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A TRADE-OFF ANALYSIS OF RECOATING METHODS FOR VAT PHOTOPOLYMERIZATION OF CERAMICS

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Abstract

Technical ceramic parts can be produced by curing ceramic-filled resins in the vat photopolymerization (stereolithography) process. Scaling up to larger ceramic product sizes and higher product quality calls for the integration of more sensing, actuation and closed-loop control solutions while taking a systems engineering approach. This paper gives a comprehensive overview of methods to deposit a layer of (ceramic-filled) resin, better known as recoating. The aim of this work is to perform a trade-off analysis of recoating methods to enable the selection of the method that best meets the requirements for scaling up the printable object size in the ceramic vat photopolymerization process.

Introduction

Additive manufacturing (AM) of ceramic parts opens up new possibilities for the high tech industry in comparison to conventional ceramic manufacturing techniques. Particularly, the ability to manufacture near-net 3D shapes in small series with high geometrical flexibility makes the industrial integration of AM into the ceramic processing chain appealing [1, 2, 3]. A predominant AM technology for producing ceramics is vat photopolymerization [4], also known as stereolithography [5, 6].

In vat photopolymerization, products are fabricated in a vat through the consecutive deposition of photopolymer resin layers and the subsequent selective irradiation according to the part's cross section. By mixing ceramic powder with the resin and adjusting the process parameters of conventional vat photopolymerization machines, AM can be used to perform the shaping step in the ceramic process chain. The resulting printed product is in the "green" state where the photopolymer acts as a binder to keep the ceramic powder together, highly similar to the state in which ceramic parts remain after injection molding [4]. The green part is then cleaned and put in an oven to pyrolyze the photopolymer in a debinding step and to finally fuse the ceramic particles together in a sintering step.

Although the accuracy of products fabricated by vat photopolymerization is among the highest of AM technologies [7], several challenges are to be solved before the technology can be adopted by the industry for the manufacturing of ceramic parts of substantial size. These challenges include increasing the density of monolithic parts, increasing printable product sizes and wall thicknesses, and avoiding crack and void formation [3], as well as the universal challenge of reducing variability in AM equipment and part quality [8, 9]. The modelling, sensing, actuation and control of the AM process are deemed key enablers to pave the road towards solving the lack of repeatable product quality [10, 8]. Viewing the ceramic 3D printer as a mechatronic system [11] illustrates the importance of each of these components, as shown in Figure 1.

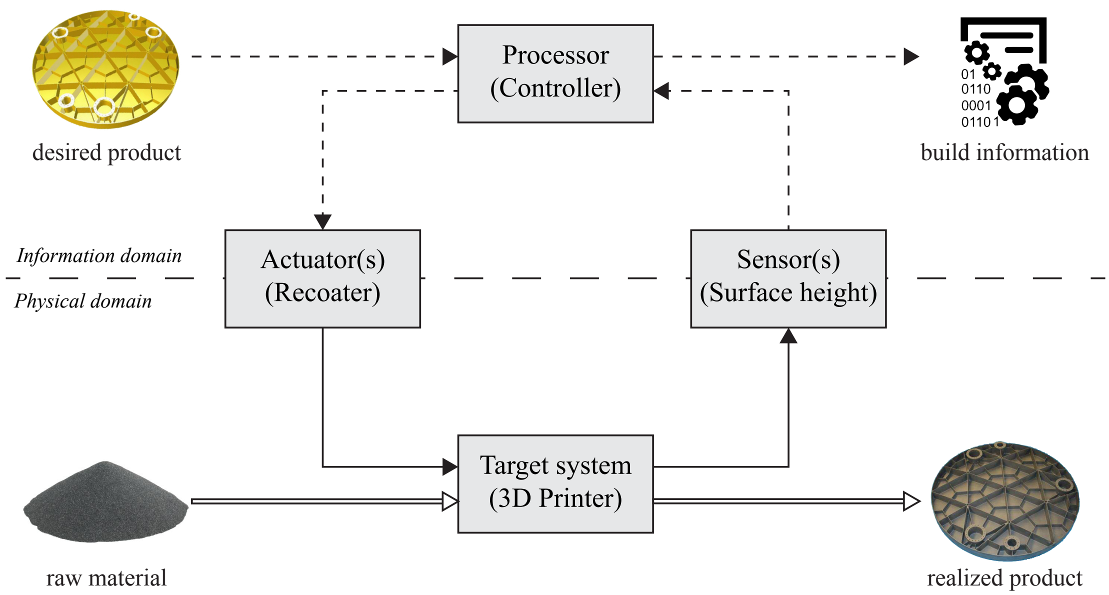


Figure 1: Ceramic 3D printer as a mechatronic system

This paper gives a comprehensive overview of methods to deposit a layer of photocurable resin, better known as recoating. The aim is to analyze trade-offs between recoating methods to enable the future selection of the recoating method that best meets the requirements for scaling up the printable object size in the ceramic vat photopolymerization process. The scope of the paper encompasses both pure photopolymer resins as well as ceramic-filled resins or slurries, since the vat photopolymerization process for ceramics is closely related to the process for pure photopolymers. Although build platform movement is considered part of the recoating step, it is hardly addressed both in literature and in this paper as it is a matter of proper engineering. Additionally, as literature on the modelling of recoating is scarce, modelling is not treated in this paper.

The outline of this paper is as follows. First, the requirements related to the recoating phase are outlined. Then an overview is given of recoating methods, sensing methods and control strategies respectively. Next, design considerations are discussed from a control systems perspective. Finally, the recoating methods are compared in a concluding discussion.

Requirements

The first step in trade-off analysis is to define the objective for the trade study itself by identifying the requirements the solution must fulfill [12]. Typical objectives for manufacturing processes in general are the minimization of production variations for product quality, the capability to change target geometries rapidly for flexibility, and the minimization of process times for productivity [13]. The main goal of the recoating phase specifically, is to deposit a layer of (ceramic-filled) resin. The underlying challenge is to obtain an as uniform as possible resin surface as quickly as possible [6]. In the following, the requirements for the recoating step in ceramic vat photopolymerization and their rationale are outlined and categorized according to application properties.

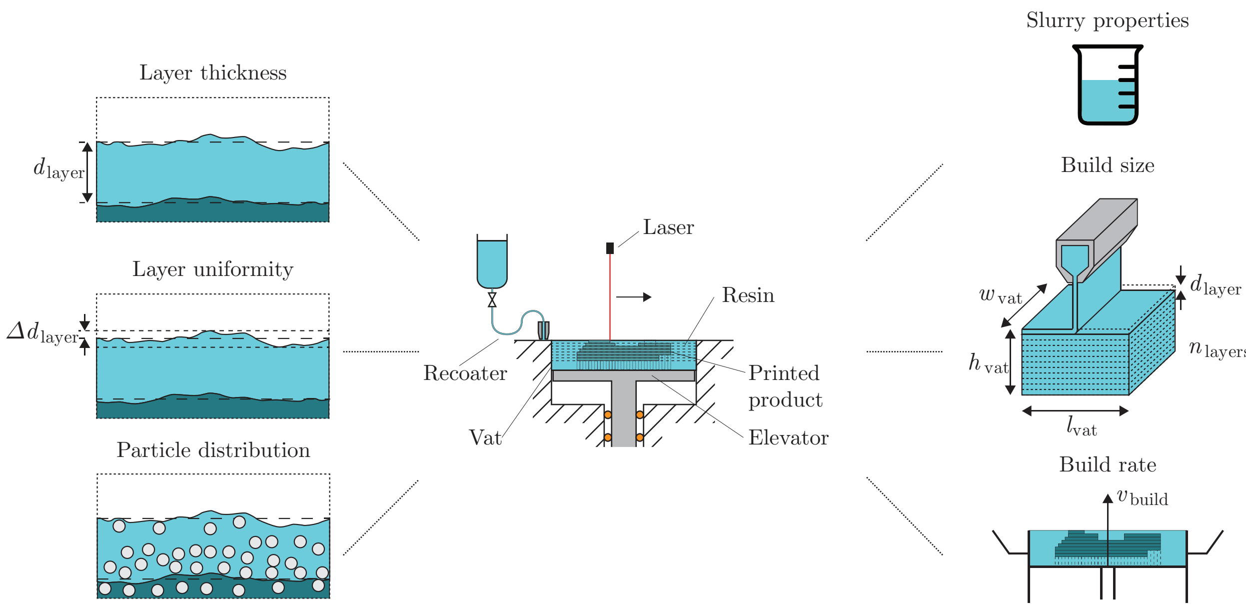


Figure 2: Requirements for the recoating step in ceramic vat photopolymerization.

Part geometry requirements

- Build area (size): the build area is defined as the product of vat length l_{vat} with vat width w_{vat} and dictates the maximum allowable part dimensions. Current industrial applications mostly encompass small objects such as medical implants, jewelry and antennas. Examples of high tech industry applications that benefit from the favorable properties of ceramics in their manufacturing equipment are the space, semiconductor and display manufacturing industries. The ever-increasing size of machine components such as substrate carriers motivates us to enable building parts with a cross-sectional area in the order of 1000×1000 [mm^2].

Material requirements

- Rheological resin properties: the recoater should be able to handle highly loaded ceramic suspensions. The mixing of resin with ceramic particles makes the resin highly viscous in comparison to pure non-filled resins. Literature states that the viscosity should be as low as possible and comparable to conventional resins, but not exceed 3 to 5 [Pa·s] for proper flow [14, 15]. Moreover, the recoater should be able to cope with density changes due to volumetric shrinkage upon photopolymerization [6].

- Optical resin properties: the recoater should be able to handle media that exhibit light scattering behaviour due to the presence of ceramic particles alongside the typical light absorbing behaviour in resins. This has consequences for the applicability of optical sensing methods.

Part quality requirements

- Layer thickness: the layer thickness typically determines the z-resolution, i.e., the smallest feature size in the vertical direction, and the surface roughness. For proper photopolymerization, the resin surface should be in the light source's focal plane and at a controlled height from the previous layer [6]. The layer thickness moreover determines the number of layers, the required energy dose or exposure per layer, and the required build time. Since thicker layers require a higher energy dose to bond to the previous layer, thicker layers do not necessarily result in shorter build times [5]. The current typical layer thicknesses of 25 - 100 [μm] are arguably acceptable.

- Layer uniformity: the layer uniformity quantifies the deviation from a flat layer and should be as uniform as possible. Resin surface nonuniformity can result in poor surface quality, undercure with resulting poor layer-to-layer adhesion (delamination), overcure with resulting excessive residual stress and distortion, and part height errors [6, 16]. Hence the deviation from the intended layer thickness Δd_{layer} should not exceed a certain value. To the authors' knowledge no literature is present on acceptable deviations in pure or ceramic-filled resins, but it is thinkable that ceramic-filled resins are more strict due to their lower light penetration depth.

- Layer particle distribution: the distribution of ceramic particles along the deposited layer should be sufficiently homogeneous. An inhomogeneous ceramic particle distribution in the green part influences the isotropy of the green part's properties and can contribute to the formation of defects such as cracks and delamination during post-processing [17, 18, 19]. Hence the settling of particles should be avoided both in printing and in storage. For similar reasons, the entrapment of air bubbles should be avoided.

Performance requirements

- Build rate: the build rate is defined as the layer thickness d_{layer} divided by the average time to print a layer t_{layer}, sometimes also multiplied by the build area. However, the recoating step is not the only contribution to the total part production time t_{total} (1) that ultimately determines productivity.

$$t_{\text{total}} = t_{\text{pre-processing}} + n_{\text{layers}} \cdot t_{\text{layer}} + t_{\text{post-processing}}, \quad t_{\text{layer}} = t_{\text{recoating}} + t_{\text{photopolymerization}} \tag{1}$$

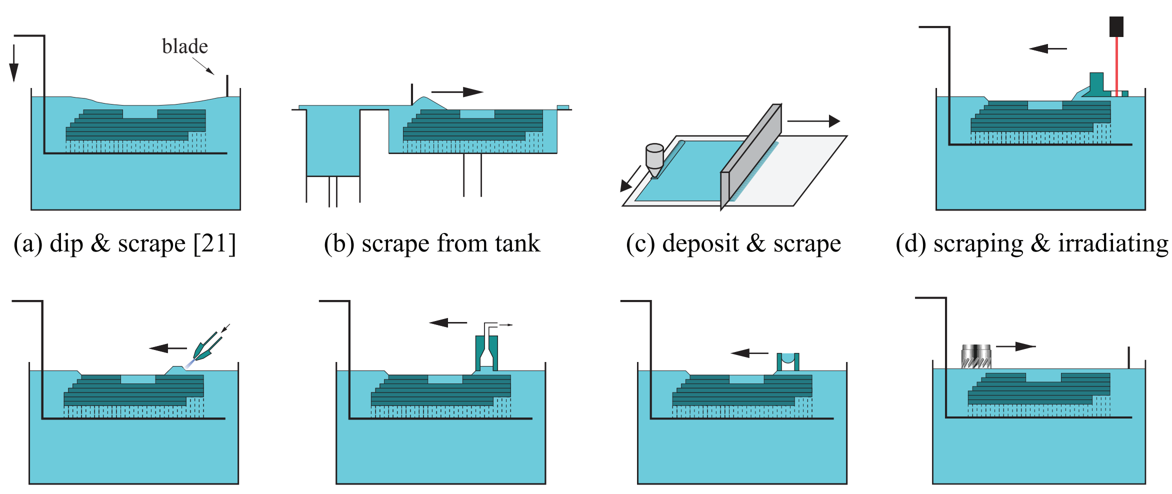
The pre-processing and especially the (thermal) post-processing steps including debinding and sintering can take more time than the build process itself. That is, for the current small product sizes post-processing can take several days [3] and will most probably increase when scaling up product sizes. For comparison, printing a 1000 [mm] high part with a layer thickness d_{layer} of 100 [μm] at a time per layer t_{layer} of 30 seconds, would take 3.5 days. Shorter production times naturally are desirable, but such build times are already an improvement with respect to the total lead time for conventionally produced ceramic parts.

Recoating (actuation) methods

Many different methods to deposit a layer of liquid are reported in literature [20]. This section attempts to give a comprehensive overview of only those methods that are utilized in the recoating step of vat photopolymerization. Most of the recoating methods developed for vat photopolymerization are derived from the coating industry. A fundamental difference with coating on solid substrates, however, is the flow behaviour when coating a solid substrate as opposed to the flow behaviour when coating a viscous free surface [21]. In vat photopolymerization both situations can occur, depending on the local cross-section of the object to be built.

Recoating methods can be categorized according to several characteristics. In *pre-metered* systems, the amount of liquid applied per unit area is predetermined by an upstream metering pump; in *self-metered* systems the final layer thickness is mostly determined by the fluid flow interactions with the coating applicator [20]. In *constrained surface* systems, the final layer surface is determined by a constraining surface rather than by a free liquid-air interface as is the case for *free surface* systems. In *non-recoating* systems, the light source is immersed in the vat and hence no recoating system is required.

Self-metered, free surface recoating systems



(a) dip & scrape [21] (b) scrape from tank (c) deposit & scrape (d) scraping & irradiating

(e) air knife (f) Zephyr blade [21] (g) viscous retention [21] (h) Solid Ground Curing

Figure 3: Self-metered recoating methods.

Dip & scrape recoating

In the first commercial vat photopolymerization system developed by 3D Systems, the SLA-1, recoating was performed by solely dipping the part in the resin bath, moving up again, and waiting for the resin level to settle [5]. In the successor SLA-250 system a recoater blade was added for sweeping the excess resin from the part and levelling. Figure 3 (a) illustrates this dip and scrape recoating method. At the start of the recoating procedure, the last cured layer is at the same height as the resin surface level. The platform is then lowered further than the intended layer height in a so-called "deep dip" step such that the part is fully immersed and resin is allowed to flow over the part [5]. Subsequently the platform is elevated to the position where the top surface of the part is one layer height below the resin level. In the final step a blade is swept across the vat one or more times to scrape away the excess resin and smoothen the resin surface. After sweeping, the resin is allowed to settle for a certain "Z-wait" period to decrease surface nonuniformity [5].

Deposit & scrape recoating

Instead of fully immersing the part by deep dipping in the resin vat, material can be supplied by depositing from an external reservoir. Recoating methods that first deposit material and then scrape the excessive material are designated here as deposit and scrape recoating methods. Both the depositing function and the scraping function can be fulfilled in different ways. One of the ways to deposit material is the scrape from tank technique in which the material is extruded from an adjacent tank by elevating a piston. Figure 3 (b) shows this technique, which was applied for vat photopolymerization of ceramics by Optoform [22]. After lowering the build platform, a blade scrapes the liquid surface one or multiple times to spread the material.

A different way to deposit the material is to dispense the resin onto the previous layer by means of an extrusion head, a syringe or jetting. Cheverton et al. [23] used a syringe on a translation stage to deposit a line of ceramic slurry in one direction and to subsequently spread the material in the orthogonal direction with a doctor blade as depicted in Figure 3 (c). Springer et al. [24] developed a similar technique that uses a jet dispensing valve on an xy-stage to selectively dispense droplets of ceramic slurry on the complete build area, a roller to smoothen the material, and a slurry suction unit to actively dispatch surplus material.

Simultaneously scraping & irradiating

In the "semi controlled liquid method" developed by Yamazawa et al. [25, 26], the resin is simultaneously scraped and irradiated directly behind the scraper where the liquid surface is semi controlled. The main idea is to improve accuracy by irradiating at a location where the layer thickness is properly defined and to increase building speed by eliminating "Z-wait" levelling time. Figure 3 (d) shows a constrained surface embodiment of the method, where the resin is irradiated through e.g. a quartz glass coated with a teflon layer [26].

Air knife recoating

The use of an air knife to control liquid film thickness by blowing off excess liquid is commonplace in the coating industry [20]. Dufaud et al. developed an air knife recoating system for vat photopolymerization of ceramics [14, 27]. Figure 3 (e) shows the principle of spreading the resin by means of an air knife recoater, which consists of an injection nozzle through which nitrogen gas is forced; nitrogen is used to prevent oxygen inhibition. Layer thicknesses ranging from 5 to 40 [μm] could be achieved by adjusting the surface-nozzle height, gas pressure, and angle of attack [27].

Inverted U recoating

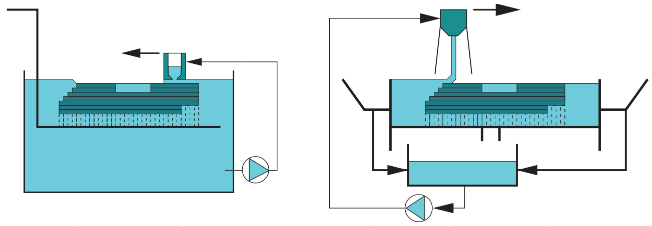
To eliminate the need for deep dipping and to improve recoating speed, the inverted U recoater was developed [21], also named Zephyr blade [7] or applicator bar [28]. The inverted U is essentially a symmetric hollow blade with a resin reservoir in the centre in which resin is sucked by means of a vacuum pump. Figure 3 (f) illustrates the inverted U recoating cycle, which starts with lowering the platform by one layer height and subsequently traversing the vat surface. During the blade sweeping, resin is deposited into regions where no resin is present and the resin reservoir is replenished during and after sweeping from the surrounding resin [29]. Alternatively, resin can be drawn from a separate vat. Inverted U recoaters using capillarity and electrostatic forces to fill the reservoir are reported in [21].

Viscous retention recoating

A recoating technique that utilizes the viscous behaviour of resins called viscous retention was developed by the company Teijin Seiki [30]. The viscous retention recoater consists of a brush or mesh between two doctor blades. As shown in Figure 3 (g) the recoater is first submerged into the vat and raised again to take up resin and then the platform is lowered. As the recoater traverses the vat, resin drains out due to gravity at a rate determined by the resin viscosity and the final layer height is determined by the trailing doctor blade [30].

Solid Ground Curing

Solid Ground Curing (SGC) was one of the earliest and now obsolete additive manufacturing techniques [7] in which the final layer height was determined by a face milling operation. SGC is essentially a free surface system, but since the final layer's surface is determined by a milling operation it is categorized here as a constrained surface system. The manufacturing process commercialized by Cubital essentially consisted out of six steps: deposit layer, develop photomask, expose mask, vacuum uncured resin, deposit wax, mill flat [30]. Figure 5 (d) shows the milling step. In a sense, the SGC system was one of the first hybrid AM systems as it integrated both additive and subtractive manufacturing methods into a single machine.



(a) slot recoating [21] (b) curtain recoating [21]

Figure 4: Pre-metered recoating methods.

Pre-metered, free surface recoating systems

Slot recoating

Slot coating is a layer deposition method derived from the coating industry and has been applied as a recoating method in vat photopolymerization as well. The principle of operation of slot coating is highly similar to that of inverted U recoating, but the essential difference is that slot coating is a pre-metered method. As Figure 4 (a) shows, after lowering the platform by one layer height an upstream metering pump regulates the resin outflow as the recoater traverses the vat surface. EOS is the only commercial vat photopolymerization system manufacturer known to have used a slot coater [21]. Haberer et al. developed a slot coater for vat photopolymerization using a highly viscous fiber-photopolymer resin composite liquid [31].

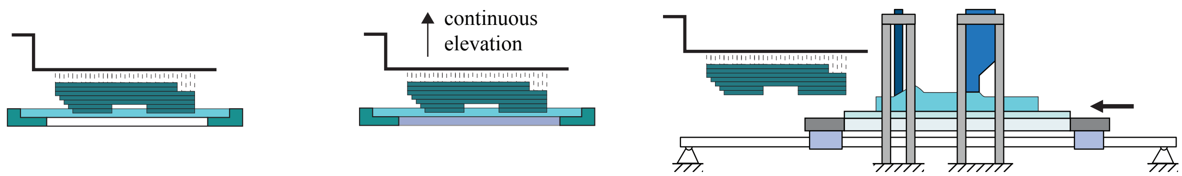
Curtain recoating

Curtain coating is a pre-metered coating technique in which a liquid curtain or sheet of liquid falls onto the surface to be coated [20]. The Catholic University of Leuven developed a curtain recoating system for vat photopolymerization [21], which was commercialized in the large-area Mammoth Stereolithography system by Materialise. Figure 4 (b) displays the curtain recoating system, essentially consisting of a recoating die, vat, collecting basin, reservoir and pump. At the start of the recoating cycle the platform is lowered by one layer thickness, the recoating die is accelerated to a constant speed. A liquid curtain is formed and a new layer of liquid is deposited as the recoating die traverses the vat. At the end the recoating die is decelerated. The resin that is impinged onto the collecting basin at the beginning and end of the recoating cycle is recollected and fed to the central reservoir, with the accompanying risk that air bubbles are formed [21].

Constrained surface recoating systems

Conventional constrained surface systems

Conventional constrained surface systems have a bottom-up irradiation orientation where the light source is directed vertically upwards and irradiates through a glass substrate. After irradiation, the platform is raised in a separation step to a height above the resin level. In some embodiments a recoater blade is incorporated to spread the resin whereas in other systems gravity is used as the only motive force to let the resin flow underneath the part [32]. In an embodiment by Lithoz



(a) constrained surface [21] (b) continuously irradiating & elevating (c) tape casting [19]

Figure 5: Constrained surface recoating methods.

GmbH, the vat rotates and a stationary blade spreads out the resin [33]. Finally, the platform is lowered again to a height where the distance between the glass substrate and previous layer is exactly one layer thickness. Figure 5 (a) illustrates the constrained surface recoating technique, which eliminates the need for adding extra components to perform the recoating function when only gravity is used.

Continuously irradiating & elevating systems

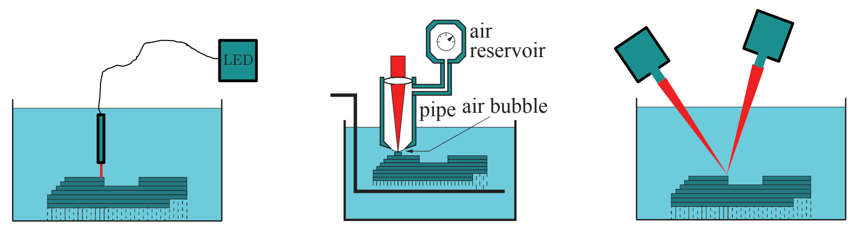
The separation, recoating, and repositioning steps in constrained surface vat photopolymerization systems can be completely eliminated if the platform is continuously elevated and irradiated simultaneously. The challenge in this configuration is to prevent the resin to adhere to the glass substrate. Recently a technology was invented named continuous liquid interface production (CLIP) that solves this by creating a dead zone or liquid interface where photopolymerization is inhibited [34, 35]. This dead zone is achieved by incorporating an oxygen-permeable window below the image plane. CLIP is a layerless technology owing to the continuous platform elevation and its printing speed is either limited by resin curing or resin flow, depending on the cross-sectional area of the momentary slice [35]. In these continuously elevating systems, resin is constantly flowing underneath the part [36]. According to the inventors, isotropic material properties are obtained with this technology [36]. Other continuously irradiating and elevating systems are currently under development by major vat photopolymerization system vendors such as 3D Systems, EnvisionTec and Prodways.

Tape casting methods

Tape casting is a manufacturing process for thin sheets of ceramic materials widely used in the production of electronic components [37]. The process involves the deposition of slurry on a moving carrier surface and the scraping of excess material by a doctor blade. Several recoating methods for vat photopolymerization were developed inspired by tape casting. Song et al. [19, 38] developed the bottom-up projection system depicted in in Figure 5 (c). In said system, the glass substrate is mounted to a linear stage to enable the depositing and scraping of a ceramic slurry. Separation is realized through a lubricative PDMS film and the linear sliding motion [38]. This is also a constrained surface system, because the dispensed slurry thickness is higher than the layer thickness. 3D Systems developed a similar technique called Film Transfer Imaging, in which a scraper deposits a thin film of resin on top of a stationary transparent material tray. Note also that tape casting methods show a high similarity to Laminated Object Manufacturing (LOM) [7].

Another recoating method closely related to tape casting is the sheet lamination process by Himmer et al. [39] for ceramic vat photopolymerization. In their method, slurry was applied to a plastic sheet and covered by a paper sheet in a lamination preprocess and subsequently pressed onto the previous layer. However, during the photopolymerization step the surface was not constrained. The recoating steps were performed manually, but an automated version was outlined as well in [39]. The method employed in the Admatec Admaflex machines [40, 41] fairly resembles this automated version. Their system consists of a foil handling system, a ceramic slurry depositor including doctor blade and a glass support plate through which the layers are irradiated bottom-up.

Non-recoating systems



(a) CNC accumulation (b) air bubble [21] (c) two photon

Figure 6: Non-recoating methods.

CNC accumulation

CNC accumulation is a non-recoating type of vat photopolymerization technology in which an accumulation tool coupled to a UV light source by a fiber optic cable is immersed in a resin vat [42]. The process is highly similar to CNC machining, as the accumulation tool is mounted to a multi-axis CNC stage. Figure 6 (a) shows the basic concept of CNC accumulation. Upon irradiation, the cured resin adheres to the curing tool tip, but due to the small contact area separation is less of an issue than it is with constrained surface systems [42]. The point-based irradiation method in the original CNC accumulation configuration was extended to a line-based irradiation method with still a considerably small contact area [43].

Irradiating through an air bubble

A non-recoating type of vat photopolymerization technology similar to the CNC accumulation process was developed at Osaka Sangyo University [21]. In the method a pipe is submersed into the resin vat and at the lower end an air bubble is formed due to an overpressure. A coaxial laser beam irradiates the resin through the air bubble as shown in Figure 6 (b). The difference with the CNC accumulation process is that there is no mechanical bonding between the cured layers and the pipe and thus no accompyanying separation issues [21].

Two-photon vat photopolymerization

In two-photon vat photopolymerization, a photoinitiator molecule requires the simultaneous absorption of two photons in order to form free radicals [14, 7]. In one configuration named beam interference solidification, two lasers are used with potentially different wavelengths. Only at their interference point a photoinitiator molecule can be excited to a high enough state to initiate polymerization as depicted in Figure 6 (c). In another configuration, a single laser is used where only near the focal spot of the laser the intensity is high enough to initiate polymerization [7]. As in both configurations polymerization can take place at any depth in the vat, the need for recoating is eliminated. However, the scattering of light in the ceramic particles most probably makes this method unsuited for ceramic vat photopolymerization.

Other recoating methods

For the sake of completeness, it is worthwhile to mention other recoating methods reported in literature. These methods include rolling with a paint roller [27], sweeping with a canvas [27], spraying [44], using counter-rotating rollers [28], material extrusion [45], and establishing a liquid bridge between two plates [46]. Note that the boundaries between different additive manufacturing technologies such as vat photopolymerization and, e.g., material jetting vanish when looking from a conceptual point of view.

Sensing methods

Few sensing technologies have been applied in the recoating phase in vat photopolymerization, but this section gives a brief overview of those that have been. Two practically the same measurands with different dimensionality are discussed: the bulk resin level, i.e., a single value representing the average resin level, and the layer surface uniformity, i.e., a 2D height map representing the resin level at each point on the layer surface. The techniques listed here are only applicable to free surface systems, as in constrained surface systems the layer height is not determined by recoating.

Bulk resin level sensing

In early vat photopolymerization systems the bulk resin level was measured by means of a mechanical float or a laser beam reflected off the resin surface onto a bi-cell and later onto a linear cell detector [6], see Figure 7 (a). However, these systems only measured the level at a single point that could potentially be unrepresentative for the bulk resin level due to local surface undulations. Pham et al. used phototransistors to measure fluctuations of the resin level during recoating at three different vat positions [47]. Renap et al. used a laser distance sensor on a linear motion stage to measure the surface level along the axis of the recoater blade [48], see Figure 7 (b).

Confocal laser scanning

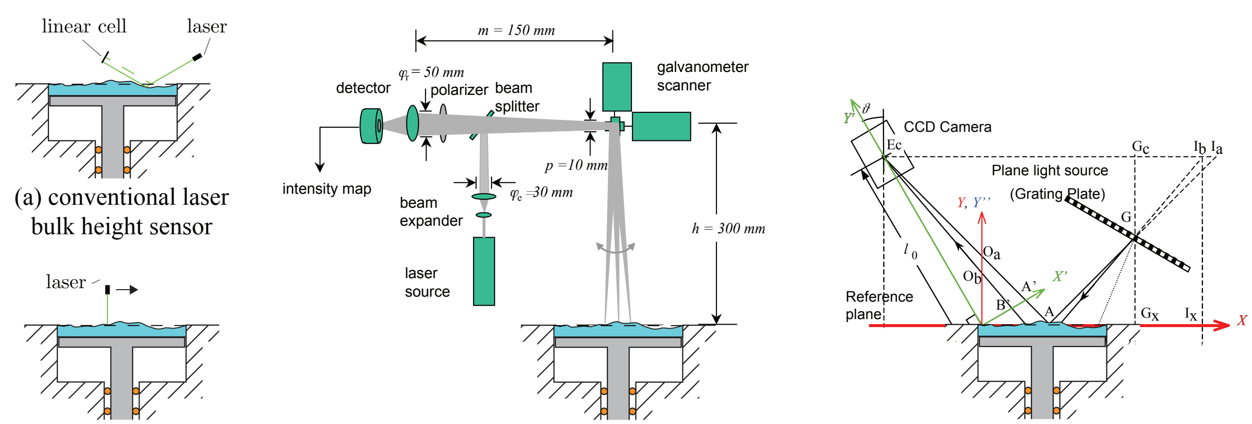
Park et al. developed a sensor system for in-process layer surface inspection of stereolithography products [49]. Their goal was to enable the detection of defects such as voids, delaminations and surface undulations. Their sensor system's measuring principle is similar to that of laser scanning confocal microscopy and is based on the fact that the diffused light intensity of a solidified region is higher than that of liquid resin. The realized imaging system consists of a laser source that was scanned over the surface by means of galvanometers, a beam splitter, lenses and a coaxial photodetector; see Figure 7 (c).

Fringe projection

Narahara et al. developed a measurement system for liquid surface flatness based on fringe projection techniques [50, 51]. Their goal was to measure the unevenness of the liquid surface to assure flatness of the layers of stereolithography parts. Their systems' measuring principle is based on projecting a stripe pattern by means of a light source and grating plate and capturing an image of the projection that appears distorted if not flat, see Figure 7 (d). In an initial implementation [50], the surface height was measured through a phase detection algorithm. In a later implementation [52], a more approximative algorithm was used to measure the surface height. For small surface angles, i.e., under 0.1 [^{o}], and small angle variations the system is capable of producing a surface height map with a maximum error up to 6 [μm]. In case the surface unevenness exceeded a certain value, a corrective step was performed in the form of an extra recoater sweep.

Machine vision

Cheverton et al. used a surface imaging camera to monitor the quality of each ceramic slurry layer, and a separate camera to monitor the slurry deposition process [23]. The goal was to notify the operator about a problem using machine vision and to make automated decisions in case of anomalies, e.g., re-wiping the layer when necessary.



(a) conventional laser bulk height sensor

(b) laser distance sensor on motion axis

(c) confocal laser scanning [51]

(d) fringe projection [52]

Figure 7: Resin surface height sensing methods applied in vat photopolymerization.

Control strategies

Currently, recoating is typically controlled in open loop, since the deposited layer quality is typically not measured nor used as a feedback signal. Conventional dip and scrape systems had some user-configurable parameters, such as the number of sweeps and sweep speed [5, 6]. Little literature exists on more advanced recoating strategies. Jacobs et al. describe a three-sweep method to move bubbles formed during the recoating process outside the build area [6]. Guangshen et al. [53] developed a dynamically optimized blade speed based on a response surface model to reduce layer thickness deviations with built object height. The following sections describe three closed-loop control schemes relevant to recoating.

Corrective sweeping

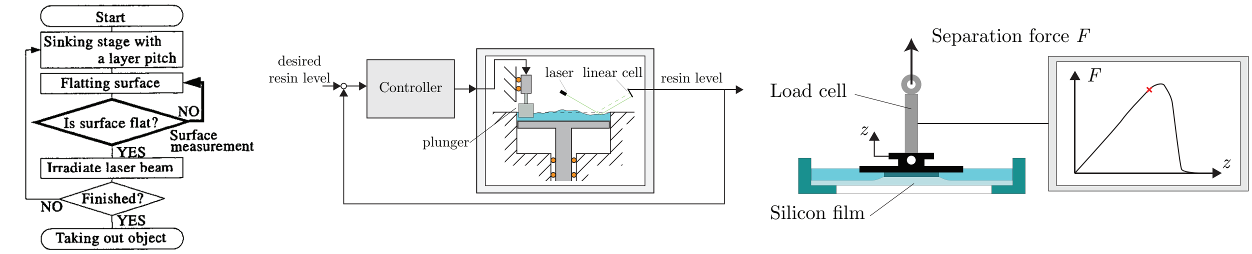
In free surface systems, the performance of the recoater can be quantified by the deposited layer surface uniformity. If information of the layer uniformity is available in the form of, e.g., a 2D height map, a decision can be made to perform another scraping or sweeping action. Yoshikawa et al. closed the loop by using layer uniformity information as a feedback signal to decide whether or not to sweep again [51], see Figure 8 (a) for the simple control algorithm. Cheverton et al. describe a similar corrective sweeping action, based on a machine vision image [23].

Resin level control

During polymerization the total photopolymer volume and consequently the resin level decrease due to shrinkage. On the other hand, fluid displacement due to elevator immersion and temperature fluctuations can affect the resin level. Resin level feedback control was implemented in early commercial vat photopolymerization systems to reject resin level disturbances [5]. Figure 8 (b) schematically shows the resin level control scheme. A laser leveling system measures the resin level and a plunger activated by a precision stepper motor corrects the resin level through simple fluid displacement [6]. In the figure the bulk level and corresponding laser reflection are shown dashed. It holds for both the measurement and the actuation that only one point is considered, although the surface actually has a nonuniform height distribution. Wang et al. developed an improved liquid level detection and control method with a resolution of ± 15 [μm] [54].

Separation force control

In constrained surface systems, a substantial separation force is required to elevate the platform after photopolymerization [55]. This separation process presents a potential threat to part quality, as defects can occur if the stresses in the part exceed a stress limit. Separation force control was developed to achieve efficient separation without breaking the part. Figure 8 (c) schematically shows the separation force control system. The pulling force on the platform is measured by means of a load cell and is fed back to the platform motion controller. Based on a predictive model of the force-displacement behavior or a simple force threshold, the separation force or platform motion is limited [56, 55].



(a) corrective sweeping [53] (b) resin level control (c) separation force control

Figure 8: Control schemes.

Control system considerations

The inventory of recoating methods, sensing methods, and control strategies conducted in the previous sections, shows that the system designer has a fair amount of design options at hand. This section discusses several considerations from a control systems perspective to enable the system designer to select a recoating method. Ideally, the method should be chosen by conducting a trade-off study in which the characteristics of each candidate are compared in order to determine the method that best balances the assessment criteria [57]. The requirements outlined in the beginning of this paper together with the following considerations constitute said criteria. Design considerations for micro-stereolithography systems are discussed in [32].

Number of actuators

Input-output controllability is the ability of achieving acceptable control performance while using the available inputs and measurements [58]. That is, the outputs need to be within specified bounds from the references. In this case the reference or desired value is a perfectly flat or uniform layer of desired thickness. Controllability is affected by choosing the amount and location of the sensors and actuators. Hence, the number of actuators is a factor in equipment and control design that needs to be considered. Table 1 shows a classification scheme that allows for distinguishing recoating methods by the geometry or spatial dimensionality of the recoater and the number of resin deposition actuators. This geometry determines the number of motion degrees of freedom (DOF) in the horizontal plane required to cover a complete area. Hence, the number of deposition actuators and motion actuators together comprise the total number of input variables.

For instance, the recoating method employed by Springer et al. [24] consisting of a single jet dispensing valve, requires two motion DOF to cover the complete area. Most traditional recoating systems, however, have a line geometry that requires a single motion DOF to traverse the surface. Note that a passive doctor blade does not have any actuation capability (represented by a 0 in Table 1), while a Zephyr blade does. A 2D array of jets would not require any motion DOF at all if the covered area would be sufficiently large, or could again be augmented with a motion stage to increase the covered area.

The reason as to why multiple actuators along the lateral y-axis can be desirable, is that fluid

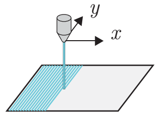
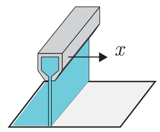
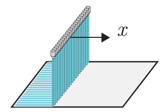
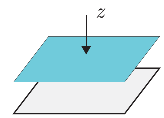
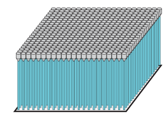
Recoating method	Extruding/ jetting	Blade/slot/ curtain	Extruding/ jetting	Tape casting/ lamination	Extruding/ jetting
# Actuators	1	0 or 1	n-point array	1	$n \times m$ point array
Geometry	Point	Line	Line	Area	Area
Schematic illustration					
# xy-Motion DOF	2	1	1	0	0

Table 1: Recoating methods classification scheme, adapted from [7].

depth variations can occur along the this axis depending on the product geometry. Hence, the suitability of a recoating method can depend on the desired product geometry. Figure 9 illustrates this by means of a block geometry with a pocket, often designated as a *trapped volume* [29]. Increasing the number of actuators can be realized by, e.g., segmenting a blade or extrusion die. A fundamental question remains, however, on what a sensible amount of segments or actuators is.

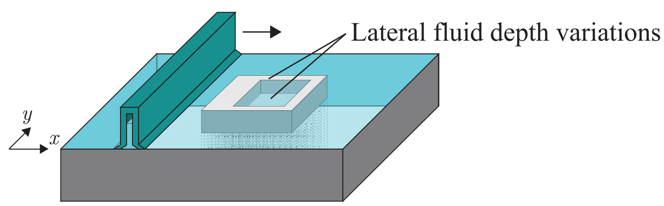


Figure 9: Motivation for multiple actuators in the lateral direction.

Resin metering

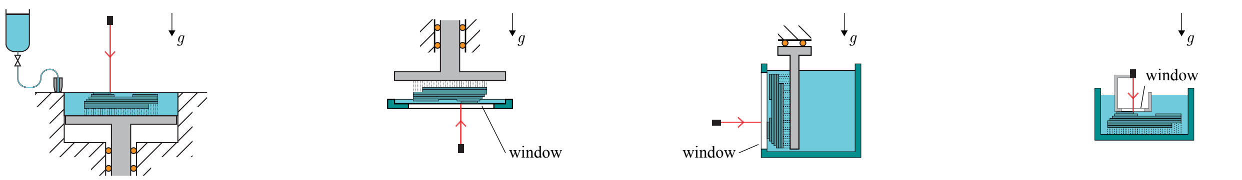
Another factor that affects controllability is whether the recoating method is able to deposit or withdraw resin. Self-metered systems typically use a surplus of material and withdraw material where it is not needed. On the contrary, pre-metered systems typically only deposit material where it is needed. This implies that pre-metered systems offer the possibility to control or exactly dose the resin outflow, potentially position dependent.

Contact

Closely related to whether the recoating method is self-metered or pre-metered, is whether the recoater is contactless or contactful. Most self-metered systems are contactful in the sense that a blade or knife is in mechanical contact with the resin and scrapes the excess away. This contact causes shear forces and moments to be exerted on the previously built layers and features, which can cause defects if the shear stress is larger than the mechanical strength of the object [27]. Moreover, the contact can cause fluid dynamic effects such as scoopout and bulges [28] that lead to a poorly controllable layer thickness. In a sense, the only contactless self-metered recoating method is the air knife. Pre-metered systems such as curtain coating are also contactless.

Surface constrainedness

Whether the resin surface is constrained or not during polymerization, impacts the system's design. Figure 10 summarizes the design options for the irradiation orientation and surface constrainedness. The main advantage of constraining the surface by means of, e.g., a transparent glass window, is that a well-defined layer thickness can be obtained. Although most constrained surface systems have a bottom-up orientation as in Figure 10 (b), alternatives exist that have a side-wise [59] and top-down [60] orientation as in Figure 10 (c) and (d) respectively. The main disadvantage of constraining the surface, however, is that in conventional systems the cured layer has to be separated from the window after each layer has been cured as opposed to free surface systems shown in Figure 10 (a).



(a) top-down, free surface

(b) bottom-up, constrained surface

(c) side-wise, constrained surface

(d) top-down, constrained surface

Figure 10: Irradiation orientation and surface constrainedness options.

The separation process requires a substantial separation force, which can be reduced by coating the window with a teflon, silicone or PDMS film [56, 61, 62]. The separation force consists of two components, namely a force due to adhesion of the cured part to the film and a force due to a vacuum state at this interface [63]. An additional fluid drag force is present due to the motion of the cured part in the resin vat. Several methods to improve the separation process have been developed by equipment designers. Gruber et al. developed a tilting mechanism to tilt the complete vat [64]. Pan et al. and Song et al. developed a horizontally translating mechanism to reduce the required separation force [65, 38]. Apart from the hardware solutions directed towards minimizing the required separation force, a control system that minimizes separation forces was developed as well.

Next to layer uniformity and whether the cured layer needs to be separated, other considerations are relevant to the choice of surface constrainedness. First of all, in free surface systems the oxygen dissolved in the resin that inhibits polymerization is repleted by oxygen from the oxygen rich build chamber. In constrained surface systems this oxygen repletion can be either prevented or promoted as is the case in CLIP [35]. Second, it is important to realize that the part being built is also mechanically loaded by the separation force and can sustain severe damage or defects when subjected to excessive forces. As the required separation force increases linearly with part cross-sectional area [56], the implication for the scalability to larger product sizes is that the required total force increases. Another mechanical consideration is that during photopolymerization the resin shrinks and this potentially induces flows that can freely flow in free surface systems, but can not in constrained surface systems. A final consideration is that in bottom-up systems the resin volume required in the build vat is independent of part height. Table 2 summarizes the considerations pertaining to the choice of surface constrainedness.

Consideration	Free surface	Constrained surface
Layer uniformity	determined by recoater	determined by substrate
Oxygen inhibition	free oxygen repletion	reduced oxygen repletion
Shrinkage	free	constrained
Separation	not required	force loads part
Build area	freely enlargeable	required force increases
Vat volume	dependent of part height	independent of part height

Table 2: Summary of considerations concerning resin surface constrainedness.

Layer nonuniformity compensation

The requirements for a flat and uniform layer of specified thickness might be relaxed in free surface systems if the philosophy of feedback control is adopted. One line of reasoning is that layers should be perfectly flat and that the exposure at each point on the resin surface should equal the predetermined nominal value. Another line of reasoning is that layers may deviate from a flat layer to some extent and that the required exposure should be calculated for each point by virtue of a surface height measurement.

If the irradiance levels or exposure times are allowed to be adapted depending on the local layer thickness, the exposure dose can be chosen such that under- and overcure are prevented. However, light attenuation within the layer limits the amount of layer nonuniformity that can be compensated for. Attenuation of light intensity occurs due to absorption by matter or scattering by irregularities in the medium. Absorption causes the light intensity to exponentially decay with distance travelled into the layer, which can be described by the Beer-Lambert law [5]. Scattering by ceramic particles typically causes the light intensity distribution to broaden and attenuate even further with depth [4].

Thus, the controllability of the exposure dose within the layer is governed by the physical laws of absorption and scattering. This limited controllability poses an upper bound on the permissible layer nonuniformity, since under- and overcure cannot be prevented in too thick layers due to the inhomogeneous exposure distribution. For green ceramic parts the allowable exposure dose inhomogeneity within the part may deviate from that of pure photopolymer parts, since the photopolymer is later pyrolyzed from the green parts.

Layer nonuniformity compensation requires a 2D height map measurement to be available at high spatial resolution, which is not trivial as exemplified by the few sensing methods applied in literature [49, 50]. Another factor that needs to be considered, is the location of the light source's focal plane. Using the same surface height information used for calculation of exposure compensation, the focal plane can be positioned at the resin surface by actuating optical components as is done in the photolithography industry [66]. Obviously the addition of aforementioned sensors and actuators for layer nonuniformity compensation come at the cost of increased system complexity.

Discussion

The characteristics of the recoating methods outlined in this paper are compared in Table 3. The table shows that not all recoating methods have been applied for the deposition of ceramic-filled resins. However, based on the absence of preceding applications one can not directly conclude that those methods are unsuited for ceramics. It does seem unlikely that two-photon systems can be used for ceramics, due to the highly scattering nature of ceramic-filled resins. Viscous retention recoating also seems inapplicable, since the brush or mesh may act as a filter for the ceramic particles. Although preliminary studies show that CLIP technology is compatible with ceramics [35], to the author's knowledge no results have been published yet.

Perhaps one of the most distinguishing aspects is the maximum build area. The inverted U and curtain recoating methods are the only ones reported to have a build area larger than the required 1 [m^2]. However, no hard conclusions can be drawn on the possibility to enlarge the build area of the recoating methods based on reported build areas. For instance, air knives that span 1 [m] are used in the coating industry, while the only application in vat photopolymerization merely spans 8 [mm] [27]. Due to the relationship of cross-sectional area with separation force, it seems unlikely that constrained surface systems are suitable for the required large build areas.

The smallest layer thickness reported is 5 [μm], which is achieved by air knife recoating. This layer thickness is already in the order of the typical ceramic particle size [27], so this represents a practical lower limit. However, the minimum achievable layer thickness is not considered a predominant assessment criterion here. The build rate is expressed in the maximum speed at which the recoater can move over the vat surface, so it is not the flow rate. As Table 3 shows, the range of maximum recoating speeds spans three orders and the curtain recoating method outperforms any other method in this respect.

Unfortunately, hardly any data is available on the performance of the respective recoating methods in terms of product quality aspects. That is, layer uniformities and layer particle distributions are not reported in literature, even though the lack of product quality is currently the main challenge in vat photopolymerization of ceramics. Quantification of the surface height deviations and the length scales over which they occur would serve two purposes. It would allow firstly for comparing the existing recoating methods and secondly for choosing a sensible number of actuators and the achievable performance improvement in, e.g., a segmented blade concept. Hence, the way forward seems to be the quantification of layer uniformities through measurements of actual surface height deviations for the most promising recoating methods.

Recoating method	Resin metering	Ceramic application	Contact	Max. build area [cm^2]	Min. layer thickness [μm]	Max. speed [mm/s]	# Deposition actuators	# xy-Motion DOF
Dip & scrape recoating	Self-metered	No	Contactful	625 [67]	150 [67]	100 [21]	0	1
Scrape from tank	Self-metered	Yes [22, 68]	Contactful	3600 [69]	25 [22]	30 [70]	1	1
Deposit & scrape recoating	Self-metered	Yes [23, 24]	Contactful	Not reported	10 [24]	3 [23]	1	2
Simultaneously scraping & irradiating	Self-metered	No	Contactful	625 [25]	50 [25]	1 [26]	0	1
Air knife recoating	Self-metered	Yes [27]	Contactless	1 [27]	5 [27]	5 [27]	1	1
Inverted U recoating	Self-metered	No	Contactful	11250 [71]	50 [67]	100 [21]	1	1
Viscous retention recoating	Self-metered	No	Contactful	2500 [67]	50 [67]	30 [72]	0	1
Solid ground curing	Self-metered	No	Contactful	1750 [67]	60 [67]	Not reported		1
Slot recoating	Pre-metered	No, FRP [31]	Contactful	86 [73]	300 [31]	10 [73]	1	1
Curtain recoating	Pre-metered	No	Contactless	14700 [74]	100 [21]	1500 [21]	1	1
Conventional constrained surface systems	Constr. surface	Yes [33]	Contactful / -	210 [75]	25 [75]	Not reported	0	0 / 1
Continuously irradiating & elevating systems	Constr. surface	No	-	219 [76]	-	-	0	0
Tape casting methods	Constr. surface	Yes [39, 38, 40]	Contactful	74 [41]	10 [38]	25 [38]	1	1
CNC accumulation	Non-recoating	No	-	Not reported	-	-	-	-
Irradiating through an air bubble	Non-recoating	No	-	Not reported	-	-	-	-
Two-photon vat photopolymerization	Non-recoating	No	-	Not reported	-	-	-	-

Table 3: Recoating methods comparison.

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