A Review on Vat Polymerization Technology: Manufacturing Process, Associated Materials, Design Considerations, Post-processing Methods and Common Applications

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Abstract – *Vat polymerization is one of the earliest forms of 3D printing. This is in fact the first technology that was used for 3d printing. Stereolithography (SLA) is a common form of vat polymerization technology used for creating models, prototypes, injection molding patterns in a layer-by-layer fashion using photo polymer resins. It is a process in which light source causes chains of molecules to bond together to form a three-dimensional solid object. The physical objects are formed by following a predetermined path which is assigned by the software based on computer aided design (CAD) model to the machine. Another form of vat polymerization printer is Direct Light Processing (DLP), with the introduction of new materials and improvements in material properties, Vat polymerization offers a good alternative for low-volume production. It is a high precision laser-based technology that cures the resin in a vat using the laser source with post-processing required in most of the cases. This also gives the user freedom to design and print parts separately. It is disrupting manufacturing process in various industries such as medical, dental, rapid prototyping, and many other service sectors.*

Key Words: Additive Manufacturing, 3D printing technology, Vat Polymerization, Stereolithography (SLA), Direct Light Processing (DLP) Computer Aided Design (CAD), rapid prototyping, post-processing.

1. INTRODUCTION

Vat polymerization is another form of manufacturing technology which utilizes a photo polymer resin in a vat which is cured by pre-determined path of a source of light [1]. Stereolithography (SLA) is well known form of vat polymerization and is also famous as original 3D printing technology. The term stereolithography was framed by Charles W. Hull, founder of 3D systems in the year 1986 [2]. The process utilizes mirrors, commonly known as galvanometers both in horizontal and vertical axis to rapidly aim the laser beam from the source to selectively cure the liquid photopolymer in a vat. This process breaks down the design into layers consisting of set of points that are given to the galvanometers as a set of coordinates for perform the operation. The major setback while using SLA is the point laser light source that takes a longer period to trace the cross section of the part and hence slower in operation [3]. DLP is quite similar in operations to SLA. DLP utilizes a light projector screen to flash images of each layer all at once. Therefore the process in DLP is relatively faster as compared to SLA as the entire layer gets exposed to light at once unlike in SLA where only a laser spot is used.

In this paper, an overview of the vat polymerization technology is discussed by introducing to two main processes of vat polymerization, namely stereolithography (SLA) and digital light processing (DLP), and then move on to discuss the characteristics and parameters of this technology. The paper then cover the associated materials and design rules associated with this manufacturing technology, such as constraints related to part orientation and design, providing some key tips for vat polymerization support structures. This is followed by a discussion on post-processing methods applicable to vat polymerized parts. A brief results and discussion section stating the summary and then a concluding section highlighting the benefits and limitations of the technology will be discussed.

2. VAT POLYMERIZATION

Unlike Fused deposition modeling (FDM) printers, vat polymerization printers do not allow more flexibility for setting printer parameters and most printer come with a predefined settings relative to the type of material that is being used [4] and [5]. The only parameters that the user can change are part orientation, layer height and material. In a typical vat polymerization printer arrangement, the surface finish and accuracy of the parts are mostly governed by two main factors the layer height (varies between 25 to 100 microns) and light source resolution (the laser spot size can vary between 130 to 150 micron). Vat polymerization machines can produce parts in two different orientations namely: the bottom-up approach [6] and top-down approach [7]. Both SLA and DLP printers come in any of these two configuration depending upon the manufacturer.

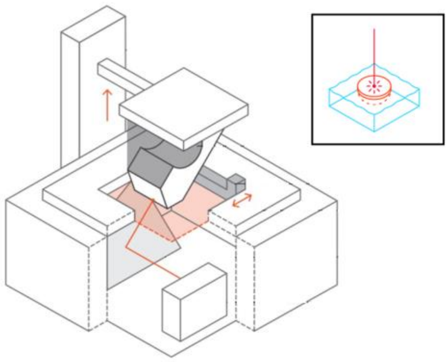


Fig -1: Typical vat polymerization mechanism[3]

Bottom-up approach: In this approach, the build platform is placed above in an upside-down position and the light source is placed under the resin tank as shown in Figure-2 below. Below the resin tank, we have a transparent bottom that allow the laser light to propagate through it and the base of resin tank is coated with silicon to avoid cured resin to stick to the base. During the build process, the cured polymer layers are separated from the bottom of the tank, and the build platform moves upwards in positive z-direction on completion of each layer. With the first layer cured and stuck to the build platform, the printer performs the separation step separating the cured first layer from the base of the vat and moving up one-layer thickness.

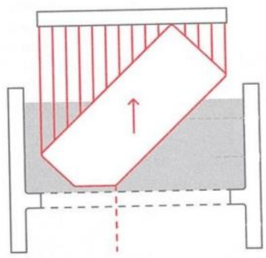


Fig -2: Bottom-up building mechanism

After separation step, a new uncured layer of resin fills the gap, A wiper is used to spread a layer of resin across the base of the vat to ensure uniform coverage, mix the resin and remove any debris (cured resin spots). This process is then repeated with build platform moving up one-layer thickness and separating the newly cured layer from the base of the vat until a solid geometrical shape is formed as desired. In bottom-up approach, during separation stage, it is very crucial to reduces forces on newly cured layers for the print to be successful.

Top-down approach: In this approach, contrary to bottom-up approach, the build platform starts at the top of the resin vat and moves downwards negative z-direction after every layer is cured. The laser source is above the resin tank and the part is built facing upwards. The part is fully submerged in the resin tank once the build process is complete. As the build progresses, the build platform continues to lower into the resin vat. And once it is complete, it is completely submerged in resin. The part is then raised out and removed from build platform. Like in bottom up, here also the first layer is most crucial during the build process. The operator should make sure that the platform moves slowly into the resin to ensure no air bubbles are created, which have detrimental effect on the print quality. Build platforms are typically perforated to reduce the disruptive forces on the platform.

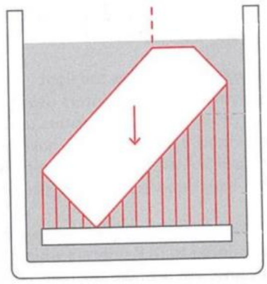


Fig -3: Top-down building mechanism

The amount of support required, and support location depends hugely on the orientation of the part that is being printed and the type of approach/mechanism machine uses for printing [4]. A very common issue among SLA printed part is curling. During the resin solidification process, due to repeated exposure to the printer's light source the cured resin shrinks slightly. When the shrinkage is considerable, large internal stresses are developed between the new layer and the previous layer, which results into curling of the part [8]. This affect is very similar to warping in FDM technology. One more possible reason could be if the parts have thin features and are not post processed immediately after printing, they could start showing this effect. Unlike FDM printed parts which can have variable infill density SLA parts are always solid.

2.1 Associated materials

Vat polymerization utilizes thermosets photo polymer resins to produce parts. It is a viscous liquid (resin) cured by a laser. The material could vary from 50-400 dollars/liter depending on the application. The number of colors available are limited and the material has limited shelf life (typically 1 year). Parts produced using SLA should be cured under UV light, to ensure they achieve their optimal properties [1], [9], [10] and [11]. The material datasheets specify for each type of material how much the green (raw) parts need to be exposed to UV light to achieve optimal properties. The materials range common from standard applications to specific applications such as dental. Some of the common materials that are available for SLA printing are standard, transparent, castable, tough, high temperature, dental and flexible. General characteristics of these type of materials is listed below in Table 1.

Material	Characteristics
Standard Resin	▪ Brittle parts ▪ Good surface finish
Clear Resin	▪ Transparent material with post-processing required
Castable Resin	▪ Suitable for mold making ▪ Percentage of ash after burnout is very low
Tough Resin	▪ Good mechanical properties ▪ Low thermal resistance
Flexible Resin	▪ Rubber-like material ▪ Less dimensionally accurate
High Temperature Resin	▪ Used in injection molding and thermoforming tooling ▪ Costly
Dental Resin	▪ Biocompatible ▪ High abrasion resistant ▪ Expensive

Table- 1. SLA printing materials and characteristics

2.2 Design rules

Before opting for any additive manufacturing technology, it is always better to have the knowledge of some basic feature that the technology can build and what are the limitations [12]. One such major limitation of this technology is that most of the prints need support material and should be oriented in a particular angle to print without failure. Even though this requires minimum support material that has some detrimental effect on the surface after removal. In general, vat polymerization printers are capable of printing intricated details with feature size as low as 0.3 mm. Therefore, most of the design rules are centered around support location on the part and the effect of support on surface finish [13].

Support Structure and Part Orientation: SLA technology can only print in one material which means the support manually cut or broken away from the final part. To assist this, support is always printed in tree-like structure that is narrowed to a point towards the part surface. This type of support leaves stubs on the surface and sanding is required if smooth surface is desired especially in case of visual prototypes. It is therefore important that the designers allow tools access that will help in removing the support structure in complex designs, failing to do so might increase the chances of damaging the part. The approach for support design requirements is different for type of machine orientation i.e., bottom-up or top-down.

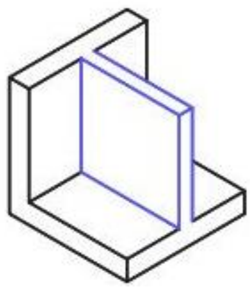
Support structure for bottom-up: It is a good practice to follow the instructions given below while using bottom-up orientation machine and trying to generate the support:

- Align the part (longest axis) parallel with the x-axis
- Rotate the part 60° around y-axis
- Rotate the part 30° around z-axis and
- Generate support material

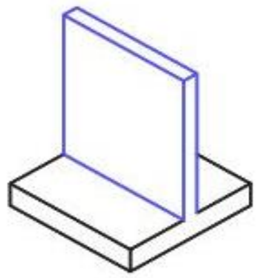
Support structure for top-down: In this type of orientation there are fewer design restrictions and placing the part flat results in optimal results and requires less support materials which in turn reduces the cost and print time.

Hollow Sections: SLA printers are popular choice for printing hollow sections because of less material use and less costs. The designer needs to make sure that no internal support is required because it is difficult to remove once printed. Hollow sections can result in issues like trapped resin and air in the gap to avoid such issues escape holes of 4.0 mm diameter should be considered while designing.

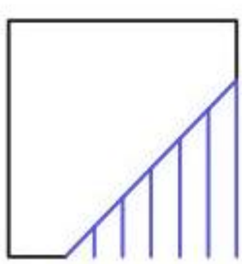
Figure 4. shows some common features that the designer needs to consider while designing parts for SLA printing. The values indicated below are only recommended values so that the print does not fail.



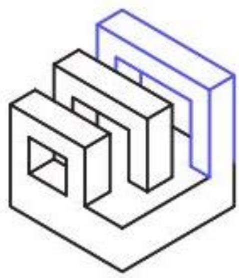
Supported wall = 0.5 mm



Unsupported wall = 1 mm



Support overhangs = Required



Horizontal bridges = NA

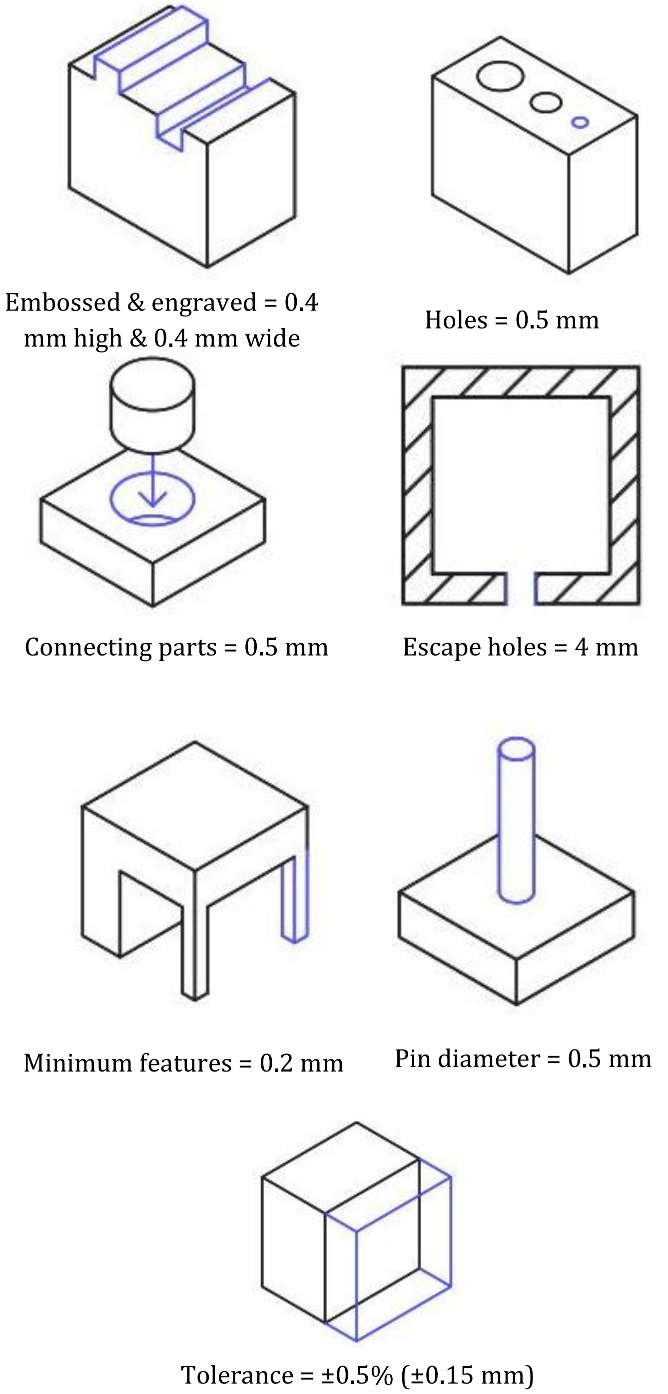


Fig -4: General design rules for vat polymerization 3D printing [3]

2.3 Post-processing methods

Table 2. shows common post processing options that are available for SLA. Following a right approach SLA printed parts can achieve smooth surface finish which could be compared to an injection molded part [14].

Type	Process
Mandatory	Support removal
Surface Finish	Sanding
Aesthetic	Mineral oil finish
	Spray painting
	Polishing

Table - 2. SLA post processing methods

Mandatory - Support removal: This is mostly a manual process where the support tree-like structure is separated from the part leaving behind an irregular surface. This irregular surface with after removal of the support structures leaves some spots on the surfaces which are called as nibs. These nibs are present wherever there was support structure in contact with the part surface. Sanding such surface could be a quick solution to achieve a smooth surface but this is possible only for large flat surfaces. If a high-quality surface finish is desired, increasing the thickness of the surface by a minimum of 100 microns, will allow for better dimensional accuracy and surface finish as well.

Surface Finish - Sanding: In order to achieve a better-quality surface finish wet sanding is preferred for SLA printed parts with different sandpaper graduations used over a surface. For the surfaces on a part where no support was needed, sanding with a single high-grade sandpaper to remove the layer lines will be enough and makes the finishing process less expensive. The supported side is often the most laborious to achieve smooth finishing, it requires at least four graduations of different grit of sandpapers. Therefore, the best way to avoid this laborious work is by orienting the part in such a way that the least visible surface has most of the support material. Further, depending on the support placement there is a possibility of extra material to be consumed, which can be easily removed. This can also affect the overall accuracy of the part.

Aesthetic - Mineral oil finish: For better aesthetics, and specially in case of parts which are in clear and transparent type of material mineral oil finishing is done. A layer of mineral oil applied on the part after sanding process to achieve better visual effects. This aids in hiding the white spots on the model which are commonly seen on SLA printed parts. This type of finishing is well suited for functional parts which reduces the friction and lubricates the surface.

Aesthetic - Spray painting: Second method of improving the aesthetics of the SLA printed part is by spraying. Spray paints conceal layer lines reducing the need to sand the part. The clear UV protective acrylic spray paint protects the model from degrading its color and shade post curing by limiting UV exposure. In case of flexible resins, acrylic paint will not work as required, to achieve a glossy finish in case of flexible resin a thin layer of resin is applied on the surface, followed by underwater curing. However, this affects the tolerances and overall details of the part.

Aesthetic - Polishing: One more method of achieving a clear transparent surface finish with SLA printed parts is polishing. Before polishing, the surface is sanded using different graduation of sandpaper with different grits until a desired surface is achieved. A polishing compound is then applied on the surface. This results in the clearest surface possible but is limited to simple or flat surfaces that can be easily sanded. It is a time-consuming process and high skill level is required for performing this operation. This often works with models where only one surface needs to be polished and does not include complex geometries and features.

2.4 Common applications

Vat polymerization is relatively slow but high precision manufacturing process that is suitable for part that are less than the size of a fist. Design verification and prototyping process and is cost effective too. It is well suited for functional as well as non-functional parts. Below are some of the common applications where SLA 3D printing is used widely:

Quick prototypes: The smooth surfaces produced by vat polymerization is often adopted to produce injection molded prototypes. This allows designers to quickly print a design to review without needing to invest in expensive tooling[1], [12] and [15].

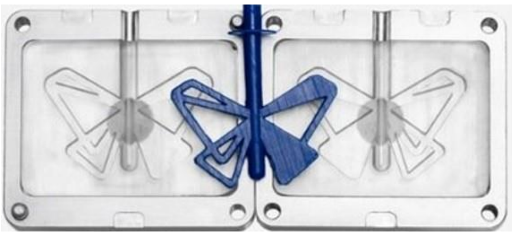


Fig-5: SLA printed parts in mold-like prototype.

Jewelry making: SLA technology is regularly used for jewelry making. The accuracy and intricate details the process can produce, coupled with the smooth surface of parts make it an ideal technology for the jewelry industry and investment casting patters[16].

Fig-6: SLA printed parts in investment casting(jewelry) patterns.

Dental industry: Dental industry has adopted this technology for a range of applications. Ranging from dental models, surgical guides, appliances, crowns, and bridges. The high level of accuracy and material available (dental & castable) makes it a truly disruptive in dental field[17] and [18].

Fig-7: SLA printed parts in dental.

3. RESULTS AND DISCUSSION

SLA printed parts are ideal for visual prototyping. Parts produced using SLA machines exhibit with very smooth surface (after post-processing) with intricate details from a range of thermoset materials which are photopolymer resins. Desktop SLA is best suitable for manufacturing parts which are as small as size of a human fist. The quality of these parts can be compared to injection molded parts at an affordable price. Typical build size of a machine is 14.5 x 14.5 x 17.5 cm, with a dimensional accuracy of 0.5% (lower limit: 0.01cm). Industrial SLA machines can produce parts with built size as large as 150 x 75 x 50 cm and dimensional accuracy of 0.15% (lower limit: 0.001cm). Common layer thickness can vary between 25 to 100 microns depending upon the type of machine and material selected. Support is always required and is usually tree-like support structure that is used in printing SLA parts[19].

Large horizontal parts when printed using SLA technology often leads to a detrimental effect on the parts known as curling. This is mainly because the light source that is used in curing process, new layer is formed on already shrunken layer leading to stress between two layers and overall part to curl, this is a common problem associated with SLA printing. Therefore, part orientation and limiting large flat layers are important factors to consider for achieving dimensional accuracy.

4. CONCLUSIONS

Stereolithography (SLA) is a high precision, low-cost 3D printing technology which can print fine intricate features with relatively accurate details as compared to any other printing technology. But like any other technology, this technology also comes with some benefits and limitations.

Benefits

- Dimensionally high accurate parts
- Intricate details with precise surface finish
- Well suited for visual prototyping
- Variety of materials for range of applications

Limitations

- Support is required always
- Difficult to post-process
- Relatively slower
- Built parts are brittle therefore not recommended for functional prototyping
- Material properties and visual effects degrade over time

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