LECTURE NOTES

ON

RAPID PROTOTYPE TECHNOLOGIES

(BCCB08)

M. Tech I semester

IARE – R18

PREPARED BY:

Dr. GVR Seshagiri Rao. Professor

INSTITUTE OF AERONAUTICAL ENGINEERING
(AUTONOMOUS)
DUNDIGAL, HYDERABAD - 500 043

UNIT-1

INTRODUCTION TO RAPID PROTOTYPING

1. Introduction

Rapid prototyping (RP) is a new manufacturing technique that allows for fast fabrication of computer models designed with three-dimension (3D) computer aided design (CAD) software. RP is used in a wide variety of industries, from shoe to car manufacturers. This technique allows for fast realizations of ideas into functioning prototypes, shortening the design time, leading towards successful final products.

RP technique comprise of two general types: additive and subtractive, each of which has its own pros and cons. Subtractive type RP or traditional tooling manufacturing process is a technique in which material is removed from a solid piece of material until the desired design remains. Examples of this type of RP includes traditional milling, turning/lathing or drilling to more advanced versions - computer numerical control (CNC), electric discharge machining (EDM). Additive type RP is the opposite of subtractive type RP. Instead of removing material, material is added layer upon layer to build up the desired design such as stereolithography, fused deposition modeling (FDM), and 3D printing.

This tutorial will introduce additive type RP techniques: Selective Laser Sintering (SLS), Stereo Lithography Apparatus (SLA), FDM, Inkjet based printing. It will also cover how to properly prepare 3D CAD models for fabrication with RP techniques.

2. Advantages and disadvantages of rapid prototyping

Subtractive type RP is typically limited to simple geometries due to the tooling process where material is removed. This type of RP also usually takes a longer time but the main advantage is that the end product is fabricated in the desired material. Additive type RP, on the other hand, can fabricate most complex geometries in a shorter time and lower cost. However, additive type RP typically includes extra post fabrication process of cleaning, post curing or finishing.

Here is some of the general advantages and disadvantages of rapid prototyping [1]: Advantages:

Fast and inexpensive method of prototyping design ideas
Multiple design iterations
Physical validation of design
Reduced product development time

Disadvantages:

Resolution not as fine as traditional machining (millimeter to sub-millimeter resolution)
Surface flatness is rough (dependant of material and type of RP)

3. Rapid Prototyping Process

The basic process is similar across the different additive type RP technologies. We will use a ball as an example here. It begins with using a CAD software such as Solidworks to design a 3D computer model. Figure 1 is a golf ball designed in Solidworks.

Figure 1 – CAD of a ball.

This 3D CAD model is next converted into a Stereolithography or Standard Tessellation Language (STL) file format. The STL file format only describes the surface geometry of a 3D CAD model. It does not contain any information on the color, texture or material. STL file format can be saved in either ASCII or binary versions, with the latter as the more compact version. The surface geometry is described with triangular facets. Each triangle facets uses a set of Cartesian coordinates to describe its three vertices and the surface normal vector using a right-hand rule for ordering. An example of how an ASCII STL file format is show in Fig. 2.

```
solid print
 facet normal 0.00000e+00 1.00000e+00 0.00000e+00
  outer loop
   vertex 0.00000e+00 0.00000e+00 2.00000e+01
   vertex 0.00000e+00 0.00000e+00 0.00000e+00
   vertex 1.00000e+00 0.00000e+00 2.00000e+01
  endloop
 endfacet
 ⋮
endsolid print.stl
```

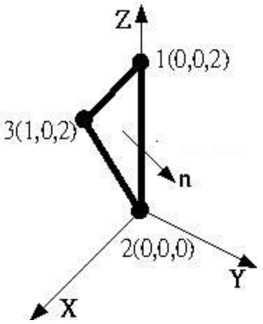


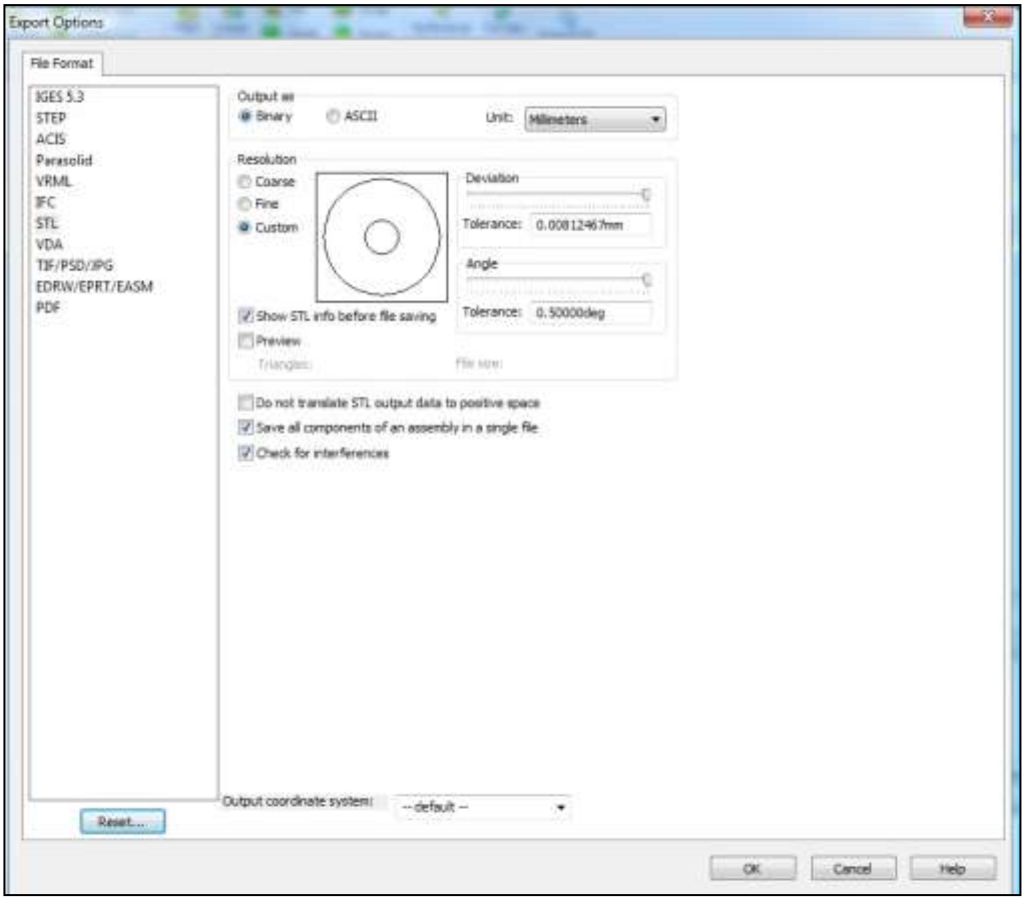
Figure 2 – ASCII STL file format.

To convert a CAD model to STL in Solidworks,

File □Save as □Change ‘Save as type’ to .STL

Select ‘Options’ for more advance export options. Figure 3 shows a print screen of the STL export option.

As shown in Fig. 3, one can select to export the STL as Binary or ASCII file format in millimeter, centimeter, meter, inches or feet depending on the unit used in the CAD model.



Output as
● Binary ○ ASCII
Unit: Millimeters

Resolution
○ Coarse
○ Fine
● Custom

Deviation
Tolerance: 0.00812467mm

Angle
Tolerance: 0.50000deg

☑ Show STL info before file saving
☐ Preview
Triangles:
File size:

☐ Do not translate STL output data to positive space
☑ Save all components of an assembly in a single file
☑ Check for interferences

Output coordinate system: -- default --

Figure 3 – Solidworks STL export option.

The resolution options allow a user to control the tessellation of non-planar surfaces. There are two preset resolutions of ‘Coarse’ and ‘Fine’. The ‘Custom’ setting allows one to adjust the deviation and angle tolerances. Lower deviation tolerance sets tighter accuracy to the tessellation where as smaller angle deviation sets smaller detail tessellation . The caveat is that tighter tolerances create more triangle facets to describe the 3D CAD model’s surface more finely which causes the file size to be large. Figure 4 shows a CAD model exported to a coarse resolution STL (114KB), fine resolution STL (300 KB), and a very fine resolution STL file (1.51 MB). A more complicated design with complicated features would also result in a large STL file size. Figure 5 shows an exaggerated view of how the export STL tolerance option affects how the 3D CAD model’s surface is described. Furthermore, depending on how fine the tolerances are set, computation power to export the CAD model and process the file for fabrication could be an issue. Once the appropriate STL file has been generated, this is then loaded into the individual RP Company’s proprietary software to be processed into 2D slices for fabrication.

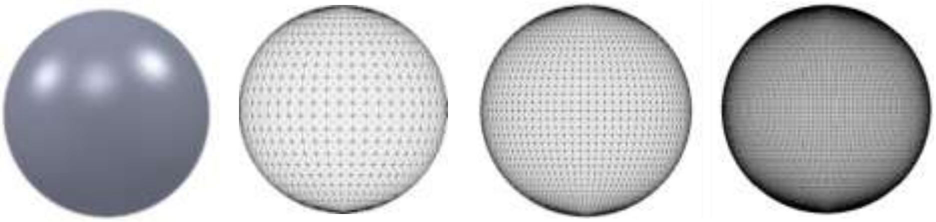


Figure 4 – CAD model to a coarse STL, fine STL, and a very fine STL file.

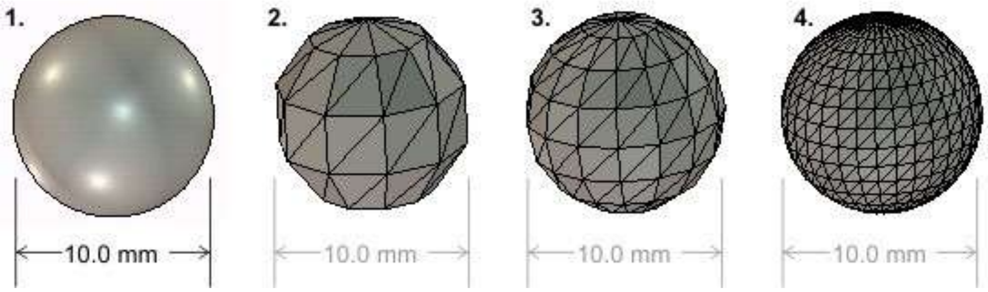
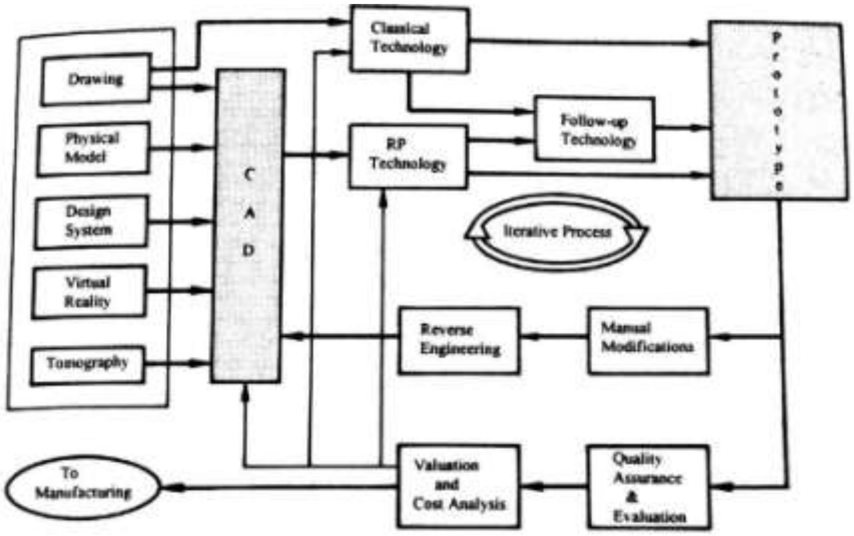


Figure 5 – Exaggerated view of different STL tolerances.

Process chain in RP in integrated CAD-CAM environment

- In all commercially developed and technically demonstrated GMP till date the development of part is done by the slicing technique.
- However a direct 3-dimensional building up technique is also under active consideration. In this technique it will not be necessary to define the part in terms of thin layers and the process will not require the generation of lower part before the upper part is generated.
- Thus, the freedom and flexibility in shape creation and enhanced, but it puts a great burden on programming the generating equipment. The figure below shows the whole processchain of rapid product development using RP technique.



Process chain for rapid prototype development

UNIT -2: TYPES OF PROTOTYPING SYSTEMS

Additive Rapid Prototyping

The different types of additive RP technologies can be categorized into three types: liquid based (SLA and Inkjet based Printing), solid based (FDM), and powder based (SLS). These are just a few examples of the different RP technologies in existence. Regardless of the different types of RP technologies, all of them require the 3D CAD model's STL file for fabrication. These STL files are then used to generate to 2D slice layers for fabrication.

Liquid base - Stereo Lithography Apparatus (SLA) and Inkjet based printing

StereoLithography Apparatus (SLA)

SLA RP technology has three main parts: a vat filled with ultraviolet (UV) curable photopolymer, a perforated build tray, and an UV laser, Fig. 6. Figure 7 shows a production level SLA system by 3DSYSTEMS. The fabrication process starts with positioning the build tray a slice layer depth below the surface of the photopolymer. A slice layer is cured on to the build tray with the UV laser. The pattern of the slice layer is "painted" with the UV laser with the control of the scanner system. Once the layer is cured, the tray lowers by a slice layer thickness allowing for uncured photopolymer to cover the previously cured slice. The next slice layer is then formed on top of the previous layer with the UV laser, bonding it to the previous layer. This process is repeated until the entire 3D object is fully formed. The finished 3D object is removed and washed with solvent to remove excess resin off the object. Finally, the object is placed in a UV oven for further curing. During the fabrication process, support scaffolding can be fabricated to support overhangs or undercuts of the 3D object. These can be cut off after fabrication.

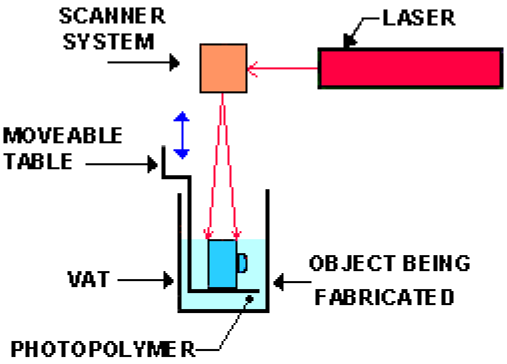


Figure 6 - StereoLithography apparatus (SLA) [3].

Figure 7 – 3DSYSTEMS SLA production RP printers [4].

Inkjet based Printing

This RP technology is similar to the SLA technology, both of which utilize UV curable photopolymer as the build material. Two types of UV curable photopolymer materials are used: model that act as the structure and support material acting as scaffolding to the object. The technology is based on inkjet systems as shown in Fig. 8 where it has 'ink' cartridges and a print head.

During fabrication, a thin layer of photopolymer is jetted on to the build tray. The jetted photopolymer is cured by UV lamps mounted to the side of the print heads. Next, the tray lowers by precisely one layer's thickness, allowing for the next slice to be jetted on to the previous slice. This process repeats until the 3D object is formed. Once completed, the support material is removed with a high pressure washer. A commercially available inkjet based RP printer by Stratasys is shown in Fig. 9.

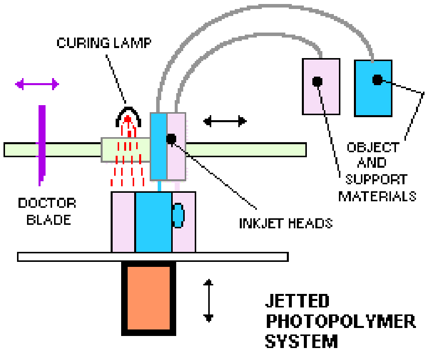


Figure 8 – Inkjet based printing [3].

Figure 9 – Stratasys inkjet based RP printer [5].

Solid based: Fused Deposition Modeling (FDM)

FDM RP technologies use a thermoplastic filament, which is heated to its melting point and then extruded, layer by layer, to create a three dimensional object, shown in Fig. 10. Two kinds of materials are used: a model material which acts as the structure and a support material which acts as a scaffolding to support the object during the fabrication process.

During the fabrication process, the filaments are fed to an extrusion nozzle unwounded from a coil. This nozzle is heated to melt the filament which is then extruded on to a build tray forming a slice of the 3D object as cools and hardens. Next, the build tray is lowered or the extrusion nozzle is raised, by a thickness of an extruded layer, for the next slice layer to be extruded on top of the previous layer. As the extruded thermoplastic cools, it also binds to the previous layer. This continues until all the slices are printed to finally form the full 3D object. After the fabrication process, the support build material is typically dissolved by water if water-soluble wax was used or broken off if polyphenylsulfone was used. An affordable desktop version by 3DSYSTEM is shown in Fig. 11.

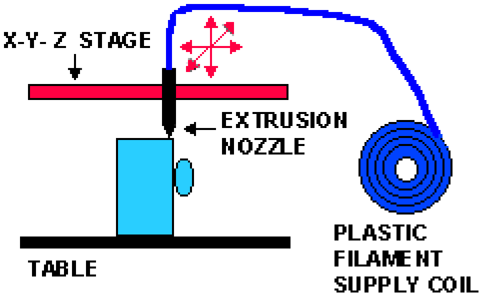


Figure 10 – Fused deposition modeling [3].

Figure 11 – 3DSYSTEMS FDM desktop RP printer [6].

UNIT-3: POWDER BASED RAPID PROTOTYPING SYSTEMS AND TOOLING

Powder Base: Selective Laser Sintering (SLS)

SLS is similar to SLA in which it also uses a laser and build tray except instead of using a vat of liquid photopolymer as the build material it uses a powder build material. The powder used can be plastic nylon, ceramic, glass or metal. A schematic of this system is shown in Fig. 12. This RP technique can be used to create both prototypes as well as final products. Figure 13 shows a production level SLS system by 3DSYSTEM.

A high power laser is used to heat the powder build material to just below its boiling point (sintering) or above boiling point (melting) to fuse it together to form the 3D object's slice layers. Once a slice layer is formed, the build tray lowers by a slice layer's thickness. Next, the roller spreads more powder build material over the previously fused slice layer for the next slice layer to be sintered. This repeats until the 3D object is formed. Another difference to the SLA RP technique is that it does not require any support scaffolding as it is supported by the powder build material surrounding the object.

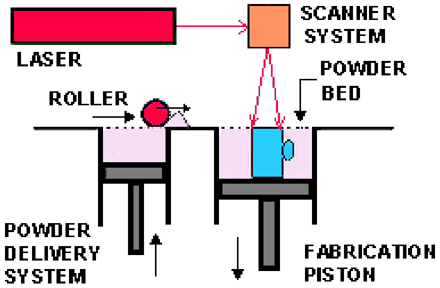


Figure 12 – Selective Laser Sintering [3].

Figure 13 –3DSYSTEMS production SLS RP printer [5].

Comparison of different RP technology

Comparison from [3].

	Stereolithography Aparatus (SLA)	Inkjet Based	Fused Deposition Modeling (FDM)	Selective Laser Sintering (SLS)
Build tray size (inches)	20 x 20 x 24	12 x 6 x 9	24 x 20 x 24	27.5 x 15 x 23
System price range	$75K-800K	$46K-80K	$10K-300K	$200K-1M+
Speed	Average	Poor	Poor	Average to good
Accuracy	Very good	Excellent	Fair	Good
Surface Finish	Very good	Excellent	Fair	Good to very good
Strengths	• Large part size • Accuracy	• Accuracy • Finish	• Price • Materials	• Accuracy • Materials
Weaknesses	• Post processing • Messy liquids	• Speed • Limited materials • Part size	• Speed • Part size	• Size and weight • System price • Surface finish

Typical applications	- Very detailed parts and models for fit & form testing - Trade show and marketing parts & models - Rapid manufacturing of small detailed parts - Fabrication of specialized manufacturing tools - Patterns for investment casting - Patterns for urethane & RTV molding	- Most detailed parts and models available using additive technologies for fit & form testing - Patterns for investment casting, especially jewelry and fine items, such as medical devices - Patterns for urethane & RTV molding	- Detailed parts and models for fit & form testing using engineering plastics - Detailed parts for patient- and food- contacting applications - Plastic parts for higher-temperature applications - Trade show and marketing parts & models - Rapid manufacturing of small detailed parts - Patterns for investment casting - Fabrication of specialized manufacturing tools - Patterns for urethane & RTV molding	- Slightly less detailed parts and models for fit & form testing compared to photopolymer-based methods - Rapid manufacturing of parts, including larger items such as air ducts - Parts with snap-fits & living hinges - Parts which are durable and use true engineering plastics - Patterns for investment casting

	Stereolithography Aparatus (SLA)	**Inkjet Based**	**Fused Deposition Modeling (FDM)**	**Selective Laser Sintering (SLS)**
Available build material	• Acrylics (fair selection) • Clear and rigid • ABS-like • Polypropylene-like (PP) • Flexible or elastomeric Water-resistant	• Polyester-based plastic • Investment casting wax	• ABS • Polycarbonate (PC) • Polyphenylsulfone Elastomer	• Nylon, including flame-retardant, glass-, aluminum-, carbon-filled and others providing increased strength and other properties • Polystyrene (PS) • Elastomeric • Steel and stainless steel alloys • Bronze alloy • Cobalt-chrome alloy Titanium

Rapid Prototyping Optomechanics

Additive RP technologies can be useful with fabricating the optomechanics in an optical system. Figure 14 shows a CAD design of a spectral image classifier and the fabricated system with an inkjet based RP printer shown in Fig. 15. New RP technology has allowed for optical systems to have an integrated design and be fabricated directly. One can design an optical system with a ray tracing program then easily design a 3D CAD model to match the optimization performed previously by the ray tracing program. The choice of additive RP technology would depend on fabrication time, cost, and build material requirements.

Typical 3D CAD design considerations that would need to be taken into account includes:

1. RP fabrication tolerances – fitting and alignment
2. Optical fine adjustment ability
3. Stiffness of material to support heavy optical devices
4. Fasteners
5. Adhesion

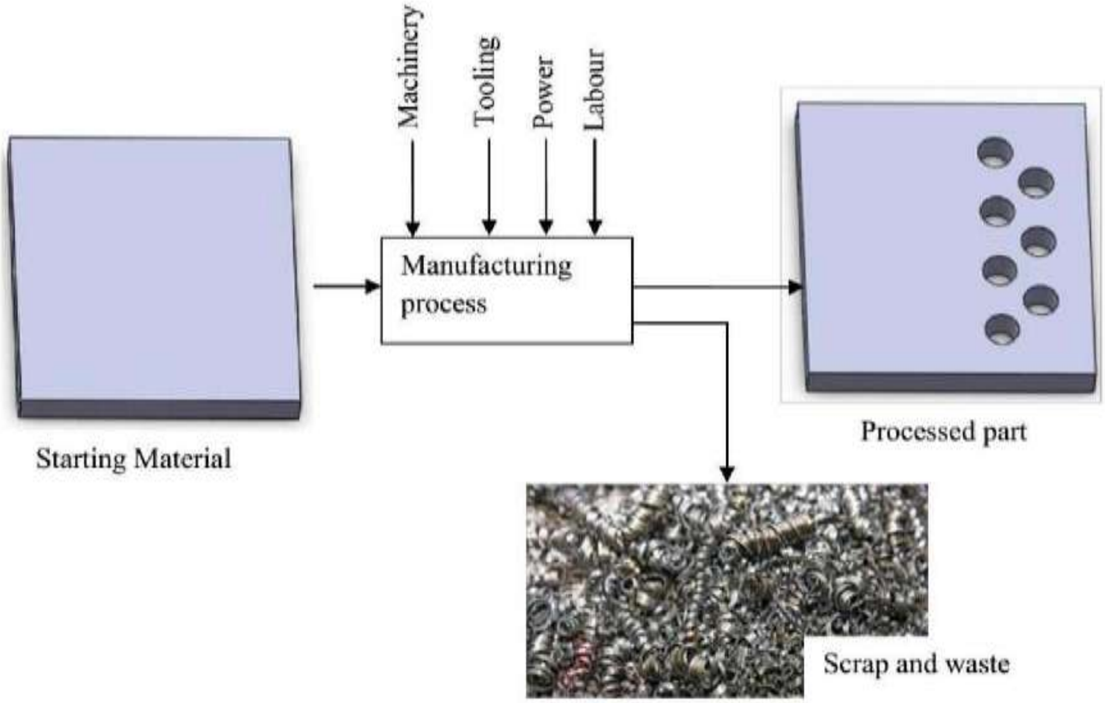
Manufacturing

The English word manufacture is several centuries old. The term manufacture comes from two Latin words, manus (hand) and factus (make). As per oxford English dictionary manufacture refers "to make or produce goods in large quantities, using machinery".

Working definition of manufacturing

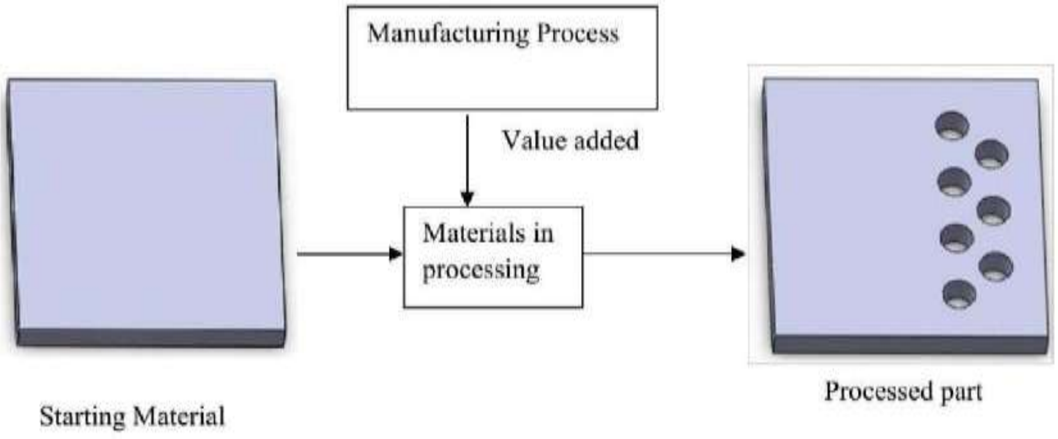
There are two types of working definitions available for manufacturing: as a technical process and as an economic process.

Technologically: Manufacturing is the application of physical and chemical processes to alter the geometry, properties and or appearance of a given starting material to make parts or product as shown in Figure

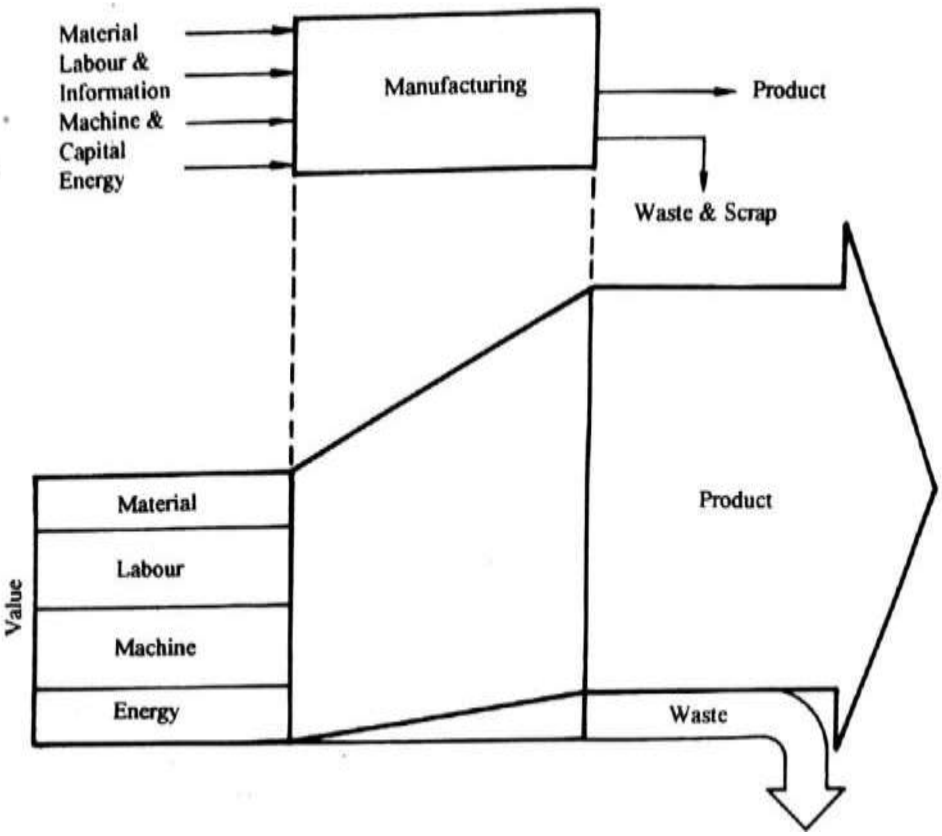


Definition of manufacturing in terms of technology

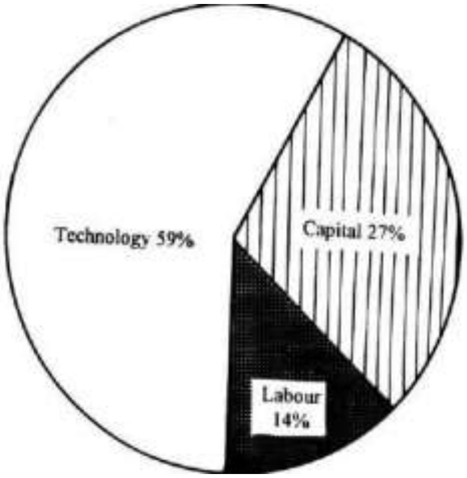
Economically: Manufacturing is the transformation of materials into items of greater value by means of one or more process and or assembly operation as shown in Figures.



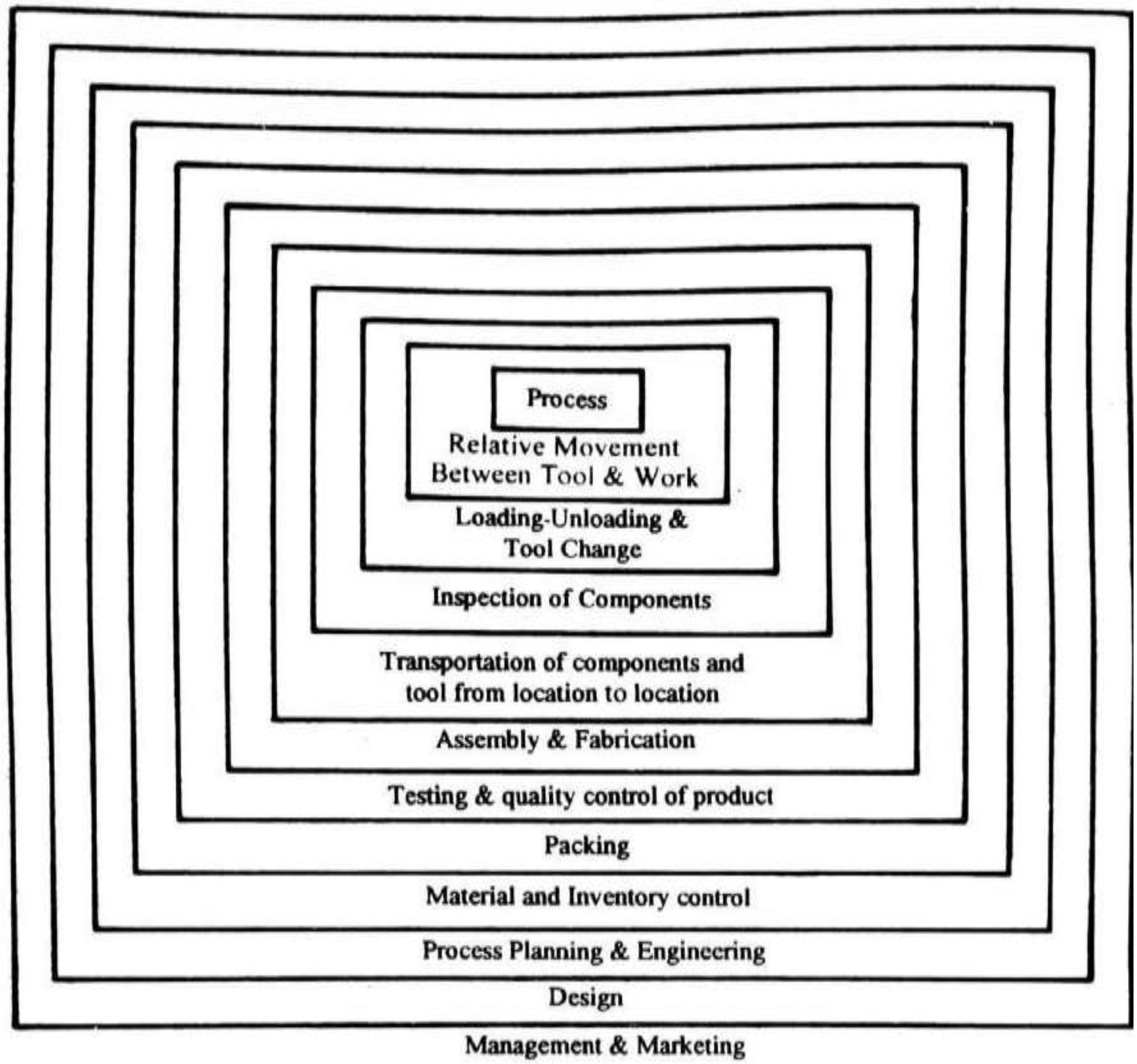
Definition of manufacturing in terms of economic value



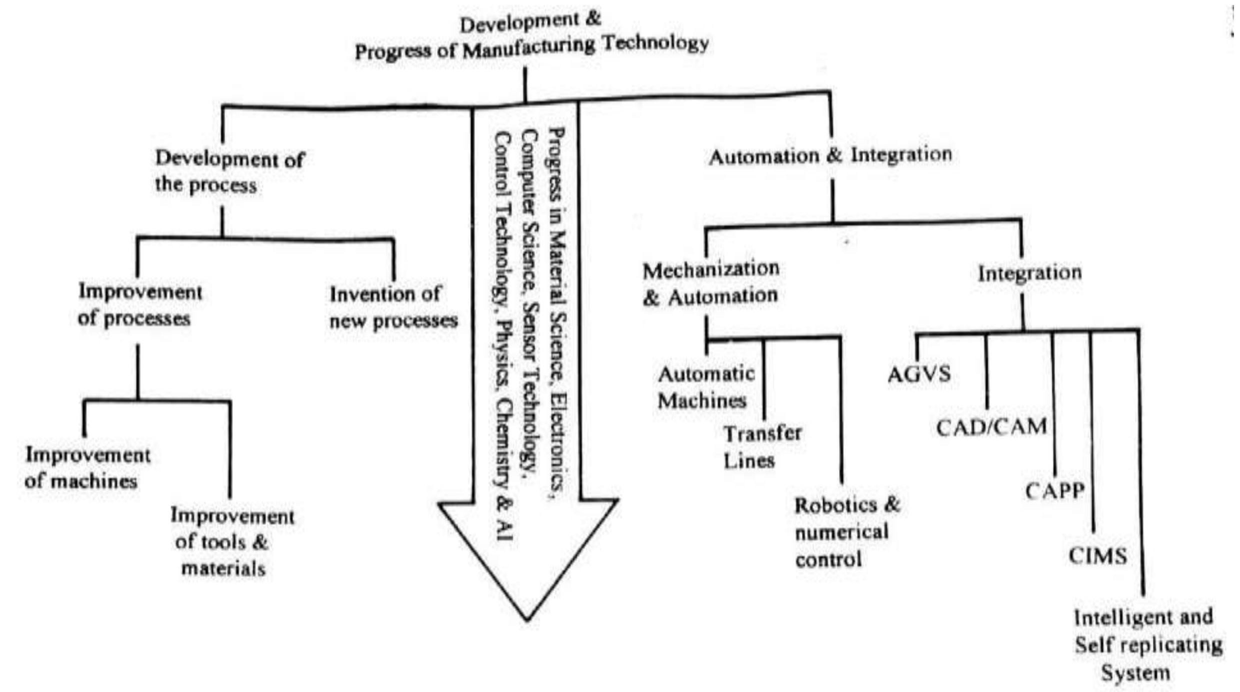
Diagrammatic representation of Manufacturing



Factors Contributing to Production Growth



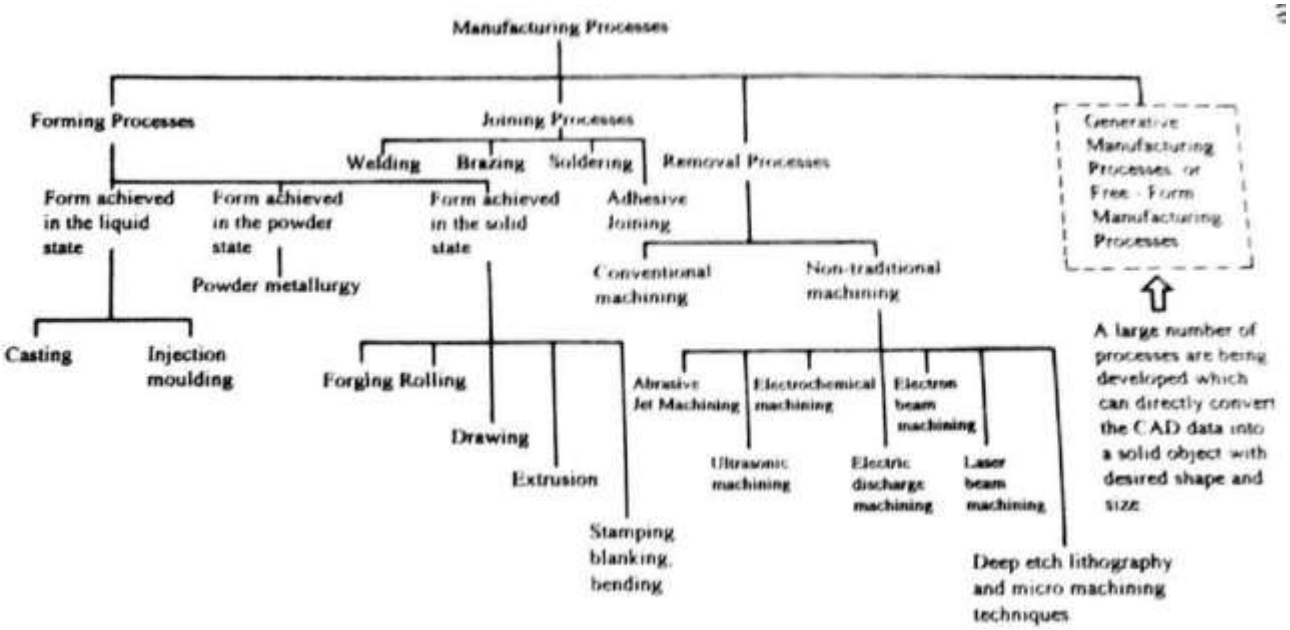
Activities involved in Manufacturing



Development and Progress of Manufacturing

Classification of the Manufacturing Process:

- The manufacturing process used in engineering industries basically perform one or more of the following functions:
  - Change the physical properties of the work material
  - Change the shape and size of the work piece.
  - Produce desired dimensional accuracy and surface finish.
- Based on the nature of work involved these processes may be divided into following seven categories:
  1. Processes for changing physical properties of the materials –
     Hardening, Tempering, Annealing, Surface Hardening.
  2. Casting Processes – Sand Casting, Permanent mold casting, die casting, Centrifugal casting
  3. Primary metal working processes – Rolling, forging, extrusion, wire drawing
  4. Shearing and Forming processes – Punching, blanking, drawing, bending, forming
  5. Joining processes – Welding, brazing, soldering, joining
  6. Machining Processes – Turning, drilling, milling, grinding
  7. Surface finishing processes – Lapping, honing, superfinishing

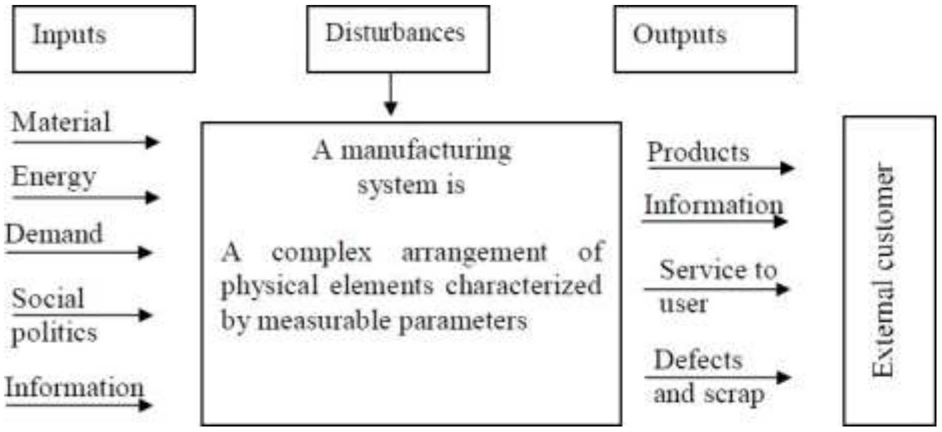


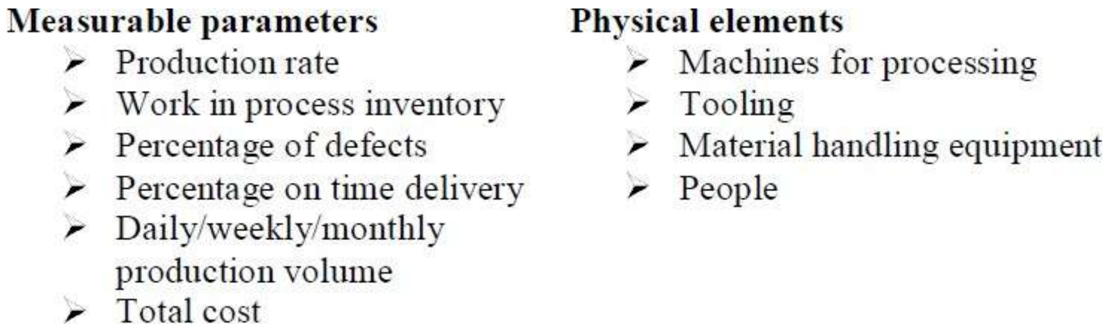
Spectrum of Manufacturing Process

MANUFACTURING SYSTEM

The term manufacturing system refers to a collection or arrangement of operations and processes used to make a desired product or component. It includes the actual equipment for composing the processes and the arrangement of those processes. In a manufacturing system, if there is a change or disturbance in the system, the systems would accommodate or adjust itself and continue to function efficiently. Normally the effect of disturbance must be counteracted by controllable inputs or the system itself. Figure below gives the general definition for any manufacturing system.

General representation of manufacturing system





Measurable parameters

- Production rate
- Work in process inventory
- Percentage of defects
- Percentage on time delivery
- Daily/weekly/monthly production volume
- Total cost

Physical elements

- Machines for processing
- Tooling
- Material handling equipment
- People

TYPES OF MANUFACTURING SYSTEMS

The manufacturing systems differ in structure or physical arrangement. According to the physical arrangement, there are four kinds of classical manufacturing systems and two modern manufacturing systems that is rapidly gaining acceptance in industries.

The classical systems are

1. Job shop
2. Flow shop
3. Project shop
4. Continuous process

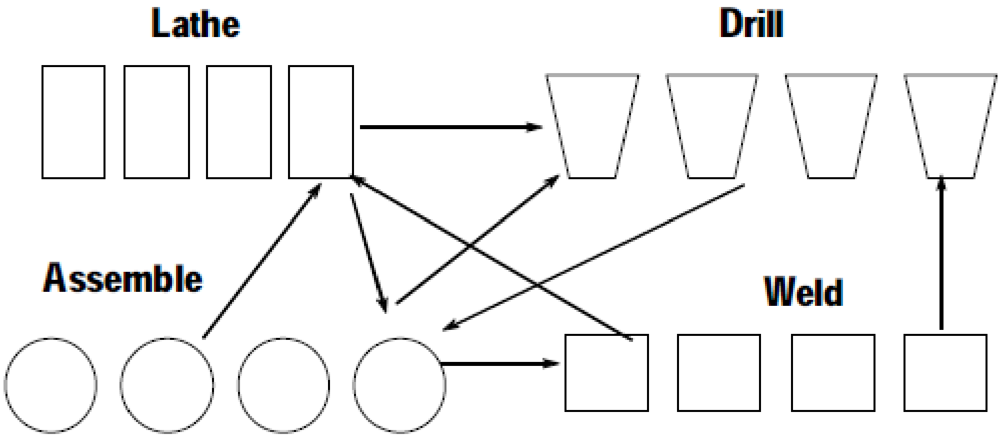
The modern manufacturing systems are

1. Linked cell system (Cellular manufacturing system)
2. Flexible manufacturing system (FMS)

Job shops

In a Job shop, varieties of products are manufactured in small lot sizes to a specific customer order. To perform a wide variety of manufacturing processes, general purpose production equipment is required. Workers must have relatively high skill levels to perform a range of different work arrangements.

The production machines are grouped according to the general type of manufacturing processes as shown in Figure below. The lathes are in one department, drill presses in another and so on. Each different part requiring its own sequence of operations can be routed through the various departments in the proper order. For this 'ROUTE SHEETS' are used. The layout made for this purpose is called as functional or process layout.



Functional or process layout

Advantages of process layouts

- Can handle a variety of processing requirements
- Not particularly vulnerable to equipment failures
- Equipment used is less costly
- Possible to use individual incentive plans

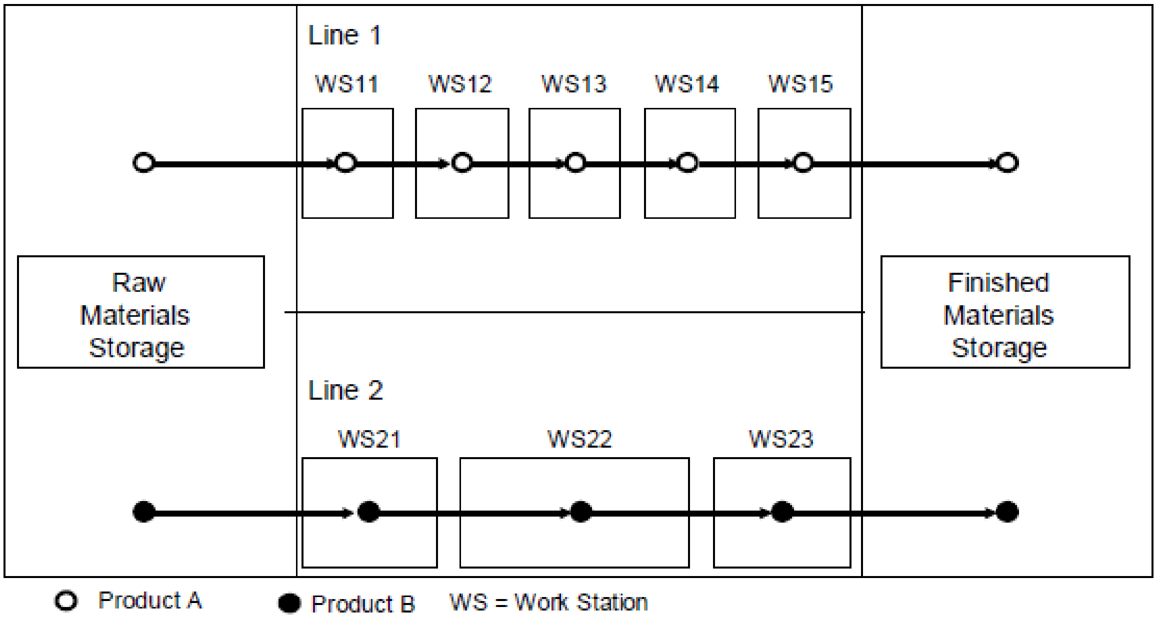
Disadvantages of process layouts

- In-process inventory costs can be high
- Challenging routing and scheduling
- Equipment utilization rates are low
- Material handling is slow and inefficient
- Complexities often reduce span of supervision
- Special attention for each product or customer
- Accounting and purchasing are more involved

Examples: Machine shops, foundries, press working shops, plastic, industries.

Flow shops

The flow shops have a “product oriented layout” composed mainly of flow lines. This system can have high production rates. The plant may be designed to produce the particular product or family, using “Special purpose machines” rather than general purpose equipment. The skill level of the laborer tends to be lower than in production job shop. When the volume of production becomes large, it is called “mass production”. The material flow is through a sequence of operations by material handling devices. The time the item spends in each station or location is fixed and equal. The workstations are arranged in line according to the processing sequence needed as shown in Figure below



Product layout

Advantages of product layout

- High rate of output
- Low unit cost
- Labor specialization
- Low material handling cost
- High utilization of labor and equipment
- Established routing and scheduling
- Routing accounting and purchasing

Disadvantages of product layout

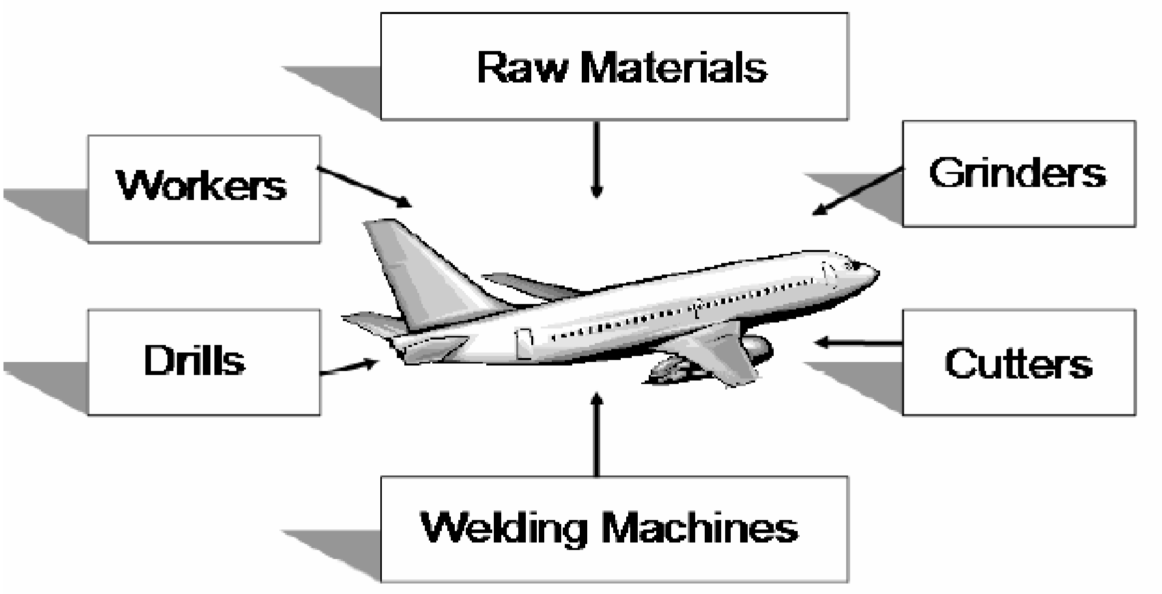
- Creates dull, repetitive jobs
- Poorly skilled workers may not maintain equipment or quality of output
- Fairly inflexible to changes in volume
- Highly susceptible to shutdowns
- Needs preventive maintenance
- Individual incentive plans are impractical

Example: Automated assembly line and Television manufacturing factory.

Project shop

In this type, a product must remain in a fixed position or location because of its size and weight. The materials, machines and people in fabrication are brought to site. The layout is also called as fixed position layout. Figure below shows the project shop layout.

Example: Locomotive manufacturing, large aircraft assembly and shipbuilding



Project shop layout

Advantages of project layout

- Minimum capital investment
- Continuity of operation

- Less total production cost.
- Offers greater flexibility
- Allows the change in production design.
- Permits a plant to elevate the skill of its operators

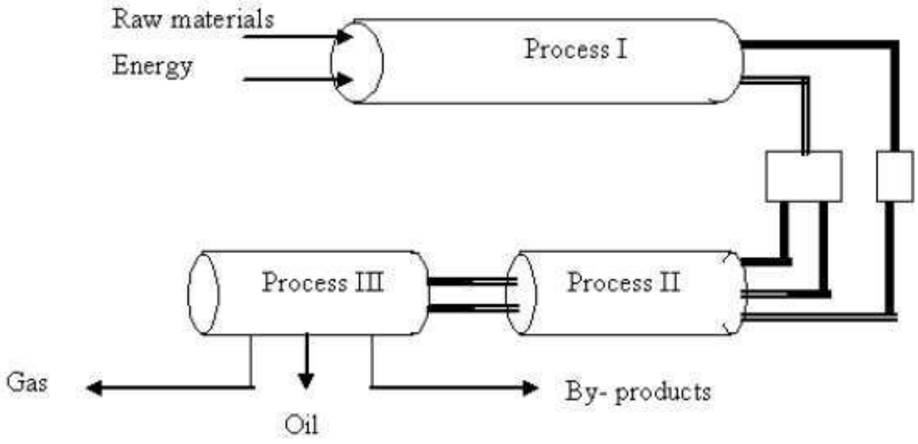
Disadvantages of project layout

- Machines, tools and workers take more time to reach the fixed position.
- Highly skilled workers are required.
- Complicated jigs and fixtures (work holding device) may be required.

Continuous process

In this continuous process, the product seems to flow physically. This system is sometimes called as flow production when referring to the manufacture of either complex single parts, such as scanning operation, or assembled products such as TVs. However, this is not a continuous process, but high volume flow lines. In continuous process, the products really do flow because they are liquids, gases, or powers. Figure 1.5 shows the continuous process layout. It is the most efficient but least flexible kind of manufacturing system. It usually has the leanest and simplest production system because this manufacturing system is the easiest to control because it has the least work- in progress(WIP).

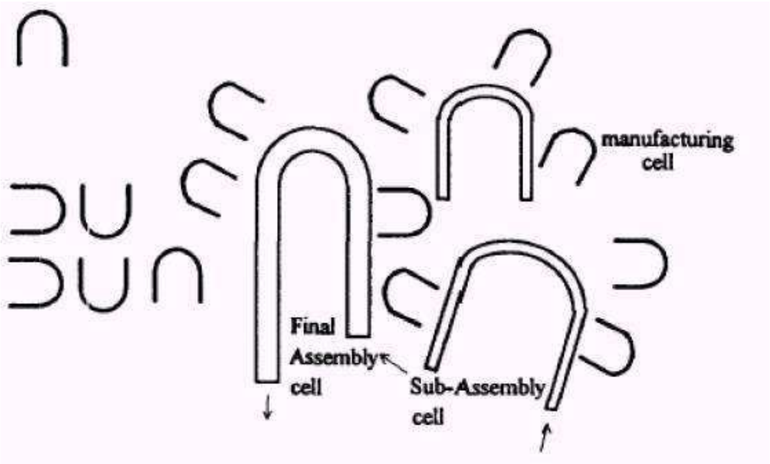
Examples: Oil refineries, chemical process plants and food processing industries



Continuous process layout

Linked cell manufacturing system

Cellular manufacturing (CM) is a hybrid system for linking the advantages of both job shops (flexibility in producing a wide variety of products) and flow lines (efficient flow and high production rate). A cellular manufacturing system (CMS) is composed of “linked cells”. Figure below shows the main structure of cellular manufacturing system. In cells, the workstations are arranged like a flow shop. The machines can be modified, retooled and regrouped for different product lines within the same “family” of parts. This system has some degree of automatic control for loading and unloading of raw materials and work pieces, changing of tools, transferring of work pieces and tools between workstations. Cells are classified as manned and unmanned cells. In manned cells multifunctional operators can move from machine to machine and the materials can be moved by the operator. In the unmanned cells, an industrial robot is located centrally in the cell for material handling. Automated inspection and testing equipment can also be a part of this cell.



Main structure of cellular manufacturing System

Advantages of CMS

The advantages derived from CMS in comparison with traditional manufacturing systems in terms of system performance have been discussed in Farrington (1998), Kannan (1999), Suresh (2000),Hug (2001) and Assad (2003). These benefits have been established through simulation studies, analytical studies, surveys, and actual implementations.

They can be summarized as follows:

Setup time is reduced: A manufacturing cell is designed to handle parts having similar shapes and relatively similar sizes. For this reason, many of the parts can employ the same or similar holding devices (fixtures). Generic fixtures for a part family can be developed so that time required for changing fixtures and tools is decreased.

Lot sizes are reduced: Once setup times are greatly reduced in CM, small lots are possible and economical. Small lots also provide smooth production flow.

Work-in-process (WIP) and finished goods inventories are reduced: With smaller lot sizes and reduced setup times, the amount of WIP can be reduced. The WIP can be reduced by 50%when the setup time is cut to half. In addition to the reduced setup times and WIP inventory, finished goods inventory is reduced. Instead of make-to-stock systems with parts either being run at long, fixed intervals or random intervals, the parts can be produced either JIT in small lots or at fixed, short intervals.

Material handling costs and time are reduced:
In CM, each part is processed completely within a single cell (wherever possible). Thus, part travel time and distance between cells is minimal.

A reduction in flow time is obtained:
Reduced materials handling time and reduced setup time greatly reduce flow time.

Tool requirements are reduced:

Parts produced in a cell are of similar shape, size, and composition. Thus, they often have similar tooling requirements.

A reduction in space required:

Reductions in WIP, finished goods inventories, and lot sizes lead to less space required.

Throughput times are reduced:

In a job shop, parts are transferred between machines in batches. However, in CM each part is transferred immediately to the next machine after it has been processed. Thus, the waiting time is reduced substantially.

Product quality is improved:

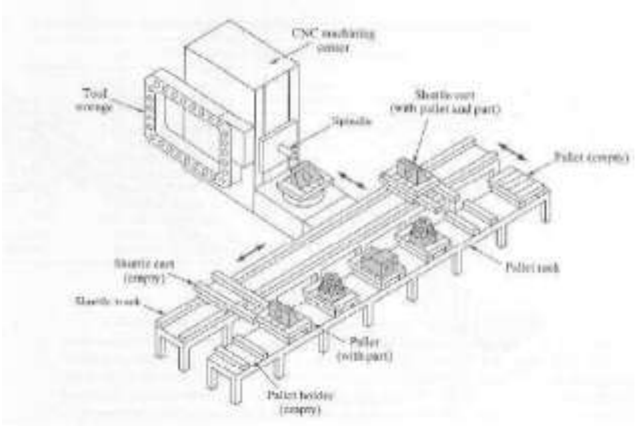
Since parts travel from one station to another as single unit, they are completely processed in a small area. The feedback is immediate and the process can be stopped when things go wrong.

Better overall control of operations:

In a job shop, parts may have to travel through the entire shop. Scheduling and material control are complicated. In CM, the manufacturing facility is broken down into manufacturing cells and each part travels with a single cell, resulting in easier scheduling and control.

Flexible manufacturing system

A FMS integrates all major elements of manufacturing into a highly automated system. The flexibility of FMS is such that it can handle a variety of part configurations and produce them in any order. Figure 1.7 shows flexible manufacturing system. The basic elements of FMS are a) works station b) automated material handling and automated storage and retrieval systems c) control systems. Because of major capital investment; efficient machine utilization is essential. Consequently, proper scheduling and process planning are crucial, that are complex in nature. Because of the flexibility in FMS, no setup time is wasted in switching between manufacturing operations; the system is capable of different operations in different orders and on different machines.



Flexible manufacturing system

Advantages:

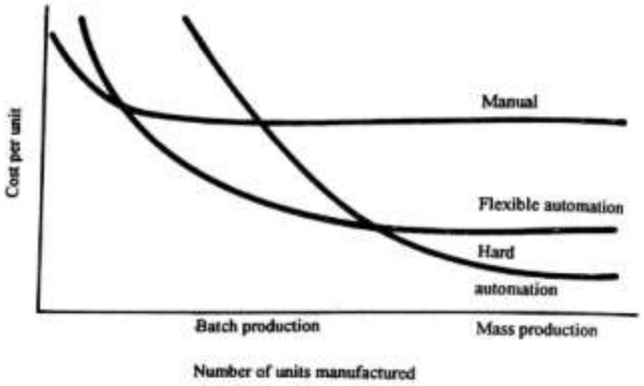
- Parts can be produced randomly in batch sizes, as small as one, and at lower cost.
- The lead times required for product changes are shorter
- Reduced WIP
- Labour and inventories are reduced
- Production is more reliable, because the system is self-correcting and so product quality is uniform.
- Increased machine utilization
- Fewer machines required
- Reduced factory floor space
- Greater responsiveness to change

Automation:

With the advent of mass manufacturing concept, the fruits of technology have reached the common man. Without mass production, cost of the products would have kept several items, which are now common, far beyond the reach of most people. To increase the productivity hence lower the production cost as much as possible automation was introduced in the engineering manufacturing industries. At the onset such automation was primarily named as Automatic Mechanization. These specially designed manufacturing units could be cost effective only when huge quantity of a particular item was needed to be manufactured. The variations in products were few and the demand for individual items was large. Thus this type of automation now- a-days called '**Hard Automation'**.

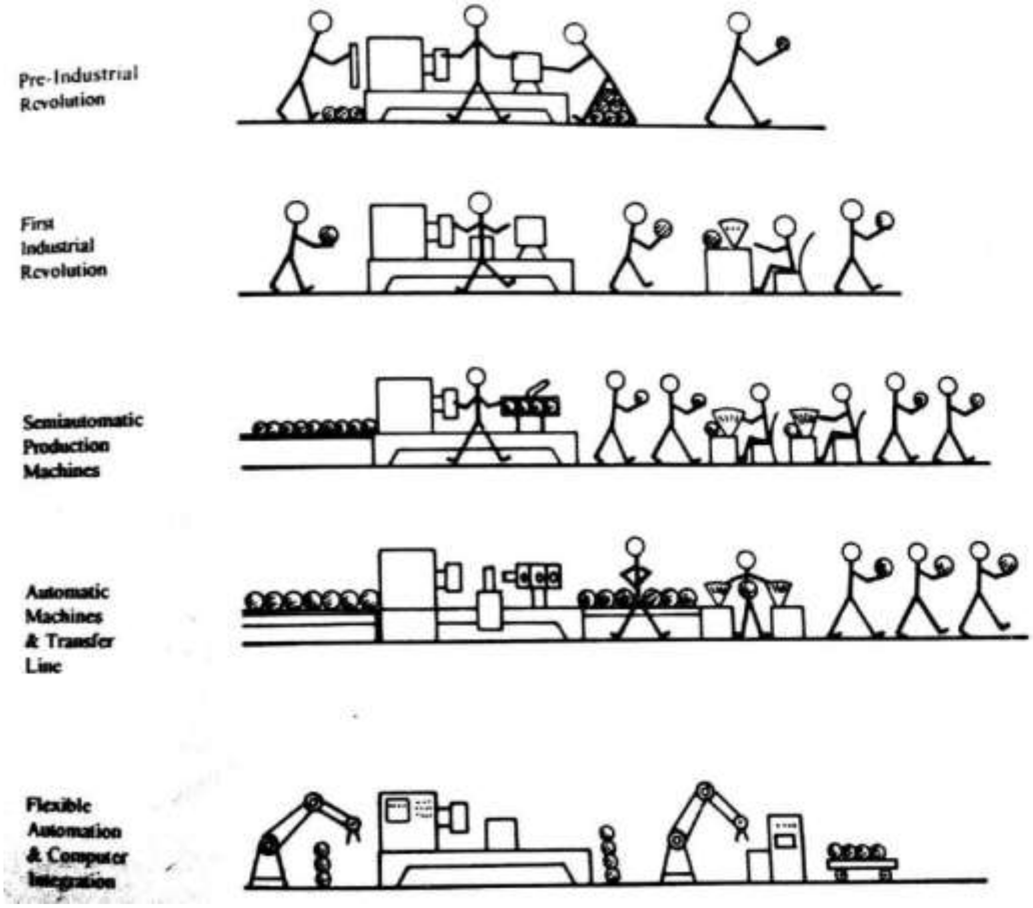
In the 1940's the concept of computer emerged and that led to the development of 'numerical control' for machine tools. Changing a set-up for switching over from one job to another involved changing a substantial amount of the hardware i. e. cams, fixtures, tooling etc. it was time consuming and was expensive also. Once the concept of computer developed it becomes possible to store and feed information with the help of numbers. Numerical control (NC) implies that the necessary information for producing a particular component in a machine can be provided with the help of numbers. Thus switching over from one job to another involved feeding new data and no major modification of the hardware is necessary. Consequently, such units are very flexible in the sense that switching over from one job to another can be done without major time delay and expense. Use of such flexible machines is termed as '**Flexible Automation**'. With the tremendous development in computer science and micro-electronics, flexible automation has become very inexpensive to achieve. The machines are also now directly controlled by computers and such a control is called '**Computer Numerical Control (CNC**)'

It is easy to visualize that with the help of such flexible automation, the requirement of specialized hardware for automatic production of a particular item is eliminated. Cost effective automatic manufacturing has hence become feasible even for small and medium size batches. Figure below indicates the cost effectiveness of different types of manufacturing automation for different ranges of production.



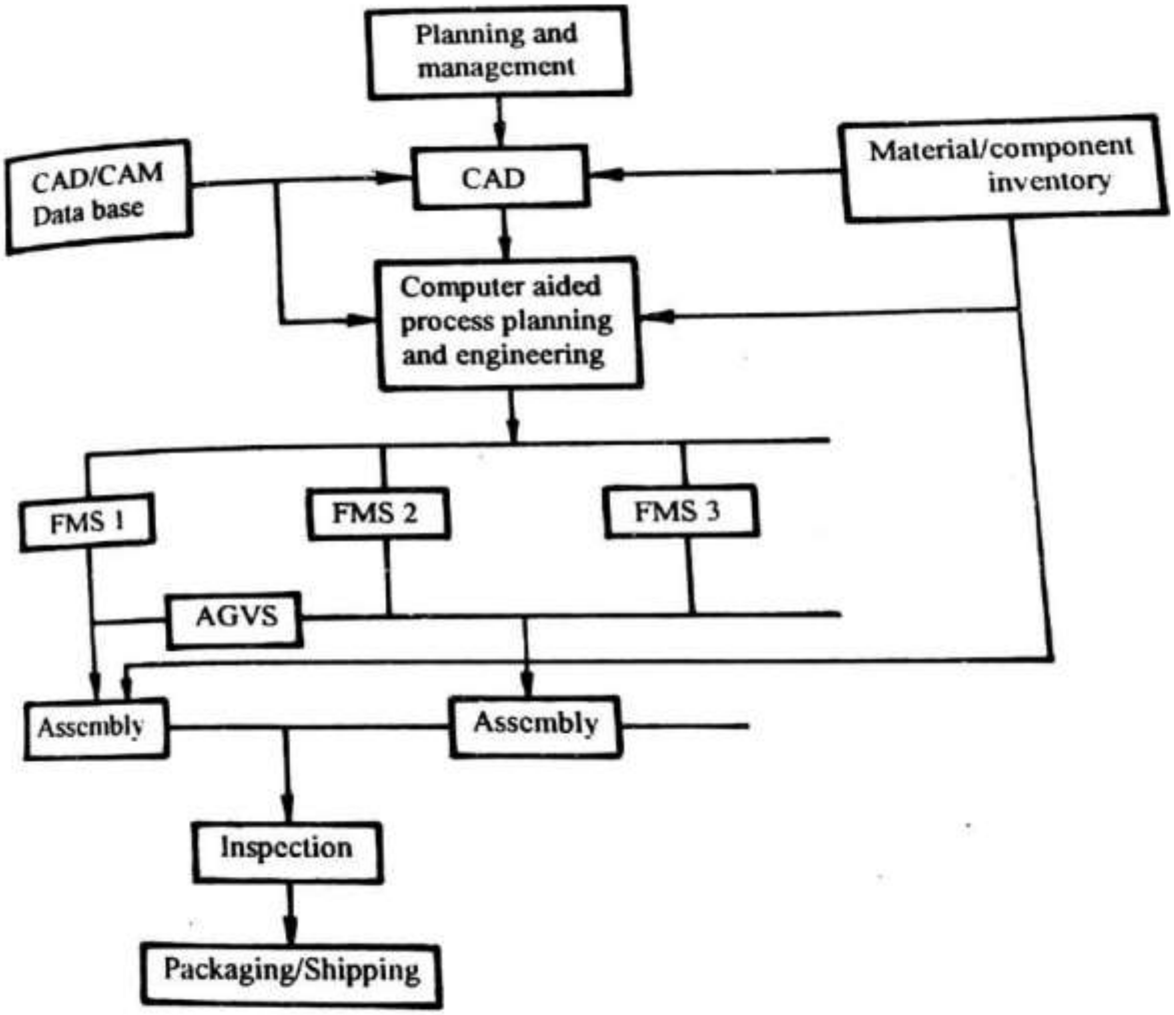
Cost effectiveness of different types of manufacturing automation

Along with the progress in computers, microelectronics and sensor technology gradually appeared in the technological world i.e. ‘**Industrial Robotics**’. With the development of industrial robots, manufacturing industry entered another era where it became possible to realize the dream of true automation. The human work force for tending machines and inspection stations and more important assembly stations could now be replaced by industrial robots. Figure below shows the various stages of mechanization and automation in the engineering manufacturing industry.



Stages of Mechanization in Manufacturing

The use of computers in assisting manufacturing started before CAD developed as useful tool. In the early days the use of computers in extending the applications of NC technology, specially to part programming, was termed as computer aided manufacturing (CAM) and it was delinked from the design activities. Initially CAD and CAM evolved as separate activities, but gradually it became evident that certain tasks were common to both. Use of CAD/CAM in an effective manner helps to improve the design as manufacturing considerations can be incorporated into the design. A substantial amount of improvement in productivity and quality has been found to be possible through the use of CAD.CAM technology. Figure below shows the scheme for CAD/CAM in a modern industry.



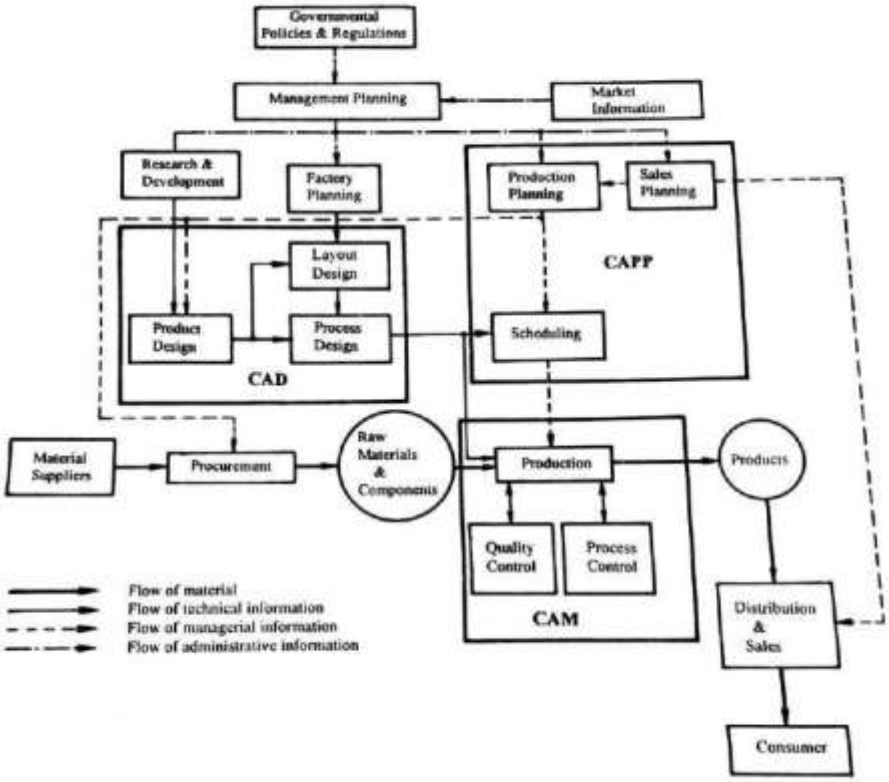
Basic scheme of a manufacturing industry using CAD/CAM

Though the application of computers in manufacturing became quite extensive, the various associated activities still remained compartmentalized and distinct. Once the technology of flexible automation matured integration of the different activities became feasible.

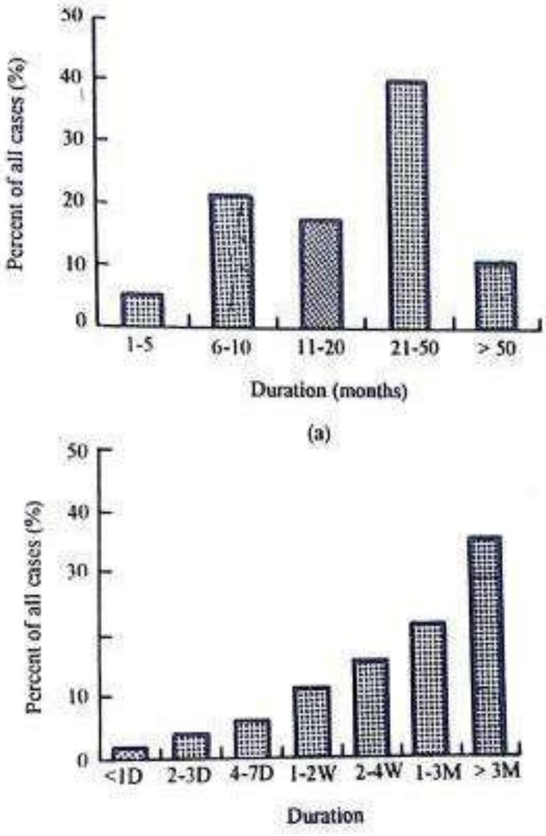
Computer Integrated Manufacturing (CIM)

In a very competitive and open global market survival is possible only if a good product variety is offered, quality and reliability are assured, cost is made attractive and the time gap between the conceptualization of a product and delivery is reduced. To satisfy so many requirements it is essential to strive for optimal use of man. Machine and material. This is possible only if all the activities associated with design and manufacturing are integrated. As mentioned earlier the required electromechanical and computer technologies for such an integration was ready in 80's. such a system is termed as 'computer integrated manufacturing system'(CIMS) and the technology has been given the name 'computer integrated manufacturing (CIM)'. CIM not only implies the use of computer in designing a product, planning inventory and production, controlling the operations and accomplishing many other designs, manufacturing, management and business related issues but suggest a marriage of the diverse functions under the control of one central supervisory computer. The figure below indicates the information flow, material flow and functions involved in CIM.

Structure of CIM

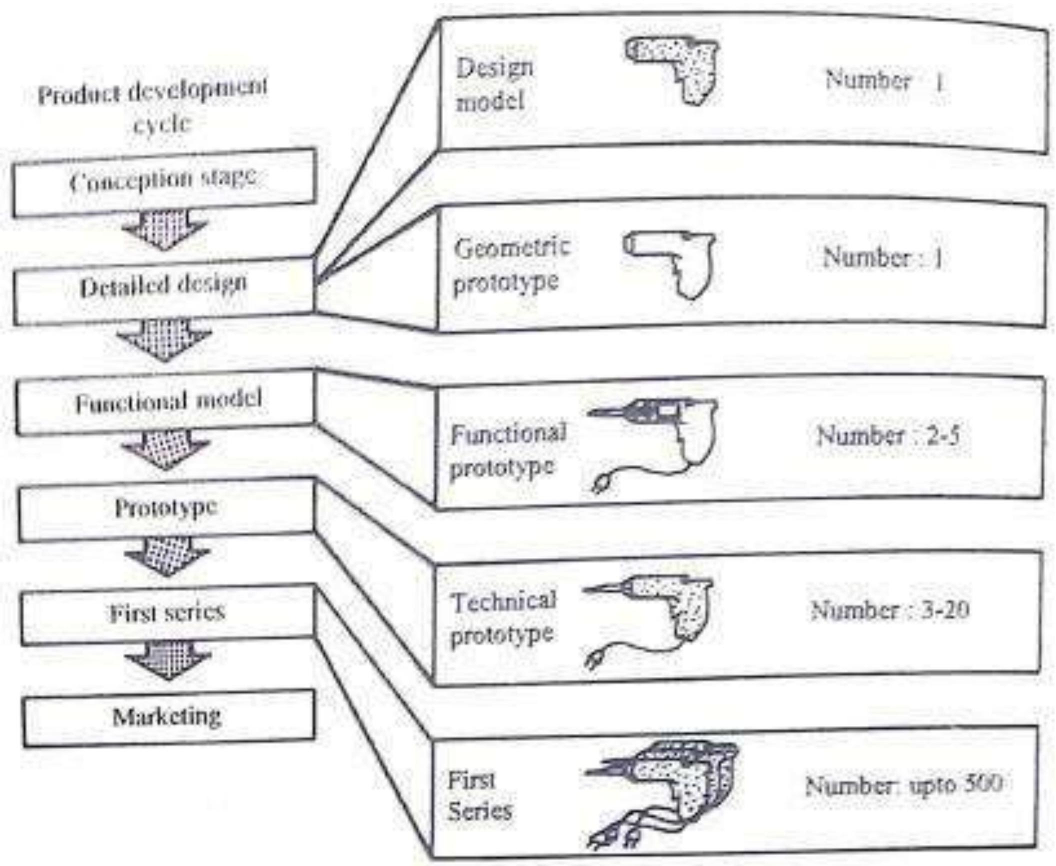


In **concurrent engineering (CE)** product is developed by a team involving engineers from both the design section and the production shop. The advantages of concurrent engineering are based on the economic leverage of addressing all aspects of design of a product as early as possible. Hence using concurrent engineering most of the design modification is incorporated as early as possible. It is also true that the importance of early modification is very significant and the ability of the early change to influence the product cost is much larger as indicated. Hence using concurrent engineering most of the design modifications are incorporated as early as possible.
The duration of prototype development is an important factor and it is found that more than 25% of the total product development time goes in fabricating the prototype. The figure below shows the typical duration of product development and prototype fabrication.



(a) Typical duration of product development, (b) typical duration of Prototype development

Figure below indicates the product development cycle and the prototype for different stages.



- In the early stage of product development a ‘design model’ and a ‘geometric prototype’ are prepared. The design model is made primarily to decide the overall appearance and it is used for ergonomics analysis. Since there is no functional requirement these models are easy to process, non metallic materials can be used for making these models.
- In geometric prototypes the dimensional features of the product,
  accuracy and tolerances are of primary importance. These prototypes are also made of model making materials as functional aspects are of secondary importance. These prototypes are used primarily for process planning. Appearance and many geometric features are not considered at this stage.

- In the next step technical prototypes are made using the same material and the same manufacturing processes as the intended final product. The technical prototypes are useful in assessing various product qualities like reliability, product life etc.
- After the necessary modifications the first series of the product is manufactured and marketed.

Rapid Prototyping (RP)

Though the principle of concurrent engineering (CE) is quite clear and the advantages of the concept for improved quality and reduced cost are implicit, it is not possible to incorporate CE effectively in the absence of some technique for quick development of prototype. To reduce the development time and adopt concurrent engineering in its true spirit, quick and inexpensive fabrication of prototype parts is essential and rapid prototyping technology has made that possible.

A family of unique fabrication processes developed to make engineering prototypes in minimum lead time based on a CAD model of the item

•**The traditional method is machining**

−Machining can require significant lead-times –several weeks, depending on part complexity and difficulty in ordering materials

•RP allows a part to be made in hours or days given that a computer model of the part has been generated on a CAD system

Why Rapid Prototyping?

Because product designers would like to have a physical model of a new part or product design rather than just a computer model or line drawing

−Creating a prototype is an integral step in design

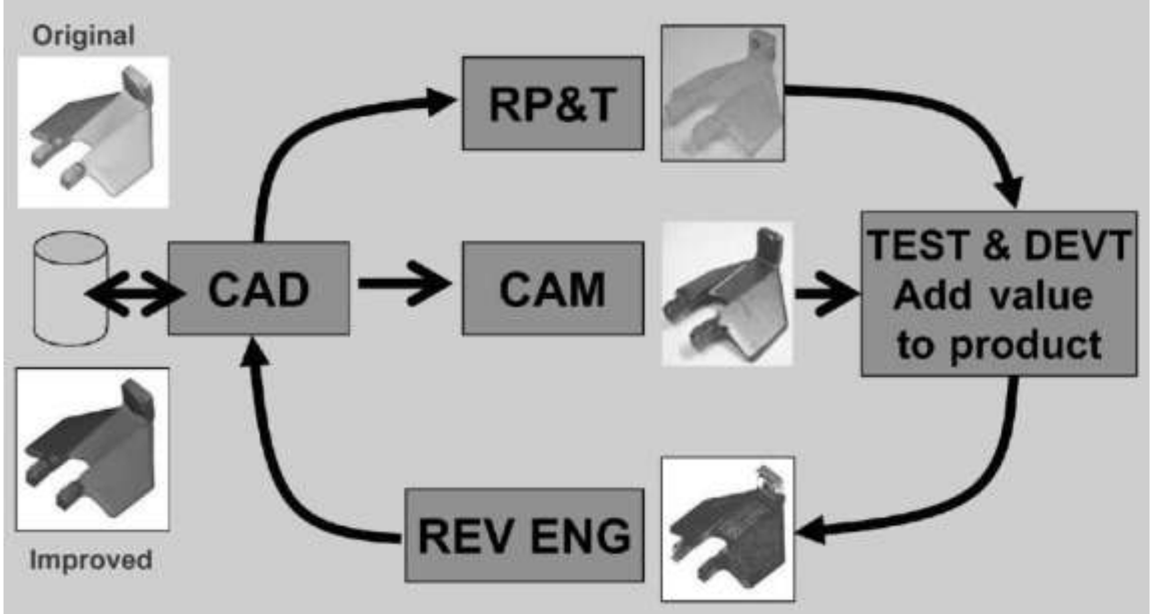
−A *virtual prototype* (a computer model of the part design on a CAD system) may not be sufficient for the designer to visualize the part adequately

−Using RP to make the prototype, the designer can visually examine and physically feel the part and assess its merits and shortcomings

Reverse Engineering:

In today's intensely competitive global market, product enterprises are constantly seeking new ways to shorten lead times for new product developments that meet all customer expectations. In general, product enterprise has invested in CADCAM, rapid prototyping, and a range of new technologies that provide business benefits. Reverse engineering (RE) is now considered one of the technologies that provide business benefits in shortening the product development cycle. Figure below depicts how RE allows the possibilities of closing the loop between what is "as designed" and what is "actually manufactured".

Product development cycle



What Is Reverse Engineering?

Engineering is the process of designing, manufacturing, assembling, and maintaining products and systems. There are two types of engineering, forward engineering and reverse engineering. Forward engineering is the traditional process of moving from high-level abstractions and logical designs to the physical implementation of a system. In some situations, there may be a physical part/product without any technical details, such as drawings, bills-of-material, or without engineering data. The process of duplicating an existing part, subassembly, or product, without drawings documentation, or a computer model is known as reverse engineering.

Reverse engineering is also defined as the process of obtaining a geometric CAD model from 3-D points acquired by scanning/digitizing existing parts/products. The process of digitally capturing the physical entities of a component, referred to as reverse engineering (RE), is often defined by researchers with respect to their specific task.

Reverse engineering is now widely used in numerous applications, such as Manufacturing, industrial design, and jewelry design and reproduction For example, when a new car is launched on the market, competing manufacturers may buy one and disassemble it to learn how it was built and how it works. In software engineering, good source code is often a variation of other good source code. In some situations, such as automotive styling, designers give shape to their ideas by using clay, plaster, wood, or foam rubber, but a CAD model is needed to manufacture the part. As products become more organic in shape, designing in CAD becomes more challenging and there is no guarantee that the CAD representation will replicate the sculpted model exactly.

Reverse engineering provides a solution to this problem because the physical model is the source of information for the CAD model. This is also referred to as the physical-to-digital process depicted in Figure 1.2. Another reason for reverse engineering is to compress product development cycle times. In the intensely competitive global market, manufacturers are constantly seeking new ways to shorten lead times to market a new product.

Rapid product development (RPD) refers to recently developed technologies and techniques that assist manufacturers and designers in meeting the demands of shortened product development time. For example, injection-molding companies need to shorten tool and die development time drastically. By using reverse engineering, a three- dimensional physical product or clay mock-up can be quickly captured in the digital form, remodeled, and exported for rapid prototyping/tooling or rapid manufacturing using multi-axis CNC machining techniques.

Why Use Reverse Engineering?

Following are some of the reasons for using reverse engineering:

- The original manufacturer no longer exists, but a customer needs the product, *e.g.*, aircraft spares required typically after an aircraft has been in service for several years.
- The original manufacturer of a product no longer produces the product, *e.g.*, the original product has become obsolete.
- The original product design documentation has been lost or never existed.
- Creating data to refurbish or manufacture a part for which there are no CAD data, or for which the data have become obsolete or lost.
- Inspection and/or Quality Control–Comparing a fabricated part to its CAD description or to a standard item.
- Some bad features of a product need to be eliminated *e.g.*, excessive wear might indicate where a product should be improved.
- Strengthening the good features of a product based on long-term usage.
- Analyzing the good and bad features of competitors' products.
- Exploring new avenues to improve product performance and features.
- Creating 3-D data from a model or sculpture for animation in games and movies.
- Creating 3-D data from an individual, model or sculpture to create, scale, or reproduce artwork.
- Architectural and construction documentation and measurement.
- Fitting clothing or footwear to individuals and determining the anthropometry of a population.

Basic principles of RP

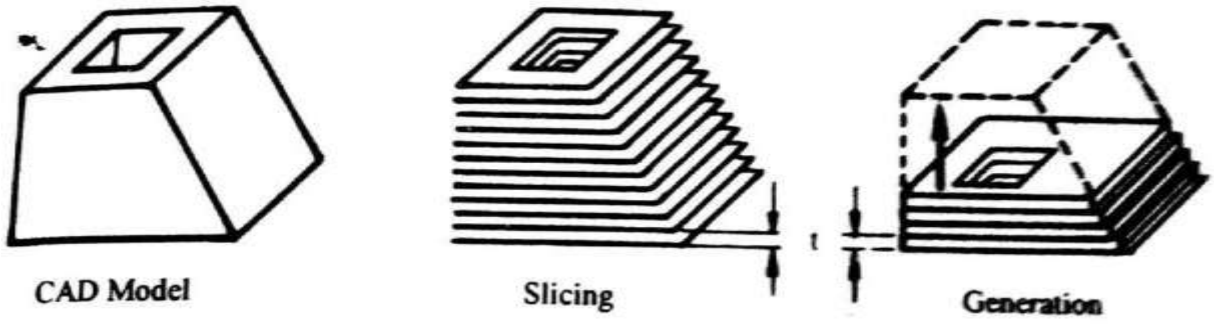
- In this process a solid object with prescribed shape, dimension and finish can be directly produced from the CAD based geometric model data stored in a computer without human intervention.
- Conventional method for producing parts like casting, forming, machining etc are not suitable for this purpose and a host of new processes for shaping objects directly from the CAD data have been developed and machines are in the market.

Rapid prototyping can be of two types:

- The parts obtained by RP technology can form the prototype directly without requiring any further processing.
- The parts obtained by RP technology can be used to make moulds for casting the prototype component. This type is needed because till today, the commercially available RP machines are non metallic materials with low strength and low melting temperature.

In general this technology is called as Generative manufacturing Process (GMP) as the shape of the work piece is not obtained by removal of chips or forming or casting. It is achieved by addition of material without any prior recognizable form or shape and no tool is necessary.

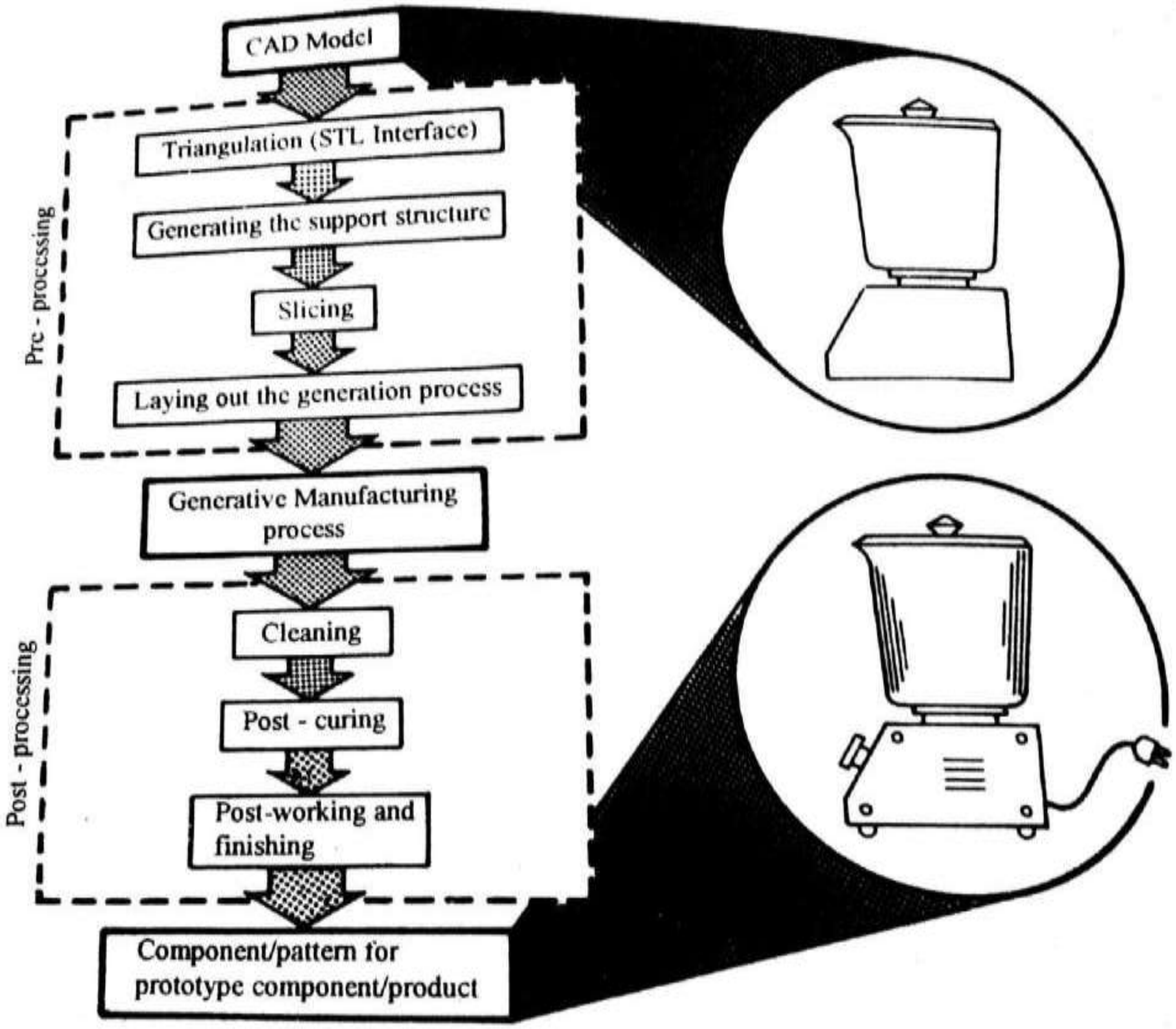
In all types of GMPs the CAD model is split into layers as indicated figure below.



Basic principle of the GMP

- The slice thickness and slicing direction can be varied for convenience of generation.
- To generate an object of same shape as that of sliced CAD model, the distance between the slicing planes (t) must be equal to the thickness of the corresponding layers during the actual generation process.

The general procedure for obtaining a solid component from a CAD file in shown below:



Steps involved in rapid prototyping

Advantages and disadvantages of rapid prototyping

Subtractive type RP is typically limited to simple geometries due to the tooling process where material is removed. This type of RP also usually takes a longer time but the main advantage is that the end product is

fabricated in the desired material. Additive type RP, on the other hand, can fabricate most complex geometries in a shorter time and lower cost. However, additive type RP typically includes extra post fabrication process of cleaning, post curing or finishing.

Here is some of the general advantages and disadvantages of rapid prototyping :

Advantages:

- Fast and inexpensive method of prototyping design ideas
- Multiple design iterations
- Physical validation of design
- Reduced product development time

Disadvantages:

- Resolution not as fine as traditional machining (millimeter to sub- millimeter resolution)
- Surface flatness is rough (dependant of material and type of RP)

Rapid Manufacturing Process Optimization: factors influencing accuracy

Accuracy of a model is influenced by the errors caused during tessellation and slicing at data preparation stage. Decision of the designer about part deposition orientation also affects accuracy of the model.

Errors due to tessellation: In tessellation surfaces of a CAD model are approximated piecewise by using triangles. It is true that by reducing the size of the triangles, the deviation between the actual surfaces and approximated triangles can be reduced. In practice, resolution of the STL file is controlled by a parameter namely chordal error or facet deviation as shown in figure 2. It has also been suggested that a curve with small radius (r) should be tessellated if its radius is below a threshold radius (r_o) which can be considered as one tenth of the part size, to achieve a maximum chordal error of $(r/r_o)^{\alpha}$. Value of α can be set equal to 0 for no improvement and 1 for maximum improvement. Here part size is defined as the diagonal of an imaginary box drawn around the part and α is angle control value (Williams et al., 1996).

Errors due to slicing: Real error on slice plane is much more than that is felt, as shown in figure 12(a). For a spherical model Pham and Demov (2001) proposed that error due to the replacement of a circular arc with stair-steps can be defined as radius of the arc minus length up to the corresponding corner of the staircase, i.e., cusp height (figure 12 (b)). Thus maximum error (cusp height) results along z direction and is equal to slice thickness. Therefore, cusp height approaches to maximum for surfaces, which are almost parallel with the x-y plane. Maximum value of cusp height is equal to slice thickness and can be reduced by reducing it; however this results in drastic improvement in part building time. Therefore, by using slices of variable thicknesses (popularly known as adaptive slicing, as shown in figure 13), cusp height can be controlled below a certain value.

Except this, mismatching of height and missing features are two other problems resulting from the slicing. Although most of the RP systems have facility of slicing with uniform thickness only, adaptive slicing scheme, which can slice a model with better accuracy and surface finish without loosing important features must be selected. Review of various slicing schemes for RP has been done by Pandey et al. (2003a).

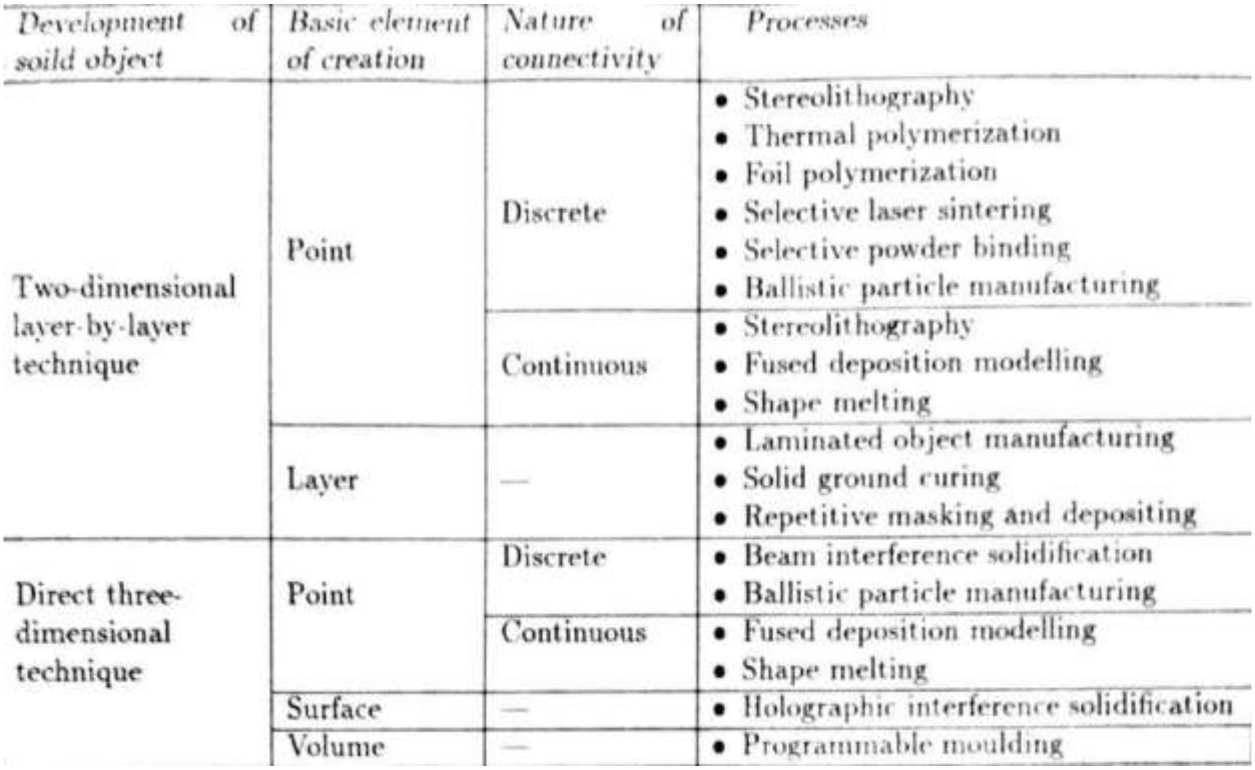
5.2. Part building

During part deposition generally two types of errors are observed and are namely curing errors and control errors. Curing errors are due to over or under curing with respect to curing line and control errors are caused due to variation in layer thickness or scan position

Rapid Manufacturing Process Optimization: factors influencing accuracy. Data preparation errors, Part building errors, Error in finishing, influence of build orientation.

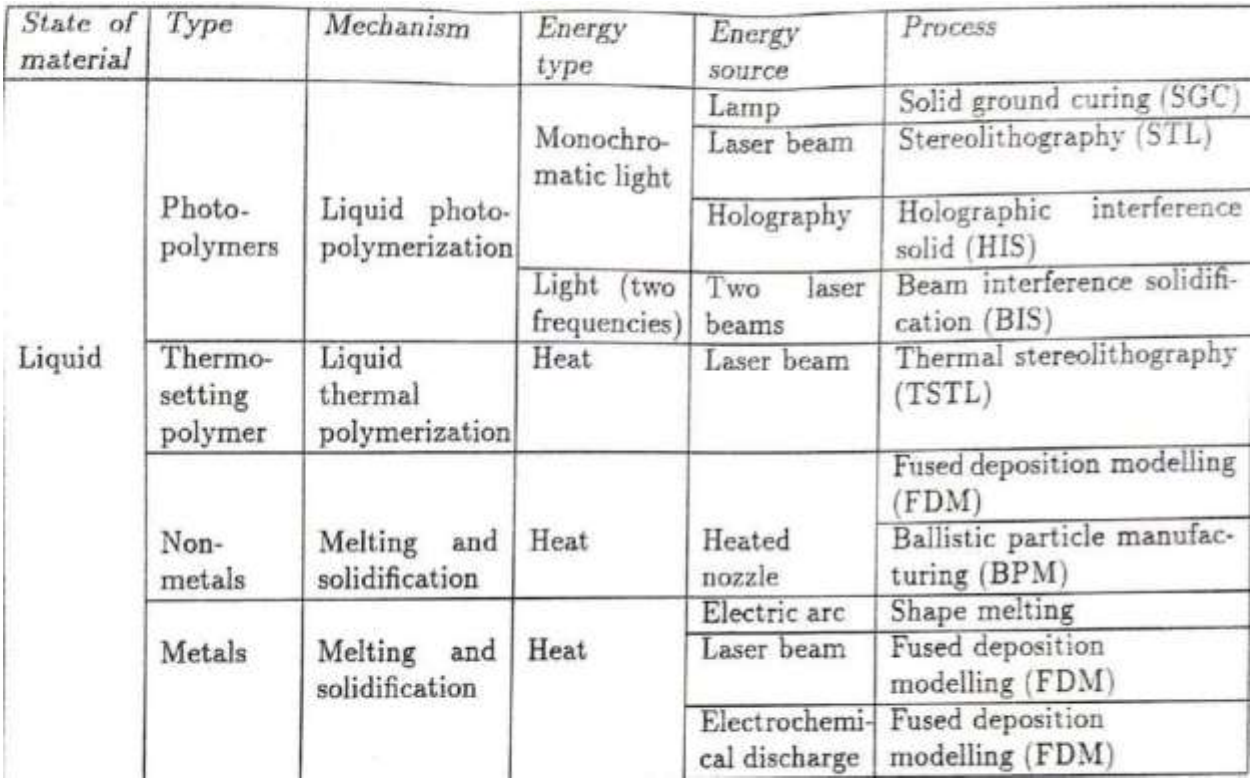
Classification of different RP techniques:

A large number of techniques and machines have already been developed in the area or RP and therefore classification/grouping of these processes will be used in presenting descriptions in a structured format. Classification of these processes can be done from two prospective (i) the way material is created/solidified and (ii) the way the shape is generated. A number of processes are still in the R&D stage and some are only in the conceptual stage.

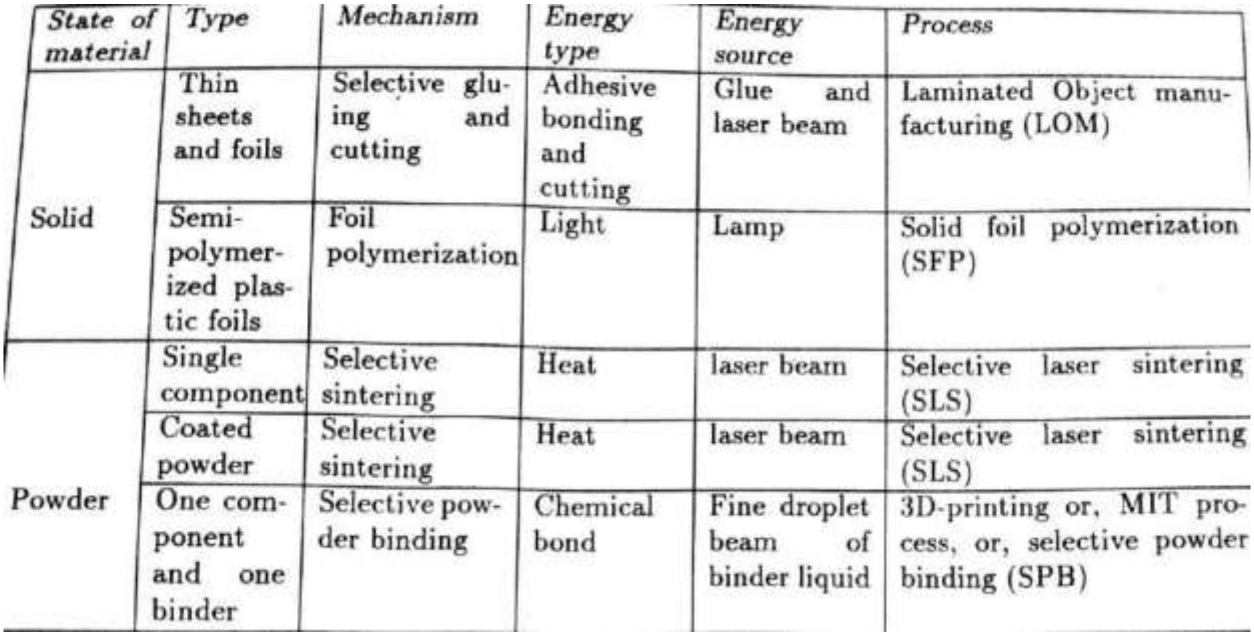


Development of soild object	*Basic element of creation*	*Nature of connectivity*	*Processes*
Two-dimensional layer-by-layer technique	Point	Discrete	• Stereolithography • Thermal polymerization • Foil polymerization • Selective laser sintering • Selective powder binding • Ballistic particle manufacturing
		Continuous	• Stereolithography • Fused deposition modelling • Shape melting
	Layer	—	• Laminated object manufacturing • Solid ground curing • Repetitive masking and depositing
Direct three-dimensional technique	Point	Discrete	• Beam interference solidification • Ballistic particle manufacturing
		Continuous	• Fused deposition modelling • Shape melting
	Surface	—	• Holographic interference solidification
	Volume	—	• Programmable moulding

Classification of RP based on layering technique (2D or 3D)



State of material	*Type*	*Mechanism*	*Energy type*	*Energy source*	*Process*
Liquid	Photo-polymers	Liquid photo-polymerization	Monochromatic light	Lamp	Solid ground curing (SGC)
				Laser beam	Stereolithography (STL)
				Holography	Holographic interference solid (HIS)
			Light (two frequencies)	Two laser beams	Beam interference solidification (BIS)
	Thermo-setting polymer	Liquid thermal polymerization	Heat	Laser beam	Thermal stereolithography (TSTL)
	Non-metals	Melting and solidification	Heat	Heated nozzle	Fused deposition modelling (FDM)
					Ballistic particle manufacturing (BPM)
	Metals	Melting and solidification	Heat	Electric arc	Shape melting
				Laser beam	Fused deposition modelling (FDM)
				Electrochemical discharge	Fused deposition modelling (FDM)

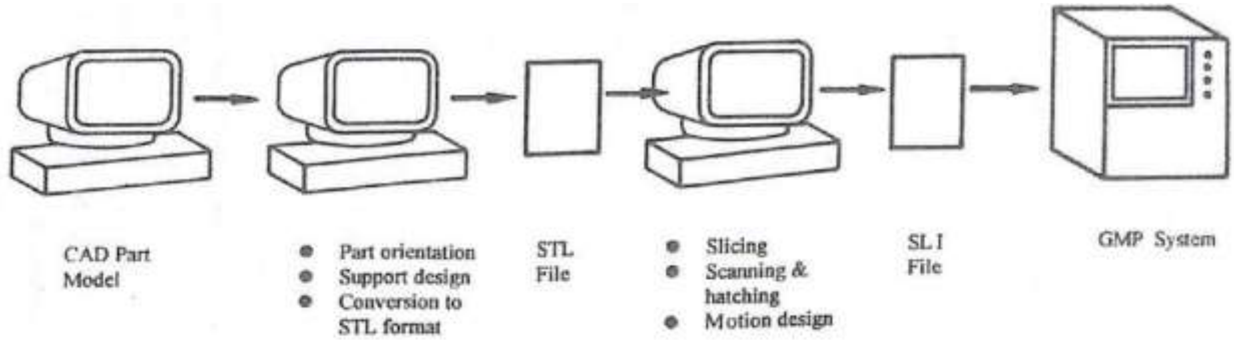


State of material	*Type*	*Mechanism*	*Energy type*	*Energy source*	*Process*
Solid	Thin sheets and foils	Selective gluing and cutting	Adhesive bonding and cutting	Glue and laser beam	Laminated Object manufacturing (LOM)
	Semi-polymerized plastic foils	Foil polymerization	Light	Lamp	Solid foil polymerization (SFP)
Powder	Single component	Selective sintering	Heat	laser beam	Selective laser sintering (SLS)
	Coated powder	Selective sintering	Heat	laser beam	Selective laser sintering (SLS)
	One component and one binder	Selective powder binding	Chemical bond	Fine droplet beam of binder liquid	3D-printing or, MIT process, or, selective powder binding (SPB)

Classification of RP based on state of raw material and energy sources

Steps in RPT

- Creation of the CAD model of the (part) design,
- Conversion of the CAD model into Standard Tessellation Language (STL) format,
- Slicing of the STL file into thin sections,
- Building part layer by layer,
- Post processing/finishing/joining.



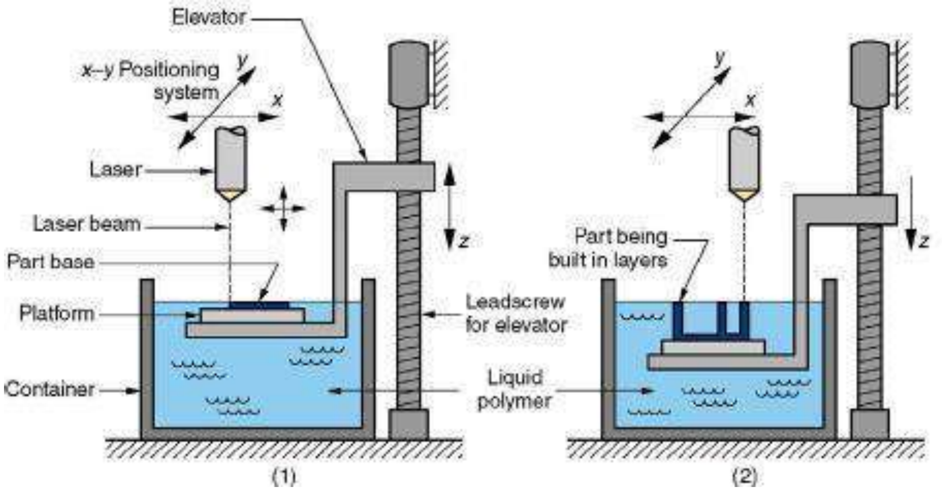
Pre-processing of CAD data

Stereolithography (STL/SLA) with photopolymerozation

- RP process for fabricating a solid plastic part out of a photosensitive liquid polymer using a directed laser beam to solidify the polymer
- Part fabrication is accomplished as a series of layers, in which one layer is added onto the previous layer to gradually build the desired 3- D geometry
- The first addition RP technology -introduced 1988 by 3D Systems Inc.
  based on the work of Charles Hull
- More installations of STL than any other RP method Some Facts

about STL

- Each layer is 0.076 mm to 0.50 mm (0.003 in to 0.020 in.) thick
  - –Thinner layers provide better resolution and more intricate shapes; but processing time is longer
- The starting materials are liquid monomers
- Polymerization occurs upon exposure to UV light produced by helium-cadmium or argon ion lasers
  - –Laser scan speeds typically 500 to 2500 mm/s



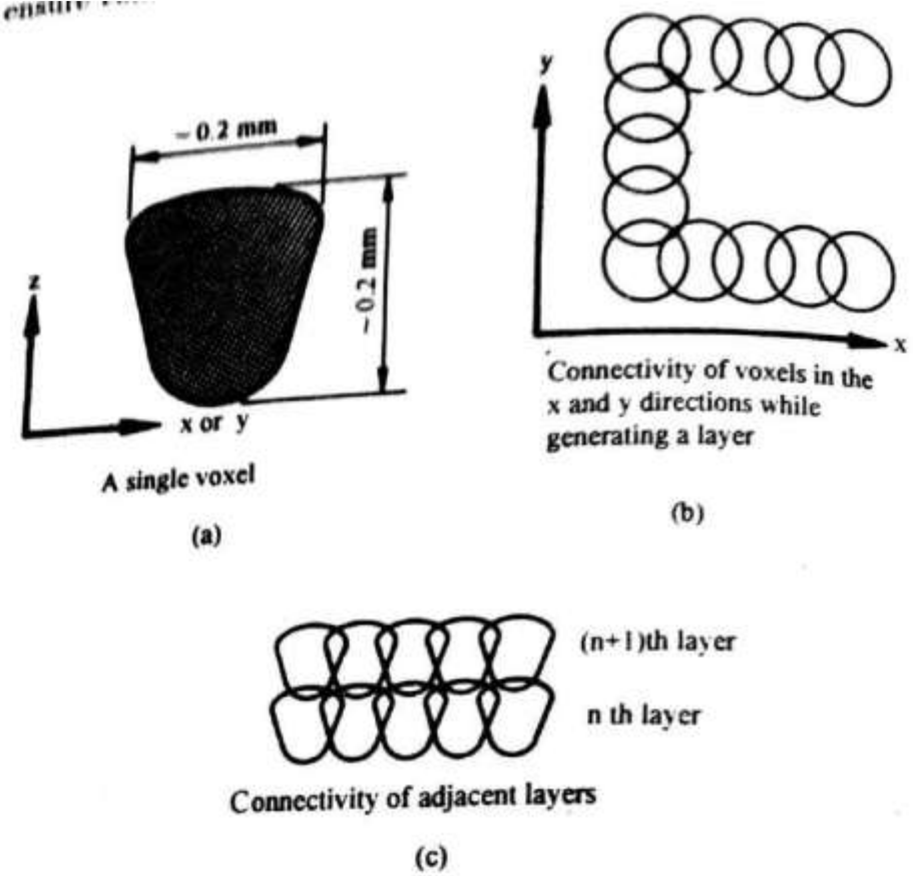
Stereolithography: (1) at the start of the process, in which the initial layer is added to the platform; and (2) after several layers have been added so that the part geometry gradually takes form

A part produced by Stereolithography

Once the first layer is cured the platform is lowered by distance equal to the thickness of a layer. Then the laser beam scans the next cross section. The cycle is repeated till the topmost layer of the object is generated.

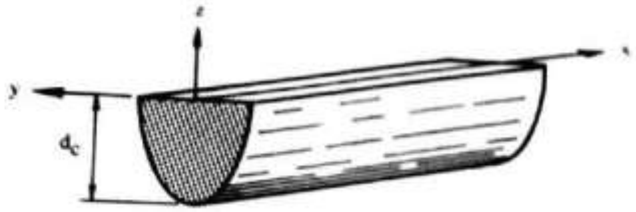
Subsequently the generated object is removed from the vat and ultrasonic cleaning removes excess material from crevices and openings. An alcohol bath is used to clean any unused polymer. The process of post curing is carried out by applying intense long wave UV radiation to solidify an uncured liquid trapped in the honeycomb like structures.

In most stereolithography machines solidification occurs in a point-by-point fashion. In some cases solidification takes place curing lines at time. A laser beam scans the liquid surface so that a series of voxels (volume picture cells) get solidified as shown figure below. The voxel size should be adequate to ensure connection with the neighboring voxels and also with the layer solidified prior to the current one.



Generation of lines and layers by voxels

The parameter which controls the voxel overlap is the distance between voxels, the laser power, the stay time and the layer thickness. Using high power lasers, continuous lines can be cured forming a solid parabolic cylinder as hown in figure below.



A parabolic prism cured by a laser beam

Solidification due to curing is achieved once the liquid receives the required dose of radiation. The depth of curing will depend on the exposure and the properties of liquid used.

$$d_C = d_p \, ln\left(\frac{E_O}{E_C}\right)$$

Where: d_C the depth of a single cured line

d_p the penetration depth of the resin

E_O the centerline exposure on the surface

E_C the critical exposure to which the resin remains liquid

Stereolithography with liquid thermal polymerization:

- This process solidifies the desired object layer by layer using a liquid polymer as in the case of streolithography.
- The primary difference lies in the process of solidification. Unlike the stereolithography process a thermosetting liquid polymer is used in place of photo polymer and the solidification process depends upon heat not light.
- In this process a 5W Ar-Ion laser is used.
- Post curing is done in an oven at 400^0C and the speed of operation is not much different from that incase of SL.
- In a system based on liquid thermal polymerization, that dissipation of heat has to be considered carefully for proper control of the voxel size and accuracy.
- Thermal shrinkage and distortion can also cause problems in quality control.
- However experts think that this problem is not any more severe than that posed by polymerization shrinkage present in other SL operations.
- The shrinkage is of the order of 5-6%in volume i.e about 1.6 to 1.8% in linear dimension.

Sterelithography with Solid Foil Polymerization:

- In this process solid to solid polymerization is employed rather than liquid to solid polymerization as in most SL systems.
- The raw material consists of semi polymerized plastic foils instead of liquid resins.
- Layer upon layer building process involves applying a foil to the newly created, topmost, layer of the object and then polymerizing the required area by a scanning light beam.

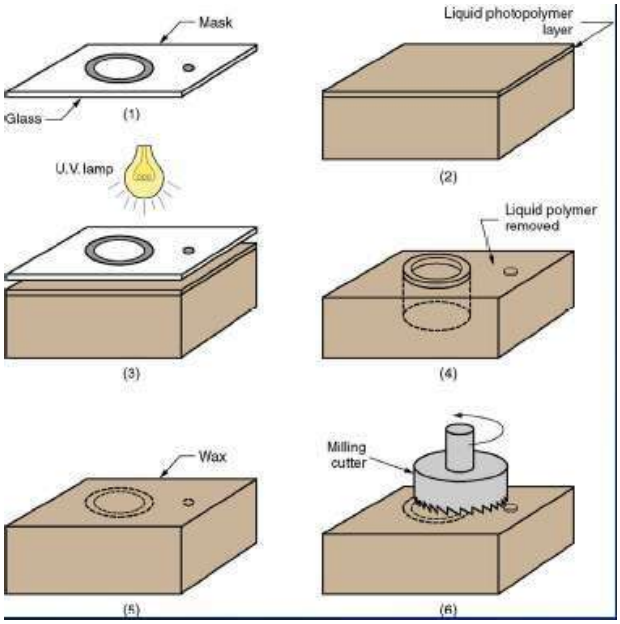
- The illuminated portions polymerize further and stick to the layer underneath. The illuminated portions also become insoluble due to polymerization. So the unexposed portion can be removed later by dissolving them and the part with required shape and size will emerge.
- Though the raw material is in the form of thin foils, the process should not be confused with the process of laminated object manufacturing. The actual creation is still done point by point (or Line by line) instead of cutting along the boundaries of a cross section.

Solid Ground Curing (SGC)

- Like stereolithography, SGC works by curing a photosensitive polymer layer by layer to create a solid model based on CAD geometric data
- Instead of using a scanning laser beam to cure a given layer, the entire layer is exposed to a UV source through a mask above the liquid polymer
- Hardening takes 2 to 3 s for each layer

A mask is generated by electro-statically charging a glass plate with negative image of cross section of the required part. In the meantime, a thin liquid polymer is spread across the surface of the work-plane. The mask plate with a negative image of the liquid polymer is positioned over the thin polymer layer and exposed under the ultraviolet laser lamp for few seconds.

All parts of the exposed photopolymer layer get solidified with one exposure. However, the area shaded by the mask is left in a liquid form and is wiped off with vacuum suction head and replaced by hot wax which acts as a support to the solidified polymer layer. A face mill makes the surface of wax and polymer flat and to desired thickness. All the above steps are repeated till final model embedded in removable wax is obtained.



SGC steps for each layer:

1. mask preparation,
2. applying liquid photopolymer layer,
3. mask positioning and exposure of layer,
4. uncured polymer removed from surface,
5. wax filling, milling for flatness and thickness

Facts about SGC

The sequence for each layer takes about 90 seconds

Time to produce a part by SGC is claimed to be about eight times faster than other RP systems

The solid cubic form created in SGC consists of solid polymer and wax

Selective laser sintering (SLA)

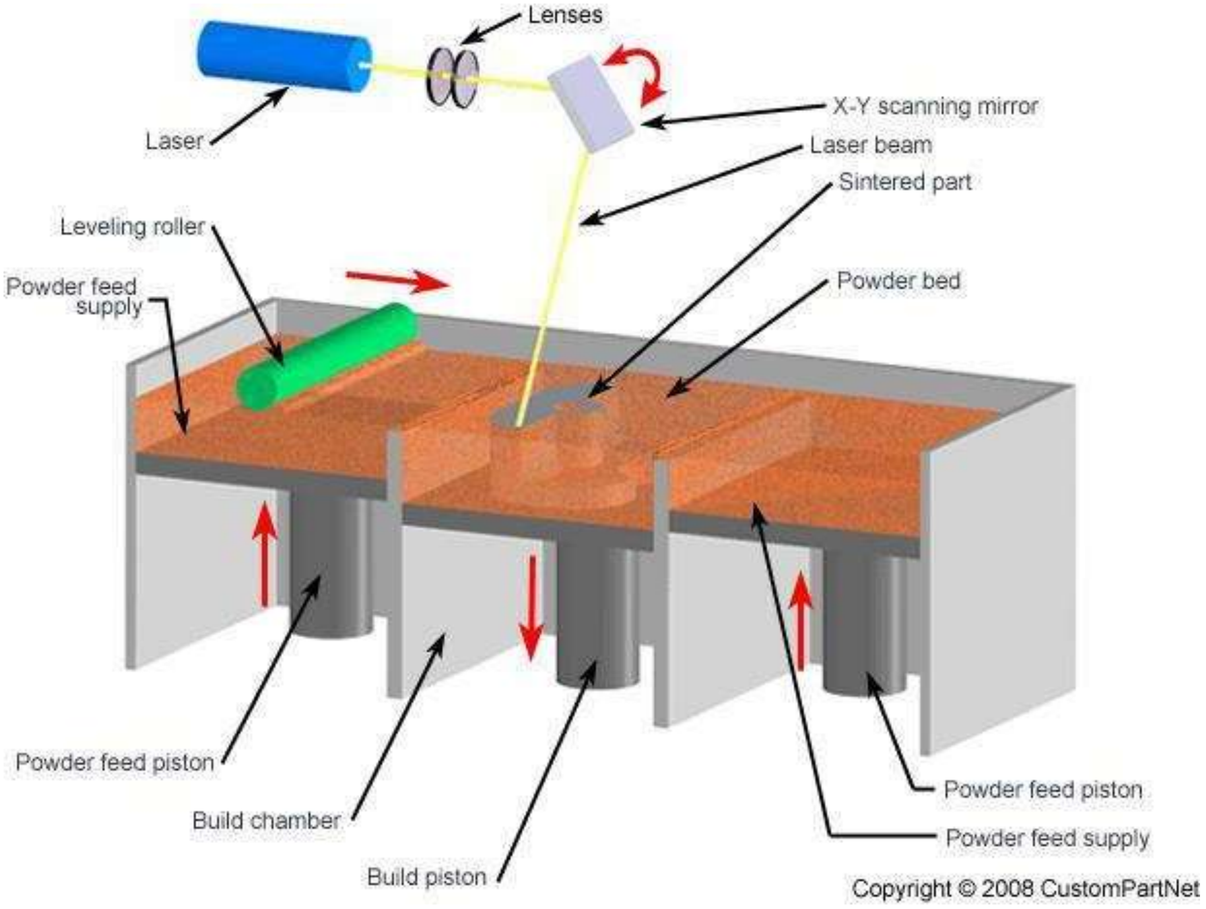
SLS was patented in 1989. *The basic concept of SLS is similar to that of SLA*. It uses a moving laser beam to trace and selectively sinter powdered polymer and/or metal composite materials. The powder is kept at elevated temperature. Unlike SLA, *special support structures are not required* because the excess powder in each layer as a support.

With the metal composite material, the SLS process solidifies a polymer binder material around steel powder (diameter ca. 0.1 mm) one slice at a time forming the part.

The part is then placed in a furnace (>900 °C), where the polymer binder is burned off and the part is infiltrated with bronze to improve its density.

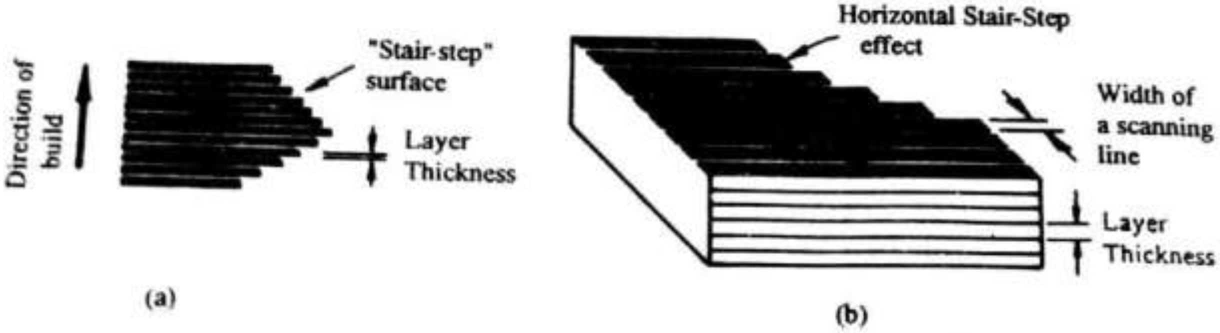
SLS allows for a wide range of materials, including nylon, glass-filled nylon, Truform (investment casting) and metal composites.

Abbreviation:	**SLS**
Material type:	Powder(Polymer)
Materials:	Thermoplastics: Nylon, Polyamide and Polystyrene; Elastomers ; Composites
Min layer thickness:	0,10mm
Surface finish:	Average
Build speed:	Fast
Applications:	Form/ fit testing, Functional testing, Less detailed parts, Parts with snap-fits & living hinges, High heat applications..



The parts produced by sintering of powder are porous. Those produced by sintering polyvinyle chloride have a relative density of only 60% (i.e. 40% of the part volume in air). New models of SLA machines are being developed in which ceramic and metal powders can be used. One distinct advantage of SLS is that different materials can be used while building a single part. For cases where higher energy may be required a high energy electron beam is proposed to be used for sintering/melting.

Almost all RP techniques produces a vertical ‘stair step’ surface finish as shown in figure below, since parts are built by creating discrete layers. The surface of parts produced by SLS process suffer additionally from roughness problems.



Vertical and Horizontal stair-step effect

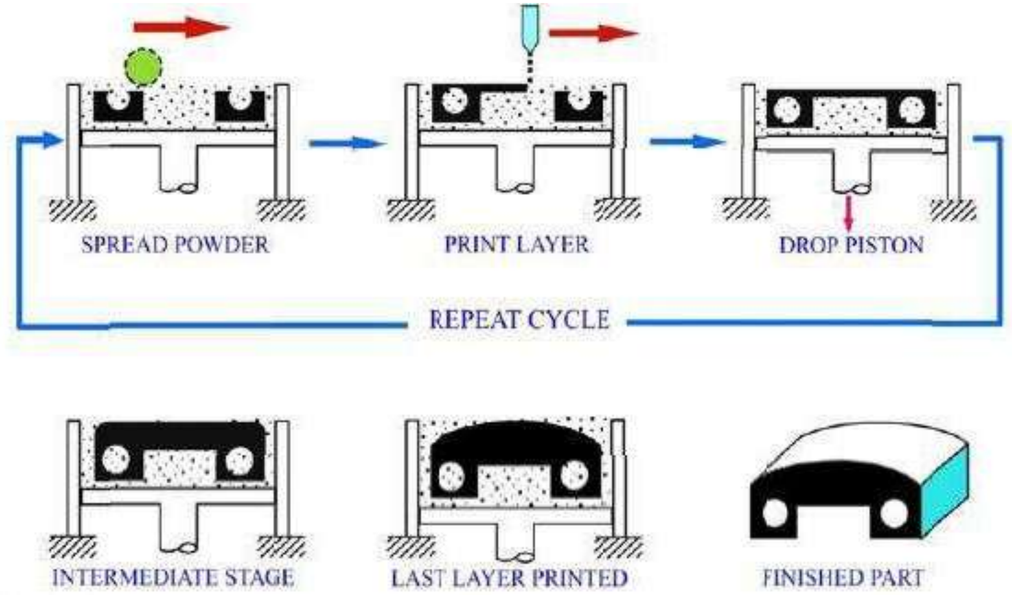
- One reason is the nature of the raw material, which is powder. Since sintering does not cause complete melting of the grains (where diameter lies in the range 80micon to 120 micron) the surfaces acquire a granular structure.
- Besides this raster0scan laser drawing also results in horizontal stair- step effect as shown in figure above.
- However to distribute the roughness evenly on all surfaces the orientation of raster is rotated by 90^0 on alternate layers.
- Further improvement of surface finish is possible by outlining each cross section prior to the drawing of rasters. But the last technique results in higher part building time.

UNIT-3 POWDER BASED RAPID PROTOTYPING SYSTEMS AND TOOLING

Selective powder binding (SBP)

In this system, in order to build a part, the machine spreads a single layer of powder onto the movable bottom of a build box. A binder is then printed onto each layer of powder to form the shape of the cross-section of the model. The bottom of the build box is then lowered by one layer thickness and a new layer of powder is spread. This process is repeated for every layer or cross-section of the model. Upon completion, the build box is filled with powder, some of which is bonded to form the part, and some of which remain loose. The steps involved in the process are Shown in figure below

This process is also called three dimensional printing; being developed by MIT is based on creating a solid object from a refractory powder by selecting binding through the application of a colloidal liquid silica binder.

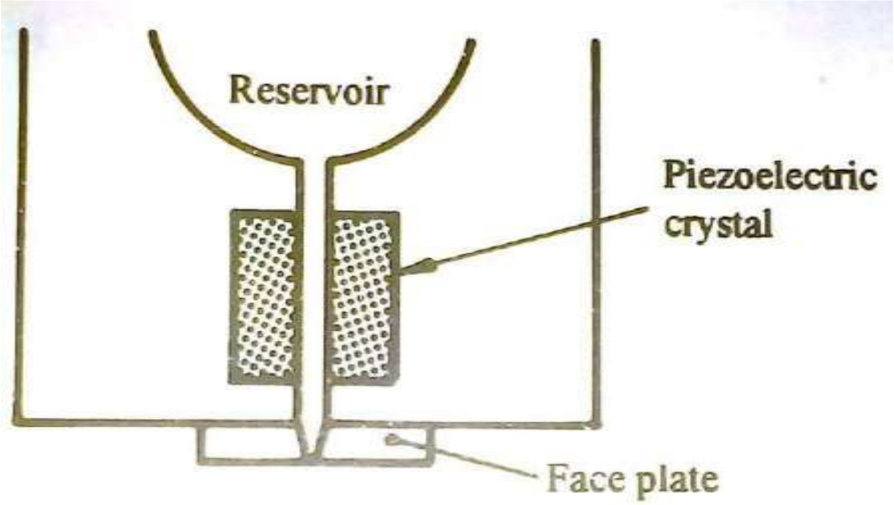


Various stages and steps of selective powder binding (SPB)

In this process a fine jet of ceramic binder in ejected onto the powder layer where solidification is desired. This is done on the inkjet mechanism scans the layer by either ejecting the binder droplets at the identified locations or by deflecting the continuously emerging drops away from the locations where solidification is not wanted. These are termed as ‘ drop-on-demand’ and ‘ continuous jet’ systems respectively. The droplets are electrically charged at the nozzle and then deflected by applying suitable voltages to electrodes located below the nozzle.

The nozzle is moved across the powder surface in a raster scan while computer generated electrical signals control the deposit of the binder.

Figure below shows an ink-jet mechanism schematically. A vacuum is applied to the reservoir such that a negative head pressure is maintained at the face plate. Capillary force at the face plate orifice prevents the binding liquid from being pulled in through the mechanism. The mechanical impulse created on applying electrical charge to the piezoelectric crystal produces a shock wave which causes the ejection of a droplet from the face plate.



Schematic view of an ink-jet mechanism

The print head consists of an array of a large number of jet ports each one capable of operating at 10KHz. With an array of high frequency jets, the layer solidification time can be 4s/layer for a drop on demand system with a layer size of 0.5mx0.5m. it can be as low as a fraction of a second for ‘continuous jet’ system.

The major problem with the parts produced by this technique is inadequate surface finish. Removal of unbound powder from narrow passages and enclosed cavities also poses difficulties. This process is however, very convenient for making moulds with integral cores. Since the fabrication of the mould and the core is done as a single unit, the registration of cores to the mould is precise.

Ballastic Particle Manufacturing(BPM) – both 2D and 3D

Perception Systems Inc. has developed the ballistic particle manufacturing technique for creating three-dimensional solid objects from the computer model directly. As the name suggests, parts are produced by shooting droplets of molten material at required places. As in the selective powder binding process, here also material is supplied through an array of drop-on-demand ink-jet ports. Molten wax droplets, approximately 50μm in diameter, are ejected at rates upon 12,500 droplets per second. BPM is possible for both layer-by-layer two-dimensional fabrication and direct three-dimensional fabrication. The two-dimensional layer-by-layer process is based on generating layers by the wax droplets. Figure 4.9(a) shows the CAD model and in Figure 4.9(b), the support structures have been added. The usual slicing of this part-support integrated model yields two-dimensional layers a portion of which belongs to the part to be generated and the rest to the support structure (Figure 4.10(a) and (b)). The part is generated from wax whereas the support is developed from polyethylene glycol, a synthetic wax that is soluble in water. The deposition of wax and polyethylene glycol is done by sorting droplets from an array of 32 piezoelectric ink jet ports operating at 10 kHz. On contact with the previously generated layer, the hot droplets momentarily melt the contact surface of the previously deposited layer. On subsequent cooling and solidification, a homogeneous material is formed of the desired shape. After all the layers have been deposited, the object

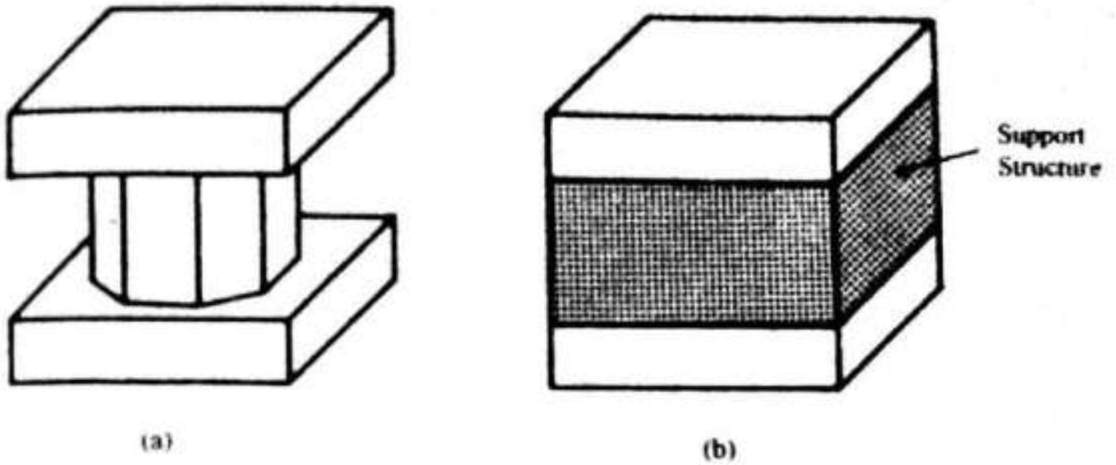


Figure 4.9: (a) CAD model of part (b) CAD model of part-cum-support

is placed in a warm water bath to dissolve the support material, leaving the desired object. The finished part is removed from the bath and cleaned.

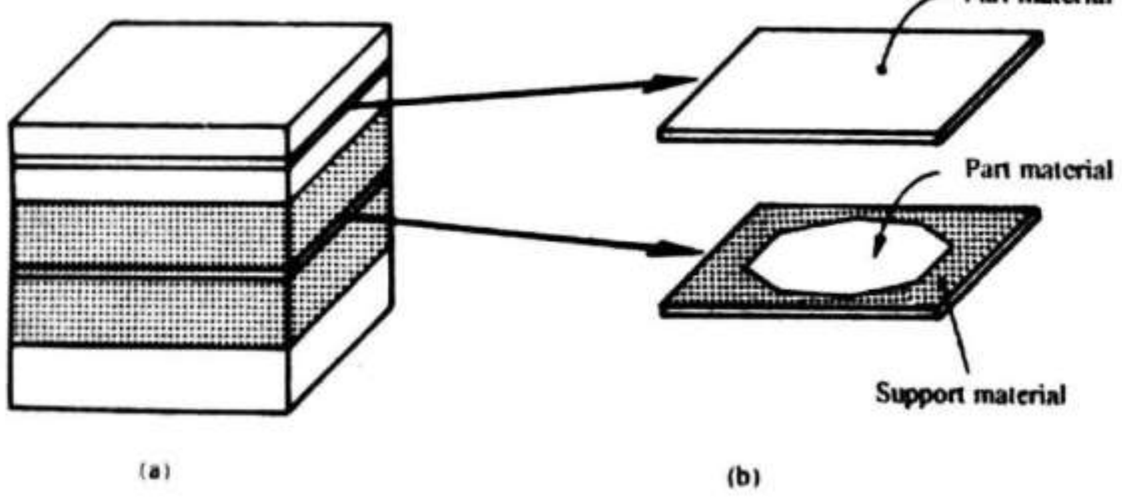
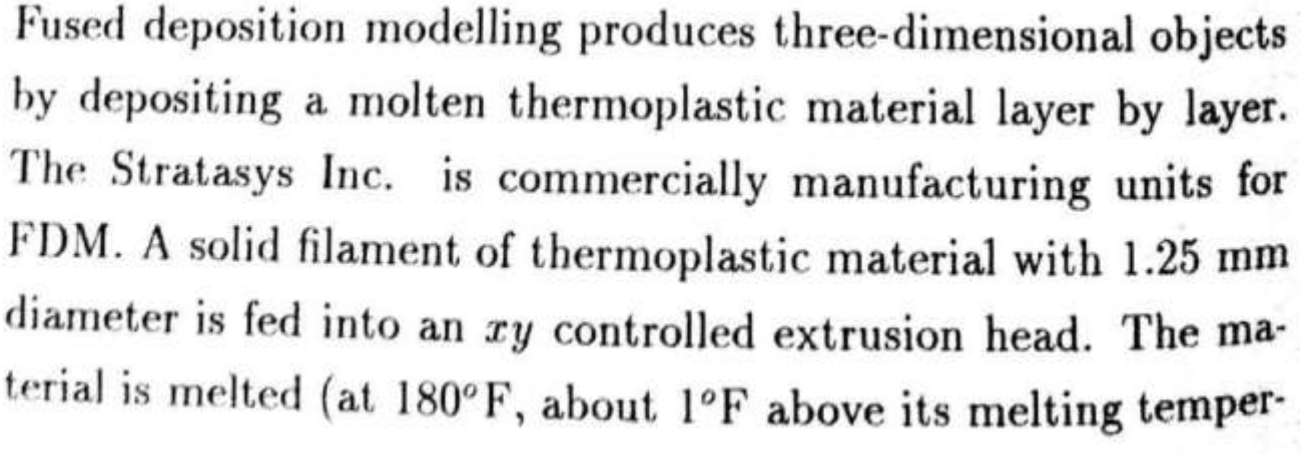


Figure 4.10: (a) Slicing of model (b) Layers showing part and support material arrangement

The accuracy depends on the accuracy of depositing wax drops which is dependent on the location of the piezoelectric jet system, and the ballistic paths of the individual droplets. Thus, it is important for the jet ports to be as close to the substrate as possible to allow for a random droplet dispersion angle of upto 5^0. The layer thickness is monitored by a feedback loop with proximity sensors measuring the distance between the jet ports and the substrate (previously deposited layer). If this distance is found to be more than the set value the frequency of droplets (i.e., the flow rate of material) is increased so as to increase the layer thickness within the operating window. In the currently available systems, parts have been generated with 90 μm layer thickness.

As the support structure is removed by dissolving it in warm water it is essential to ensure that the support structure material is not completely enclosed by the part material. Small holes provided in such cases are usually adequate to allow the support material to be dissolved from internal cavities. The wax models produced by this technique can be very useful for investment casting.

Fused deposition modeling



Fused deposition modelling produces three-dimensional objects by depositing a molten thermoplastic material layer by layer. The Stratasys Inc. is commercially manufacturing units for FDM. A solid filament of thermoplastic material with 1.25 mm diameter is fed into an xy controlled extrusion head. The material is melted (at 180°F, about 1°F above its melting temperature) by a resistance heater. As the head is guided along the required path under computer control, the thermoplastic material is extruded through a nozzle by a precision volumetric pump. The extruded material, deposited as a fine layer, being just above the melting temperature, resolidifies by natural cooling within 1/10th of a second. Building up of the desired object is achieved through deposition of such fused layers. To ensure proper adhesion of the deposited fused material with the previously deposited layer, the model temperature is maintained just below the solidification temperature. After every layer is deposited, the piston (upon which the model is built) is lowered by one layer thickness. Figure 4.11 shows the process schematically.

The flow rate of the extruded molten filament is accurately controlled and matched with the travelling speed of the depositing head (which can be as high as 380 mm/sec), the desired thickness of the layer (in the range 0.025 mm to 1.25 mm) and the width of the extruded layer which may vary from 0.23 mm to 6.25 mm. The repeatability and positional accuracy of this process are claimed to be about ± 0.025 mm with an overall tolerance of 0.125 mm over a cube with 305 mm sides. However, the parts produced by FDM show some roughness and the process may not be suitable for parts with smaller details.

Theoretically, any thermoplastic material may be suitable for the process. Parts built up with different materials or colours can be conveniently produced by this process. The typically used materials for FDM include investment casting wax, wax-filled plastic adhesive material (machinable wax) and tough nylon-

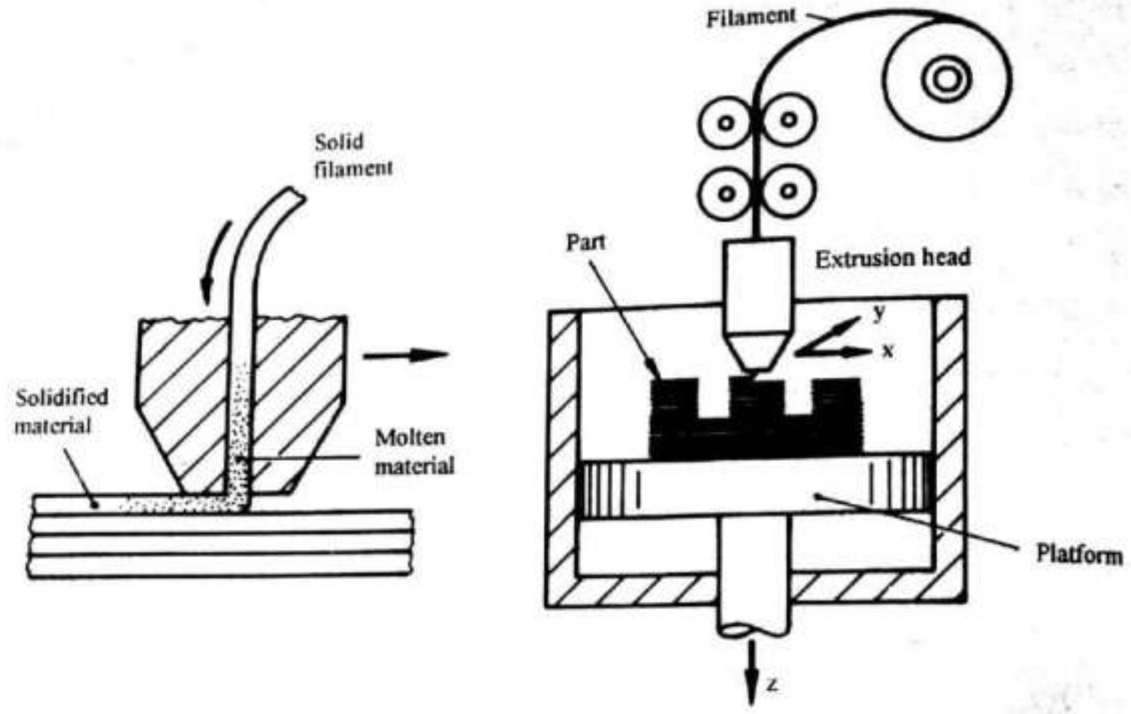


Figure 4.11: Scheme of fused deposition modelling (FDM)

like material. A polymer like material with good strength and flexibility has also been used recently and Stratasys claims that it features improved bonding and surface finish. Parts made from investment casting wax can be directly used for casting. The other materials under development are a silicone rubber sealing material and an automotive body foam material. All these materials are non-toxic and, so, the process is suitable for the office environment.

When the deposition of a layer is completed, the head pauses while the platform indexes downward to make room for the next layer. This results in a seam at the location where the deposition head

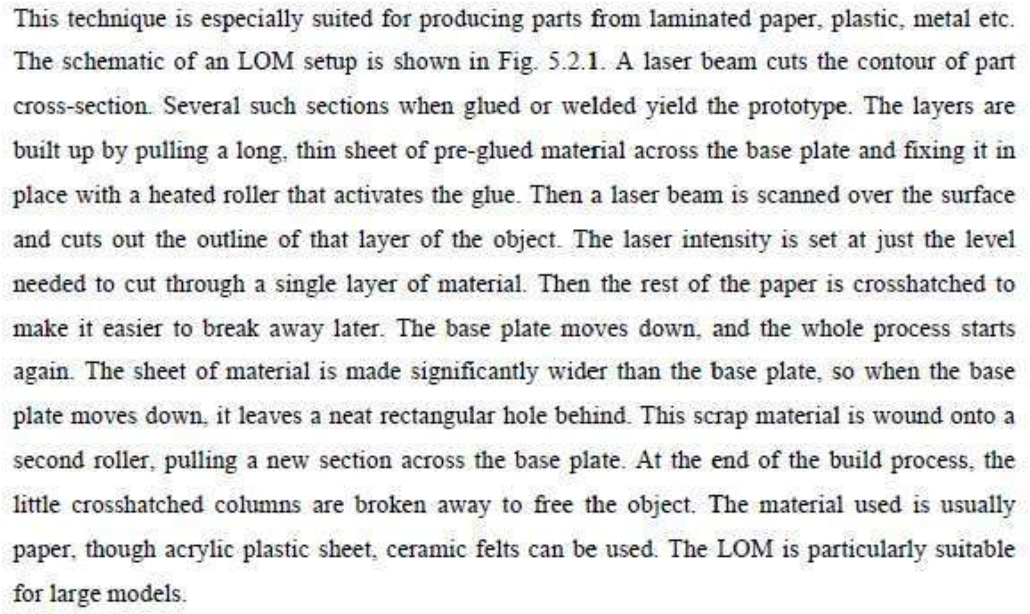
head pauses. It is being proposed to develop a system which will provide a quick downward movement when the head is still in motion. This may eliminate the above mentioned problem. It is important that the head be kept in motion at all times. Otherwise material melts near the tip and forms little bumps which may be visible on the surface layers. Temperature control of the FDM head and the part is crucial for the success. There is no wastage of material in this process and parts produced by FDM do not require a major cleaning operation after fabrication.

Shape melting

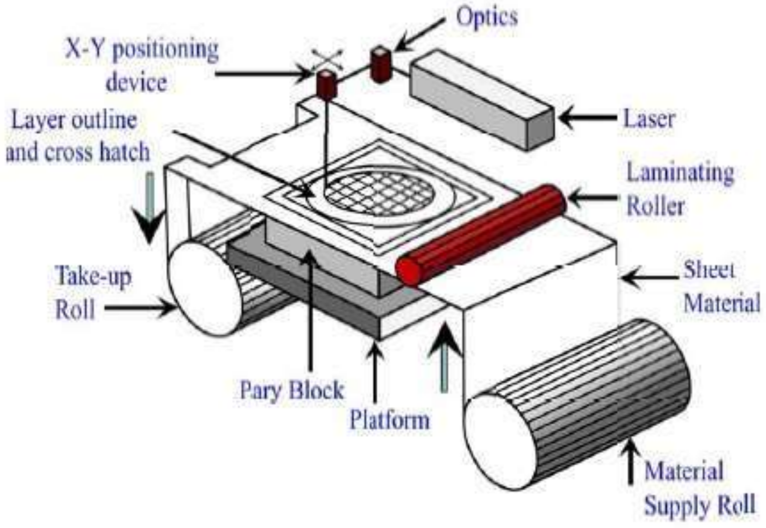
The process is very similar to fused deposition modeling and was developed by Babcock and Wilcox. The basic idea behind this process is to build parts directly from welding material melted by sticking an arc as in arc welding. This is similar to the technique often used in the industry to repair worn components, broken gear teeth etc. A band or thread of metal is melted and deposited by arc welding and the desired shape is obtained by controlling the position of the welder with the help of a robot. A controlled cooling system is used to ensure fast solidification. With the currently available system, the major limitations are the accuracy and finish. Accuracy better than 1mm is presently not possible. Further there are problems in producing parts of sizes smaller than 7 mm.

The major advantage of this process is that the metal parts produced by this process can be directly used for making functional prototypes. Materials used till date includes Iconel (alloy625), tungsten carbide and other alloy. The advantage also includes high strength isotropic material properties and the possibility of developing multi material parts with tailored properties. Moreover, a uniform fine grained micro structure is produced by this process.

Laminated object manufacturing

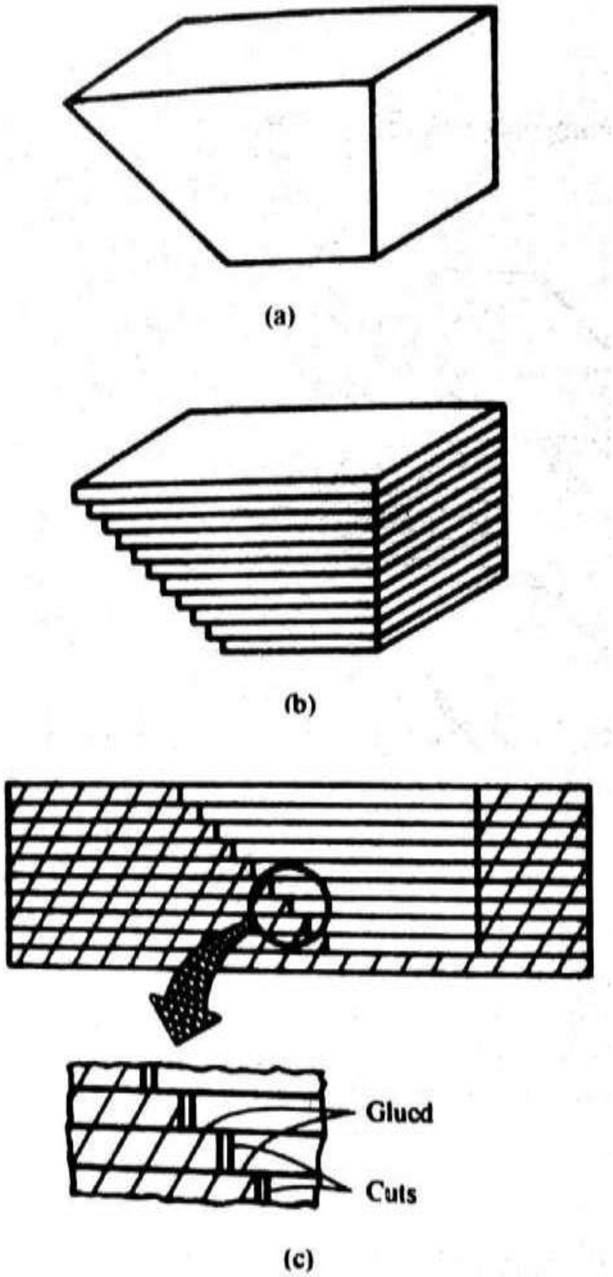


This technique is especially suited for producing parts from laminated paper, plastic, metal etc. The schematic of an LOM setup is shown in Fig. 5.2.1. A laser beam cuts the contour of part cross-section. Several such sections when glued or welded yield the prototype. The layers are built up by pulling a long, thin sheet of pre-glued material across the base plate and fixing it in place with a heated roller that activates the glue. Then a laser beam is scanned over the surface and cuts out the outline of that layer of the object. The laser intensity is set at just the level needed to cut through a single layer of material. Then the rest of the paper is crosshatched to make it easier to break away later. The base plate moves down, and the whole process starts again. The sheet of material is made significantly wider than the base plate, so when the base plate moves down, it leaves a neat rectangular hole behind. This scrap material is wound onto a second roller, pulling a new section across the base plate. At the end of the build process, the little crosshatched columns are broken away to free the object. The material used is usually paper, though acrylic plastic sheet, ceramic felts can be used. The LOM is particularly suitable for large models.



Laminated object manufacturing process

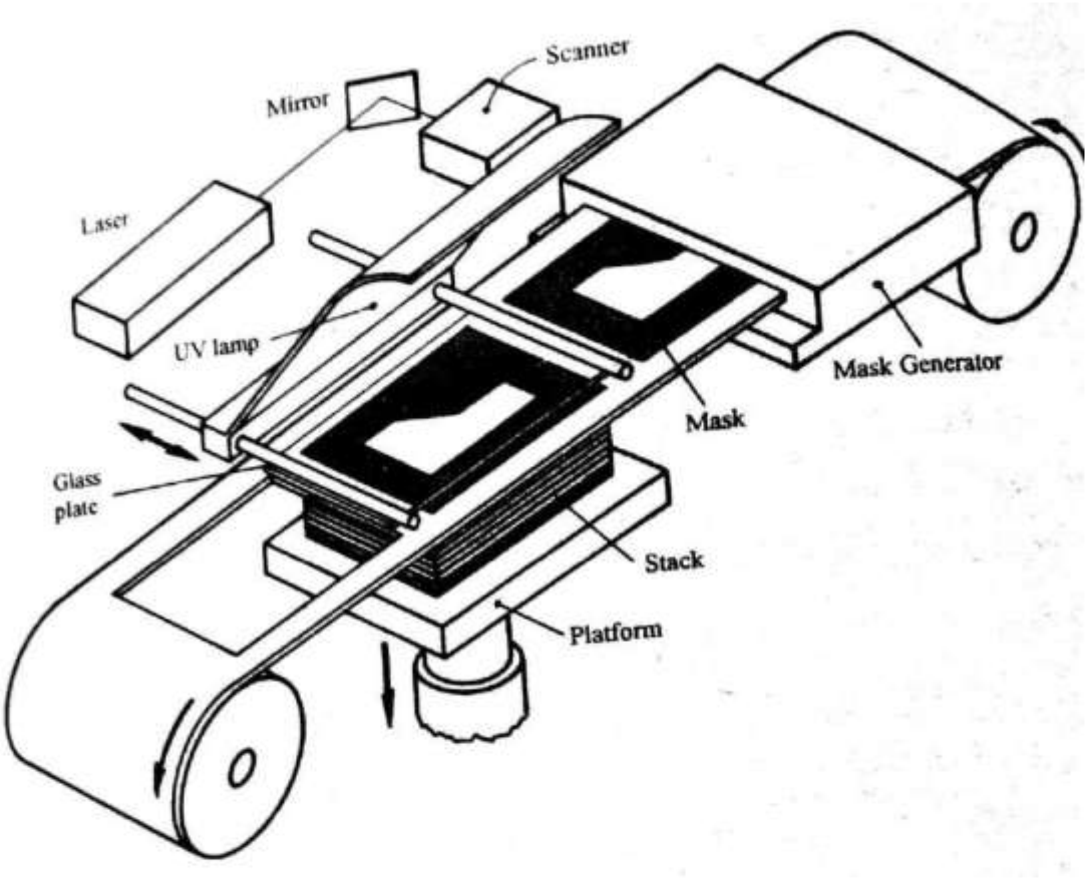
The entire surface of the sheet material is coated with adhesive, there fore each layer adheres to the previously laid layer at all points of contact. Though the laser beam cut the layers to separate a corss section from the ribbon of the work material it cannot separate the layers once they are glued. These results in a problem where an unwanted part of an upper layer remains glued to the previous cross section. Figure (a) shows a tapered object under fabrication by LOM, Fig (b) shows the lamination pattern to be generated by laser cutting and layer deposition.



Inter layer adhesion problem in LOM

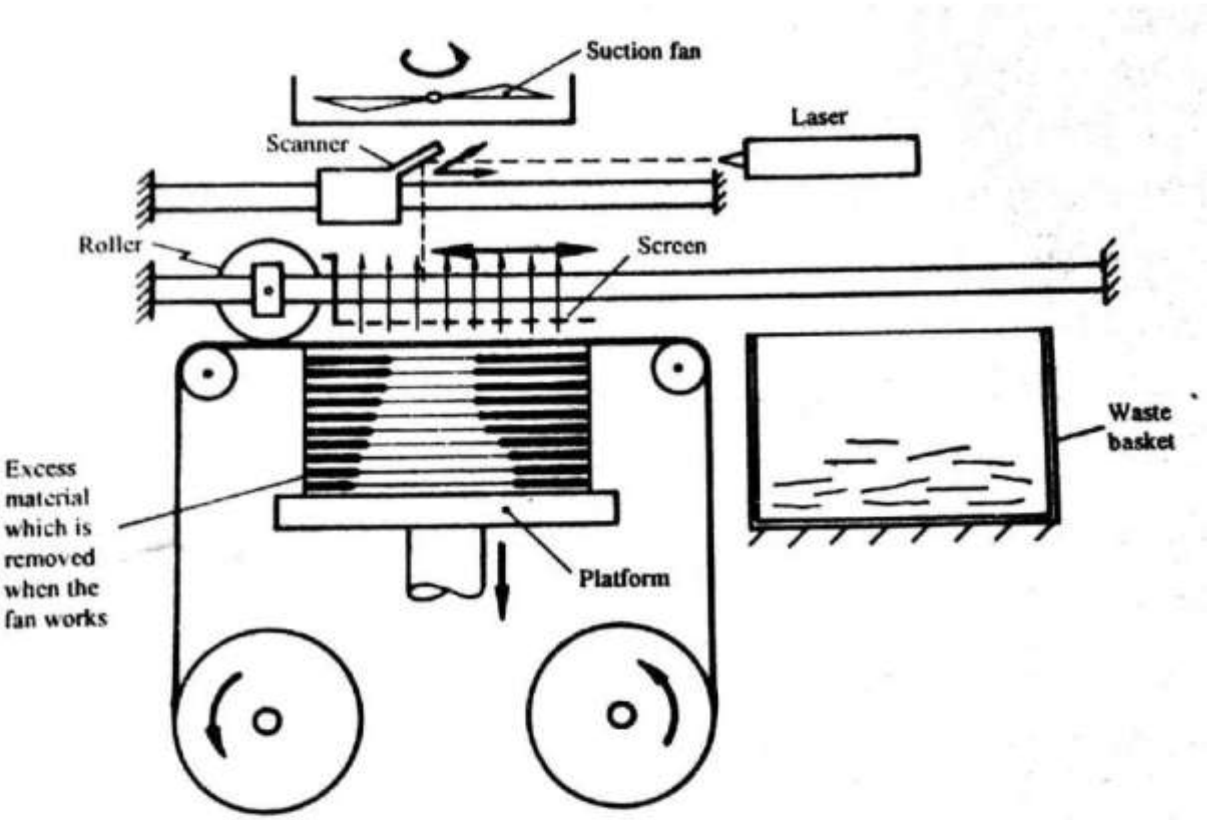
Figure c above shows the actual fabrication process and the undesirable gluing between the desired and undesired parts of successive layers. Thus all down facing surfaces of the part tend to adhere to the block and separation becomes difficult after the generation is over. Currently the problem is reduced by a method called burn out. The area on the previously laid layer where gluing is undesirable, is cut with a tightly spaced cross hatch pattern. However this problem of LOM is a serious hurdle till now. Attempt is being made to develop techniques to glue the sheet only within the parts cross section. One way to achieve this is to apply a heat sensitive glue all over the surface and then scan the cross sectional area with a laser beam thus heating and thus gluing the sheets only at the desired area.

Another way to solve this unwanted gluing problem is to use an UV sensitive glue along with. Selective gluing can be achieved by scanning the required area with an UV laser. Another technique is that of printing a mask to the foil and then illuminating with UV lamps through a glass plate pressing the sheet on the stack. The principle is shown below.



Scheme of using mask and UV lamp for selective gluing

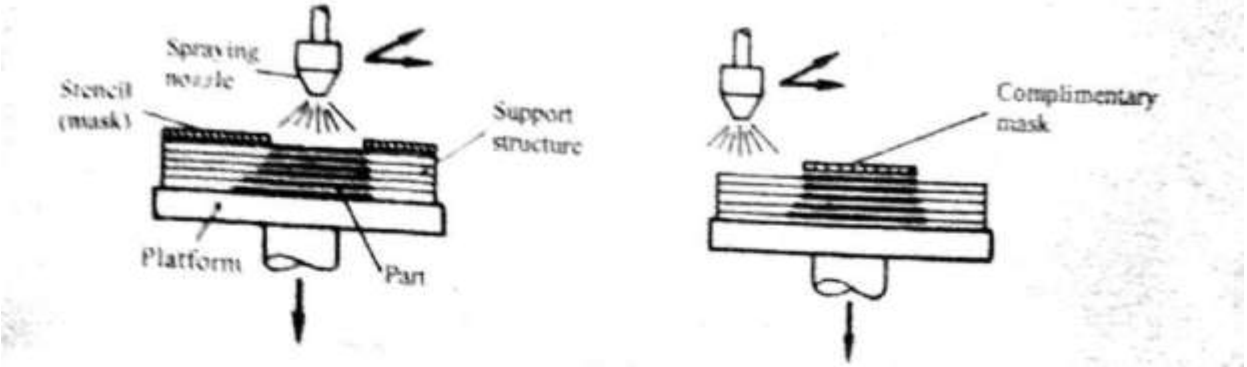
- A hollow part cannot be generated by LOM as the excess material remains trapped inside.
- Such parts can be generated in pieces.
- The difficulty in removing the unwanted material can be resolved by removing the excess material as it is produced on each layer. This is proposed to be done by a vacuum pump to suck away the loosened pieces to get attached to a screen. As the screen is moved to an area without suction the pieces fall into a waste bin. Figure below explain the principle schematically.
- However it is noted that removing the excess material layer wise also
- eliminate a major advantage of LOM
- Once the part is not build within a block of material, support structure has to be used for supporting cantilevers and disjoined areas.



Use of suction fan and screen for removing excess material in LOM

Repetitive masking and deposition

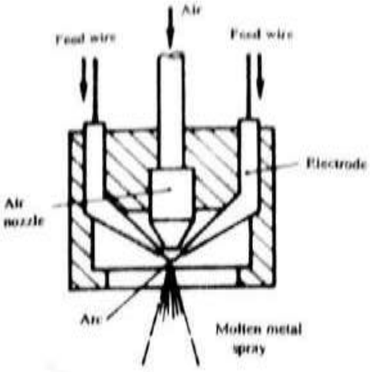
Robotics Institute of Carnegie-Mellon University has developed a GMP based on repetitive masking and depositing which has been given the name MD* (pronounced MD star). In this process a part is built layer by layer by selective deposition of metals from a thermal spray gun. The surface is covered by a stencil (made of thin disposable paper) cut by a laser beam and atomized droplets of the desired metal are sprayed onto the surface. Thus, a thin metal layer gets deposited on the uncovered area, solidifying very quickly, which forms the required layer with the desired cross section. The work area is then covered with a complimentary mask in which the uncut area corresponds to the cross section exposed previously, hence covering the previously exposed area. Next, a thin layer of a low-melting point alloy is deposited by spraying. Thus, a layer of uniform thickness is obtained which constitutes both the sections of the part and the support structure. Figure 4.17 shows the process schematically. The process of masking and spraying is repeated till all



Scheme of MD process

the layers are deposited. The previously deposited layer acts as the substrate for the spray deposition. When all the layers are deposited, the support metal is removed by melting at about 138°C and the three-dimensional part is obtained. The operation is carried out in either a vacuum or an inert gas atmosphere to prevent formation of oxides which can cause brittleness of the part. Working in vacuum is more difficult but it also eliminates entrapped air during droplet solidification and near zero porosity is obtained.

To maintain uniformity, the metal arc spray gun is manipulated by a robot. Figure 4.18 shows the basic features of a typical arc spray gun. Two spools of metal wire are fed through the electrodes and the two wire tips form the consumable electrodes. A large current is passed through the electrodes, striking an arc which melts the wire tips. The molten metal is atomized and sprayed by a high-velocity air jet directed at the arc. The atomized particles strike the substrate surface where they flatten out and solidify quickly. Parts can be built by the MD* process



Electric arc spray gun

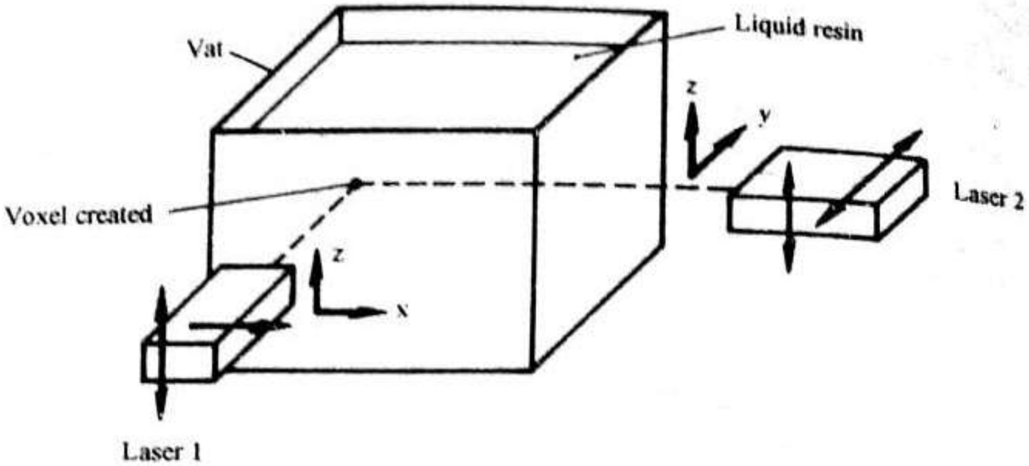
with layers of 0.03 mm thickness. Since a number of metals can be deposited within the same object, complete assemblies can be fabricated by the process as in the case of SGC process. Even integrated electromechanical systems are possible with integrated circuits inserted during part building and all components are encapsulated within one module. In future the process can be of significant importance in the field of 'mechatronics'.

Masks are made of pressure sensitive paper, cut by lasers, and alignment of each mask is accomplished using registration pins. Very fine features can be produced as spraying of features as narrow as 0.1 mm has been achieved. Furthermore, spray deposition with such fine atomized droplets leads to fabrication of parts with very little porosity and the resulting density can be higher than 99%.

Due to shrinkage on cooling, residual stresses may be generated which remain locked in the part. Shot peening of the deposited layers during the process can help reducing these stresses.

Beam Interference Solidification (BIS)

This early method for creating three-dimensional objects directly was patented by Formiographic Engine and Batelle participated in its development in the sixties. The material which is used in the process is a photo sensitive transparent liquid plastic (monomer). When the liquid is hit by a laser beam of a specific frequency, it reaches a reversible meta stable state and no bonding reaction takes place. But when a part of the liquid that is already in such a meta stable state is hit by another laser beam of a specific but different frequency, polymerization of the meta stable state takes place resulting in solidification of a voxel represented by the intersection of the two beams. Such a liquid resin is kept in a transparent vat and two laser beams are placed on adjacent sides (as shown in Figure 4.19) with the beams at right angles to each other. Pattern creation takes place by solidifying the resin at the point of intersection of the two beams



Principle of Beam Interference solidification and by moving the laser beams so that their point of intersection traces the required volume.

Though the principle is conceptually very elegant, till now it has not found much practical application because of a number of serious difficulties. The intensity of beam decreases continuously during its passage through the resin because of absorption. This makes it difficult to programme the laser beam movement so that all voxels are of uniform characteristics. The problem is further complicated because of shadow effects produced by the parts already solidified. To overcome this, an elaborate planning of beam movement is necessary to avoid the formation of a voxel after the front portion is solidified. This eliminates a major advantage the direct three-dimensional fabrication techniques claim to possess over the two-dimensional layer-by-layer building processes.

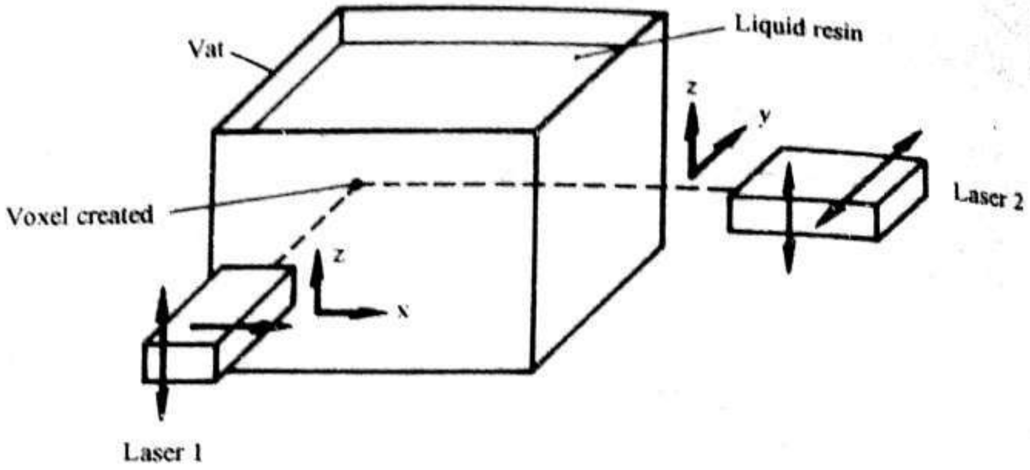


Figure 4.19: Principle of beam interference solidification

Beam Interference Solidification (BIS)

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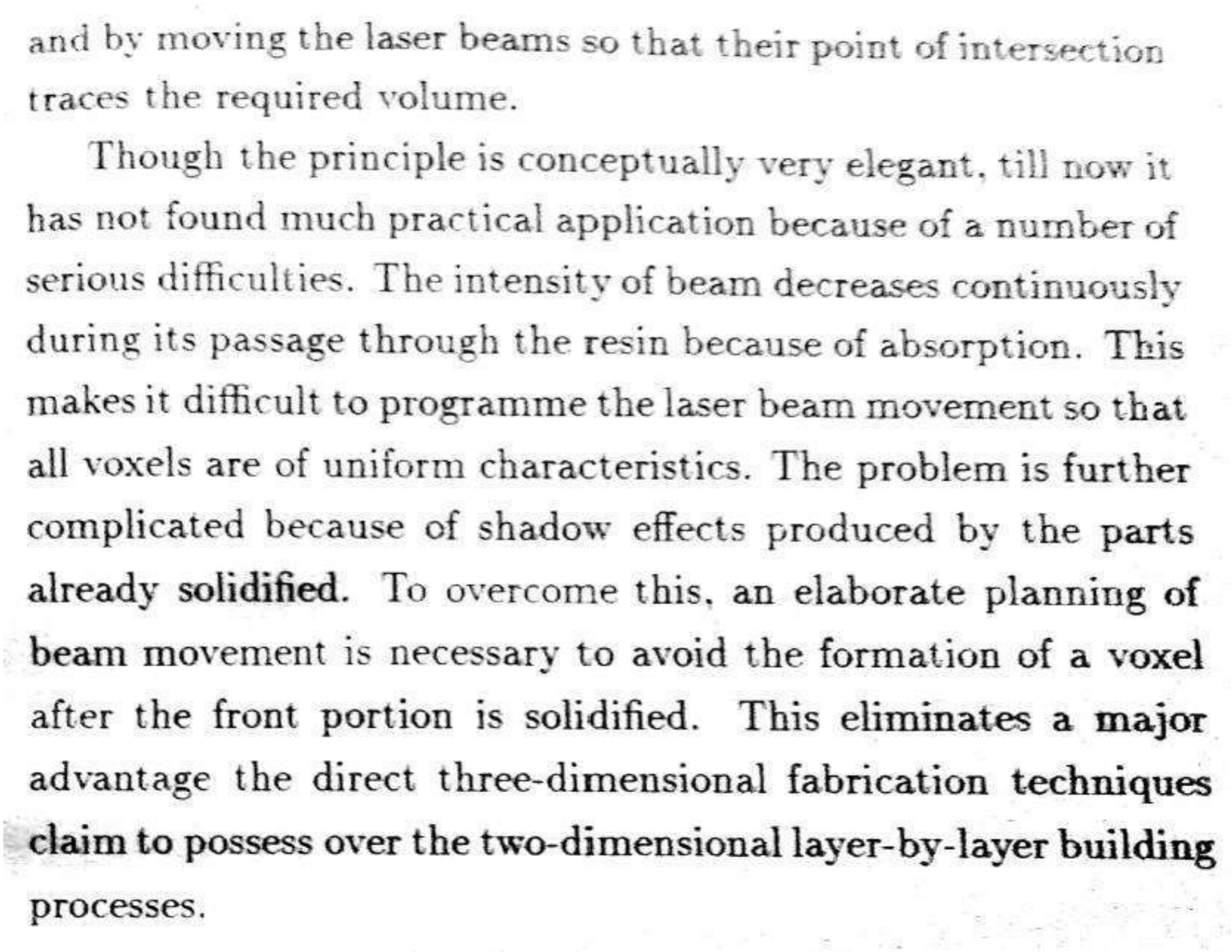


and by moving the laser beams so that their point of intersection traces the required volume.

Though the principle is conceptually very elegant, till now it has not found much practical application because of a number of serious difficulties. The intensity of beam decreases continuously during its passage through the resin because of absorption. This makes it difficult to programme the laser beam movement so that all voxels are of uniform characteristics. The problem is further complicated because of shadow effects produced by the parts already solidified. To overcome this, an elaborate planning of beam movement is necessary to avoid the formation of a voxel after the front portion is solidified. This eliminates a major advantage the direct three-dimensional fabrication techniques claim to possess over the two-dimensional layer-by-layer building processes.

Holographic interference solidification

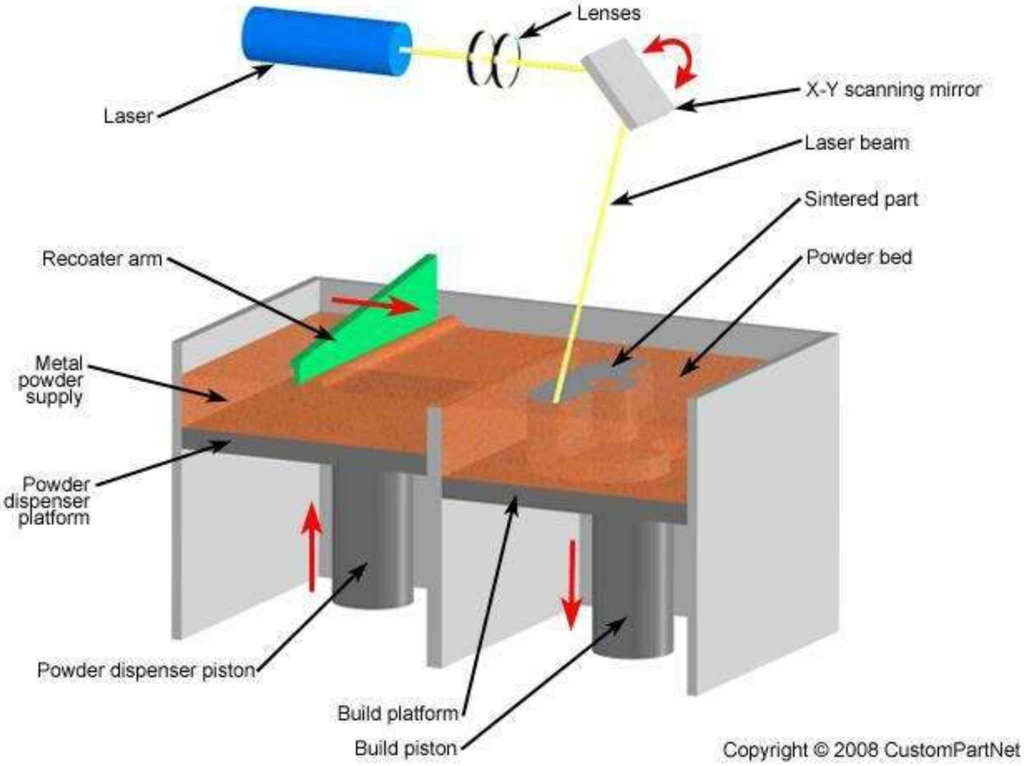
The exotic process process is also based on photo polymerization of photo sensitive resins. But in this process the part creation is not done voxel by voxel instead a three dimensional holographic image is projected in a vat containing a photo sensitive liquid monomer and a whole three dimensional surface gets solidified at once. The holographic film for projecting the image is created with a CAD system. A system based on this principle has been developed.

Special topic on RP using metallic alloys

DIRECT METAL LASER SINTERING (DMLS)

DMLS technology was developed jointly by Rapid Prototyping Innnovations (RPI) and EOS Gmbh in 1994. *It was the first commercial RP-method to produce metal parts in a single process*. Metal powder (20 µm diameter) without binder is completely melted by scanning of a *high power laser beam*. *The density of a produced part is about 98 %.* SLS has about 70 %. One advantage of DMLS compared to SLS is the small size of particles which enables very detailed parts.

Abbreviation:	**DMLS**
Materialtype:	Powder(Metal)
Materials:	Ferrous metals such as Steel alloys, Stainless steel, Tool steel; Aluminium, Bronze,Cobalt-chrome, Titanium, Ceramics..
Min layerthickness:	0,02mm
Surfacefinish:	Average
Buildspeed:	Fast
Applications:	Form/fit testing,Functional testing, Rapid tooling, High heat applications, Medical implants, Aerospace parts..



Direct Metal Laser Sintering (Dmls)

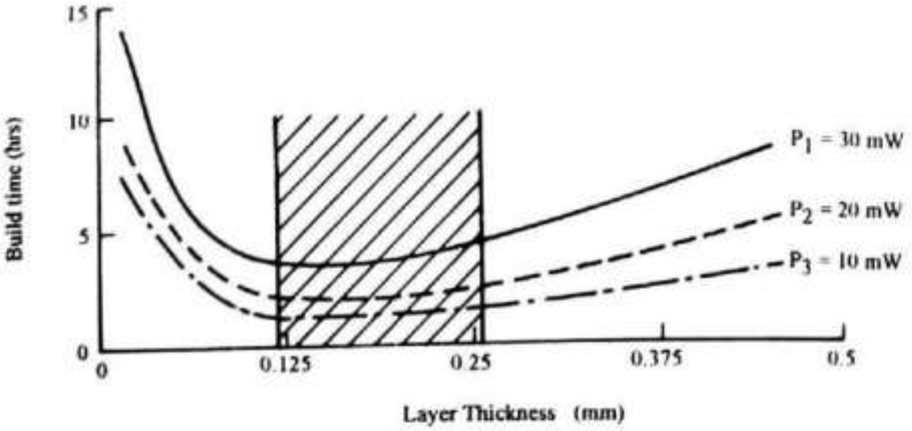


Figure 3.6: Effect of layer thickness on build time

0.125 mm to 0.25 mm is the optimum irrespective of the beam power.

Internal Hatching and Surface Skin Fills

To solidify (or to create) the area inside the part surrounded by the outer boundaries, internal hatching is used to reduce build time. Initially the boundary lines are created and then the interior is criss-crossed with lines, giving the part adequate internal stiffness. The style of hatching can vary. The pattern may consist of parallel lines making 0^o, 60^o and 120^o with the x-axis resulting in an internal structure which consists of equilateral triangles as indicated in Figure 3.7. The spacing between the consecutive lines is about 0.625 mm, and this common hatching pattern is called Tri-Hatch. When liquid photopolymers are used in the process, the material trapped inside the triangles remains liquid till the part is post cured following the comple-

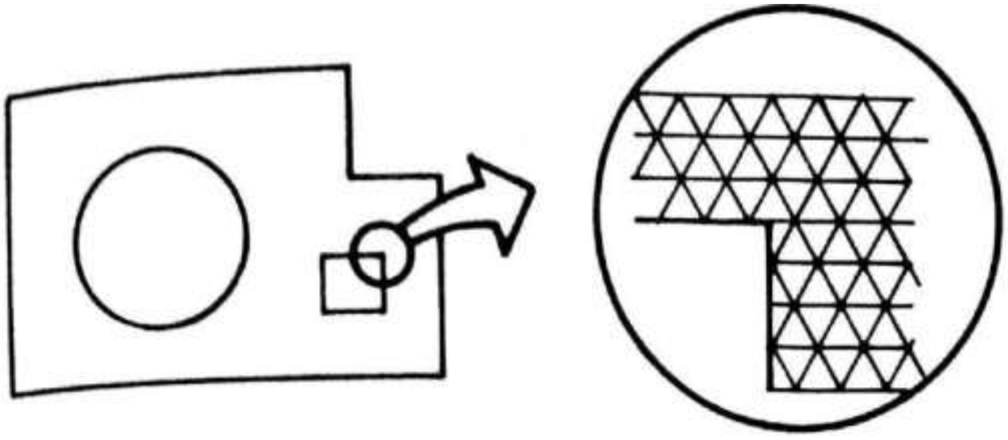


Figure 3.7: Tri-Hatch pattern

tion of the shaping process. Recently, a new pattern has been introduced which is called WEAVE^{TM}. In this, the scanning lines are parallel to the x- and y-axis, the spacing being about 0.28 mm when the layer thickness is about 0.25 mm. When the layer thickness is 0.127 mm, the spacing is made to be 0.229 mm. In the Tri-Hatch system too much ($\approx 50\%$) liquid material remains trapped and this leads to considerable post curing distortion. Attempts to reduce the fraction of trapped volume in the Tri-Hatch system by reducing the hatch spacing lead to increased curl distortion. With the WEAVE^{TM} system, a reduction of the fraction of trapped residual volume without resulting in large curl distortion is possible.

It is obvious that the outer surfaces of the generated solid cannot end up being porous. Thus, skins are created by skin fills which consist of closely spaced scan lines. The spacing between the scan lines is in the range 0.0762 mm to 0.127 mm. The skin fills are scanned after the borders and internal hatch. However, with the introduction of WEAVE^{TM} the importance of skin fill has been greatly reduced since very little residual liquid remains trapped inside.

Support Design

While slicing the CAD model into layers isolated islands may be produced as shown in Figure 3.8. The sectional view in plane 1-1 shows an isolated island which belongs to a projection from

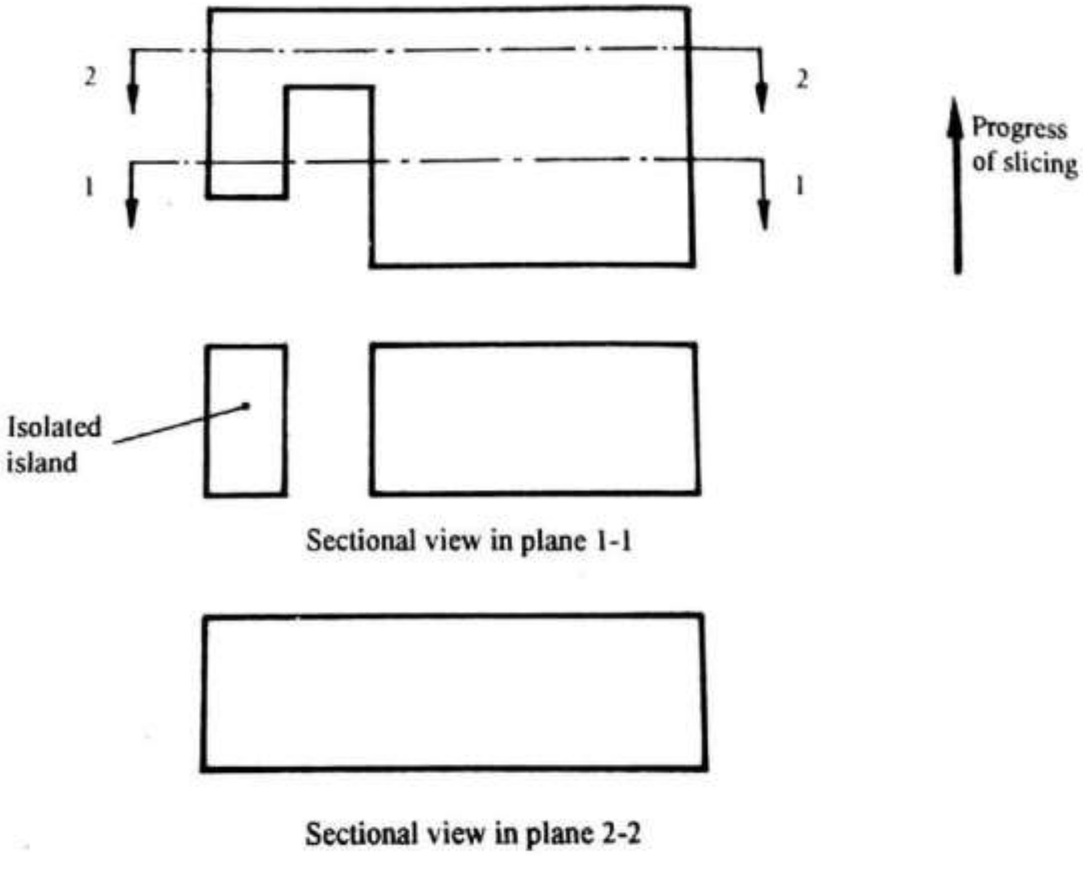
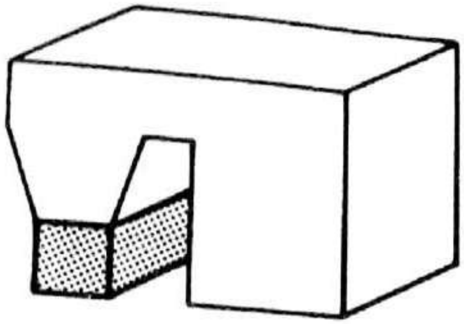
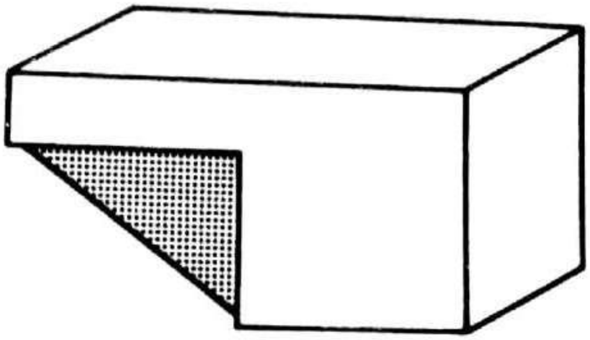


Figure 3.8: Formation of isolated islands

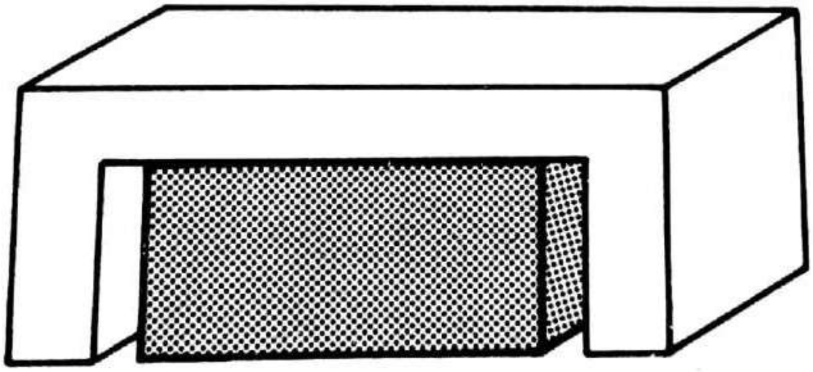
the main object. The connection of the projection to the parent body is from the top and while generating the shape by a GMP it will be built later. Thus it becomes essential to de-



Island



Gussets

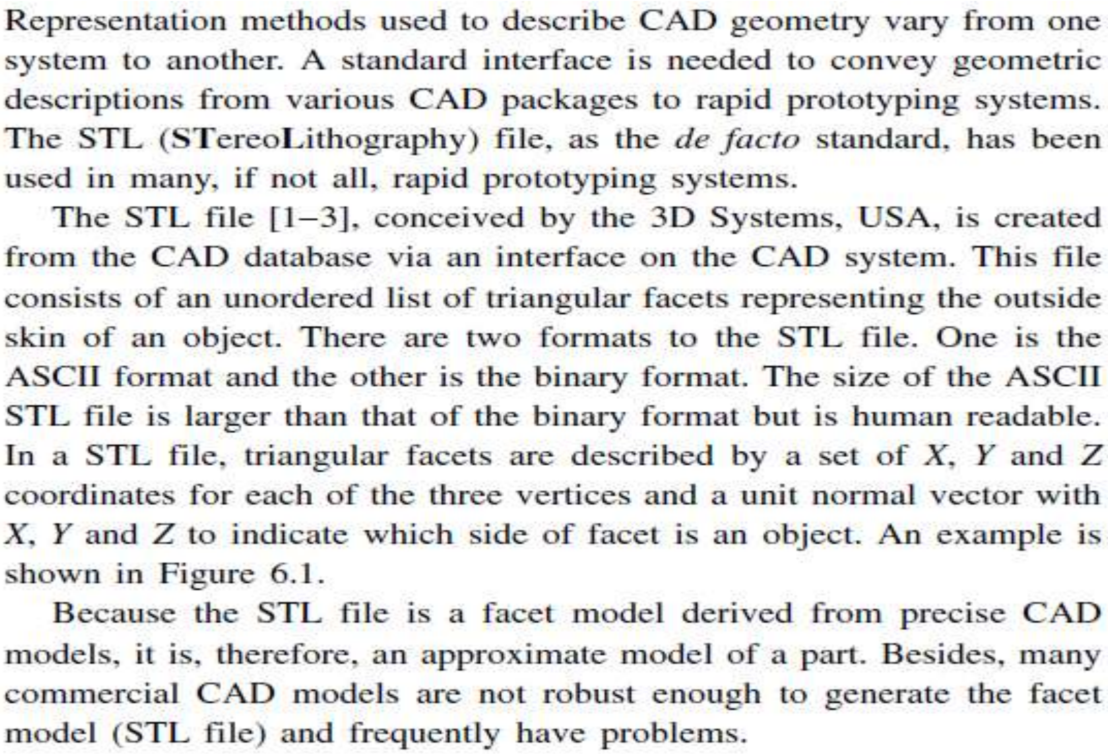


Ceiling

Various types of supports

UNIT –IV: RAPID PROTOTYPING DATA FORMAT

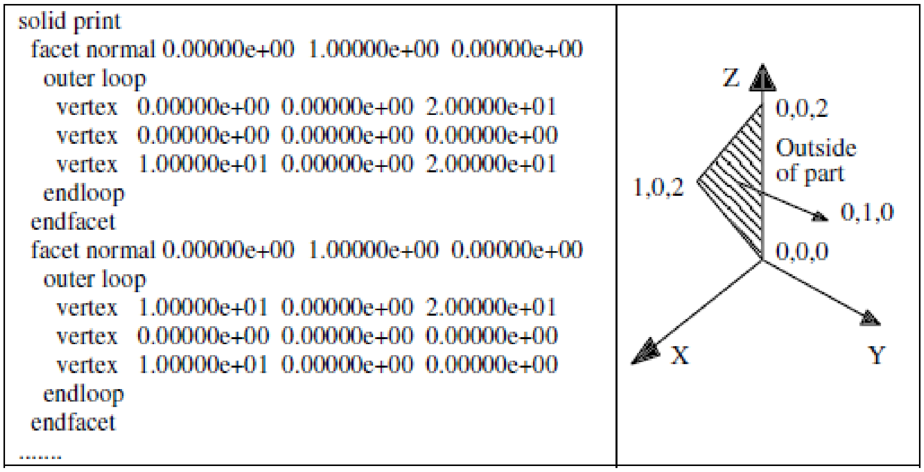
STL FORMATS



Representation methods used to describe CAD geometry vary from one system to another. A standard interface is needed to convey geometric descriptions from various CAD packages to rapid prototyping systems. The STL (**ST**ereo**L**ithography) file, as the *de facto* standard, has been used in many, if not all, rapid prototyping systems.

The STL file [1–3], conceived by the 3D Systems, USA, is created from the CAD database via an interface on the CAD system. This file consists of an unordered list of triangular facets representing the outside skin of an object. There are two formats to the STL file. One is the ASCII format and the other is the binary format. The size of the ASCII STL file is larger than that of the binary format but is human readable. In a STL file, triangular facets are described by a set of X, Y and Z coordinates for each of the three vertices and a unit normal vector with X, Y and Z to indicate which side of facet is an object. An example is shown in Figure 6.1.

Because the STL file is a facet model derived from precise CAD models, it is, therefore, an approximate model of a part. Besides, many commercial CAD models are not robust enough to generate the facet model (STL file) and frequently have problems.



```
solid print
 facet normal 0.00000e+00  1.00000e+00  0.00000e+00
  outer loop
   vertex   0.00000e+00  0.00000e+00  2.00000e+01
   vertex   0.00000e+00  0.00000e+00  0.00000e+00
   vertex   1.00000e+01  0.00000e+00  2.00000e+01
  endloop
 endfacet
 facet normal 0.00000e+00  1.00000e+00  0.00000e+00
  outer loop
   vertex   1.00000e+01  0.00000e+00  2.00000e+01
   vertex   0.00000e+00  0.00000e+00  0.00000e+00
   vertex   1.00000e+01  0.00000e+00  0.00000e+00
  endloop
 endfacet
.......
```

A SAMPLE OF STL FORMAT

Several problems plague STL files and they are due to the very nature of STL files as they contain no topological data. Many commercial tessellation algorithms used by CAD vendors today are also not robust [4–6], and as a result they tend to create polygonal approximation models which exhibit the following types of errors:

(1) Gaps (cracks, holes, punctures) that is, missing facets.
(2) Degenerate facets (where all its edges are collinear).
(3) Overlapping facets.
(4) Non-manifold topology conditions.

The underlying problem is due, in part, to the difficulties encountered in tessellating trimmed surfaces, surface intersections and controlling numerical errors. This inability of the commercial tessellation algorithm to generate valid facet model tessellations makes it necessary to perform model validity checks before the tessellated model is sent to the Rapid Prototyping equipment for manufacturing. If the tessellated model is invalid, procedures become necessary to determine the specific problems, whether they are due to gaps, degenerate facets or overlapping facets, etc.

STL FILE REPAIR

The STL file repair can be implemented using a generic solution and dedicated solutions for special cases.

Generic Solution

In order to ensure that the model is valid and can be robustly tessellated, one solution is to check the validity of all the tessellated triangles in the model. This section presents the basic problem of missing facets and a proposed generic solution to solve the problem with this approach.

In existing RP systems, when a punctured shell is encountered, the course of action taken usually requires a skilled technician to manually repair the shell. This manual shell repair is frequently done without any knowledge of the designer's intent. The work can be very time-consuming and tedious, thus negating the advantages of rapid prototyping as the cost would increase and the time taken might be longer than that taken if traditional prototyping processes were used.

Unit –V Rapid Prototyping Applications

Areas of applications are closely related to the purposes of prototyping and consequently the materials used. As such, the closer the RP materials to the traditional prototyping materials in physical and behavioral characteristics, the wider will be the range of applications. Unfortunately, there are marked differences in these areas between current RP materials and traditional materials in manufacturing. The key to increasing the applicability of RP technologies therefore lies in widening the range of materials.

In the early developments of RP systems, the emphasis of the tasks at hand was oriented towards the creation of "touch-and-feel" models to support design, i.e., creating 3D objects with little or without regard to their function and performance. These are broadly classified as "Applications in Design". It is the result that influenced, and in many cases limited by, the materials available on these RP systems. However as the initial costs of the machines are high, vendors are constantly in search for more areas of applications, with the logical search for functional evaluation and testing applications, and eventually tooling. This not only calls for improvements in RP technologies in terms of processes to create stronger and more accurate parts, but also in terms of developing an even wider range of materials, including metals and ceramic composites. Applications of RP prototypes were first extended to "Applications in Engineering, Analysis and Planning" and later extended further to "Applications in Manufacturing and Tooling". These typical application areas are summarized in Figure 7.1 and discussed in the following sections.

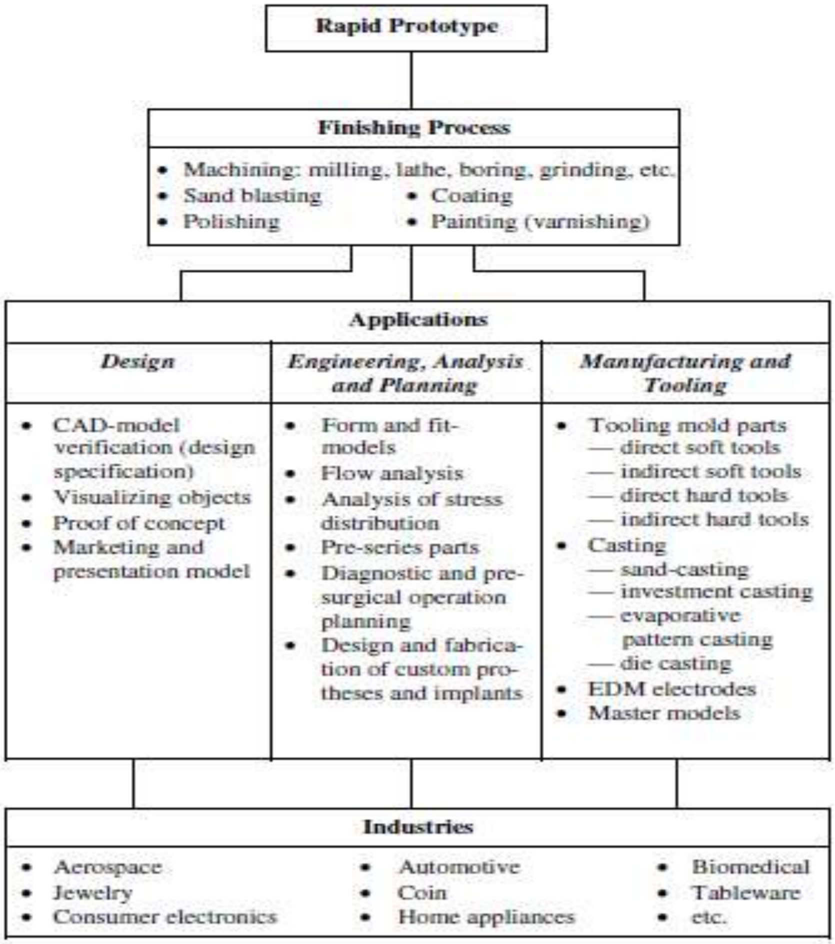


Figure 7.1: Typical application areas of RP

APPLICATIONS IN DESIGN

CAD Model Verification

This is the initial objective and strength of RP systems, in that designers often need the physical part to confirm the design that they have created in the CAD system. This is especially important for parts or products designed to fulfill aesthetic functions or that are intricately designed to fulfill functional requirements.

Visualizing Objects

Designs created on CAD systems need to be communicated not only amongst designers within the same team, but also to other departments, like manufacturing, and marketing. Thus, there is a need to create objects from the CAD designs for visualization so that all these people will be referring to the same object in any communications. Tom Mueller in his paper entitled, "Application of Stereolithography in injection molding" [1] characterizes this necessity by saying:

> *"Many people cannot visualize a part by looking at print. Even engineers and toolmakers who deal with print everyday requires several minutes or even hours of studying a print. Unfortunately, many of the people who approve a design (typically senior management, marketing analysts, and customers) have much less ability to understand a design by looking at a drawing."*

APPLICATIONS IN ENGINEERING, ANALYSIS AND PLANNING

Other than creating a physical model for visualization or proofing purposes, designers are also interested in the engineering aspects of their designs. This invariably relates to the functions of the design. RP technologies become important as they are able to provide the information necessary to ensure sound engineering and function of the product. What makes it more attractive is that it also save development time and reduce costs. Based on the improved performance of processes and materials available in current RP technologies, some applications for functional models are presented in the following sections.

APPLICATIONS IN MANUFACTURING AND TOOLING

Central to the theme of rapid tooling is the ability to produce multiple copies of a prototype with functional material properties in short lead-times. Apart from mechanical properties, the material can also include functionalities such as color dyes, transparency, flexibility and the like. Two issues are to be addressed here: tooling proofs and process planning. Tooling proofs refer to getting the tooling right so that there will not be a need to do a tool change during production because of process problems. Process planning is meant for laying down the process plans for the manufacture as well as assembly of the product based on the prototypes produced.

Rapid tooling can be classified into soft or hard, and direct or indirect tooling [3], as schematically shown in Figure 7.3. Soft tooling, typically made of silicon rubber, epoxy resins, low melting point alloys and foundry sands, generally allows for only single casts or for small

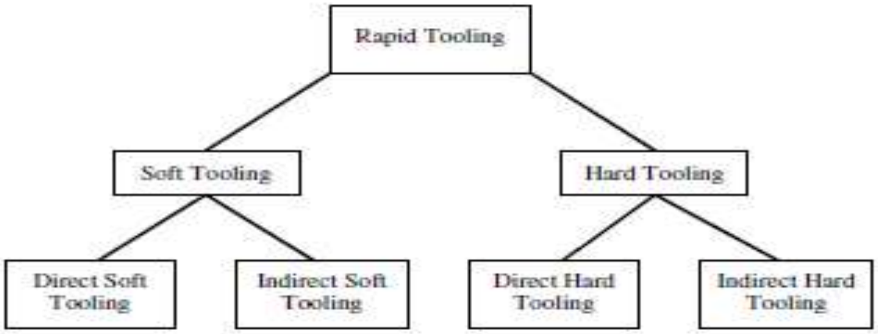


Figure 7.3: Classification of rapid tooling

batch production runs. Hard tooling, on the other hand, usually made from tool steels, generally allows for longer production runs.

Direct tooling is referred to when the tool or die is created directly by the RP process. As an example in the case of injection molding, the main cavity and cores, runner, gating and ejection systems, can be produced directly using the RP process. In indirect tooling, on the other hand, only the master pattern is created using the RP process. A mold, made of silicon rubber, epoxy resin, low melting point metal, or ceramic, is then created from the master pattern.

AEROSPACE INDUSTRY

With the various advantages that RP technologies promise, it is only natural that high value-added industries like the aerospace industry have taken special interest in it even though initial investment costs may be high. There are abundant examples of the use of RP technology in the aerospace industry. The following are a few examples.

AUTOMOTIVE INDUSTRY

Prototyping Complex Gearbox Housing for Design Verification

Volkswagen has utilized Helysis's LOM to speed up the development of a large, complex gearbox housing for its Golf and Passat car lines [26]. The CAD model for the housing was extremely complex and difficult to visualize. VW wanted to build a LOM part to check the design of the CAD model and then use the part for packaging studies.

Using traditional methods, such a prototype would be costly and time consuming to build, and it may not be always possible to include all fine details of the design. Fabrication of the model based on drawings was often subjected to human interpretation, and consequently is error-prone, thus further complicating the prototyping process. All these difficulties were avoided by using RP technology as the fabrication of the model was based entirely on the CAD model created.

The gearbox housing was too large for the build volume of the LOM machine. The CAD model was thus split into five sections and re-assembled after fabrication. It took about ten days to make and finish all five sections, and once they were completed, patternmakers glued them together to complete the final model. The LOM model was first used for verifying the design, and subsequently, to develop sand-casting tooling for the creation of metal prototypes. The RP process had shrunk the prototype development time from eight weeks to less than two, and considerable time and cost savings were achieved.

BIOMEDICAL INDUSTRY

From manufacturing of medical devices and creating customized implants and prostheses to surgical planning and education, RP can be applied to enhance medical applications and healthcare delivery. The following sections relate examples of how RP can play a valuable role in the biomedical industry.

JEWELRY INDUSTRY

Figure 7.16: An investment cast silver alloy prototype of a broach (right), the full-scale wax pattern produced from the silicon rubber molding (center), and the two-time scaled SLA model to aid visualization (left)

The jewelry industry has traditionally been regarded as one which is heavily craft-based, and automation is generally restricted to the use of machines in the various individual stages of jewelry manufacturing. The use of RP technology in jewelry design and manufacture offers a significant breakthrough in this industry. In an experimental computer-aided jewelry design and manufacturing system jointly developed by Nanyang Technological University and Gintic Institute of Manufacturing Technology in Singapore, the SLA (from 3D Systems) was used successfully to create fine jewelry models [45]. These were used as master patterns to create the rubber molds for making wax patterns that were later used in investment casting of the precious metal end product (see Figure 7.16). In an experiment with the design of rings, the overall quality of the SLA models were found to be promising, especially in the generation of intricate details in the design. However, due to the nature of the step-wise building of the model, steps at the "gentler" slope of the model were visible. With the use of better resin and finer layer thickness, this problem was reduced but not fully eliminated. Further processing was found to be necessary, and abrasive jet deburring was identified to be most suitable [46].

Though post-processing of SLA models is necessary in the manufacture of jewelry, the ability to create models quickly (a few hours compared to days or even weeks, depending on the complexity of the design) and its suitability for use in the manufacturing process offer great promise in improving design and manufacture in the jewelry industry.

COIN INDUSTRY

Similar to the jewelry industry, the mint industry has traditionally been regarded as very labor-intensive and craft-based. It relies primarily on the skills of trained craftsmen in generating the "embossed" or relief designs on coins and other related products. In another experimental coin manufacturing system using CAD/CAM, CNC and RP technologies developed by Nanyang Technological University and Gintic Institute of Manufacturing Technology in Singapore, the SLA (from 3D Systems) was used successfully with a Relief Creation Software to create tools for coin manufacture [47]. In the system

Figure 7.17: Two-dimensional artwork of a series of Chinese characters and a roaring dragon

involving RP technology, its working methodology consists of several steps.

Firstly, 2D artwork is read into ArtCAM, the CAD/CAM system used in the system, utilizing a Sharp JX A4 scanner. Figure 7.17 shows the 2D artwork of a series of Chinese characters and a roaring dragon. In the ArtCAM environment, the scanned image is reduced from a color image to a monochrome image with the fully automatic "Gray Scale" function. Alternatively, the number of colors in the image can be reduced using the "Reduce Color" function. A color palette is provided for color selection and the various areas of the images are colored, either using different sizes and types of brushes or the automatic flood fill function.

The second step is the generation of surfaces. The shape of a coin is generated to the required size in the CAD system for model building. A triangular mesh file is produced automatically from the 3D model. This is used as a base onto which the relief data is wrapped and later combined with the relief model to form the finished part.

The third step is the generation of the relief. In creating the 3D relief, each color in the image is assigned a shape profile. There are various fields that control the shape profile of the selected colored

Figure 7.18: Three-dimensional relief of artwork of the roaring dragon

region, namely, the overall general shape for the region, the curvatures of the profile (convex or concave), the maximum height, base height, angle and scale. The relief detail generated can be examined in a dynamic Graphic Window within the ArtCAM environment itself. Figure 7.18 illustrates the 3D relief of the roaring dragon artwork.

The fourth step is the wrapping of the 3D relief onto the coin surface. This is done by wrapping the three-dimensional relief onto the triangular mesh file generated from the coin surfaces. This is a true surface wrap and not a simple projection. The wrapped relief is also converted into triangular mesh files. The triangular mesh files can be used to produce a 3D model suitable for color shading and machining. The two sets of triangular mesh files, of the relief and the coin shape, are automatically combined. The resultant model file can be color-shaded and used by the SLA to build the prototype.

The fifth step is to convert the triangular mesh files into the STL file format. This is to be used for building the RP model. After the conversion, the STL file is sent to the SLA to create the 3D coin pattern which will be used for proofing of design [47].