM category	Main working principle	Typical materials	Strengths	Main limitation	Relevance compared with VPP
Material extrusion	Material is extruded through a nozzle	Thermoplastics, polymer composites	Low cost, simple operation and broad accessibility	Layer lines, anisotropy, limited surface quality	Less precise than VPP for fine features and smooth surfaces
Powder bed fusion	Powder particles are fused by thermal energy	Metals, polymers, ceramics	Strong parts and complex geometries	Thermal defects, powder handling, high cost	Better for load-bearing metals; less suitable for fine photopolymer structures

Directed energy deposition	Material is melted during deposition	Metals and alloys	Repair, coating, large parts	Lower resolution, rough surface	Not directly competitive with VPP in micro/high-resolution applications
Binder jetting	Binder is deposited onto powder	Metals, ceramics and sand	Scalable and relatively fast	Requires sintering/infiltration; green-part limitations	Useful for powder systems; VPP offers direct light-curing of resins
Material jetting	Droplets of material are deposited and solidified	Photopolymers, waxes and multi-material inks	Smooth surface, multi-material capability	Limited mechanical robustness	Similar material family, but different delivery and curing mechanism
Sheet lamination	Sheets are bonded and cut	Paper, polymers, metals and composites	Fast for selected laminates	Limited internal complexity	less relevant for high-resolution resin-based structures
Vat photopolymerization	Liquid resin is cured by light	Photopolymers , composites , ceramics, hydrogels	High resolution, smooth surface, fine features	Brittleness, shrinkage, post-curing sensitivity, resin limitations	Central focus of this review

The comparison clearly illustrates that VPP is not just another type of AM processes it is a different approach to manufacture, which is founded on a controlled conversion of liquid resin into solid networks through light–matter interaction. This has a high degree of geometrical fidelity but also changes the final part to a degree that is highly dependent on the resin, the optical exposure, the depth of cure, post-curing, and environmental ageing [3], [4], [7]. The scientific value of a VPP review is to consider these coupled variables, not just as a high resolution printing method [24], [54], [55].

Therefore, the basic concepts of vat photopolymerization such as the photopolymerization mechanism, curing depth, light penetration, oxygen inhibition, shrinkage behavior and post-curing effects are discussed in the following section. Before exploring the various VPP techniques such as SLA, DLP, LCD/mSLA and CLIP, it is essential to establish this foundation

3. Fundamentals of Vat Photopolymerization

Vat photopolymerization relies on the selective solidification of liquid photocurable resin into a structures using light exposure. During this process, ultraviolet or visible light is absorbed by photoinitiators in the resin and causes a generation of reactive species which subsequently initiate polymerization reaction and establish a cross-linked polymer network [5], [56]. The unique light-induced solidification mechanism of vat photopolymerization distinguishes it from the material extrusion- and powder-based additive manufacturing processes, as the quality of the printed part is affected not only by machine resolution, but also due to complex interactions of resin chemistry, light penetration depth, exposure energy and post-curing conditions [57], [58].

Generally, the printing process will start with a thin layer of liquid resin poured along the vat. Then, a laser or other light pattern that corresponds to a corresponding area of the digital model is selectively applied to cure it. After each layer is cured, the build platform moves up, a new resin layer is poured and the process continues until the entire 3D object has been printed[5], [59]. It might seem simple, but this curing behavior is really complicated since the resin needs a certain amount of energy for the layer to be stable without causing over curing, shrinkage or warpage [26], [60]. Refer to figure 1 for detailed insights on factors that influence VPP performance. Thus, the manipulation of exposure time, light intensity, layer thickness and resin formulation are necessary for the successful production of accurate and mechanically efficient printed components[7], [61].

Light Penetration and Curing Depth A prominent feature of vat photopolymerization. If the exposure energy is too slow, then the resin may stay in a partially cured state generating weak interlayer adhesion and less mechanical strength [6], [62]. On the contrary, too much exposure causes over curing, in some cases, more than expected dimensionality loss of original shape and leads to internal stress and greater brittleness[63], [64]. This is relevant, in loaded resins/pigmented materials/ceramic suspensions/hydrogel systems, where additives and particles scatter or absorb light and then lower curing uniformity [65].

The resin composition is considered as a core parameter of printability and final performance. Depending on the type of vat photopolymerization resin, it may include monomers or oligomers, photosensitizers, inhibitors, absorbers and sometimes compounds acting as fillers or functional additives[66], [67]. These elements influence viscosity, curing speed, crosslink density, shrinkage and mechanical properties [68], [69]. This is why resin design not only involves chemical issues but also manufacturing ones. A resin with fast curing time can print faster at the cost of brittle structures or high shrinkage [70]. The addition of fillers also resist in stiffness, thermal stability or bioactivity while it may increase viscosity and decrease light penetration [71], [72].

In vat photopolymerization, post-curing is another critical step. Thermal post-treatment steps are often necessary to increase the extent of reaction and

stabilize the final properties for many printed parts, which is demanding from an energy perspective[4], [7], [73]. Although proper post-curing can enhance hardness, strength and dimensional stability [74]. Excessive or poorly controlled post-curing can, however, increase the brittleness, color change or deformation [75]. To this end, post-curing has increasingly been studied experimentally as a significant processing variable rather than just an intermediate finishing step[76].

Generally, the principles of vat photopolymerization illustrate an inherent correlation between light exposure, resin formulation, curing behavior and post-processing [3], [61]. This is why VPP can be used to form very accurate and smooth components but at the same time, it can lead to challenges such as shrinkage, brittleness, anisotropy phenomenon, under curing of the polymer materials and loss of printing quality over time due to material aging [77]. Since these techniques each use different methods to control how light is delivered and how the building layers are formed, we will need to discuss these principles first before going into main vat techniques including SLA, DLP, and CLIP.

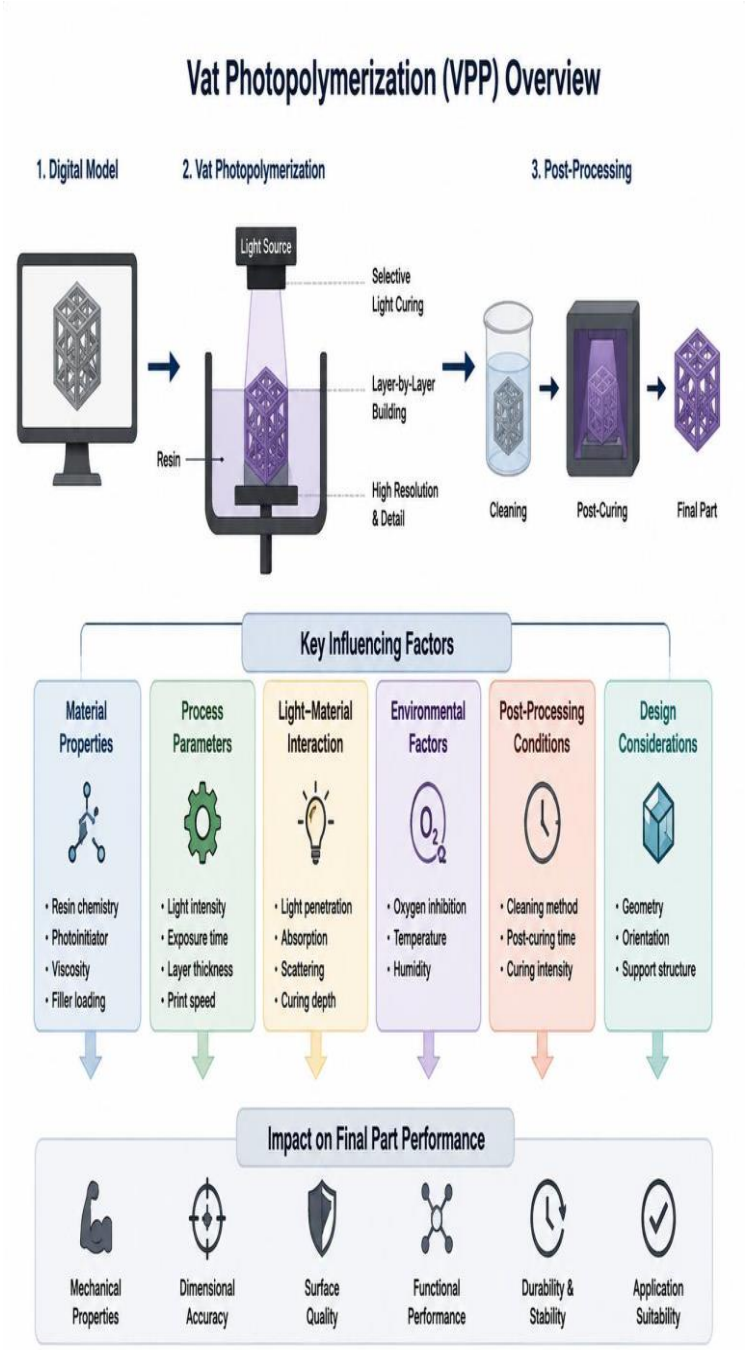


Figure 1. Schematic illustration of the factors that control the performance of Vat Photopolymerization (VPP). The figure shows how the resin formulation parameters (light intensity, exposure time and layer thickness) and the post-processing parameters (mechanical, functional and biological) are linked together.

4. Vat Photopolymerization Techniques

There are several closely related and highly used techniques which fall within vat photopolymerization, where the method of delivering light to the resin as well as each layer is formed, may vary. Common techniques include stereolithography, digital light processing, LCD/masked stereolithography and continuous liquid interface production [2], [78]. All of them work on the same principle, which is curing liquid photopolymer resin by light exposure; however, their differences in exposure strategy determining printing speed, resolution, surface quality and

uniformity of curing process as well as material compatibility and final mechanical performance [13], [79].

Stereolithography is among the oldest well-established vat photopolymerization methods. It usually employs a focused beam of laser to scan and cure the resin surface in accordance with the digital cross-section of the part [10]. While SLA is known for its detail resolution, scanning process provides an efficient and high precision alternative with good surface quality that can be used to build prototypes, dental models biomedical devices and small engineering components [30]. On the other hand, since a laser cures geometry sequentially point by point or line by line, it can be slower than projection-based systems when printing larger / highly repeated geometries. Furthermore, the quality of SLA parts is still highly dependent on some important parameters, including exposure dose, layer thickness, resin reactivity, build orientation and post-cure conditions [15].

Digital light processing is different from the SLA as it does not use an individual laser to scan the geometry but projects a full picture of every layer onto the resin surface[80]. This layer-wise projection can notably reduce printing time, particularly for parts with high layers cross-sectional areas or several components printed at the same time [81]. Ultimately, the final quality of DLP also depends on pixel size, projected light uniformity, resin absorption behavior and exposure control accuracy [66]. In recent years, work on DLP-based VPP has progressed from establishing basic printability to in-situ monitoring of the curing behavior such that online cure dynamics can be monitored readily and used as a basis for understanding the spatial heterogeneity of material development during printing[57], [78]

DLP systems are related in a way to LCD or masked stereolithography systems where one uses an LCD mask to expose certain areas of the resin. Since they are relatively inexpensive and can cure bulk layers at a time these systems have gained popularity [82], [83]. But, lower cost does not imply simplified process control. It has been observed that layer orientation, build-platform position and resin type have a large effect on tensile stress , elastic modulus and hardness [84]. in experimental work on LCD-based VPP only recently. This implies that LCD printing should not be characterized purely by the nominal printer resolution, that mechanical reliability is also controlled by how uniformly the resin cures across the platform and through the printed structure [3], [85].

Masked stereolithography and mSLA are relevant in recent work as they enable a hands-on, experimental assessment of how structure processing conditions affect mechanical behavior [83], [86]. There are many published studies that relate additive manufacturing process parameters and post-treatment time to compressive and flexural properties of mSLA materials. These results are essential for the rigorous discussion of different VPP techniques because they underscore that comparisons between VPP modalities cannot be performed based solely on speed or resolution but also need to be made from a standpoint of curing network stability, post-curing sensitivity and mechanical reproducibility [61].

Continuous liquid interface production is an evolution on vat photopolymerization. In contrast to traditional layer-by-layer printing, where material is distributed in a vertical manner during the build process, CLIP utilizes oxygen inhibition at the interface of the optical window and thick uncured region which has been described as a persistent liquid interface [87]. This promotes more continuous part formation and minimizes the repetitive separation steps characteristic of traditional bottom-up VPP systems. CLIP has the strong advantage of improved printing speeds more akin to liquid phase printing and a finer resolution when forming parts, but requires fine-tuning of oxygen transport, resin flow, exposure time and viscosity. Other objects via Injection CLIP have also been realized using high-viscosity composite resins and multiple materials, demonstrating potential movement of continuous VPP toward more complicated material systems when the delivery of resin and process control are optimized [12], [88].

While these methods are showing promise, they all have underlying limitations. SLA is incredibly accurate but slow with large area production. While DLP and LCD systems which expose a full layer at once are able to achieve foil with speed, they are inherently constrained by pixilation, light non-uniformity and platform-position effects [89], [90]. While CLIP achieves enhanced continuity and rapidity, it has also faced challenges in terms of oxygen management, resin replenishment as well as material compatibility [91]. High-speed VPP discussions have recently mentioned that faster printing is by no means indicative of improved manufacturing, as high-speed curing can induce issues with resin flow, heat generation, conversion gradients and mechanical uniformity[92], [93]. An overview and comparison of prevalence VPP techniques in Fig. 2.

From a critical review point of view, the main difference between SLA, DLP, LCD/mSLA and CLIP is not limited to the light source alone - it lies with how each technique regulates the balance of accuracy in curing, print productivity (speed), behavior of resin material and final properties [93]. And this is why technique selection depends on the particular application. When production speed is less important than fine details and surface quality, then SLA may be more preferable. DLP and LCD systems may be better suited for quick layer-wise fabrication and repeat small-part production[94]. Visualization of the estimated performing volume, required actions and structure of solutions in CLIP perspectives towards rapid and continuous functionalities with support from advanced resin-flow control and oxygen management. Nevertheless, none of these methods can be deemed better than the other in all situations due to the dependency on application needs such as material choice, geometry, properties and post-processing protocols [95].

Recent trends also indicate, however, that vat photopolymerization is evolving from single-material printing to multi-material and functional additive manufacturing. In efforts of reducing switching time, the selection and evaluation of multi-material VPP has been a focus to facilitate functional printing device but significant challenges such as material exchange/contamination, microstructure mismatch, resin compatibility and process integration still exist[96], [97]. This is particularly useful for future applications in soft robotics, biomedical devices, sensors, graded materials, and functional composites where a single resin may not provide the necessary overall properties [25], [98].

Taken together, SLA, DLP, LCD/mSLA and CLIP can be interpreted as different process-control strategies in the same photopolymerization family. Its scientific and practical importance lies in how well they handle delivery of light, cure resin, construct layers, and post-process[98]. Thus, the choice of VPP method should be connected to material design and end-use goals instead of focusing solely on speed or theoretical printing resolution [68]. This knowledge forms the basis for a subsequent section that outlines the materials employed in vat photopolymerization with emphasis on how resin chemistry governs printability, mechanical behavior and application viability. Table 2 lists the major characteristics, benefits, constraints and potential future opportunities of the SLA, DLP, LCD/mSLA and CLIP technologies.

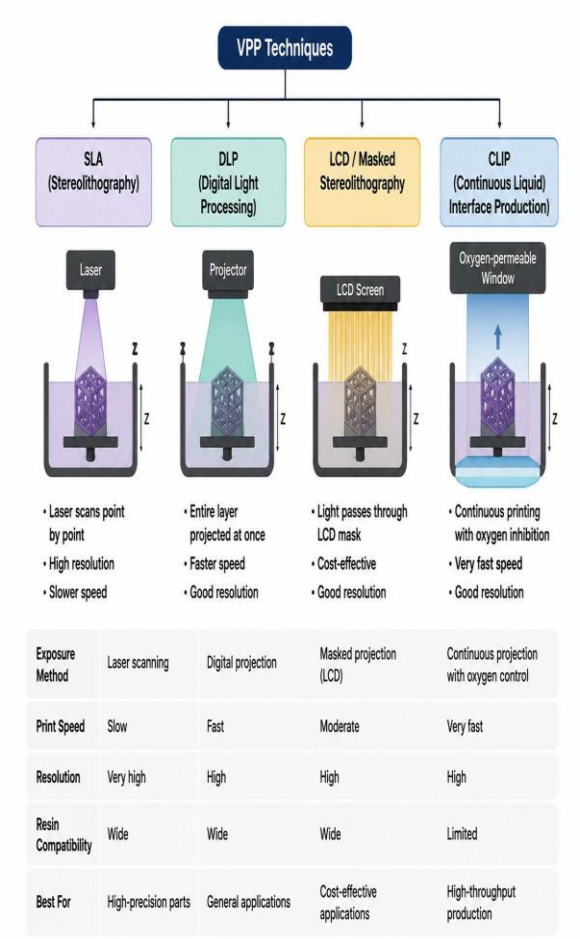


Figure 2. Introduction and comparison of the key Vat Photopolymerization technologies – SLA, DLP, LCD/mSLA and CLIP. This figure illustrates the variations in light delivery, formation of layers, printing properties and common applications

Table 2. Critical comparison of major vat photopolymerization techniques, including advantages, limitations, and future opportunities.

Technique	Light delivery mechanism	Main advantages	Main limitations	Current challenges and future opportunities
Stereolithography (SLA)	A focused laser beam selectively scans and cures the resin point-by-point or along predefined paths.	High dimensional accuracy, good surface quality, well matured technology, wide range of resin compatibility.	Low-speed of fabrication for large cross sections, mechanical scanning systems needed, production efficiency is limited.	Advancement of quicker scan methods, higher performing resins and the introduction of automated monitoring systems for industrial production.
Digital Light Processing (DLP)	The entire layer pattern is projected onto a resin surface with the aid of a digital micromirror device and simultaneously cured.	High printing speed, efficient layer fabrication and applicable to batch production of multiple small components.	Resolution is influenced by light intensity distribution, optical distortion, and pixel size and curing uniformity can be a challenge.	Better optical control, adaptive exposure strategies, and incorporating real-time curing monitoring to improve reliability.
Liquid Crystal Display-based masked Stereolithography (LCD/mSLA)	An LCD mask selectively blocks or allows light to pass through to cure specific areas of each resin layer.	Low Equipment Cost, High Accessibility, Fast Layer-by-Layer Fabrication and Desktop Manufacturability.	Absorption, non-uniform illumination of the build area and mechanical property variation due to printing position and orientation.	Seeking to develop better light engines, calibration techniques and improved resins for uniform mechanical characteristics.
Continuous Liquid Interface Production (CLIP)	Continuous oxygen-controlled photopolymerization near an oxygen-permeable window enables continuous resin curing.	Printing speed increased significantly, layer separation effects reduced, and potential for continuous printing manufacturing.	Strictly needs to manage oxygen, resin flow and use high performance materials that are compatible.	Growth into multi-material systems, industrial scale production and intelligent control of processes for continuous manufacturing.

While all the SLA, DLP, LCD/mSLA, and CLIP methods rely on the same photopolymerization principle, the performance of each method in practice is the result of the interplay between light delivery strategy, resin behavior, manufacturing speed and required part properties. While the DLP and LCD/mSLA are more productive as optical uniformity and curing consistency needs to be better controlled, SLA still has its merits for the applications where the highest accuracy and surface quality are required. While CLIP is a promising path to continuous and fast VPP manufacturing, it is still limited in its industrial use due to the advancement of resin, process control and scalable multi-material fabrication. So the choice of an appropriate VPP technique should not be only determined by printing speed or nominal resolution, but also by the relationship between process capability, material properties and application needs.

5. Materials Used in Vat Photopolymerization

The materials for vat photopolymerization are one of the major governing criteria controlling both printability and performance in post-processed parts. VPP differs from the extrusion or powder based AM since it is dependent on liquid photocurable formulations which simultaneously need to provide desirable viscosity, suitable penetration depth of light, controlled polymerization kinetics, dimensional stability and adequate mechanical or functional properties[57], [99]. Thus, material selection is more than just selecting a resin that prints well and necessitates considering the iterative nature of curing behavior, post-processing response, and application-specific requirements.

Typical VPP systems utilize polymers including acrylate- and methacrylate-based resins, which provide fast curing and high resolution, but suffer from defects such as brittleness, shrinkage, incomplete conversion concerning residual monomers, sensitivity to ageing with time elapsed after curing is completed by exposure to air or moisture [100], [101]. Studies have demonstrated that tensile strength, modulus and hardness can vary drastically with resin type, layer orientation and build-platform position revealing a strong coupling between material chemistry and processing conditions [3], [102], [103].

Efforts to mitigate these shortcomings involve developing resin containing customized monomer–oligomer structures, reactive diluents, photoinitiators and absorbers, and/or hybrid polymer networks with superior toughness, thermal stability and durability [104], [105]. As a result, heat-assisted VPP has reached higher micro hardness and flexural properties in dental applications, but the elevated processing temperatures may jeopardize the dimensional accuracy of 3D printed objects, leaving room for optimized thermal–photonic processing [24].

Composite resins are a large family of VPP materials and fillers enhance stiffness, wear resistance, bioactivity or optical response and even antimicrobial activity in this domain material class [6]. On the contrary, fillers can increase viscosity, light scattering and decrease curing depth, thus requiring to finely tune filler content, particle size, dispersion quality and exposure conditions for maintaining print ability and structural integrity [106], [107].

Ceramic-filled resins build on VPP for engineering and biomedical applications toward complex ceramic green body fabrication. Ceramic VPP needs to balance curing depth, curing speed, rheology, solid loading and green-body strength. The same considerations are valid for hydrogel and bioactive resins, which provide a high content of water and biological functions but poor mechanical strength, high swelling, and sensitivity to photopolymerization conditions [108], [109], [110], [111].

The sustainable and bio-based strategy has emerged as a new emerging direction for the replacement of petroleum-derived monomers without trading off viscosity, curing kinetics, and mechanical performance[69], [112], [113]. Recent studies of both vegetable-oil epoxies and bio-derived acrylates have reported desirable thermo-mechanical properties alongside successful DLP printability [51], [107], [114].

In brief, the historical perspective on the VPP materials have developed from simple rigid photopolymers to a more broad range of functional systems such as dental resins , ceramic suspensions , hydrogels, bioactive composites and bio-based formulations [25], [115]. Such an extension enriches the VPP complexity, as any material change effects will be for viscosity, light absorption , cure depth, conversion shrinkage , mechanical response and post-processing sensitivity [107], [116], [117]. Thus, the central challenge in VPP material development is designing resin systems with stable, reproducible curing behavior and reliable final properties suitable for their intended applications.

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6. Applications of Vat Photopolymerization

Vat photopolymerization is now an important manufacturing process for high-resolution, high-precision manufacturing of complex shapes with smooth surfaces. It use is particularly significant application in dental implants, biomedical scaffolds, ceramic parts, microfluidic devices, and functional composite parts [69], [118]. The main applications of Vat Photopolymerization (VPP) in different fields are shown and related to the practical examples in Fig. 3. The ability of VPP to maintain print fidelity is not only dependent on the accuracy of the printing method, but also on the chemistry of the resin, exposure parameters, post-curing, and stability of the final mechanical, biological, and functional properties [117], [119], [120].

6.1 Dental Applications

Dental applications are one of the most advanced vat photopolymerization applications. Dentists use VPP to create patient-specific dental models, surgical guides,

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temporary crowns, splints, and orthodontic appliances, where the ability of VPP to generate patient-specific geometries with high accuracy and surface quality is useful. Experimental research indicates that printing temperature, resin type, post-curing time, and process parameters have significant influence on dimensional accuracy, micro hardness, flexural properties and clinical reliability [24], [121]. Hence, dental VPP should be regarded as a controlled manufacturing process instead of an easy shape fabrication process as inadequate optimization may lead to loss in mechanical properties of the material and prosthetic fit [24], [30], [122].

6.2 Biomedical Scaffolds

The use of vat photopolymerization is growing in biomedical scaffolds as it allows the production of scaffolds with controlled geometry and reproducible internal features with porous scaffolds [123]. Hydrogel based and bioactive resin systems are especially significant for tissue engineering applications depending on the properties of the scaffold: pore structure, swelling behavior, degradation rate, response to compression and cytocompatibility [51]. In fact, experimental studies performed in GelMA/PEGDA–CeO_2 hydrogels and PEGDA–hydroxyapatite composite scaffolds have yielded scaffolds with functional properties, while at the same time demonstrating that the biological and mechanical properties are highly dependent on the loading of the fillers, the curing behavior and the build orientation [51], [124].

6.3 Ceramic Components

The manufacturing of complex ceramic green bodies by ceramic vat photopolymerization from photocurable ceramic suspensions, followed by debinding and sintering, is possible [125], [126]. This is useful for biomedical ceramics, dental ceramics, precision ceramic parts, and high-temperature ceramics, etc. [127], [128]. Experimental studies have shown that printability, density, dimensional stability, and mechanical properties are key factors, which are directly affected by ceramic solid loading, slurry viscosity, dispersion of particles, the curing depth, the debinding strategy, and the sintering conditions. The principal constraint is the challenge of achieving high ceramic loading along with the ability to provide good light transmittance and stable resin flow [22], [129], [130].

6.4 Microfluidic Devices

Another advantage of VPP is that it can be used to fabricate small channels and complex 3D flow paths that are difficult to obtain using many conventional methods for manufacturing microfluidic devices [131], [132]. However, experimental investigations reveal that it is highly sensitive to light penetration, over-curing, transparency of the resin, exposure dose and post-print cleaning processes when using VPP to manufacture micro channels [133], [134]. Specifically, over or under cured small channels may be partially closed or blocked, which will decrease the reliability of printed microfluidic systems. Hence, the careful control of the optical behavior of the resin and the printing parameters is important for successful VPP-microfluidics [134], [135].

6.5 Functional Composite Structures

Experimental studies have now been expanded from structural photo-phopolymer materials to functional composite materials in the form of VPP. Addition of functional fillers to photocurable resins can result in optical, electrical, antimicrobial, magnetic, or mechanoluminescent response. The incorporation of functional particles, however, may introduce viscosity increase, light scattering, and light cure depth reduction and/or non-uniform polymerization [23], [115], [136]. Therefore, optimization of the filler concentration, the thickness of the layers, the cure depth and the final response is required simultaneously to realize a functional VPP. Experimental testing for VPP with particle filled composites for complex functional structures proves that process optimization is crucial to achieve a compromise between printability and functional performance, with the goal of optimizing both structural and functional properties [137], [138].

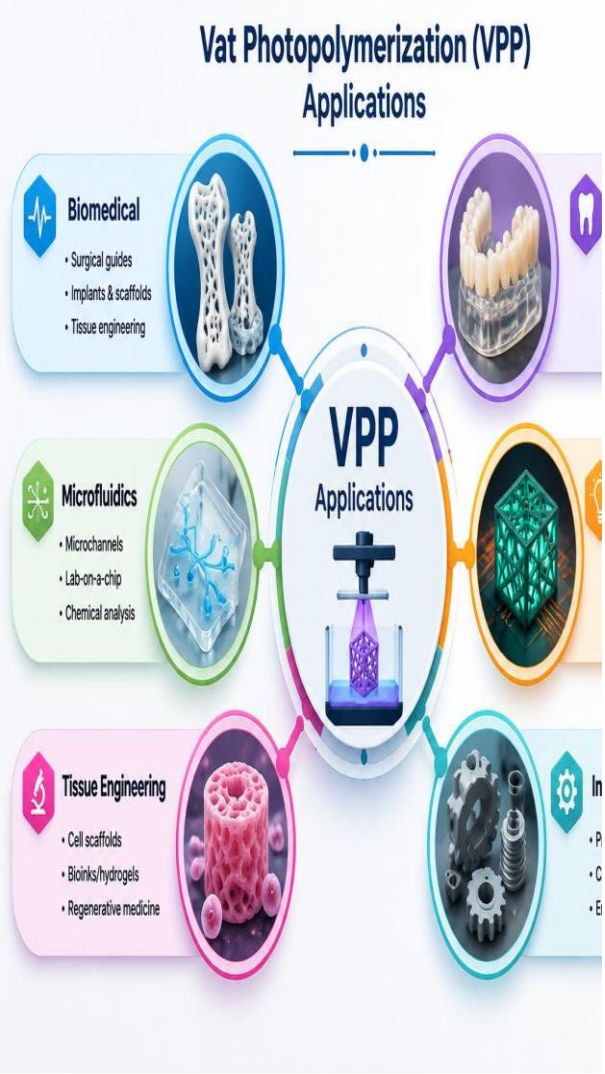


Figure 3. Examples of the use of Vat Photopolymerization (VPP) in dental, biomedical, ceramic, microfluidic, functional composite and industrial applications. The high resolution of the fabrication and the versatility of the material enable structures to be fabricated for each specific application that have the required mechanical, biological and functional properties.

6.6 Industrial Scalability and Economic Considerations

While vat photopolymerization has shown great promise in higher value applications, its movement from lab to industry is yet to be overcome. There are multiple variables that affect economic viability of VPP, such as printer costs, resin costs, materials availability, production rates, post-processing needs, and material stability over time[18], [139]. VPP systems can provide high resolution and surface quality compared to other AM technologies, but the cost of using specialized photocurable resins and the need for washing and post-curing can restrict use in applications that demand a low cost[140], [141], [142].

Today, VPP is very successful in industrial applications where high precision and customization is a requirement and the manufacturing cost is warranted, including dental manufacturing, medical models, jewellery manufacturing and micro-scale devices[143], [144]. But there is a need for speeding up printing, automated printing, material recycling, process monitoring, and quality control to broaden the industrial implementation[145], [146]. To achieve improved economic competitiveness, development of sustainable and inexpensive resin systems, along with establishing standard evaluation methods, will be critical.

The future use of VPP for industrial applications is expected to be based on the following: (1) intelligent process control, (2) automatic post-processing, (3) scalability of the multi-material fabrication, and (4) data-driven optimization approaches. The advances may help VPP go from prototyping to functional and end-use components in a more reliable format.

7. Conclusion and Recommendation for Future Work

Vat photopolymerization has evolved from a niche rapid-prototyping technology to a versatile platform that can be used to manufacture high-resolution and functionally complex parts in biomedical, ceramic, microfluidic and multi-functional composite applications. The overall findings indicate that printer resolution and exposure patterns alone cannot determine the performance and reliability of VPP-fabricated structures. Instead, these properties are governed by the complex interactions among resin chemistry , incorporation of fillers, the penetration of light, the process of building layers, post-curing processes, and environment conditions. Experimental investigations have repeatedly demonstrated that the process, material and function are inter-dependent and that for successful implementation of VPP, these factors must be tightly coupled. Directions for future research include:

- **Rational Design of Functional Resins:** Design of composite and bioactive resins with tunable viscosity, controlled photopolymerization kinetics and predictable curing depth in order to achieve complex shapes without compromising mechanical or functional properties.
- **Advanced Process Monitoring and Control:** With in-situ optical and thermal sensors, adaptive exposure, and machine learning-based optimization, all designed to reduce over-curing, incomplete polymerization, and spatial heterogeneities in high-aspect-ratio and/or filler loaded structures.
- **Multi-material and Hybrid Fabrication:** Pushing the limits of VPP by moving towards seamless multi-material systems that integrate structural, bioactive and functional domains, with an emphasis on challenges related to interfacial adhesion, material compatibility, and scalability.
- **Standardized Evaluation Protocols:** Development of consistent test procedures for mechanical, biological, and functional performance, for the purposes of reproducibility and comparability between

different research studies and industrial applications.

- **Sustainable and Bio-derived Systems:** Using renewable monomers, bio-based fillers and eco-friendly processing conditions to meet sustainable manufacturing systems without compromising resolution and performance of VPP technology.

Commercialization aspects, such as reducing the material and processing costs, short production cycles, development of quality standards and application-specific systems, will be crucial for future advancement in VPP. These developments will help to move VPP from laboratory demonstrations to commercially viable production platforms.

Finally, VPP is a new paradigm in additive manufacturing that offers an advanced level of control over micro-architecture, material functionality and end-use application potential. The potential must be realized through the synergy of materials science, photochemistry, process engineering and computational optimization, which will enable resilient, reproducible and multifunctional 3D-printed systems.

boldface type. Affiliations of the authors are to be shown after the listing of the author names. In the case of multiple authorship, the respective affiliations are to be identified by superscript, as illustrated above. Include e-mail addresses if possible. Tow 12-point blank lines should follow author information.

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