

# Additive Manufacturing & 3D Printing



**Dr. Yogesh Kumar**

Assistant Professor

Mechanical Engineering Department

National Institute of Technology Patna

Bihar - 800 005, India

# Module - 2



## Additive Manufacturing & 3D Printing



**Dr. Yogesh Kumar**

Assistant Professor

Mechanical Engineering Department

National Institute of Technology Patna

Bihar - 800 005, India

# Additive Manufacturing Technologies

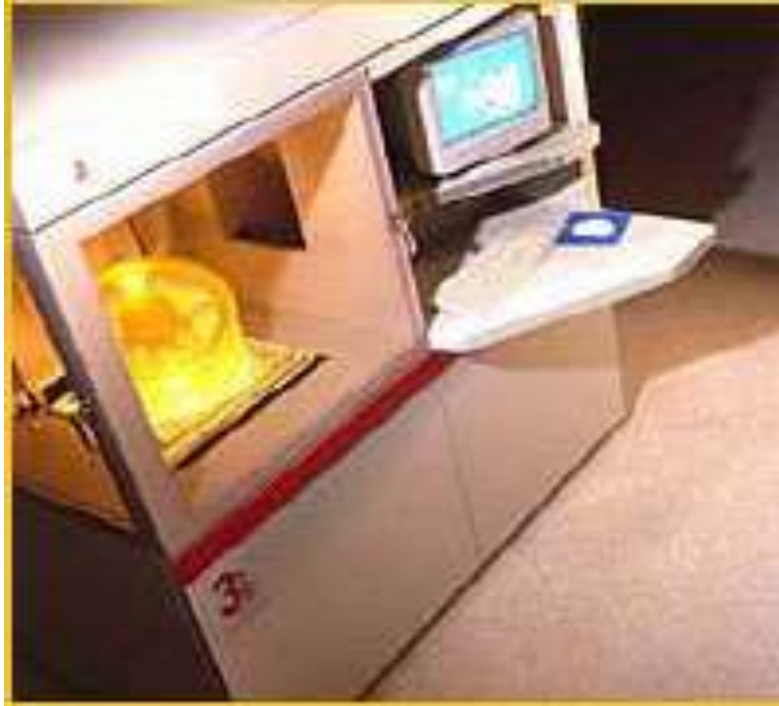


1. **Vat Polymerization:** a platform is dropped through or raised above a vat of liquid resin where light is used to selectively solidify it.
2. **Material Extrusion:** material is fed through a nozzle in a liquid state after which it solidifies;
3. **Material Jetting:** material is jetted in liquid droplet form after which it solidifies;
4. **Sheet Lamination:** sheets of material are bonded together either before or after the part outline is separated from the sheets;
5. **Powder Bed Fusion:** an energy beam (laser or electron beam) is focused onto the powder bed and rastered across the powder surface in a pattern to fill the area defined by one slice of the desired 3D model.
6. **Binder Jetting:** droplet printing of a liquid used to bind powder particles together;
7. **Directed Energy Deposition:** material is simultaneously fed into a moving focused energy region;

# Vat Polymerization

- Stereolithography
- Digital light Processing
- Two-Photon Polymerization
- Volumetric 3D Printing

# Stereolithography Apparatus (SLA)



- Manufactured by 3D Systems
- Invented by Charles W. Hull
- The first commercial RP system
- Use photo-curable liquid resins
- Use UV laser

# Stereolithography (SLA)

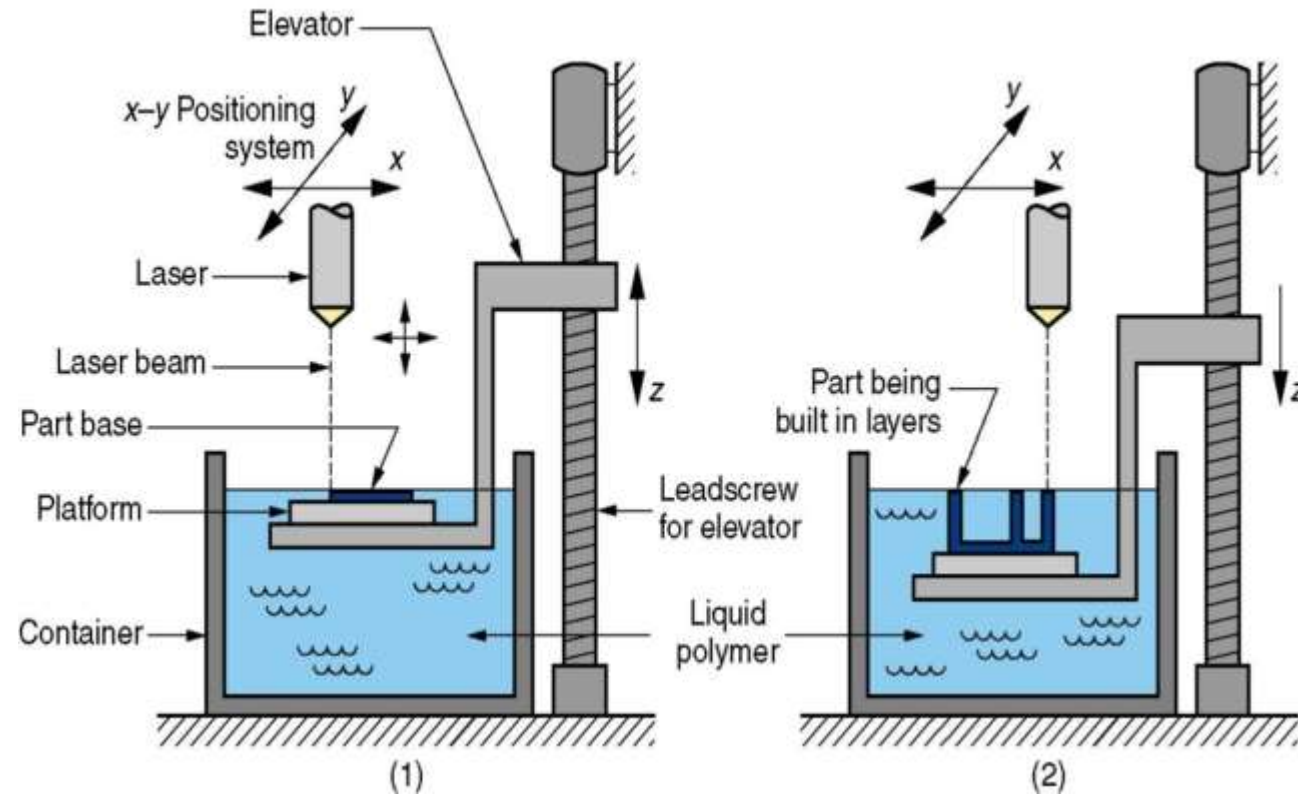
- **Stereolithography (SLA).** SLA is a process based on the principal of **hardening** (curing) a liquid photopolymer, using a directed **laser beam** to solidify polymer into a **specific shape**.
- Containing a mechanism whereby a **platform** can be **lowered** and **raised**, is filled with a photocurable liquid acrylate polymer.
- The liquid is a **mixture** of **acrylic monomers**, **oligomers** (polymer intermediates) and a **photoinitiator**.
- When the platform is at its **highest position**, the layer of liquid above it is **shallow**.
- A **laser** generating an ultraviolet beam, is now focused upon a **selected surface area** of the photopolymer and then moved in the x-y direction.

# Stereolithography (SLA)

- The **beam cures** that portion of the **photopolymer** and thereby produces a **solid body**.
- The **platform** is then **lowered** sufficiently to **cover** the **cured polymer**, and the sequence is repeated. The process is repeated until **level-b is reached**.
- **Generate a cylindrical part** with a constant wall thickness, the **platform** is now **lowered** by a **vertical distance-ab**.
- At **level-b**, the x-y movements of the beam are wider, a **flange-shaped** portion that is being **produced**.
- Process is repeated, **producing** another **cylindrical** section between **levels-b** and **c**.
- **Tolerance** depends on sharpness of the laser, typically 0.0125 mm.
- **Cycle times** range from a **few hours** to a **day**.
- Maximum **part size** is 0.5 m x 0.5 m x 0.6 m.



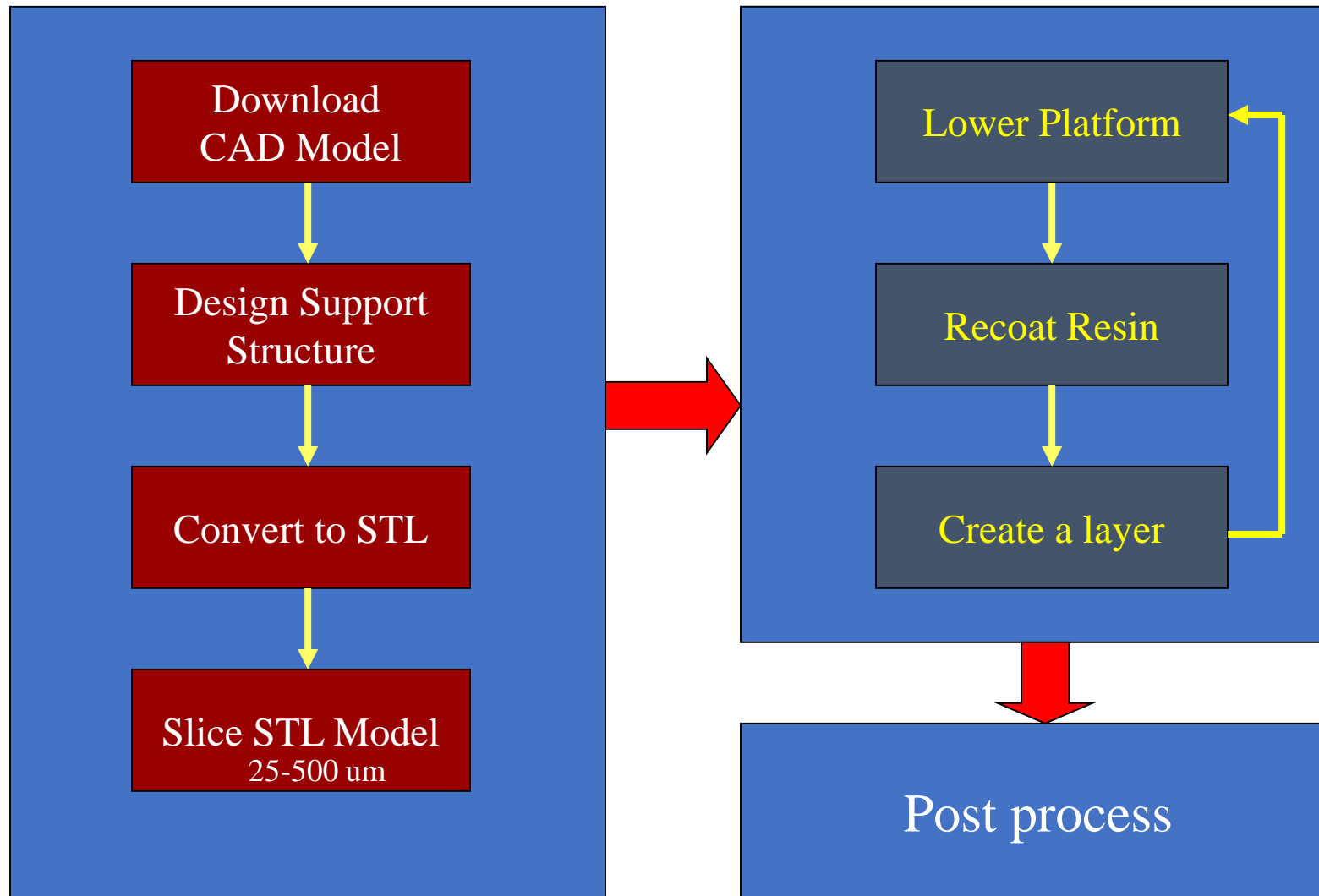
# Stereolithography (SLA)



**Schematic illustration of the stereolithography process and part of SLA**

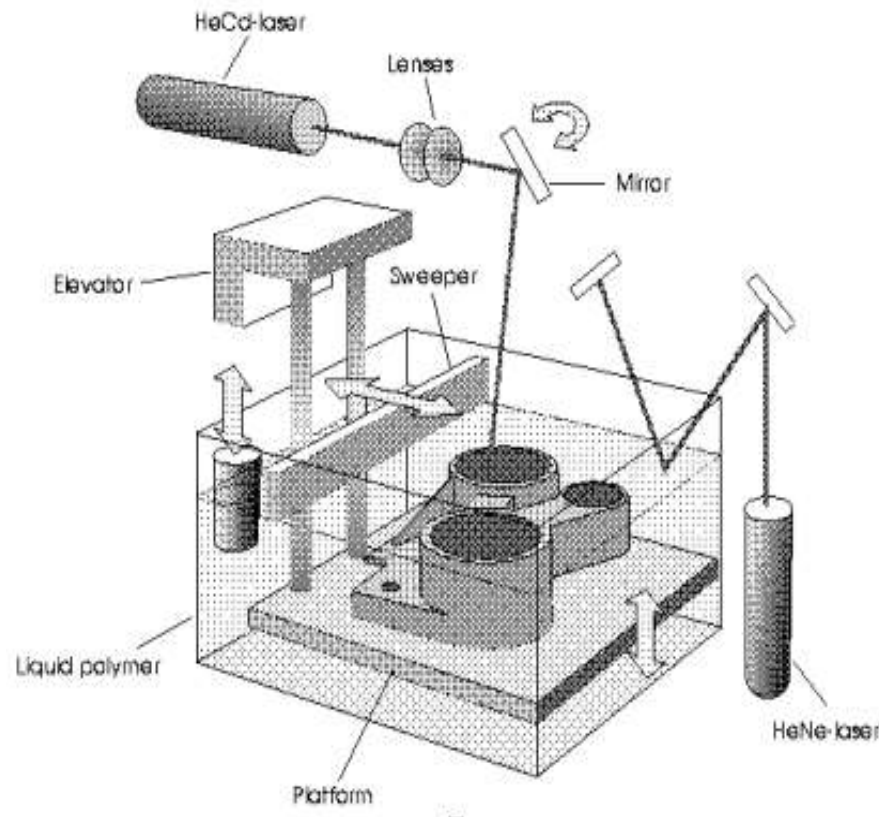


# SLA Process



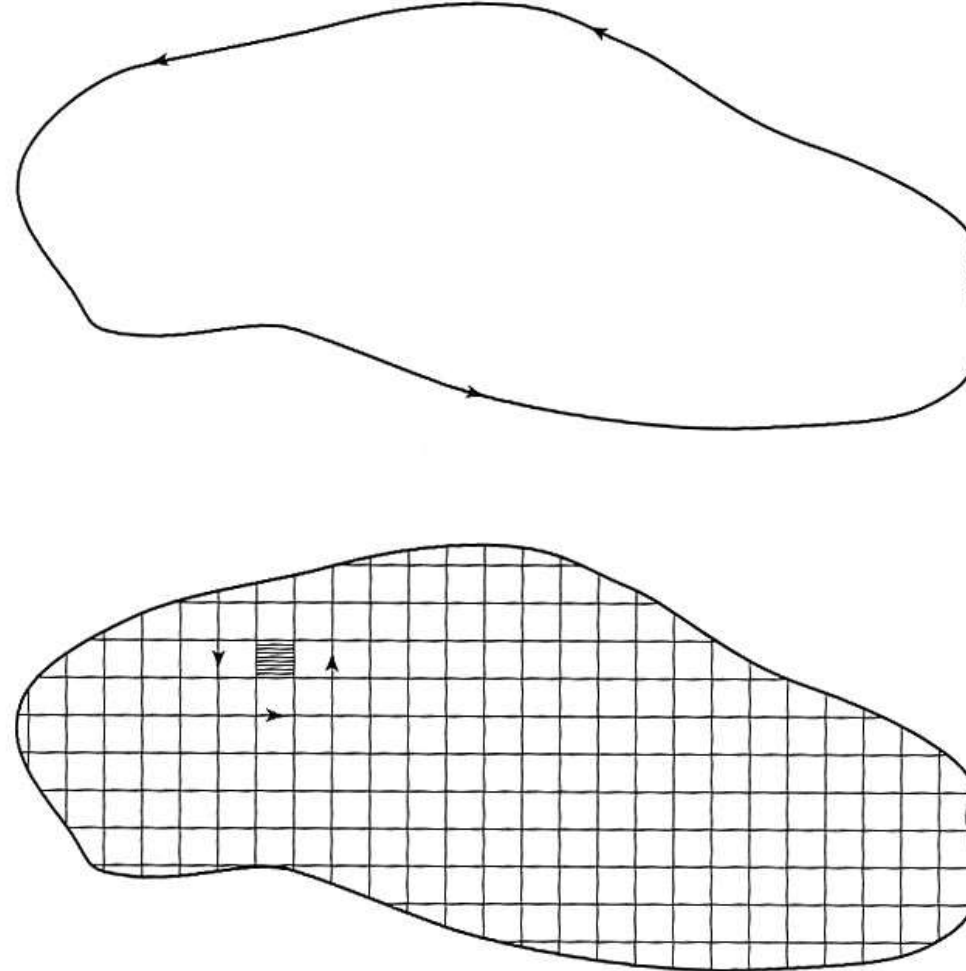
# Principle of SLA

Physical models are built from liquid photosensitive polymers.



Liquid polymer is solidified after exposed to UV light along the scan path.

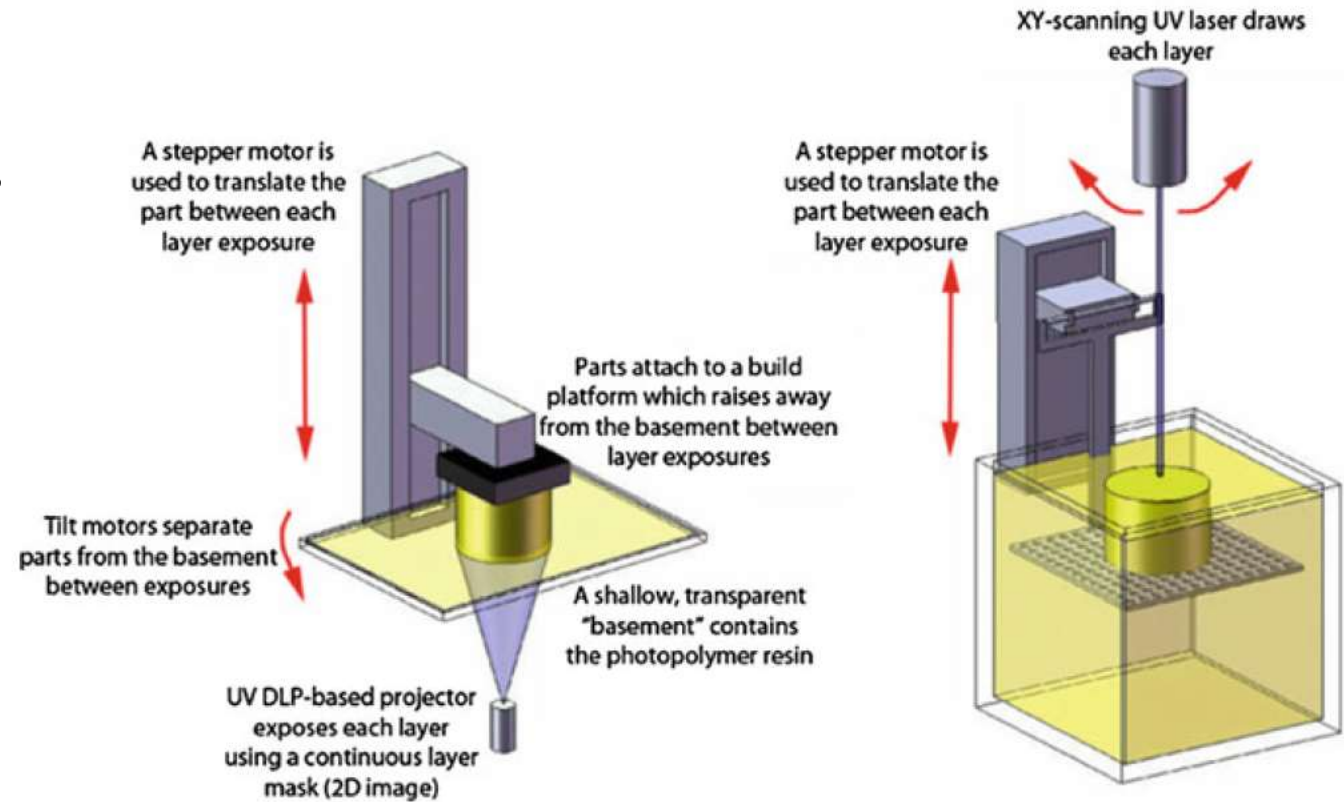
# Layer Creation with SLA



# Stereolithography (SLA)

There are two primary configurations in this technology:

- an upright style
- inverse configurations



# Photopolymerization Materials



**Dr. Yogesh Kumar**

Assistant Professor

Mechanical Engineering Department  
National Institute of Technology Patna  
Bihar - 800 005, India  
[yogesh.me@nitp.ac.in](mailto:yogesh.me@nitp.ac.in)

# M02 Lecture No 02

## Photopolymerization Materials

# Photopolymerization Materials (UV Curable Photopolymers)



- Photopolymers were developed in the late 1960s.
- Various types of radiation may be used to cure commercial photopolymers:
  - Gamma Rays
  - X-rays
  - Electron Beams
  - UV, and
  - in some cases Visible light
- In SL systems, UV radiation is used exclusively although, in principle, other types could be used. In the SLA-250 from 3D Systems, a helium-cadmium (HeCd) laser is used with a wavelength of 325 nm. In contrast, the solid-state lasers used in the other SL models are Nd-YVO<sub>4</sub> (Neodymium-doped yttrium orthovanadate).
- In mask projection DMD-based systems, UV and visible-light radiation are used.



# UV Curable Photopolymers

- Thermoplastic polymers that are typically injection molded have a linear or branched molecular structure that allows them to melt and solidify repeatedly.
- SL photopolymers are cross-linked and, as a result, do not melt and exhibit much less creep and stress relaxation.

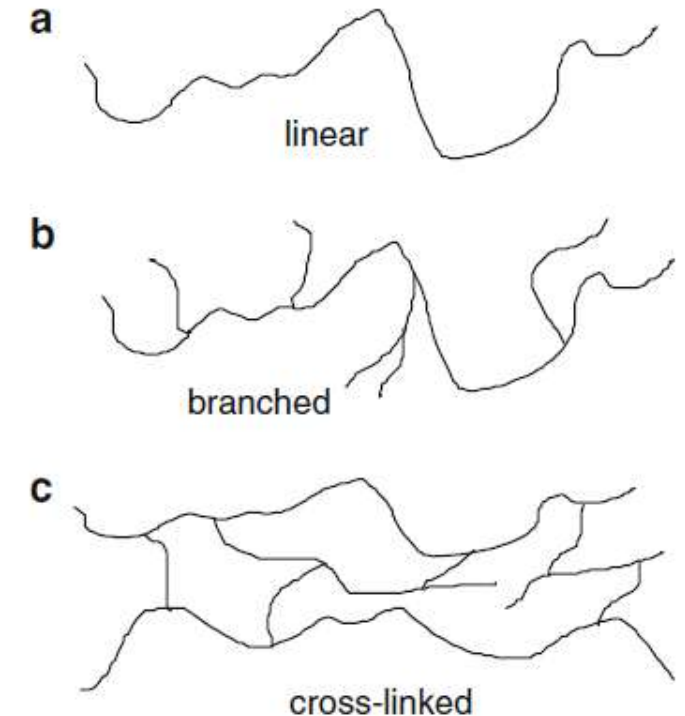


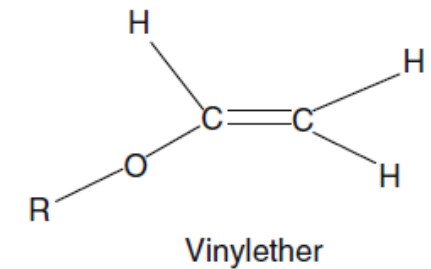
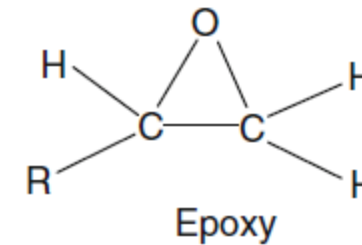
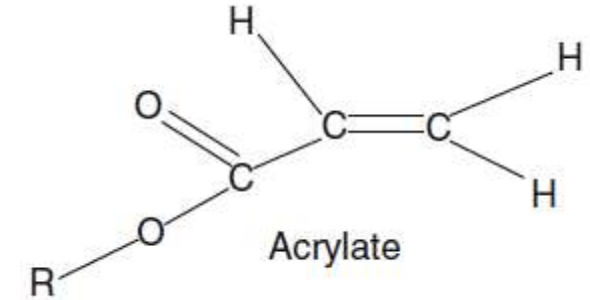
Fig. Schematics of polymer types

# Photopolymer Chemistry

- SL photopolymers are composed of several types of ingredients:
  1. Photoinitiators,
  2. Reactive diluents,
  3. Flexibilizers,
  4. Stabilizers, and
  5. Liquid Monomers
- When UV radiation impinges on SL resin, the photoinitiators undergo a chemical transformation and become “reactive” with the liquid monomers.
- A “reactive” photoinitiator reacts with a monomer molecule to start a polymer chain.
- Subsequent reactions occur to build polymer chains and then to cross-link-creation of strong covalent bonds between polymer chains.

# Photopolymer Chemistry

- Polymerization is the term used to describe the process of linking small molecules (monomers) into larger molecules (polymers) composed of many monomer units.
- Two main types of photopolymer chemistry are commercially evident:
  1. Free-radical photopolymerization – Acrylate
  2. Cationic photopolymerization – Epoxy and Vinyl ether



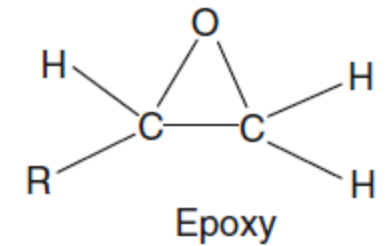
# Photopolymer Chemistry

Continued....

- Free-radical photopolymerization was the first type that was commercially developed. Such SL resins were acrylates.
- Acrylates form long polymer chains once the photoinitiator becomes “reactive,” building the molecule linearly by adding monomer segments.
- Cross-linking typically happens after the polymer chains grow enough so that they become close to one another.
- Acrylate photopolymers exhibit high photospeed (react quickly when exposed to UV radiation), but have a number of disadvantages including significant shrinkage and a tendency to warp and curl.
- The most common cationic photopolymers are epoxies, although vinyl ethers are also commercially available.

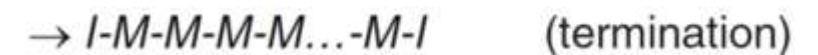
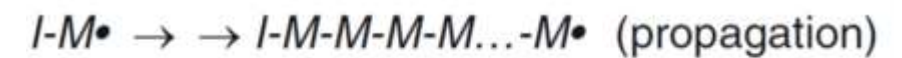
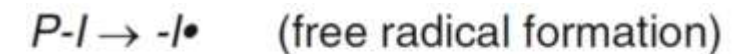
Continued....

- Epoxy monomers have rings, when reacted, these rings open, resulting in sites for other chemical bonds.
- Ringopening is known to impart minimal volume change on reaction, because the number and types of chemical bonds are essentially identical before and after reaction.
- Epoxy SL resins have much smaller shrinkages, and much less tendency to warp and curl.
- Almost all commercially available SL resins have significant amounts of epoxies.



# Photopolymer Chemistry - Free-Radical Photopolymerization

- Polymerization of SL monomers is an exothermic reaction, with heats of reaction around 85 kJ/mol for acrylate monomer.
- Despite high heats of reaction, a catalyst is necessary to initiate the reaction. photoinitiator acts as the catalyst.
- On average, for every two photons (from the laser), one radical will be produced.
- One radical can easily lead to the polymerization of over 1,000 monomers, as shown in the intermediate steps of the process, called propagation.
- In general, longer polymer molecules are preferred, yielding higher molecular weights. This indicates a more complete reaction.



# Photopolymer Chemistry - Free-Radical Photopolymerization

- Polymerization **terminates** from one of three causes: **Recombination**, **Disproportionation**, or **Occlusion**.
- **Recombination** occurs when two polymer chains merge by joining two radicals.
- **Disproportionation** involves essentially the cancelation of one radical by another, without joining.
- **Occlusion** occurs when free radicals become “trapped” within a solidified polymer, meaning that reaction sites remain available, but are prevented from reacting with other monomers or polymers by the limited mobility within the polymer network. These occluded sites will most certainly react eventually, but not with another polymer chain or monomer. Instead, they will react with oxygen or another reactive species that diffuses into the occluded region.



# Photopolymer Chemistry - Cationic Photopolymerization

- Cationic photopolymerization shares the same broad structure as free-radical polymerization, where a photoinitiator generates a cation as a result of laser energy, the cation reacts with a monomer, propagation occurs to generate a polymer, and a termination process completes the reaction.
- A typical catalyst for a cationic polymerization is a Lewis Acid.
- Initially, cationic photopolymerization received little attention, but that has changed during the 1990s due to advances in the microelectronics industry, as well as interest in SL technology.
- The ringopening reaction mechanism of epoxy monomers is similar to radical propagation in acrylates.

# Vector Scan SL



**Dr. Yogesh Kumar**

Assistant Professor

Mechanical Engineering Department

National Institute of Technology Patna

Bihar - 800 005, India

yogesh.me@nitp.ac.in

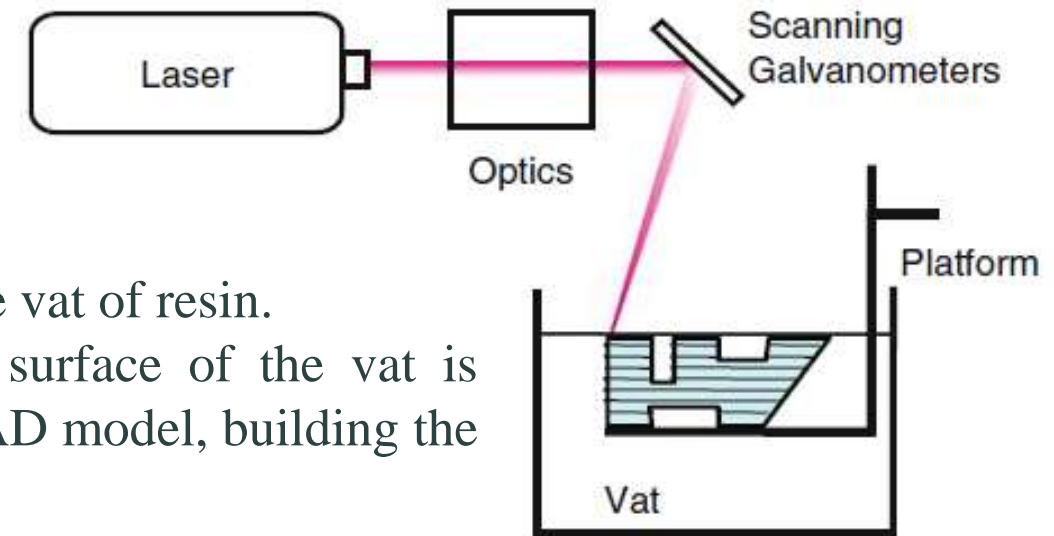
# M02 Lecture No 03



## Vector Scan SL

# Vector Scan SL

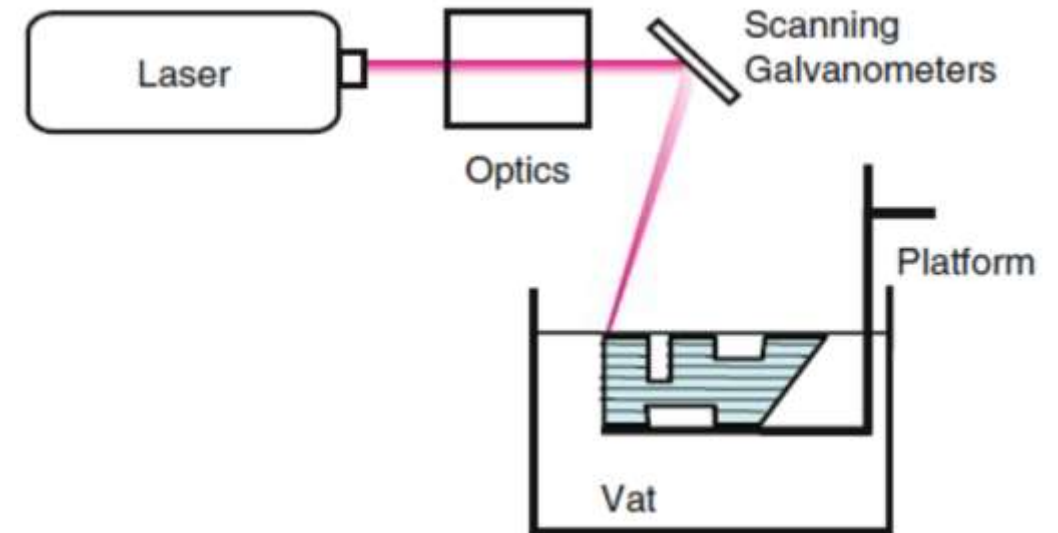
- SL creates solid parts by selectively solidifying a liquid photopolymer resin using an UV laser.
- The physical parts are manufactured by fabricating cross-sectional contours, or slices, one on top of another.
- The part being built rests on a platform that is dipped into the vat of resin.
- After each slice is created, the platform is lowered, the surface of the vat is recoated, then the laser starts to trace the next slice of the CAD model, building the prototype from the bottom up.
- The creation of the part requires a number of key steps: **input data**, **part preparation**, **layer preparation**, and **finally laser scanning of the two-dimensional cross-sectional slices**.
  1. The **input data** consists of a STL created from a CAD file or reverse engineering data.
  2. **Part preparation** is the phase at which the operator specifies support structures, to hold each cross section in place while the part builds, and provides values for machine parameters.
  3. **Layer preparation** is the phase in which the STL model is divided into a series of slices, as defined by the part preparation phase, and translated by software algorithms into a machine language.
  4. The **laser scanning** of the part is the phase that actually solidifies each slice in the SL machine.
- After building the part, the part must be cleaned, post-cured, and finished.



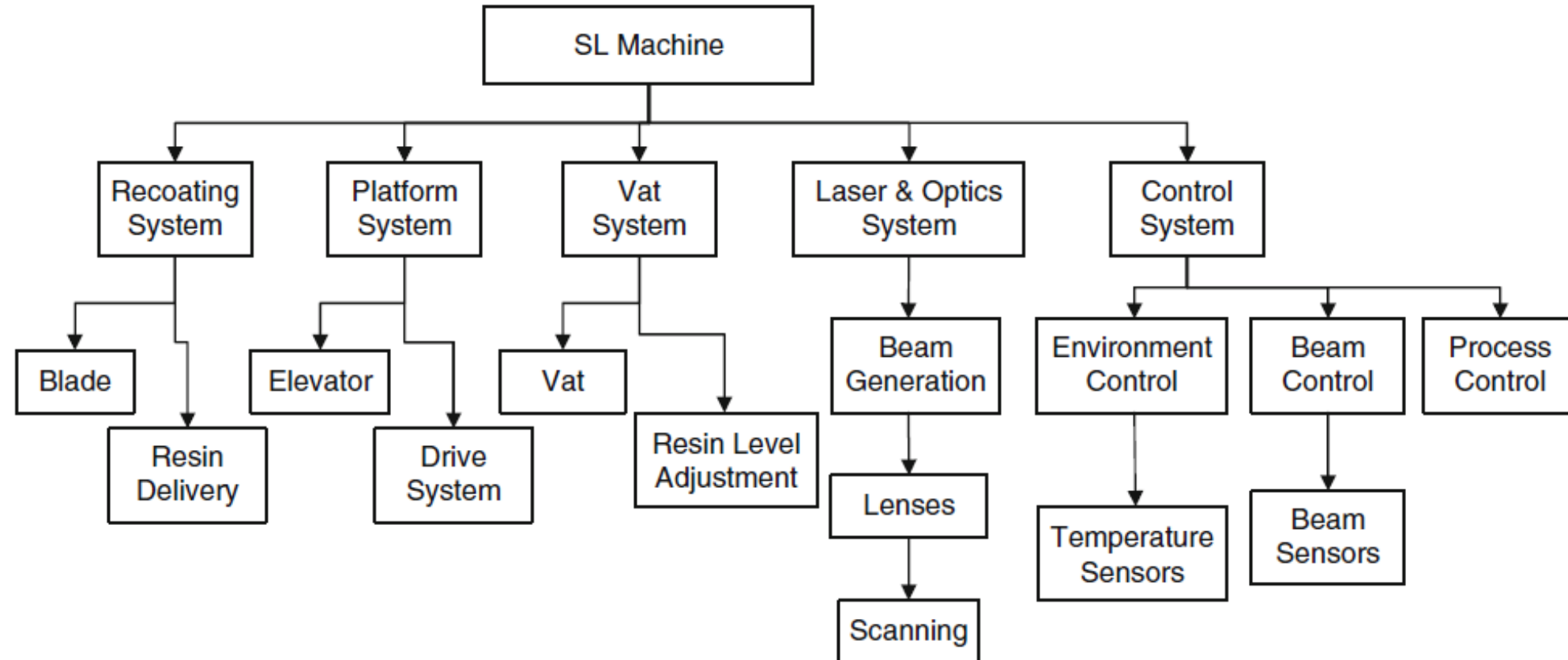
# SL Machines

## Main Subsystems:

- Recoating system,
- Platform system,
- Vat system,
- Laser and optics system, and
- Control System



# SL Machines



# SL Machines

## Recoating System

- Recoating is done using a shallow dip and recoater blade sweeping. The process can be described as follows:
  1. After a layer has been cured the platform dips down by a layer thickness.
  2. The recoater blade slides over the whole build depositing a new layer of resin and smoothing the surface of the vat.
- A common recoater blade type is the zephyr blade, which is a hollow blade that is filled with resin.
- A vacuum system pulls resin into the blade from the vat. As the blade translates over the vat to perform recoating, resin is deposited in regions where the previous part cross section was built.
- When the blade encounters a region in the vat without resin, the resin falls into this region since its weight is stronger than the vacuum force.
- Blade alignment is critical to avoid “blade crashes,” when the blade hits the part being built and often delaminates the previous layer.



# SL Machines

## Platform System

- The platform system consists of a build platform that supports the part being built and an elevator that lowers and raises the platform.
- The elevator is driven by a lead-screw.

## Vat System

- The vat system is simply the vat that holds the resin, combined with a level adjustment device, and usually an automated refill capability.

## Optics System

- The optics system includes a laser, focusing and adjustment optics, and two galvanometers that scan the laser beam across the surface of the vat.
- Modern SL machines have solid-state lasers that have more stable characteristics than their predecessors, various gas lasers.

# SL Machines

## Control System

- First, a **process controller** controls the sequence of machine operations. Typically, this involves executing the sequence of operations that are described in the build file that was prepared for a specific part or set of parts. Commands are sent to the various subsystems to actuate the recoating blade, to adjust resin level or changing the vat height, or to activate the beam controller. Sensors are used to detect resin height and to detect forces on the recoater blade to detect blade crashes.
- Second, the **beam controller** converts operation descriptions into actions that adjust beam spot size, focus depth, and scan speed, with some sensors providing feedback.
- Third, the **environment controller** adjusts resin vat temperature and, depending on machine model, adjusts environment temperature and humidity.

# SL Resin Curing Process

- Investigation into the fundamental interactions of laser energy with photopolymer resins.

$C_d$  = cure depth = depth of resin cure as a result of laser irradiation [mm]

$D_p$  = depth of penetration of laser into a resin until a reduction in irradiance of  $1/e$  is reached = key resin characteristic [mm]

$E$  = exposure, possibly as a function of spatial coordinates [energy/unit area] [mJ/mm<sup>2</sup>]

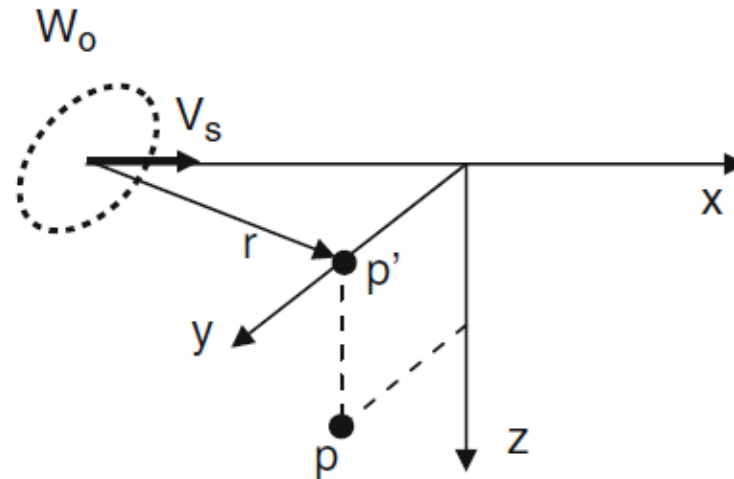
$E_c$  = critical exposure = exposure at which resin solidification starts to occur [mJ/mm<sup>2</sup>]

$E_{\max}$  = peak exposure of laser shining on the resin surface (center of laser spot) [mJ/mm<sup>2</sup>]

# SL Resin Curing Process - Irradiance and Exposure

the irradiance at any point  $x, y$  between  $x = 0$  and  $x = b$  is given by:

$$H(x, y) = \frac{2P_L}{\pi W_0^2} e^{-2x^2/W_0^2} e^{-2y^2/W_0^2}$$



# SL Resin Curing Process - Irradiance and Exposure



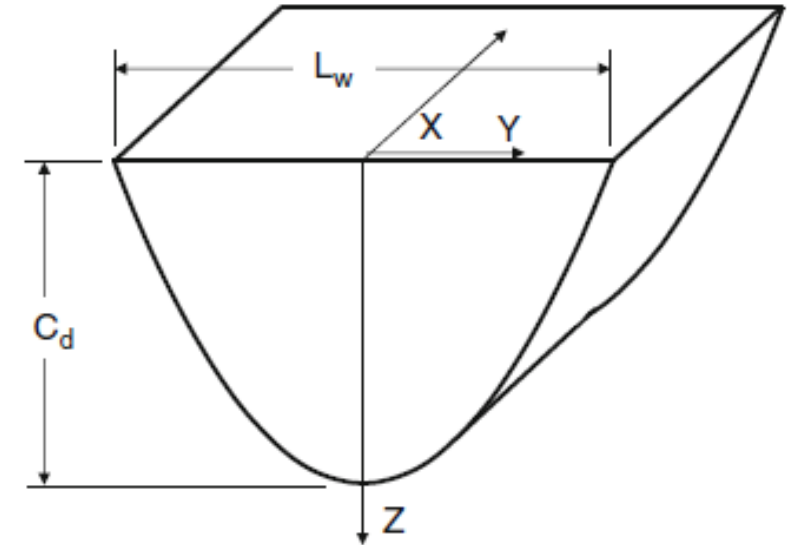
the fundamental general exposure equation:

$$E(x, y, z) = \sqrt{\frac{2}{\pi}} \frac{P_L}{W_0 V_s} e^{-2y^2/W_0^2} e^{-z/D_p}$$

# SL Resin Curing Process - Laser-Resin Interaction

- The cross-sectional shape of a cured line becomes a parabola.

$$C_d = D_p \ln \left( \frac{E_{\max}}{E_c} \right)$$



# SL Resin Curing Process - Photospeed



- Photospeed is typically used as an intuitive approximation of SL photosensitivity.

$$V_s = \sqrt{\frac{2}{\pi}} \frac{P_L}{W_0 E_c} e^{-C_d/D_p}$$



# SL Resin Curing Process - Time Scales



- On the short end of the time scale, the time it takes for a photon of laser light to traverse a photopolymer layer is about a picosecond ( $10^{-12}$  s). Photon absorption by the photoinitiator and the generation of free radicals or cations occur at about the same time frame. A measure of photopolymer reaction speed is the **kinetic reaction rates**,  $t_k$ , which are typically several microseconds.
- The time it takes for the laser to scan past a particular point on the resin surface is related to the size of the laser beam. This time is called the **characteristic exposure time**,  $t_e$ . Values of  $t_e$  are typically 50–2000  $\mu\text{s}$ .

# SL Scan Patterns



- Layer-Based Build Phenomena and Errors
- WEAVE
- STAR-WEAVE
- ACES Scan Pattern

# SL Resin Curing Process

- Investigation into the fundamental interactions of laser energy with photopolymer resins.

$C_d$  = cure depth = depth of resin cure as a result of laser irradiation [mm]

$D_p$  = depth of penetration of laser into a resin until a reduction in irradiance of  $1/e$  is reached = key resin characteristic [mm]

$E$  = exposure, possibly as a function of spatial coordinates [energy/unit area] [mJ/mm<sup>2</sup>]

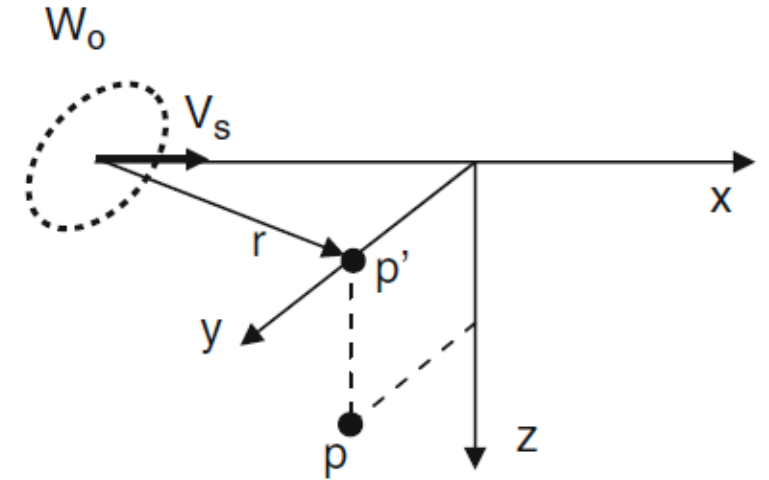
$E_c$  = critical exposure = exposure at which resin solidification starts to occur [mJ/mm<sup>2</sup>]

$E_{\max}$  = peak exposure of laser shining on the resin surface (center of laser spot) [mJ/mm<sup>2</sup>]

# SL Resin Curing Process - Irradiance and Exposure

The first concept of interest here is irradiance, the radiant power of the laser per unit area,  $H(x,y,z)$ . As the laser scans a line, the radiant power is distributed over a finite area (beam spots are not infinitesimal). Laser scanning a line along the  $x$ -axis at a speed  $V_s$ . Consider the  $z$ -axis oriented perpendicular to the resin surface and into the resin, and consider the origin such that the point of interest,  $p'$ , has an  $x$  coordinate of 0. The irradiance at any point  $x,y,z$  in the resin is related to the irradiance at the surface, assuming that the resin absorbs radiation according to the Beer–Lambert Law. The general form of the irradiance equation for a Gaussian laser beam is given;

$$H(x, y, z) = H(x, y, 0)\exp(-z/D_p)$$



# SL Resin Curing Process - Irradiance and Exposure



From this relationship, we can understand the meaning of the penetration depth,  $D_p$ . Setting  $z = D_p$ , we get that the irradiance at a depth  $D_p$  is about 37% ( $e^{-1}=0.36788$ ) of the irradiance at the resin surface. Thus,  $D_p$  is the depth into the resin at which the irradiance is 37% of the irradiance at the surface. Furthermore, since we are assuming the Beer–Lambert Law holds,  $D_p$  is only a function of the resin.

Without loss of generality, we will assume that the laser scans along the x-axis from the origin to point b. Then, the irradiance at coordinate x along the scan line is given by

$$H(x, y, 0) = H(x, y) = H_0 e^{-2x^2/W_0^2} e^{-2y^2/W_0^2}$$

where  $H_0 = H(0,0)$  when  $x = 0$ , and  $W_0$  is the  $1/e^2$  Gaussian half-width of the beam spot. Note that when  $x = W_0$ ,  $H(x,0) = H_0 e^{-2} = 0.13534 H_0$ .

# SL Resin Curing Process - Irradiance and Exposure

The maximum irradiance,  $H_0$ , occurs at the center of the beam spot ( $x = 0$ ).  $H_0$  can be determined by integrating the irradiance function over the area covered by the beam at any particular point in time. Changing from Cartesian to polar coordinates, the integral can be set equal to the laser power,  $P_L$ , as

$$P_L = \int_{r=0}^{r=\infty} H(r, 0) \, dA$$

When solved,  $H_0$  turns out to be a simple function of laser power and beam half-width, as

$$H_0 = \frac{2P_L}{\pi W_0^2}$$

As a result, the irradiance at any point  $x, y$  between  $x = 0$  and  $x = b$  is given by:

$$H(x, y) = \frac{2P_L}{\pi W_0^2} e^{-2x^2/W_0^2} e^{-2y^2/W_0^2}$$

# SL Resin Curing Process - Irradiance and Exposure



However, we are interested in exposure at an arbitrary point,  $p$ , not irradiance, since exposure controls the extent of resin cure. Exposure is the energy per unit area; when exposure at a point in the resin vat exceeds a critical value, called  $E_c$ , we assume that resin cures. Exposure can be determined at point  $p$  by appropriately integrating along the scan line, from time  $0$  to time  $t_b$ , when the laser reaches point  $b$ .

$$E(y, 0) = \int_{t=0}^{t=t_b} H[x(t), 0] dt$$



# SL Resin Curing Process - Irradiance and Exposure

It is far more convenient to integrate over distance than over time. If we assume a constant laser scan velocity, then it is easy to substitute  $t$  for  $x$ , as

$$E(y, 0) = \frac{2P_L}{\pi V_s W_0^2} e^{-2y^2/W_0^2} \int_{x=0}^{x=b} e^{-2x^2/W_0^2} dx$$

The exponential term is difficult to integrate directly, so we will change the variable of integration. Define a variable of integration,  $v$ , as

$$v^2 \equiv \frac{2x^2}{W_0^2}$$

Then, take the square root of both sides, take the derivative, and rearrange to give

$$dx = \frac{W_0}{\sqrt{2}} dv$$



# SL Resin Curing Process - Irradiance and Exposure

Due to the change of variables, it is also necessary to convert the integration limit to  $b = \sqrt{2}/W_0 x_e$ .

Several steps in the derivation will be skipped. After integration, the exposure received at a point  $x,y$  between  $x = (0,b)$  can be computed as:

$$E(y, 0) = \frac{P_L}{\sqrt{2\pi} W_0 V_s} e^{-\frac{2y^2}{W_0^2}} [\text{erf}(b)]$$

where  $\text{erf}(x)$  is the error function evaluated at  $x$ .  $\text{erf}(x)$  is 0 throughout almost the entire range of  $x$  between  $-\infty$  and  $\infty$ . Only near  $x = 0$  is it nonzero, which localizes the exposure within a narrow range around the scan vector. This makes sense since the laser beam is small and we expect that the energy received from the laser drops off quickly outside of its radius.

# SL Resin Curing Process - Irradiance and Exposure

$$E(y, 0) = \frac{2P_L}{\pi V_s W_0^2} e^{-2y^2/W_0^2} \int_{x=-\infty}^{x=\infty} e^{-2x^2/W_0^2} dx$$

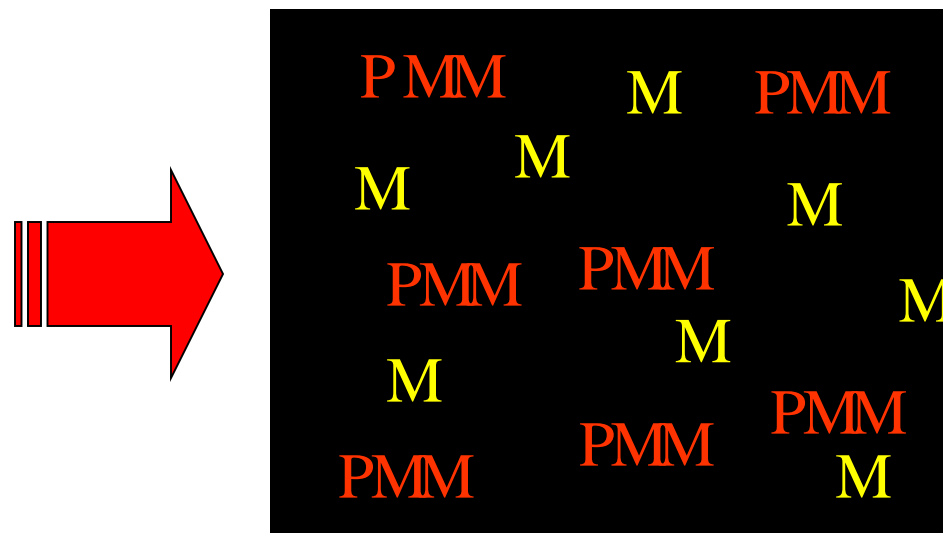
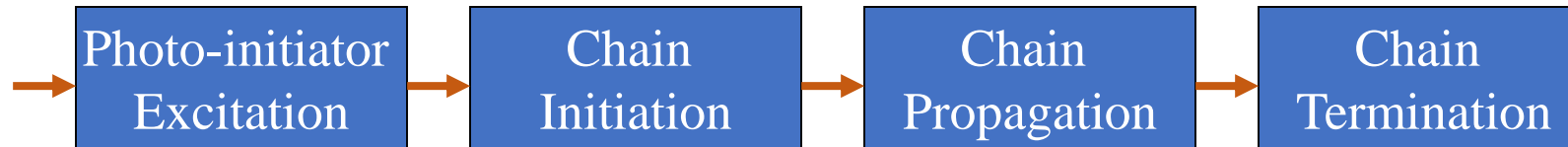
and after integration, exposure is given by

$$E(y, 0) = \sqrt{\frac{2}{\pi}} \frac{P_L}{W_0 V_s} e^{-2y^2/W_0^2}$$

the fundamental general exposure equation:

$$E(x, y, z) = \sqrt{\frac{2}{\pi}} \frac{P_L}{W_0 V_s} e^{-2y^2/W_0^2} e^{-z/D_p}$$

# Photo Polymerization



# Materials for SLA

Materials used in most liquid based AM systems are photopolymers that are cured when exposed to light. They are composed of three components:

1. Photo-initiator that generates free radicals upon exposure to UV
2. Epoxy- (or Acrylate-) based Monomers
3. A reactive acrylic diluents to lower the viscosity of the polymer

# Fundamental Relationships

From the Beer-Lambert exponential law of absorption, the variation of laser exposure  $E(z)$  within the resin may be assume by

$$E(z) = E_0 \exp\left(-\frac{2\pi k z}{\lambda}\right)$$

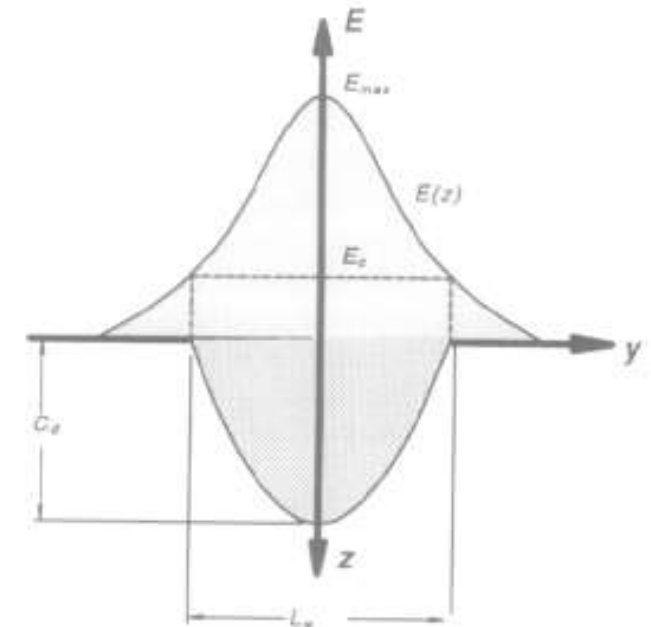
$$E(z) = E_0 \exp\left(-\frac{z}{D_p}\right)$$

Where  $E_0$  = laser exposure on the surface of resin (mJ/c

$D_p$  = penetration depth of the resin whereby

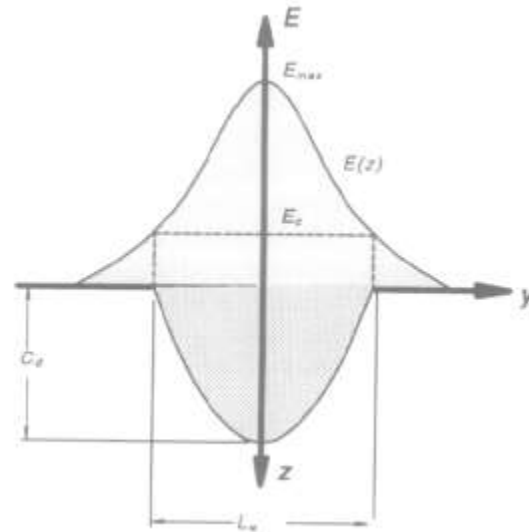
$$E(z) = E_0 \exp(-1)$$

$z$  = depth from the surface of the resin ( m)



# Fundamental Relationships

In practice, polymerization doesn't proceed beyond the cured depth  $C_d$  where the laser exposure is below a critical exposure  $E_c$  which is required to initiate gelation in a resin.



$$E_c = E_{\max} \exp\left(-\frac{C_d}{D_p}\right)$$

$$C_d = D_p \ln\left(\frac{E_{\max}}{E_c}\right)$$

$$C_d = D_p \ln E_{\max} - D_p \ln E_c$$

# Fundamental Relationships

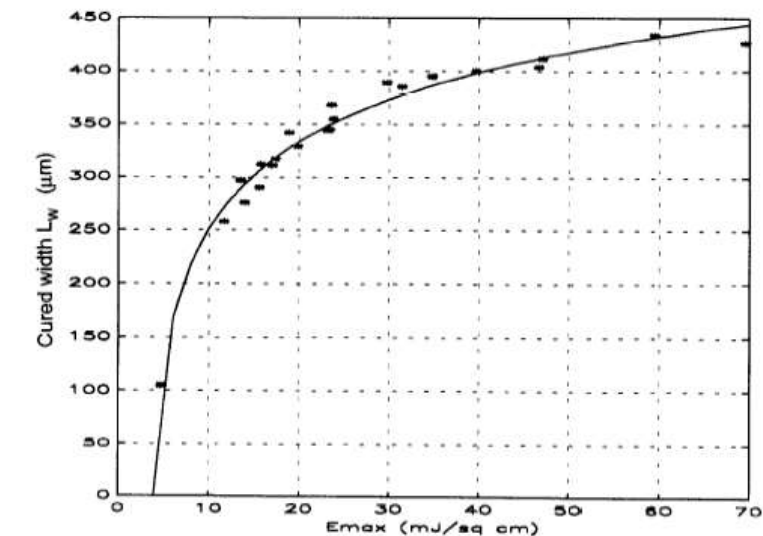
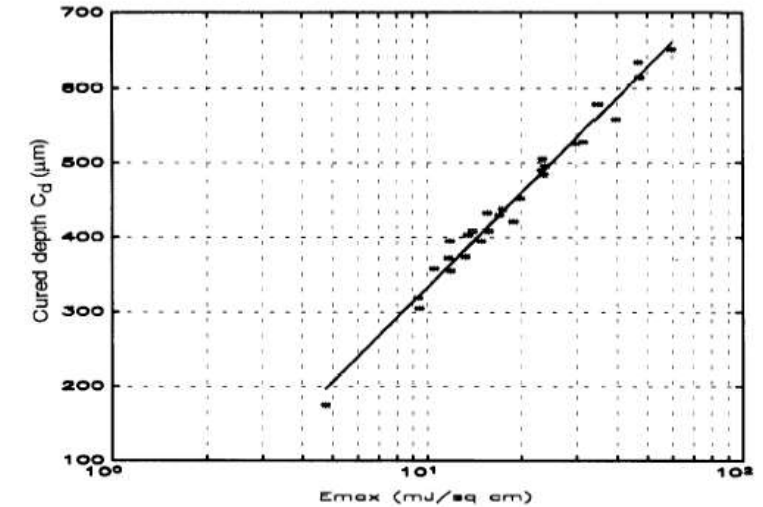
## Cured Depth

$$C_d = D_p \ln E_{\max} - D_p \ln E_c$$

## Cured Width

$$L_w = \sqrt{2} W_0 \sqrt{\ln \left( \frac{E_{\max}}{E_c} \right)}$$

$W_0$  is the Gaussian half-width of laser irradiance at  $1/e^2$



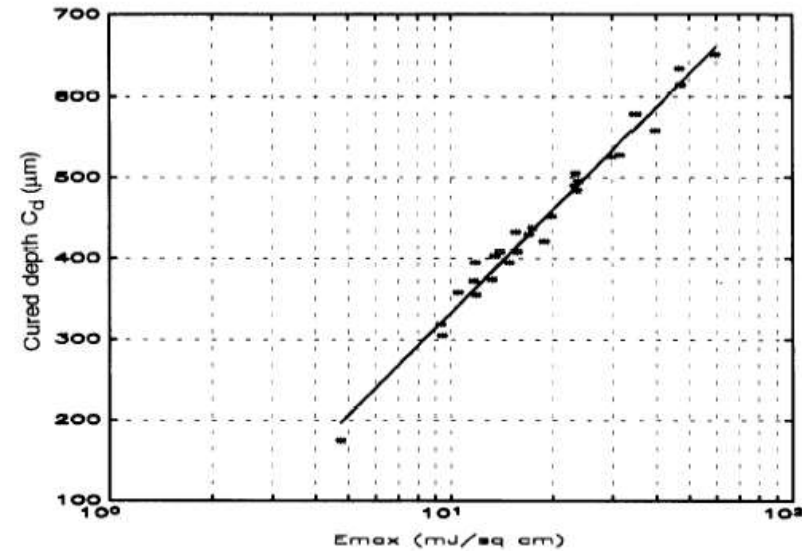
# Fundamental Relationships

Required power

$$E_{\max} = \sqrt{\frac{2}{\pi}} \frac{P_L}{W_0 V_s}$$

$$P_L = \sqrt{\frac{\pi}{2}} W_0 V_s E_{\max}$$

$V_s$  is scan speed





# Fundamental Relationships

During layer building, the laser beam is scanned in a raster fashion with scan pitch  $p$ . Therefore, the laser exposure at any point on the surface will be equal to the sum of the exposure from adjacent lines within the zone of influence.

$$E_t = E_m + E_{+p} + E_{-p}$$

$$E_m = E_{\max} \exp\left(-\frac{2y^2}{W_0^2}\right)$$

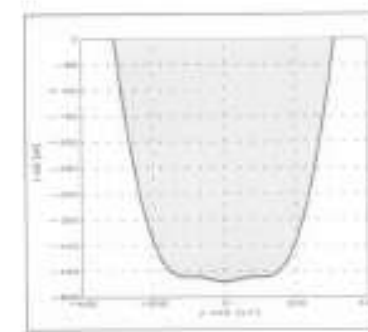
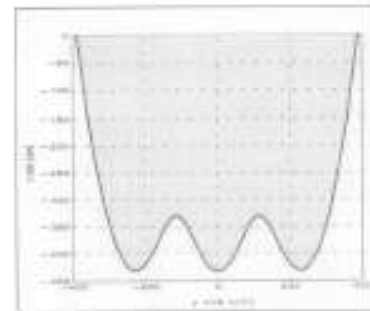
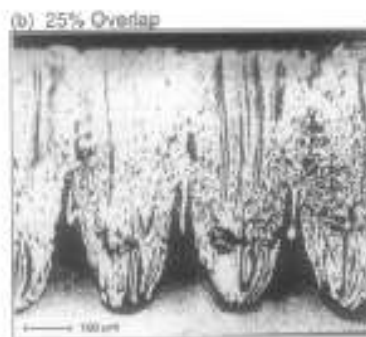
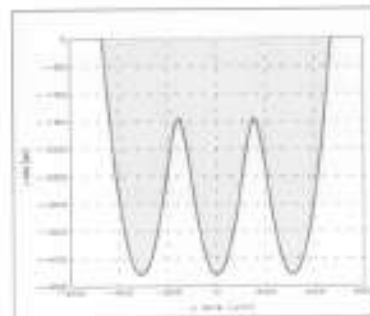
$$E_{+p} = E_{\max} \exp\left(-\frac{2(y-p)^2}{W_0^2}\right)$$

$$E_{-p} = E_{\max} \exp\left(-\frac{2(y+p)^2}{W_0^2}\right)$$

# Single Layer Building

Cured Profile of the layer

$$L_d = D_p \ln \left( \frac{E_t}{E_c} \right)$$



# Strengths and Weaknesses of SLA

## Strengths

- Fully Automatic
- Good Accuracy
- High precision
- Very Smooth Surface

## Weaknesses

- Shrinkage and Distortion
- Messy & Tedious Finishing Operation
- Post-Curing

# Applications of SLA

- Models for conceptualization, packaging, and presentation
- Prototypes for design, analysis, verification and functional testing
- Parts for prototype tooling and low volume production tooling
- Patterns for investment casting, sand casting and molding
- Tools for fixture and tooling design

# R&D on SLA

- Working on new resins which have better mechanical properties, faster and easier to process, and withstand high temperature
- The realization of prototype molds and production tooling inserts



# Module - 2



## Additive Manufacturing & 3D Printing



**Dr. Yogesh Kumar**

Assistant Professor

Mechanical Engineering Department

National Institute of Technology Patna

Bihar - 800 005, India

## Material Jetting & Binder Jetting AM Processes

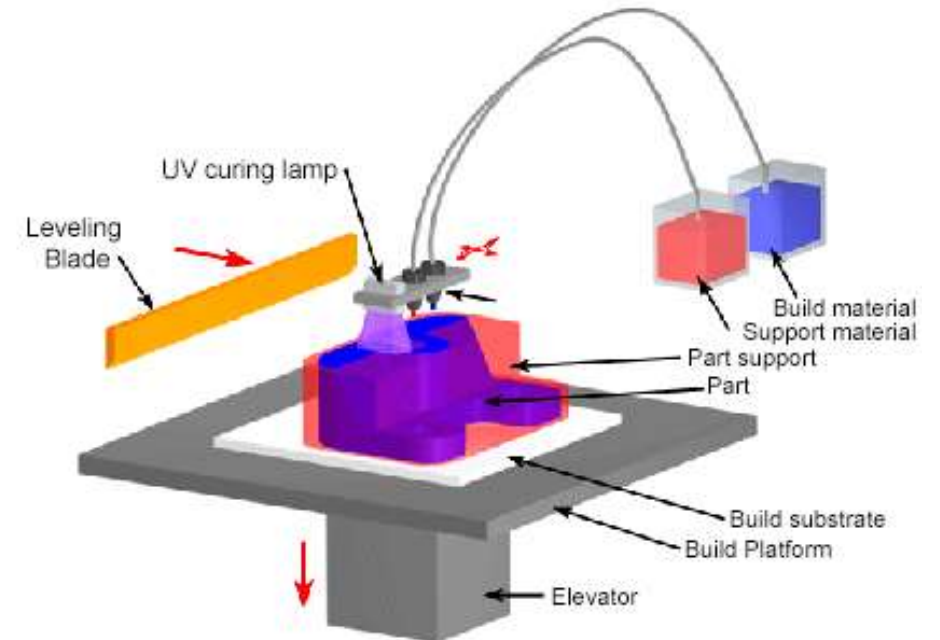


# Material Jetting

- Material jetting creates objects in a similar method to a two dimensional ink jet printer. Material is jetted onto a build platform using either a continuous or Drop on Demand (DOD) approach.
- Material is jetted onto the build surface or platform, where it solidifies and the model is built layer by layer. Material is deposited from a nozzle which moves horizontally across the build platform. Machines vary in complexity and in their methods of controlling the deposition of material. The material layers are then cured or hardened using ultraviolet (UV) light.
- As material must be deposited in drops, the number of materials available to use is limited. Polymers and waxes are suitable and commonly used materials, due to their viscous nature and ability to form drops.

# Material Jetting – Step by Step

- The print head is positioned above build platform.
- Droplets of material are deposited from the print head onto surface where required, using either thermal or piezoelectric method.
- Droplets of material solidify and make up the first layer.
- Further layers are built up as before on top of the previous.
- Layers are allowed to cool and harden or are cured by UV light. Post processing includes removal of support material.



# Material Jetting – Step by Step

- **Material Jetting** builds objects in a similar method to a two dimensional ink jet printer. Multiple materials can be used in one process and the material can be changed during the build stage. Material is jetted onto the build platform surface in droplets, which are formed using an oscillating nozzle. Droplets are then charged and positioned onto the surface using charged deflection plates. This is a continuous system which allows for a high level of droplet control and positioning. Droplets which are not used are recycled back into the printing system.
- **Drop on Demand (DOD)** is used to dispense material onto the required surface. Droplets are formed and positioned into the build surface, in order to build the object being printed, with further droplets added in new layers until the entire object has been made. The nature of using droplets, limits the number of materials available to use. Polymers and waxes are often used and are suitable due to their viscous nature and ability to form drops. Viscosity is the main determinant in the process; there is a need to re-fill the reservoir quickly and this in turn affects print speed. Unlike a continuous stream of material, droplets are dispensed only when needed, released by a pressure change in the nozzle from thermal or piezoelectric actuators. Thermal actuators deposit droplets at a very fast rate and use a thin film resistor to form the droplet. The piezoelectric method is often considered better as it allows a wider range of materials to be used. The designs of a typical DOD print head changes from one machine to another but according to Ottnad, typically include a reservoir, sealing ring, Piezo elements and silicon plate with nozzle, held together with high temperature glue.
- **Post processing:** Support material can be removed using a sodium hydroxide solution or water jet. Due to the high accuracy of the process technology, the level of post processing required to enhance the properties is limited and the functional and aesthetic qualities of a part are largely determined during the printing stage. Stratasys polyjet technology cures the material using UV light and therefore no post curing process is needed.

# Material Jetting – Materials

The material jetting process uses polymers and plastics.

## Polymers:

1. **Polypropylene:** Thermoplastic polymer
2. **HDPE:** High-density polyethylene
3. **PS:** Polystyrene is a synthetic aromatic hydrocarbon polymer made from the monomer known as styrene.
4. **PMMA:** Poly(methyl methacrylate) belongs to a group of materials called engineering plastics.
5. **PC:** Polycarbonates are a group of thermoplastic polymers containing carbonate groups in their chemical structures.
6. **ABS:** Acrylonitrile butadiene styrene is a common thermoplastic polymer.
7. **HIPS:** HIPS (High Impact Polystyrene), also known as PS (Polystyrene), is an amorphous thermoplastic material, used in lower heat applications.

# Material Jetting

## Advantages:

- The process benefits from a high accuracy of deposition of droplets and therefore low waste.
- The process allows for multiple material parts and colours under one process.

## Disadvantages:

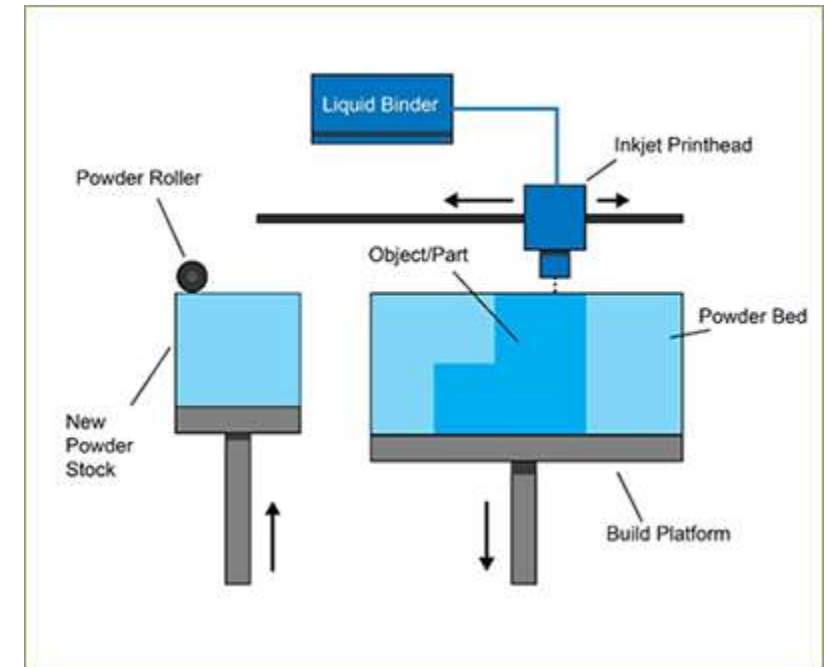
- Support material is often required.
- A high accuracy can be achieved but materials are limited and only polymers and waxes can be used.

# Binder Jetting

- The binder jetting process uses two materials; a **powder based material** and a **binder**. The binder acts as an adhesive between powder layers. The binder is usually in liquid form and the build material in powder form. A print head moves horizontally along the **x** and **y** axes of the machine and deposits alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform.
- Due to the method of binding, the material characteristics are not always suitable for structural parts and despite the relative speed of printing, additional post processing can add significant time to the overall process.
- As with other powder based manufacturing methods, the object being printed is self-supported within the powder bed and is removed from the unbound powder once completed. The technology is often referred to as 3DP technology and is copyrighted under this name.

# Binder Jetting – Step by Step

- Powder material is spread over the build platform using a roller.
- The print head deposits the binder adhesive on top of the powder where required.
- The build platform is lowered by the model's layer thickness.
- Another layer of powder is spread over the previous layer. The object is formed where the powder is bound to the liquid.
- Unbound powder remains in position surrounding the object.
- The process is repeated until the entire object has been made.



# Binder Jetting

The **binder jetting** process allows for colour printing and uses metal, polymers and ceramic materials. The process is generally faster than others and can be further quickened by increasing the number of print head holes that deposit material. The two material approach allows for a large number of different binder-powder combinations and various mechanical properties of the final model to be achieved by changing the ratio and individual properties of the two materials. The process is therefore well suited for when the internal material structure needs to be of a specific quality.

Layers of build material, often in granular and powder form, are held together using the adhesive binder. The print head deposits the binding material in micro amounts and the powder material is used in creating the majority of the overall object mass. A heated build chamber can help to speed up the printing process by increasing the viscosity of the materials (Chua et al., 2010).

**Post Processing:** The overall process time is extended as it requires the binder to set and the part is often allowed to cool in the machine to fully solidify to achieve a high quality finish (Gibson et al., 2010). Post processing is often required to make the part stronger and give the binder-material better mechanical and structural properties.



# Binder Jetting - Materials

- Metals: Stainless steel
- Polymers: ABS, PA, PC
- Ceramics: Glass

All three types of materials can be used with the binder jetting process.

# Binder Jetting

## Advantages:

- Parts can be made with a range of different colours.
- Uses a range of materials: metal, polymers and ceramics.
- The process is generally faster than others.
- The two material method allows for a large number of different binder-powder combinations and various mechanical properties.

## Disadvantages:

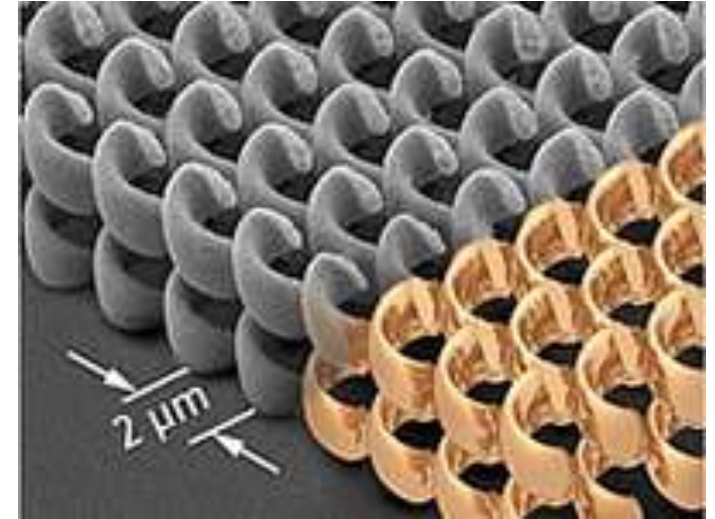
- Not always suitable for structural parts, due to the use of binder material.
- Additional post processing can add significant time to the overall process.



## 2-Photon Polymerization

Lithography on the sub-micrometer scale has long been limited to planar objects. In 1997, the emergence of two-photon polymerization enabled three-dimensional fabrication in the 100 nm regime. Since then, an increasing demand in miniaturized devices like nanotubes or scaffolds for micro- and nanotechnologies lead to a fast development of lithographic techniques. Allowing for fabrication of arbitrary 3D structures with resolution beyond the diffraction limit of light, two-photon polymerization (TPP) has the potential to play a key role in laser lithography.

- Microfabrication with two-photon polymerization
- High penetration depth
- Fast writing process
- Average power 50 - 500 mW (depending on processing speed)
- Pulse width typically 100 .. 200 fs



Gold-plated helices written with 3D laser lithography courtesy of Karlsruhe Institute of Technology (KIT), J. Gansel et al.

# Process of 2-photon polymerization

- Two-photon polymerization as a direct laser writing technique allows for creating complex three-dimensional structures down to feature sizes on the order of 100 nm. Key elements of two-photon polymerization are lasers providing femtosecond pulses, suitable photosensitive materials (photoresists), a precise positioning stage and a computer to control the procedure.
- Two-photon polymerization is a non-linear optical process based on the simultaneous absorption of two photons in a photosensitive material (photoresist). This process changes the photosensitive material, i.e. it leads to a polymerization by activating so-called photo-initiators in the resist. These turn into radicals that polymerize the resist locally. In a subsequent step, the non-polymerized photoresist is washed out to uncover the structure. The material of the structures is not restricted to just polymers but can be converted for example into silicon via a secondary chemical process.

# Advantages of 2-photon polymerization

- Two-photon absorption requires high intensities - these are provided by a tightly focused femtosecond laser beam. As two-photon absorption is proportional to the square of the intensity, it only takes place in the focus providing high spatial resolution. Accordingly, the resist polymerizes only in the ellipsoidal focus, termed “voxel” (abbr. for volume pixel). Scanning the laser through the resist in all three dimensions “writes” the desired structure voxel by voxel. During two-photon polymerization the surrounding oxygen quenches the radicals to a certain extent. This results in feature sizes down to ~100 nm. Another advantage of 2-photon polymerization is that many polymers have next-to-none linear absorption in the near-infrared, allowing the laser to penetrate deeply into the material. These two aspects allow creating nano-structures that are otherwise not possible to produce.
- Computer-aided exposure of a multitude of photoresists as well as established 3D casting techniques make direct laser writing an indispensable tool for a large variety of applications in life sciences (e.g. extra cellular matrices, lab-on-a-chip,...), (opto-)electronics or photonics (e.g. photonic crystals).

# Advantages of 2-photon polymerization

- Two-photon absorption requires high intensities - these are provided by a tightly focused femtosecond laser beam. As two-photon absorption is proportional to the square of the intensity, it only takes place in the focus providing high spatial resolution. Accordingly, the resist polymerizes only in the ellipsoidal focus, termed “voxel” (abbr. for volume pixel). Scanning the laser through the resist in all three dimensions “writes” the desired structure voxel by voxel. During two-photon polymerization the surrounding oxygen quenches the radicals to a certain extent. This results in feature sizes down to ~100 nm. Another advantage of 2-photon polymerization is that many polymers have next-to-none linear absorption in the near-infrared, allowing the laser to penetrate deeply into the material. These two aspects allow creating nano-structures that are otherwise not possible to produce.
- Computer-aided exposure of a multitude of photoresists as well as established 3D casting techniques make direct laser writing an indispensable tool for a large variety of applications in life sciences (e.g. extra cellular matrices, lab-on-a-chip,...), (opto-)electronics or photonics (e.g. photonic crystals).

# Thanks