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A Review of Recent Developments on Stereolithography

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***Abstract*:- Stereolithography (most commonly known as SLA) is the oldest additive manufacturing process which uses an ultraviolet laser to mainly convert liquid photopolymer to solid cross-sections. In spite of being the oldest technology it is still the most important one as no other additive manufacturing process addresses a wider range of applications for highly accurate and durable prototypes of all shapes. This paper comprises of an outline of SLA process while discussing about the process variables and applications. Recent developments and modern trends in the technology are also briefed in the paper besides presenting a sketch of the mechanical properties of the SLA processed parts.**

***Keywords:- Stereolithography (SLA), Photopolymerization, Process parameters, Optimisation, Color stereolithography*.**

1. INTRODUCTION

1.1. History: The first significant work associated with modern photolithographic technique only emerged during the 1970s [1]. In 1971, Swainson [2] presented a patent for a system where two intersecting beams of radiation produce a phase change in a material to build 3D objects. The object through this process could be formed by either photo-chemically cross-linking or degrading a polymer[3]. However, the major problem of this process was that due to the photonic absorption by the photopolymeric system used, which occurs somewhere along the paths of each laser, polymerizations was initiated in spots that differed from the planned ones. In the 1980s, the idea was abandoned due to funding problems, without achieving optimum working parameters, adequate materials, and good accuracy of final models[4].

Kodama in 1981 described an automatic method for fabricating 3D models inlayered stepped stages using a photosensitive polymer[5]. Light capable of curingthe polymer was directed onto the surface, and the desired shape of a layer wascreated by using an appropriate mask (Fig. 1a,b) or an optical fiber manipulatedby an X–Y plotter (Fig. 1c)

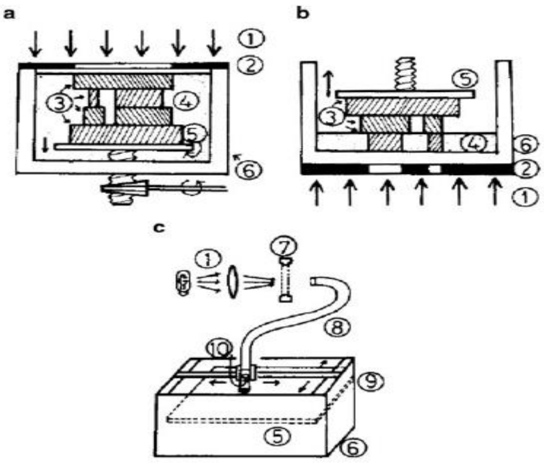

Figure 1 Schematics of the three systems studied by Kodama [5]

The present term Stereolithography was coined by Chuck Hull when he filed his patent in 1984 (6). According to the principles of Chuck’s stereolithography (Fig. 2), a 3D object is formed layer by layer in a stepwise fashion out of a material capable of solidification upon exposure to ultraviolet (UV) radiation. Moreover, the non-transformed layers typically stick to the previously formed layers through the natural adhesive properties of the photosensitive polymer upon solidification. Almost in parallel, Alain and Andre from France, who filed different patent applications [7] conducted similar work in France.

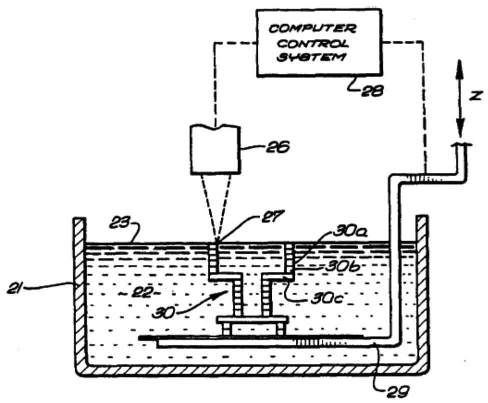

Figure 2 Hull's Stereolithography Apparatus [8]

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1.2. Principle of Present Day Stereolithography

Modern day SLA works on the principle of photopolymerization. The UV light on selectively striking the liquid monomer layer activates the initiators in the resin. The initiators when activated create strong unbreakable bonds between the monomer carbon chains. When enough bonds have been created the result is in the form of a solid layer[9].
This process is irreversible and there is no way to convert the SLA parts back to their liquid form: when heated, they will burn instead of melting.

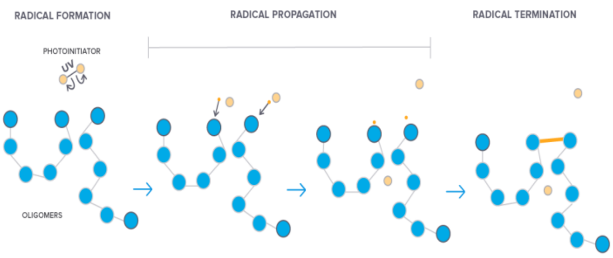

Figure 3 Photopolymersation

1.3. Process and Setup

The SLA fabrication process works in the following steps:

1) The platform is first placed in the tank of liquid photopolymer, at a distance of one-layer height from the surface of the liquid.
2) Then a UV laser creates the next layer by selectively curing and solidifying the photopolymer resin. The laser beam is focused in the predetermined path using a set of mirrors. The whole cross sectional area of the model is scanned, so the produced part is fully solidified.
3) When a layer is finished, the platform moves at a safe distance and the sweeper blade re-coats the surface. The process then repeats until the part is complete.
4) After printing, the part is in a green, no-fully-cured state and requires further post processing under UV light if very high mechanical and thermal properties are required.

Stereolithography apparatus consists of the following components:

- A tank filled with the liquid photopolymer: The liquid resin is usually a clear and liquid plastic.
- A platform immersed in a tank: The platform is lowered into the tank and can move up and down according to the printing process.
- A high-powered ultraviolet laser.
- A computer interface which manages both the platform and the laser movements.

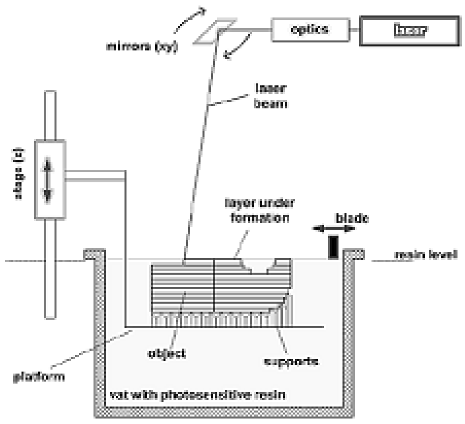

Figure 4 Sketch of Stereolithography Process

Stereolithography Process is widely used for industrial applications like visual prototypes, patterns for investment casting, jewelry, low volume production of complex geometry. Mostly thermoset polymers can be processed by SLA. Other materials that can be processed using SLA are castable resin, tough resin, ABS, PLA and their blends. Some of the advantages that make the process favorable are accuracy, surface finish obtained, higher build volumes and the scope of providing intricate features or complex geometry to the part.

The processes have some drawbacks like limited material and color choices, fragility, cost considerations and longer printing time which limits its widespread uses in high volume production areas.

2. *Process Parameters of Stereolithography (SLA) for the Betterment of Part Quality*

Although SLA technology has evolved rapidly and gained tremendous attention over the recent years, it is still in the developing stage where many researchers have found solutions of complex real life problems.
The main focus of research works conducted have been on specifying, evaluating and controlling the process parameters so that accurate and high quality products can be made.
Determination and optimization of process parameters is a highly complex process due to the interacting parameters and non linear relations between end results and parameters.

Fig 5 represents some of the parameters while encountering the SLA process that need to be optimized.

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Figure 5 Process Parameters of SLA

E. R. Khorasani and H. Baseri presented the following definitions for some of the process parameters which are shown in Fig. 5 [10].

Layer Thickness (l_{th})–It is the depth of a layer, the region that solidifies at the same elevation (mm).

Over-cure (O_C)– It isthe depth of a strand pierces in to the lower adjacent layer. This is what keeps the individual layers connected together to form a complete part. The presence of the over-cured is caused by over penetration of the laser beam in SL process (mm).

Cure Depth (C_d)–It is the depth of strands (mm).

Hatch Spacing (h_s)- It is the distance between the centerlines of adjacent parallel hatch strands or is the distance between two successful movement of laser (mm).

Beam Radius (w_o) - It is the radius of laser beam focused on the resin (mm).

Laser Power (L_p) – It is the power of the laser beam (mW).

Maximum exposure (Emax) - It is the Peak exposure of laser shining on the resin surface (centre of laser spot) or the exposure at the resin surface. (mJ/mm^2)

Scan Speed (S_v) – It is the scanning speed of the laser that polymerizes the photopolymer resin (mm/seconds).

Blade gap - It allows the vertical separation between the bottom of the recoated blade and the top of the previous (cured) layer to be increased per sweep (mm).

Blade Velocity - It is the velocity of the blade (mm/seconds).

Blade Width - It is the width of the sweeper (mm).

Recoater time/ sweep time – It is the time taken by the recoater to sweep over the part (seconds).

Raju et al[11] investigated the effect of three parameters namely layer thickness, orientation and hatch spacing on the tensile, flexural and impact strength of the SLA prototype made of CIBATOOL 5530 epoxy resin. The STL file was generated using CATIA V5 R16 and the tests were conducted on Universal Testing Machine and impact tester model IT-30. The parameters were analysed using Taguchi Method after conducting nine experimental runs.

It was found that the parameters thickness, orientation and hatch spacing significantly affect the part characteristics. Among the three process parameters, the Lt and O were major contributing parameters for the tensile strength; O and Hs were major contributing parameters for the flexural strength; and O had more significance among the parameters for the impact strength.

The same is shown in the Fig 6, 7 and 8.

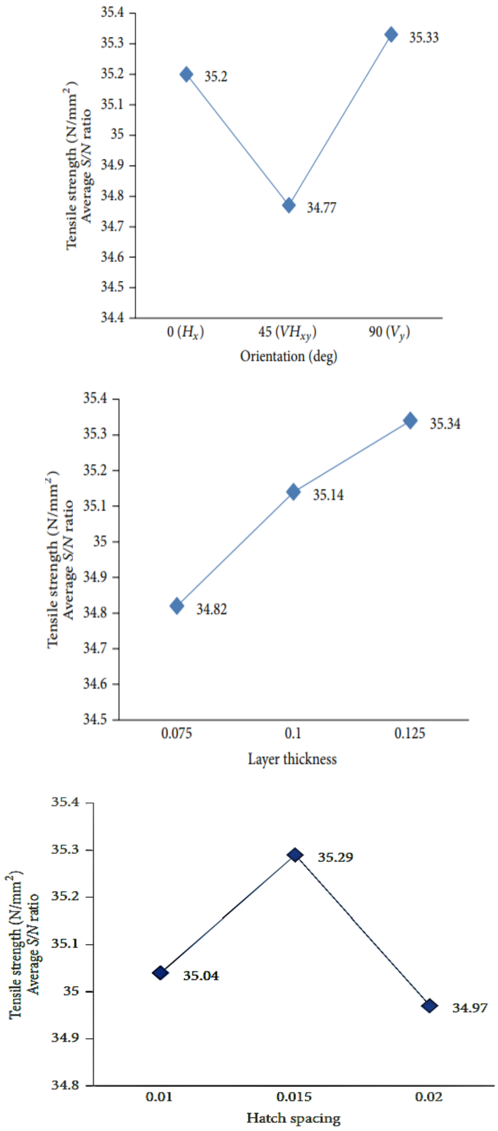

Figure 6 S/N Graph for Tensile Strength Analysis[12]

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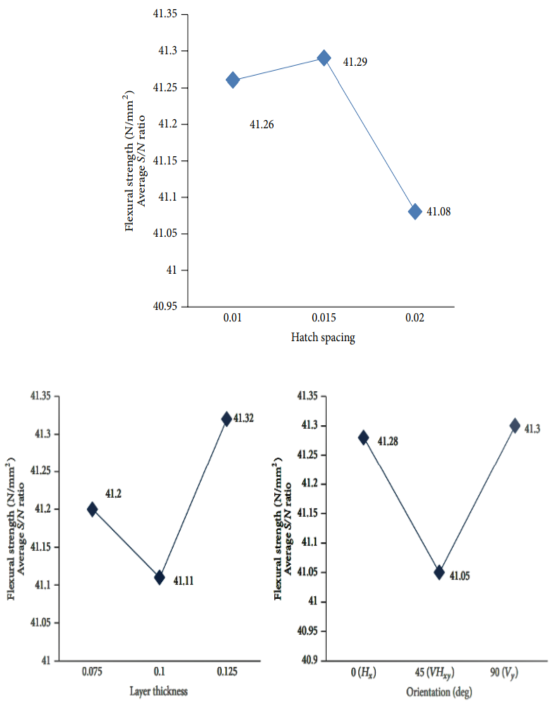

Figure 7 S/N Graph for Flexural Strength Analysis[12]

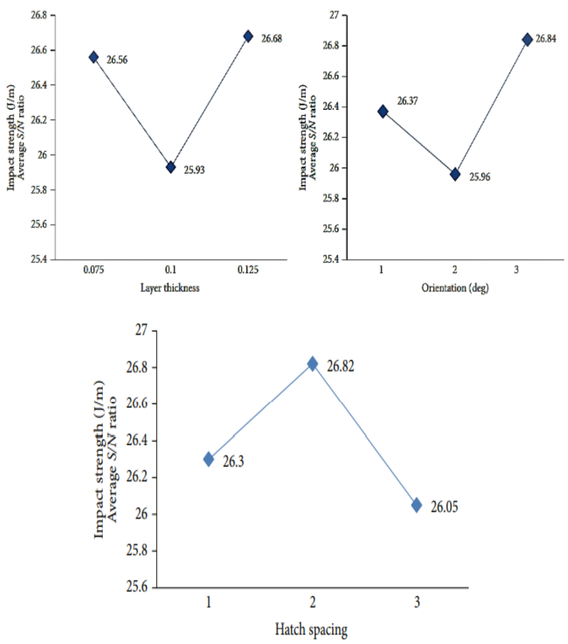

Figure 8 S/N Graph for Impact Strength Analysis[12]

Lee et al[12]determined the process parameters using neutral network and developed a new setup having optimum parameter values. A three-dimensional prototype was built using the new SLA, and the effect of processing parameters such as scan speed, hatching spacing, and layer thickness on quality of prototypes was investigated. Efficiency of the neural network SLA was compared with that of the traditional SLA by evaluating surface roughness and build time of prototypes.

They found that when hatching spacing or layer thickness was large, build time was decreased, but surface roughness was deteriorated.

The surface roughness for layer thickness was calculated as equation 1:[12]

$$H = \frac{L}{sin\theta.\tan(\theta - \Phi) - \cos\theta}$$

Where,
θ= the slope of angle of cured prototype.
Φ = the angle of facet normal with respect to the vertical axis
L= layer thickness,
H= surface roughness

From eq. 1 it can seen that as layer thickness is small surface roughness became better. However, in practice, when layer thickness is kept small, number of slices increases which further increases the build time and surface roughness gets deteriorated.
On the contrary, if layer thickness is kept large, build time reduces, but the curing process doesn't gets completed which deteriorates the surface finish. So appropriate layer thickness should be determined.

In their work, it was suggested that in order to obtain shorter build time along with good surface finish, different layer thickness can be used for different layers depending upon the shape of the product. Layer thickness is kept large for perpendicular area and small for sloped areas. It will give a drastic improvement against the phenomenon known as 'Staircase Effect'.

In 1999 Jack G. Zhou (13) from US employed Taguchi L27 orthogonal array and found the most important five parameters out of many to optimize the quality and build time. The five parameters were layer thickness, resultant overcure, hatch space, blade gap, and the part location.
The analysis results obtained using RSM and ANOVA also suggested the best setting of these controlled factors for each individual geometrical feature. For example, they suggested that to build a square (or rectangular) hole vertically, a low value of resultant overcure (say, 0.001 inches) and medium layer thickness (say, 0.009 inches) should be used to effectively reduce the dimensional error caused by the extra overcure at the down facing layer, and to provide adequate support so that the sagging problems can be eliminated.

Benay Sager and David W. Rosen (14) of Georgia Institute of Technology suggested the use of slanted laser beams to improve the surface finish of the product.

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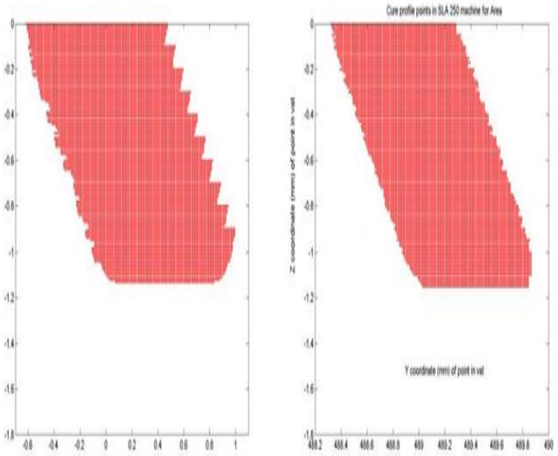

Figure 9 Surface Finish Improvement using Slanted Laser Beams[14]

In Figure 9a, a ten layer cross-section, which has a 30-degree sidewall, was first scanned with a vertical laser beam. Significant stair steps can be seen on the upfacing surface, where the surface roughness average was measured to be around 8 microns. On the other hand, when the laser beam was parallel to the sidewall at 30 degrees, the stair steps reduced dramatically and the surface roughness average dropped to 2.4 microns. This is shown in Figure 9b. By incorporating thinner layers and slanted laser beams into SLA process planning and using parameter estimation, significant surface finish improvement can be achieved.

3. COLOR STERELITHOGRAPHY

Colors provide life to the prototype improving aesthetics of the part designed making it stand out over the competition. Other than that sometimes highlights are required in the designed parts for application specific purposes. But not all additive manufacturing processes are color receptive due to incompatibility of standard dyes and pigments with resins, laborious setups, and cost considerations.
However limitations have always paved ways for new solutions. Researchers are already working towards creating solutions for commercializing color stereolithography.

Some of the significant approaches used for involving colors and highlights in SLA are:

3.1. Swaelens and Vancraen[15] worked towards providing highlights in the parts simultaneously with building of the part layer by layer. The process used a clear resin which contained additives that color upon exposure to high doses of UV radiations. Each layers were cured in the usual manner and then the places requiring highlights were rescanned by laser at a lower speed providing the high doses of UV radiations. The process allowed the parts to get highlighted features.

3.2. A more laborious approach was presented by Im et al [16]. The approach allowed multiple colors or levels of highlights that can be used. The steps can be seen clearly in the Fig 10.

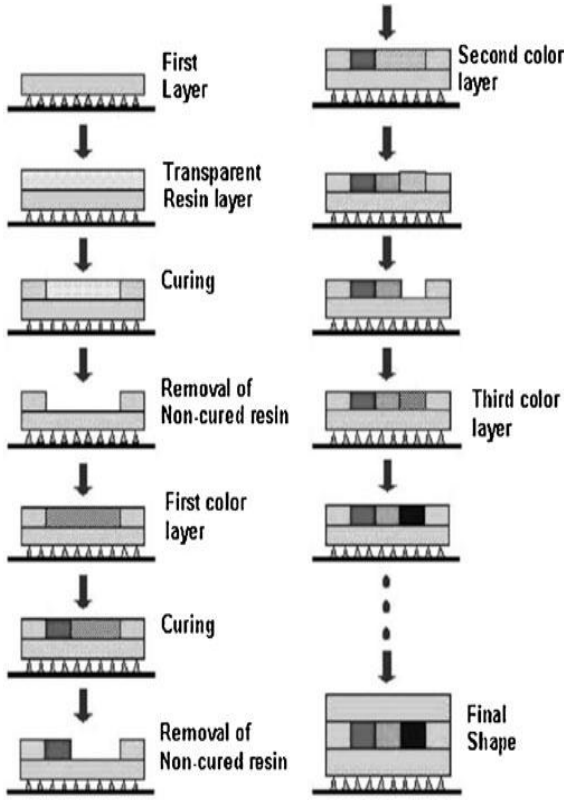

Figure 10 Color Stereolithography (16)

3.3. Gong and Wang[17] from China in 2010 invented a color SLA method based on time pressure dispensing process. They also designed a positioning control system to conduct the motion of syringe which extrudes color resin. The rheological behavior of the colored resin was also studied.

3.4. Recently Formlabs[18] which is a pioneer in 3DP technology has launched a SLA Color Kit which comprises of five color pigments, a recipe book and syringes for easy measurements. The color can be mixed directly into the base material of the resin and then can be used just like any other standard resin for SLA.

Some of the applications made possible with true colour 3D printing are:

- Finite element analysis
- Concept molding
- Textures
- Footwear and clothing design
- Packaging
- GIS (for flood and evacuation planning)
- MCAD form fit models

4. CONCLUSION

The research work conducted in the field of stereolithography is studied and presented in brief. The areas covered in the paper are process parameters and color stereolithography. After studying several research papers it

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Vol. 8 Issue 08, August-2019

is safe to mention that layer thickness is the most crucial parameter.

The main focus of works conducted till date is on improving the physical part characteristics like dimensional accuracy, surface finish etc and less emphasis is made on improving mechanical properties. In fact the compressive strength was the least addressed objective in all the researches.

After successfully reviewing a number of papers, it can be concluded that Stereolithography ,though the oldest technology, is still in a budding stage and needs to be researched upon to address the major issues like commercialization, overhang structures, micro-stereolithography, limitations on materials that can be used.

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