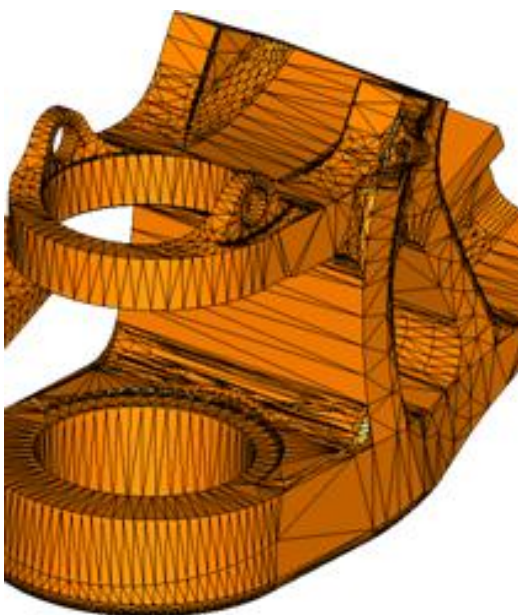
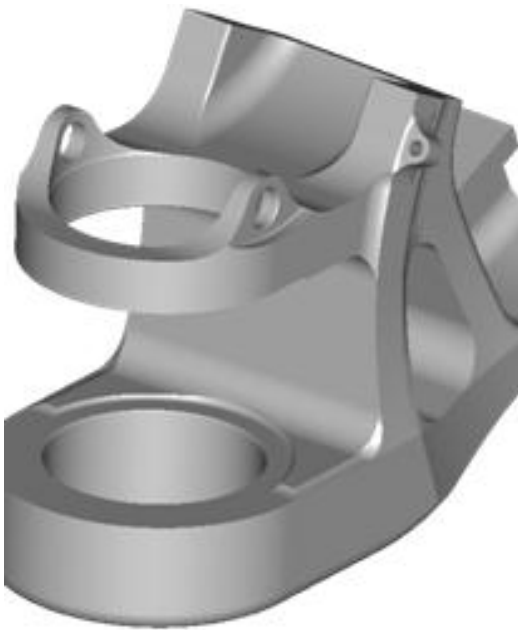


1

Introduction



Course Contents

- 1.1** Introduction
- 1.2** Traditional Prototyping Vs. Rapid Prototyping
- 1.3** Classification of Rapid Prototyping Systems

1.1 Introduction

- The current marketplace is undergoing an accelerated pace of change that challenges companies to innovate new techniques to rapidly respond to the ever-changing global environment.
- A country's economy is highly dependent on the development of new products that are innovative with shorter development time.
- Organizations now fail or succeed based upon their ability to respond quickly to changing customer demands and to utilize new innovative technologies.
- In this environment, the advantage goes to the firm that can offer greater varieties of new products with higher performance and greater overall appeal.
- At the center of this environment is a new generation of customers.
- These customers have forced organizations to look for new methods and techniques to improve their business processes and speed up the product development cycle.
- As the direct result of this, the industry is required to apply new engineering philosophy such as *Rapid Prototyping*.

Prototype:

- It is the first or preliminary version of a product from which other forms are developed.
- It is a model from which further models and eventually the final product will be derived.
- It is the representation of a solution to a design problem in such a way that a user can experience it. It is not meant to function but rather to let users interact with them so as to provide feedback.

Rapid Prototyping:

- The term rapid prototyping (RP) refers to a class of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data.
- It is a process for rapidly creating a system or part representation before final release or commercialization.
- It is a process for fabricating of a physical, three – dimensional part of arbitrary shape directly from a numerical description (typically a CAD model) by a quick, totally automated and highly flexible process.
- Alternative names for RP:
 - ❖ Additive Manufacturing
 - ❖ Layer Manufacturing
 - ❖ Direct CAD Manufacturing
 - ❖ Solid Freeform Fabrication

1.1.1 Fundamental Automated Processes

- There are three fundamental fabrication processes as shown in the below figure. They are Subtractive, Additive and Formative processes.

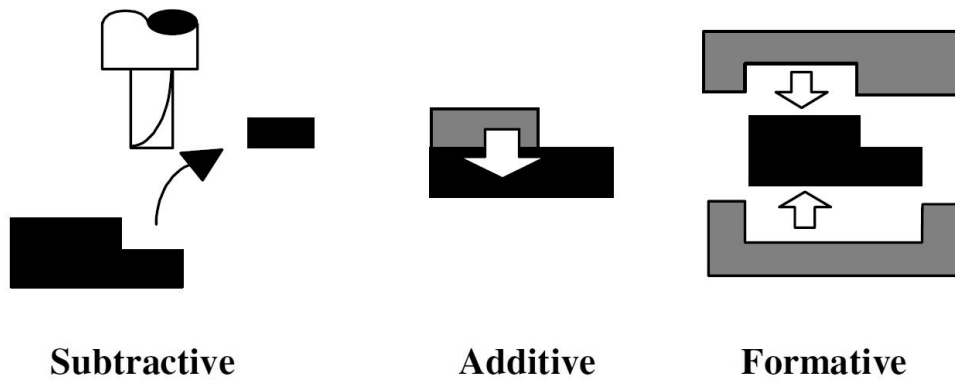


Fig 1.1 Three types of fundamental fabrication processes

- In the **subtractive process**, one starts with a single block of solid material larger than the final size of the desired object and material is removed until the desired shape is reached.
- In contrast, an **additive process** is the exact reverse in that the end product is much larger than the material when it started.
- A material is manipulated so that successive portions of it combine to form the desired object.
- Lastly, the **formative process** is one where mechanical forces or restricting forms are applied on a material so as to form it into the desired shape.
- There are many examples for each of these fundamental fabrication processes.
- Subtractive fabrication processes include most forms of machining processes — CNC or otherwise. These include milling, turning, drilling, planning, sawing, grinding, EDM, laser cutting, water-jet cutting and the likes.
- Most forms of rapid prototyping processes such as Stereolithography and Selective Laser Sintering fall into the additive fabrication processes category.
- Examples of formative fabrication processes are: Bending, forging, electromagnetic forming and plastic injection molding.
- These include both bending of sheet materials and molding of molten or curable liquids. The examples given are not exhaustive but indicative of the range of processes.
- Hybrid machines combining two or more fabrication processes are also possible. For example, in progressive press-working, it is common to see a hybrid of subtractive (as in blanking or punching) and formative (as in bending and forming) processes.

1.1.2 Generic RP process:

- Before the application of RP, computer numerically controlled (CNC) equipments were used to create prototypes either directly or indirectly using CAD data.
- CNC process consists of the removal of material in order to achieve the final shape of the part and it is in contrast to the RP operation since models are built by adding material layers after layers until the whole part is constructed.
- In RP process, thin-horizontal-cross sections are used to transform materials into physical prototypes. Steps in RP process are illustrated in the below figure.

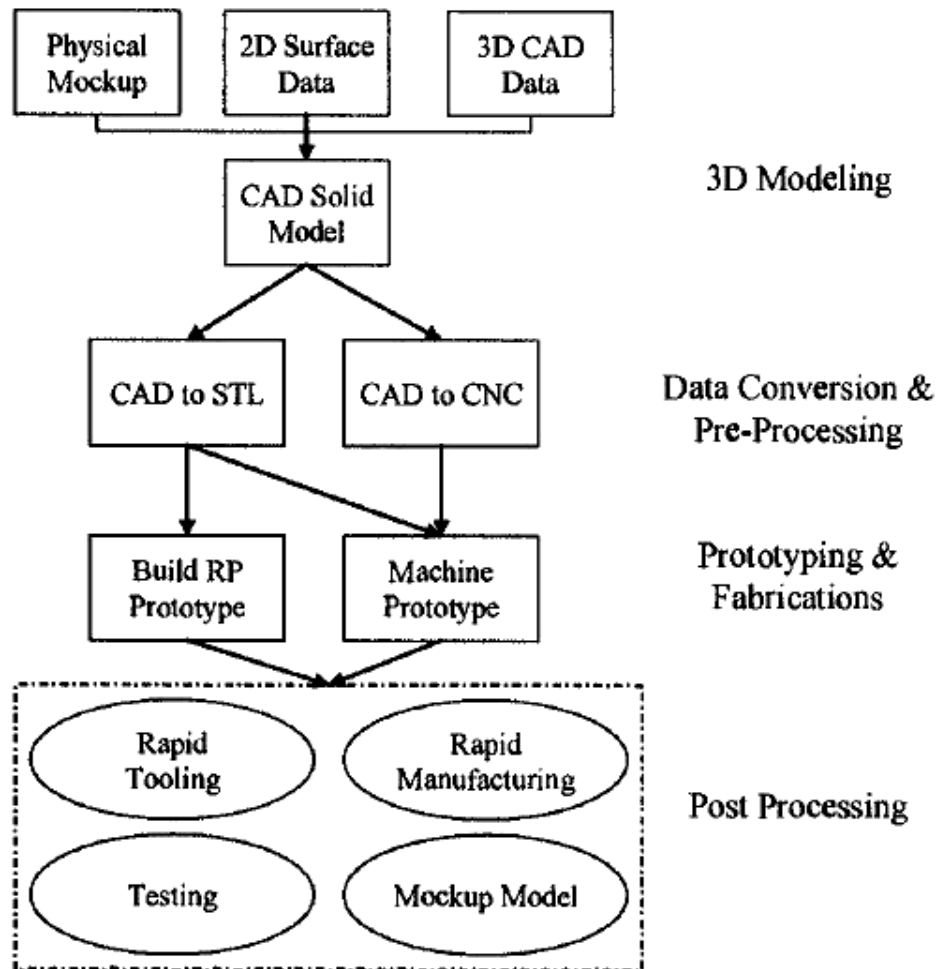


Fig 1.2 Generic RP process

- Depending on the quality of the final prototype, several iterations are possible until an acceptable model is built.
- In this process, CAD data is interpreted into the Stereolithography data format. Stereolithography or "STL" is the standard data format used by most RP machines.
- By using "STL", the surface of the solid is approximated using triangular facets with a normal vector pointing away from the surface in the solid.
- Since chordal deviation is used to approximate real mathematical surface, it is important to minimize this deviation to better approximate the real surface.
- This impacts the size of the required triangles and it will also increase the processing time.
- A wide range of technologies are developed to transform different materials into physical parts. For RP process, materials are categorized into liquid, solid and powdered.
- As Rapid Prototyping (RP) technology becomes more mature, it is beginning to lend itself to other applications such as rapid tooling and rapid manufacturing.
- Some traditional tool making methods are considering the use of RP technologies to directly or indirectly fabricate tools.

- The Indirect method of rapid tooling (RT) uses the RP pattern as mold. This is considered as a good alternative to the traditional mold making since it is more efficient and requires less lead-time.
- This approach is also less expensive and allows for quick validation of designs. In direct RT method, the RP process is used for direct fabrication of the tools.

1.1.3 A TYPICAL RAPID PROTOTYPING PROCESS

- There are many different RP processes, but the basic operating principles are very similar. Below figure shows the data-flow diagram of the basic process.

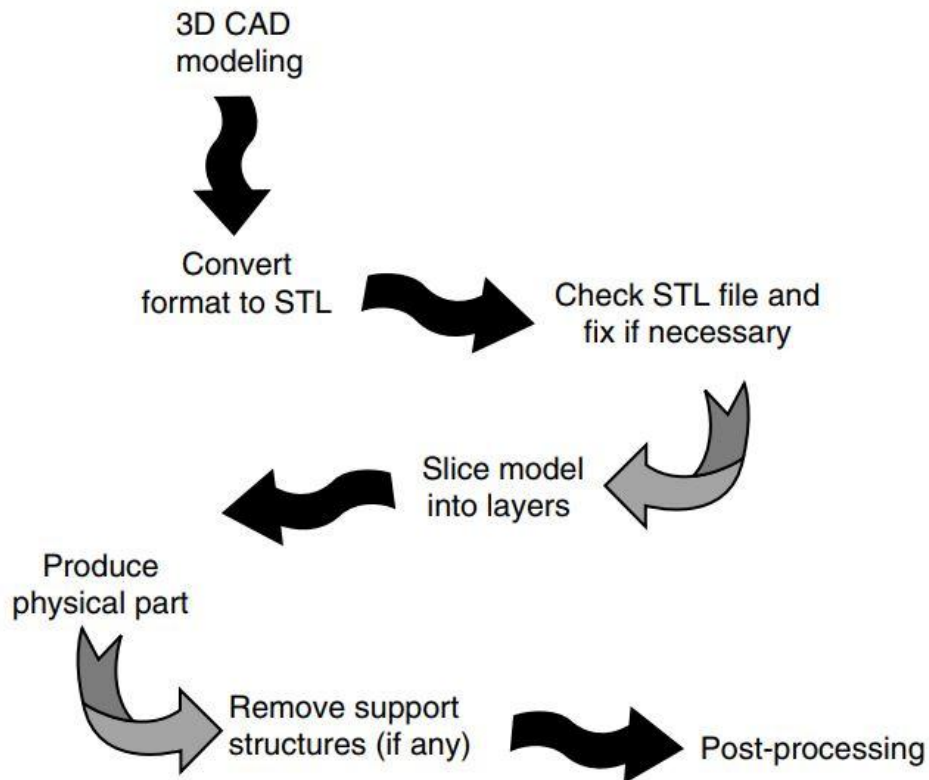


Fig 1.3 The data flow of the basic RP process

- It includes the following steps:
 - 1) Construct the CAD model
 - 2) Convert the CAD model to STL format
 - 3) Check and fix STL file
 - 4) Generate support structures if needed
 - 5) Slice the STL file to form layers
 - 6) Produce physical model
 - 7) Remove support structures
 - 8) Post-process the physical model
- The RP input can be described as the electronic information required to specify the physical object with 3D data.
- There are two possible starting models, i.e., a computer model and a physical model.
- A computer model created from a CAD system can be either a surface model or a solid model.

- A physical model can be obtained by digitizing or scanning the geometry of a physical part.
- Three-dimensional data from digitizing a physical part is not always straightforward.
- It generally requires data acquisition through a method known as reverse engineering, using a CMM or laser digitizer.
- The industry standard for rapid prototyping is the STL file, a file extension from STereoLithography.
- Basically, it is a file that uses a mesh of triangles to form the shell of the solid object, where each triangle shares common sides and vertices. The CAD software generates a tessellated object description.
- In STL format, the file consists of the X, Y, and Z coordinates of the three vertices of each surface triangle, with an index to describe the orientation of the surface normal.
- Normally, the support structure is generated before slicing to hold overhanging surfaces during the build.
- Most current CAD packages can export a CAD file in STL file format, and good STL files will assure a speedy quote turnaround, and good quality RP models. The STL format is an ASCII or binary file used in the RP process.
- It is a list of triangular surfaces that describe a computer-generated solid model. The binary files are smaller when compared to ASCII files.
- The facets define the surface of a 3D object. As such, each facet is part of the boundary between the interior and the exterior of the object.
- The orientation of the facets (which way is “out” and which way is “in”) is specified redundantly in two ways that must be consistent.
- First, the direction of the normal is outward. Second, the vertices are listed in counterclockwise order when looking at the object from the outside (right-hand rule) as shown in below figure.

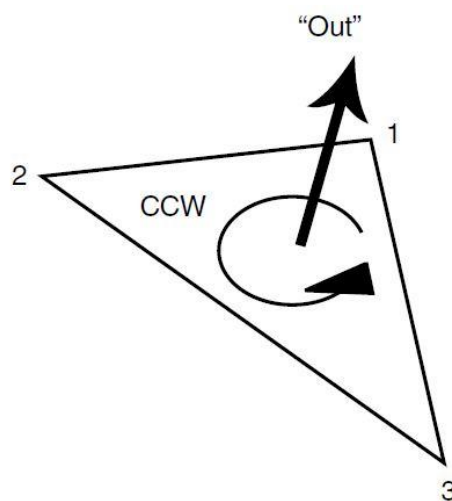


Fig 1.4 A triangle with three vertices. The sequence of the storage of the vertices indicates the direction of the triangular face.

WHY STL FILES?

- The STL files translate the part geometry from a CAD system to the RP machine.
- All CAD systems build parts and assemblies, store geometry, and generally do many things in their own independent and proprietary way.
- Instead of having a machine that has to communicate with all of these different systems, there is a single, universal file format that every system needs to be able to produce so that an RP machine can process what a part looks like for slicing. This is the STL file.
- Why is STL format used? The reason is because slicing a part is easier compared to other methods such as B-rep (boundary representation) and CSG (constructive solid geometry), which will need geometric reasoning and data conversion.
- Below figure shows the representation of a cube in B-rep.

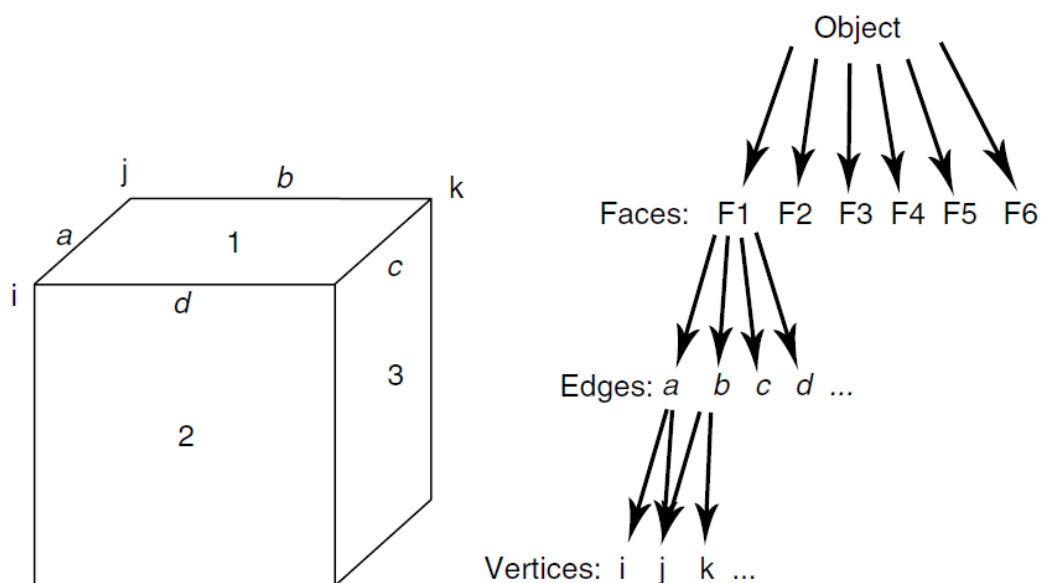


Fig 1.5 Boundary representation of a cube and its data structure

- The right-hand side of the figure shows the data structure of the geometric entities.
- To calculate the intersection between the geometry and a plane that represents the slicing operation is not very efficient.
- The slicing operation is computed by “intersecting” a ray of virtual lines with the object of interest. In other words, it is necessary to compute the intersections between a lot of lines and the object.
- The STL format allows us to transfer the slicing operation into a routine of finding the interactions between lines and triangles.
- Basically, this operation judges whether the intersection point is within or outside the triangles, and there are very efficient codes to do just that.
- The reason that the STL format is the industry standard is because it can make the process robust and reliable to get the correct result the first time, and because high-end data processing tools, such as surface and STL repair and translation tools, are available in the market.

- The model presenting the physical part to be built should be presented as closed surfaces that define an enclosed volume.
- The meaning of this is that the data must specify the inside, outside, and boundary of the model. This requirement is redundant if the modeling used is solid modeling.
- This approach ensures that all horizontal cross-sections essential to RP are closed curves.
- The internal representation of a CAD model as shown in the below figure can be in B-rep or CSG representations, while its STL representation is shown in the next figure.



Fig 1.6 An example of a CAD model

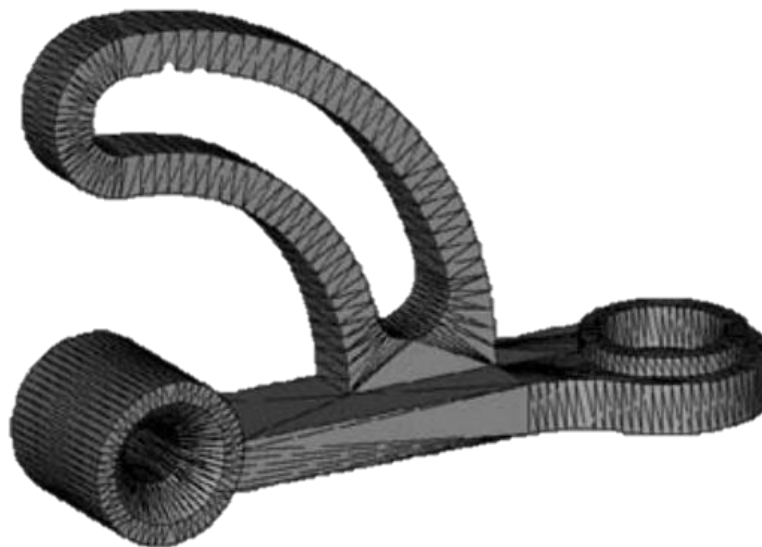


Fig 1.7 An example of an STL triangulation model

- The STL representation is often used as the standard format to interact between the CAD model and an RP machine.
- The STL representation approximates the surfaces of the model by polygons, meaning that STL files for curved parts can be very large in order to represent the original geometry well.
- In other words, the CAD models can have smooth curved surfaces, but the RP process must have the model broken down into discrete volumes to build the part.
- To have a continuous smooth curved surface, the volumes for each discrete piece would have to be close to zero, which would require the number of entities to be infinite, which makes for a very large file size in the real world.
- In order to minimize the file size to something that is more manageable, the system makes the volumes of the discrete pieces larger.
- The larger these volumes, the fewer are needed to approximate the part. Keep in mind that the fewer the pieces used, the less accurate the approximation is when compared to the original model.
- Triangulation, as shown in figure, is breaking the model into these discrete pieces and the trick is balancing the number and size of these pieces to make a practical file size without sacrificing too much accuracy.

1.2 Traditional Prototyping Vs. Rapid Prototyping

- Prototypes play a very important role in product development as stated above it can be very easy to have a negative impact on the development of a product.
- Prototyping has huge implications on product cost, quality, and time. Obviously prototypes are necessary for all products and the more useful prototypes that are made, the higher the quality of the product.
- However, it is important when building prototypes that they are built by adding low cost to the overall product and that the final product still has the shortest time-to-market possible.
- Therefore, it is important that the prototype serves a purpose for the development of the product.
- Whether it is to study the function of the product, the appearance or “feel” of a product, to visualize improvements to a product, etc. there is a point where prototyping can increase the cost of a product and its time-to-market. This is why material and process criteria for every prototype are important.
- When building a prototype, to keep cost to a minimum, it is very important to use cheap, readily available materials that will still serve the same purpose as the actual product materials.
- Depending on availability, function, and cost, it is also important to select a prototyping process that not only serves the prototype’s purpose, but also keeps cost low.

- Prototyping is an approximation of the product along one or more dimensions of interest which includes prototypes ranging from concept sketches to fully functional artifacts.
- Prototyping can help everyone visualize the same end result so that there is no ambiguity, and everyone is on the same page.
- Depending on various prototyping applications, prototyping methods can be classified into physical or analytical methods. For example, simulation approach is an analytical method, and a clay mock-up is a physical prototype.
- From a different angle, prototypes can also be classified as comprehensive or focused prototypes.
- For example, when a prototype is used to test the “look” of a product, this prototype may be made from Styrofoam for the purpose, and thus it is a look focused prototype.
- On the contrary, a full vehicle prototype built to test its full functions would be a comprehensive prototype.
- Virtually every business uses prototyping. A wide range of businesses use prototypes, from airplane manufacturers to toy producers to computer system developers.
- Prototypes are one of the most useful and cost-effective quality tools businesses have. Prototypes can be a source of creativity, and they allow the user to interact with the product so the developer can receive feedback.
- Prototyping is not limited to product development. It can also be used as process development.
- Every department can use prototypes to help them excel. For example, marketing departments use prototyping to determine why consumers buy products.
- A nonworking mock-up of the product can be reviewed by customers prior to acceptance. Sometimes these basic prototypes are used at trade shows.
- For example, the auto industry refers to them as concept cars.
- Rapid prototyping can be used to accelerate the design process, and it leads to high quality, defect-free products and reduces risk. This technique has proven essential to market leaders such as Microsoft, Intel, GM, Boeing, Ford, and Cisco, etc.
- In the software industry, a series of drawings that are created by the developers are used to obtain the acceptance by decision makers. For example, sticky notes can be used when designing graphical user interfaces so users can see the proposal.
- Before a prototype is made, the goal of the prototype needs to be well defined. For example, it could be a “rough version” to answer a single or set of binary (yes/no) questions or to visualize and brainstorm possible improvements.
- It could also be a concept model with no working features to obtain early feedback from customers.

- It could be a study of the product features and models to refine difficult features, a simulated walk-through of product activities, or simply the creation of a photographic quality model to create a demonstration video for marketing and evaluating the product in use.
- Since product development is an iterative process, it usually requires building several prototypes in the iterative manner to produce a quality product.
- These prototypes may need to serve in various purposes and in various stages of product development.
- Sometimes it is required to create as soon as possible a 3-D “free-form” part for evaluation in its application context that could include visualization, tactile feedback, function verification, and simulation of final use.

Evolution of Prototyping:

- Prototyping methods started from traditional prototyping and moved to virtual prototyping and rapid prototyping.
 - ❖ Conventional Prototyping
 - ❖ Digital or Virtual Prototyping (i. e. CAD Model)
 - ❖ Rapid Prototyping

Table 1.1 Traditional Prototyping Vs. Rapid Prototyping

Traditional Prototyping	Rapid Prototyping
It could include building a model from CLAY, carving from wood, bending wire meshing etc.	It could include building a model from thermoplastic, photopolymer, metals, paper, titanium alloys etc.
These methods are time consuming.	These methods consume less time.
Lack the quality to serve its purpose.	Gives better quality.
It can't effectively evaluate the alternative design concepts in the product definition stage.	It can effectively evaluate the alternative design concepts in the product definition stage.
Generally these methods are performed manually.	Generally these methods are performed automatically.
Increases product launch time.	Reduces product launch time.

1.3 Classification of Rapid Prototyping Systems

- Fundamentally, the development of RP can be seen in four primary areas.
- The Rapid Prototyping Wheel as shown in below figure depicts these four key aspects of Rapid Prototyping. They are: Input, Method, Material and Applications.

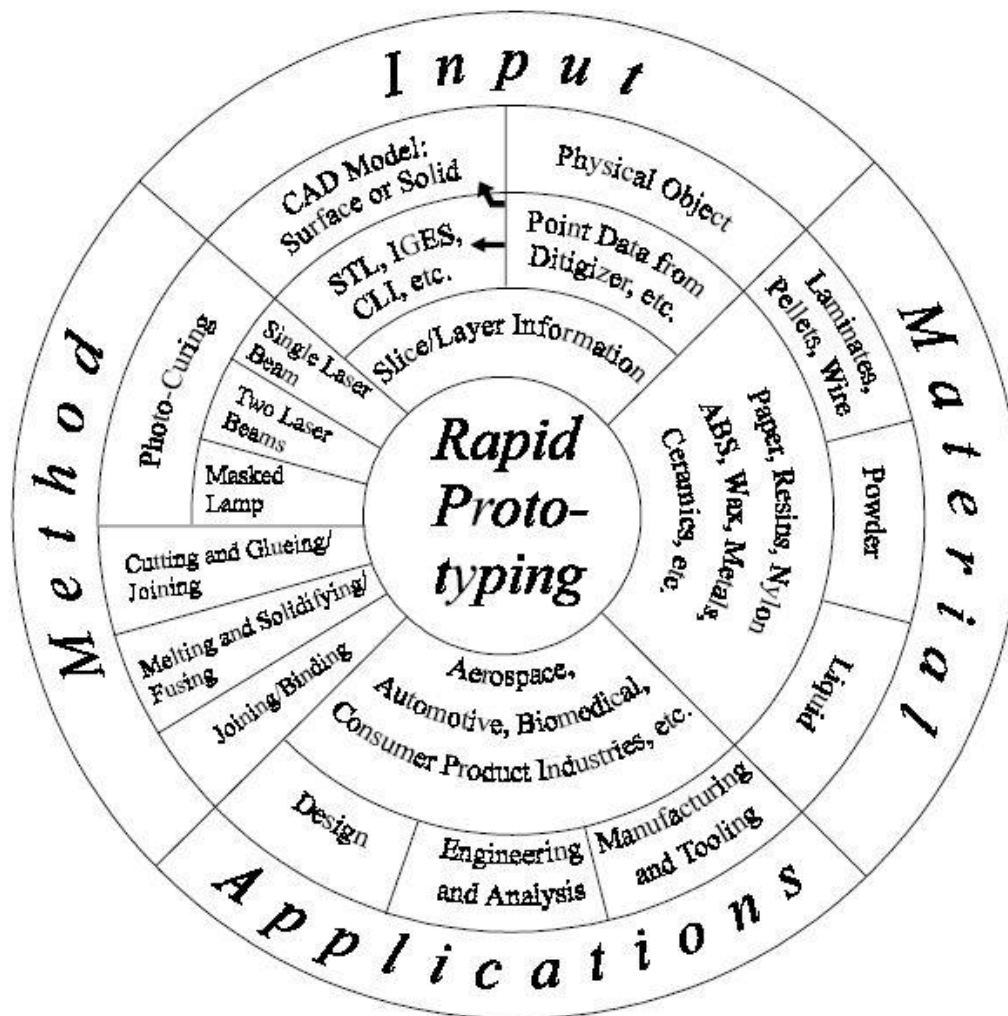


Fig 1.8 The Rapid Prototyping Wheel

- While there are many ways in which one can classify the numerous RP systems in the market, one of the better ways is to classify RP systems broadly by the initial form of its material, i.e. the material that the prototype or part is built with.
- In this manner, all RP systems can be easily categorized into (1) liquid-based (2) solid-based and (3) powder-based.

1.3.1 Liquid-based RP systems

- Liquid-based RP systems have the initial form of its material in liquid state.
- Through a process commonly known as curing, the liquid is converted into the solid state.
- The following RP systems fall into this category:
 - 1) 3D Systems' **Stereolithography Apparatus (SLA)**
 - 2) Cubital's **Solid Ground Curing (SGC)**
 - 3) Sony's **Solid Creation System (SCS)**
 - 4) CMET's **Solid Object Ultraviolet-Laser Printer (SOUP)**
 - 5) Autostrade's E-Darts
 - 6) Teijin Seiki's Soliform System
 - 7) Meiko's Rapid Prototyping System for the Jewelry Industry

- 8) Denken's SLP
- 9) Mitsui's COLAMM
- 10) Fockele & Schwarze's LMS
- 11) Light Sculpting
- 12) Aaroflex
- 13) Rapid Freeze
- 14) Two Laser Beams
- 15) Microfabrication

- Each of these RP systems will be described in more detail in next chapters.

1.3.2 Solid-based RP systems

- Except for powder, solid-based RP systems are meant to encompass all forms of material in the solid state.
- In this context, the solid form can include the shape in the form of a wire, a roll, laminates and pellets.
- The following RP systems fall into this definition:
 - 1) Cubic Technologies' **Laminated Object Manufacturing (LOM)**
 - 2) Stratasys' **Fused Deposition Modeling (FDM)**
 - 3) 3D Systems' **Multi-Jet Modeling System (MJM)**
 - 4) Kira Corporation's **Paper Lamination Technology (PLT)**
 - 5) Solidscape's ModelMaker and PatternMaster
 - 6) CAM-LEM's CL 100
 - 7) Ennex Corporation's Offset Fabbers
 - 8) Beijing Yinhua's Slicing Solid Manufacturing (SSM), Melted Extrusion Modeling (MEM) and Multi-Functional RPM Systems (M-RPM)

1.3.3 Powder-Based RP systems

- In a strict sense, powder is by-and-large in the solid state.
- However, it is intentionally created as a category outside the solid-based RP systems to mean powder in grain-like form.
- The following RP systems fall into this definition:
 - 1) 3D Systems's **Selective Laser Sintering (SLS)**
 - 2) Precision Optical Manufacturing's **Direct Metal Deposition (DMD)**
 - 3) Z Corporation's **Three-Dimensional Printing (3DP)**
 - 4) Optomec's **Laser Engineered Net Shaping (LENS)**
 - 5) Acram's **Electron Beam Melting (EBM)**
 - 6) Soligen's Direct Shell Production Casting (DSPC)
 - 7) Fraunhofer's Multiphase Jet Solidification (MJS)
 - 8) Aeromet Corporation's Lasform Technology
 - 9) EOS's EOSINT Systems
 - 10) Generis' RP Systems (GS)
 - 11) Therics Inc.'s Theriform Technology
 - 12) Extrude Hone's Prometal 3D Printing Process

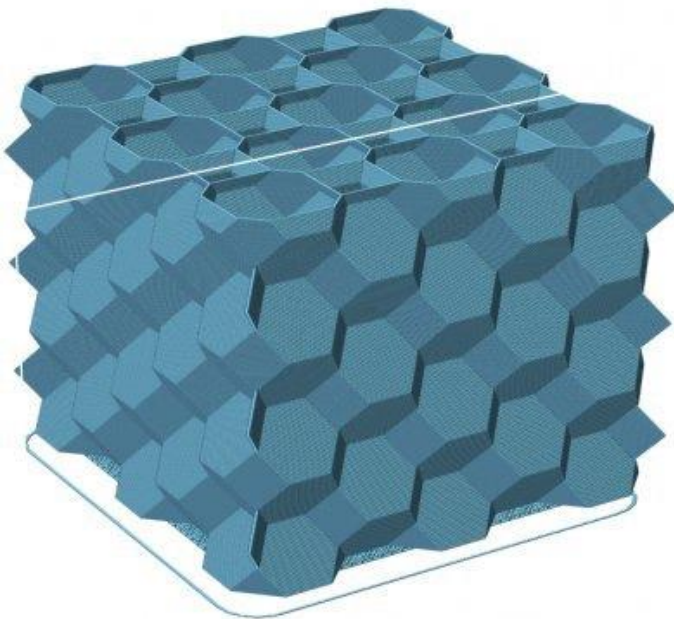
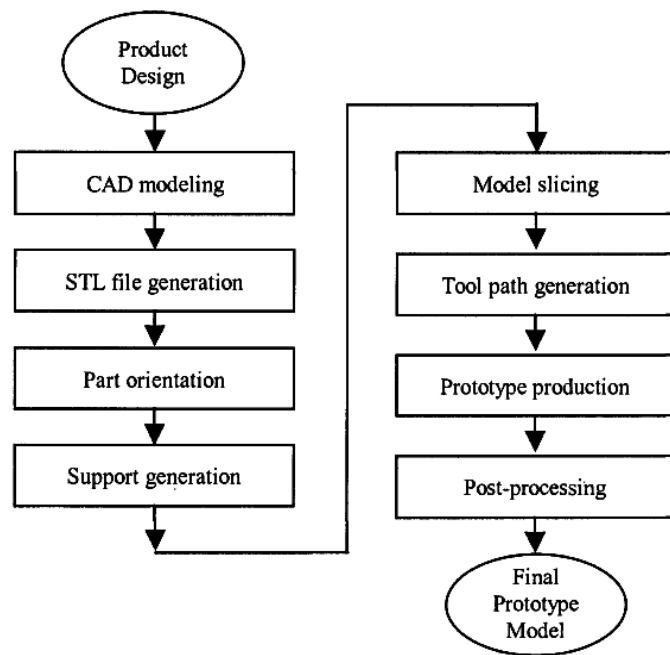
- Following table shows some important RP systems and materials used for that particular technology.

Table 1.2 RP systems and related base materials

Prototyping Technologies	Base Materials
Selective laser sintering (SLS)	Thermoplastics, Metals powders
Fused Deposition Modeling (FDM)	Thermoplastics, Eutectic metals.
Stereolithography (SLA)	Photopolymer
Laminated Object Manufacturing (LOM)	Paper
Electron Beam Melting (EBM)	Titanium alloys
3D Printing (3DP)	Various materials

2

CAD Modelling & Data Processing for RP



Course Contents

- 2.1 Data Interfacing Formats
- 2.2 CAD Model Preparation
- 2.3 Part Orientation and Support Generation
- 2.4 Support Structure Design
- 2.5 Model Slicing and Skin Contour Determination
- 2.6 Identification of Internal and External Contours
- 2.7 Contour Data Organization
- 2.8 Direct and Adaptive Slicing
- 2.9 Tool Path Generation

2.1 Data Interfacing 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.
- Examples of data interfacing formats are: STL, SLC, CLI, RPI, LEAF, IGES, HP/GL, CT, STEP etc.

2.1.1 STL (STereoLithography)

- The STL (STereoLithography) file standard has been used in most of the rapid prototyping systems.
- The STL file conceived by the 3D Systems, USA, is created from the CAD database via an interface on the CAD system.
- The STL file, 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 an 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 the below figure.

```
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
end loop
end facet
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
end loop
end facet
```

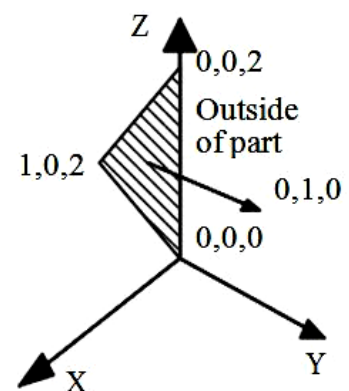


Fig 2.1 A sample STL file

- 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.
- Nevertheless, there are several advantages of the STL file. First, it provides a simple method of representing 3D CAD data.
- Second, it is already a widely accepted standard and has been used by most CAD systems and rapid prototyping systems.
- Finally, it can provide small and accurate files for data transfer for certain shapes.
- On the other hand, several disadvantages of the STL file exist. First, the STL file is many times larger than the original CAD data file for a given accuracy parameter.
- The STL file carries much redundancy information such as duplicate vertices and edges shown in the below figure.

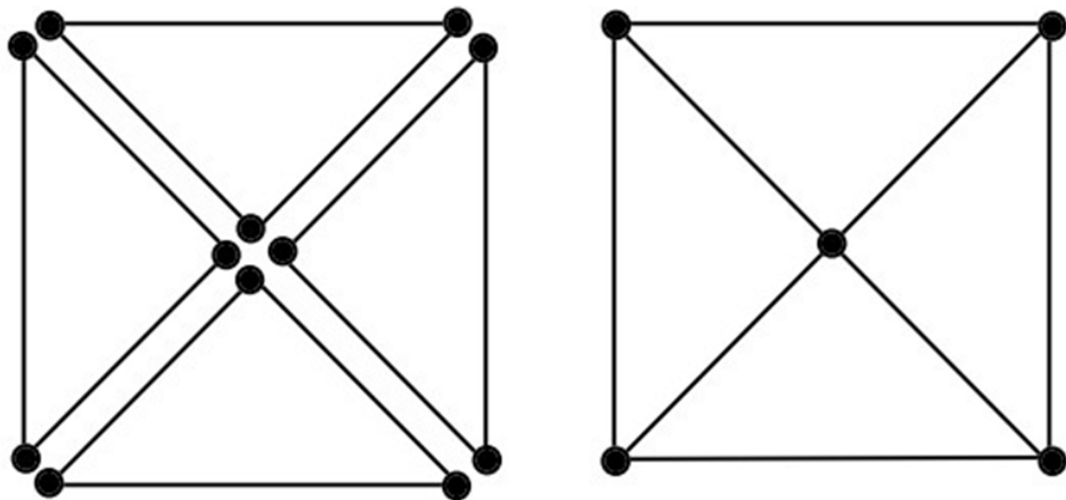


Fig 2.2 Edge and vertex redundancy in STL format

- Second, the geometry flaws exist in the STL file because many commercial tessellation algorithms used by CAD vendor today are not robust. This gives rise to the need for a “repair software” which slows the production cycle time.
- Finally, the subsequent slicing of large STL files can take many hours. However, some RP processes can slice while they are building the previous layer and this will alleviate this disadvantage.

2.1.1.1 STL FILE PROBLEMS

- 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, 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.
- Early research has shown that repairing invalid models is difficult and not at all obvious.
- However, before proceeding any further into discussing the procedures that are generated to resolve these difficulties, the following sections shall clarify the problems, as mentioned earlier.
- In addition, an illustration would be presented to show the consequences brought about by a model having a missing facet, that is, a gap in the tessellated model.

(1) Missing Facets or Gaps:

- Tessellation of surfaces with large curvature can result in errors at the intersections between such surfaces, leaving gaps or holes along edges of the part model.
- A surface intersection anomaly which results in a gap is shown in the below figure.

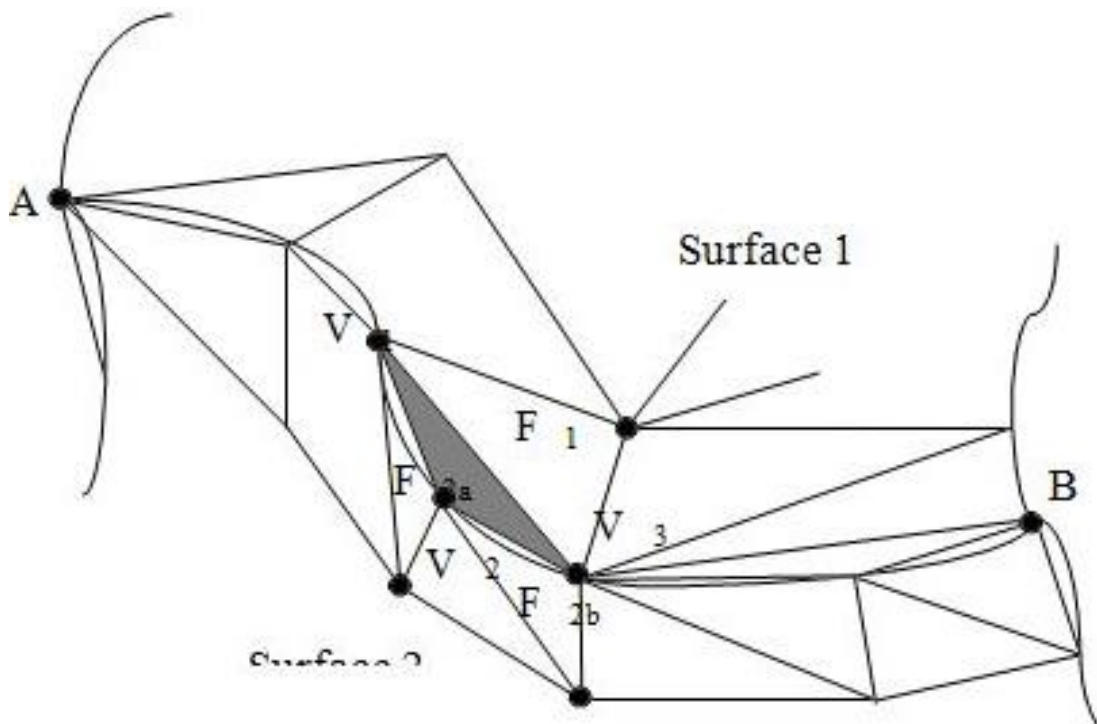


Fig 2.3 Gaps due to missing facets

(2) Degenerate Facets:

- A geometrical degeneracy of a facet occurs when all of the facets' edges are collinear even though all its vertices are distinct.
- This might be caused by stitching algorithms that attempt to avoid shell punctures as shown in the below figure.

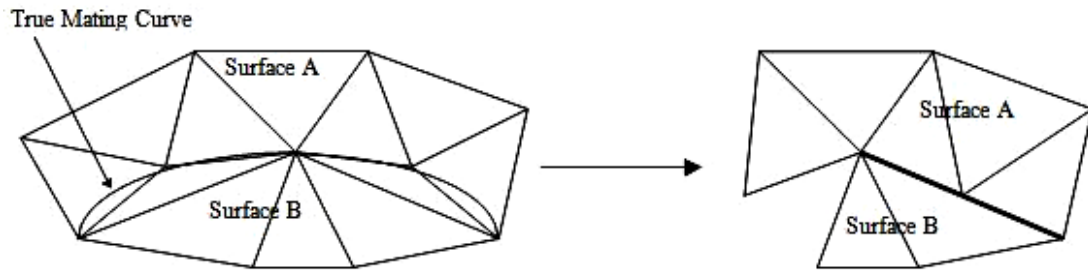


Fig 2.4 Degenerated Facet

- The resulting facets generated, shown in the above figure, eliminate the shell punctures. However, this is done at the expense of adding a degenerate facet.
- While degenerate facets do not contain valid surface normal, they do represent implicit topological information on how two surfaces mated. This important information is consequently stored prior to discarding the degenerate facet.

(3) Overlapping Facets:

- Overlapping facets may be generated due to numerical round-off errors occurring during tessellation.
- The vertices are represented in 3D space as floating point numbers instead of integers.
- Thus the numerical round-off can cause facets to overlap if tolerances are set too liberally.
- An example of an overlapping facet is illustrated in the below figure.

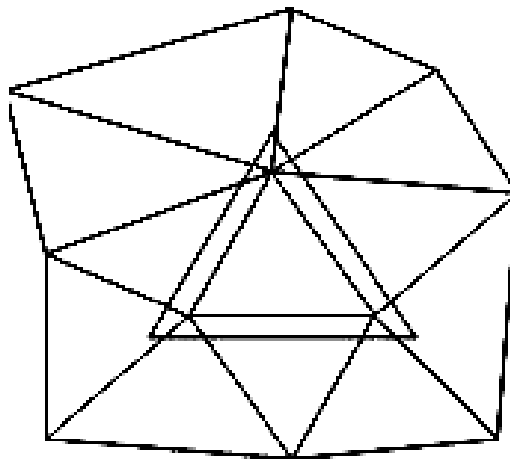


Fig 2.5 Overlapping facets

(4) Non-manifold Conditions:

- There are three types of non-manifold conditions, namely:
 - (1) A non-manifold edge.
 - (2) A non-manifold point.
 - (3) A non-manifold face.
- These may be generated because tessellations of the fine features are susceptible to round-off errors.
- An illustration of a non-manifold edge is shown in the below figure.

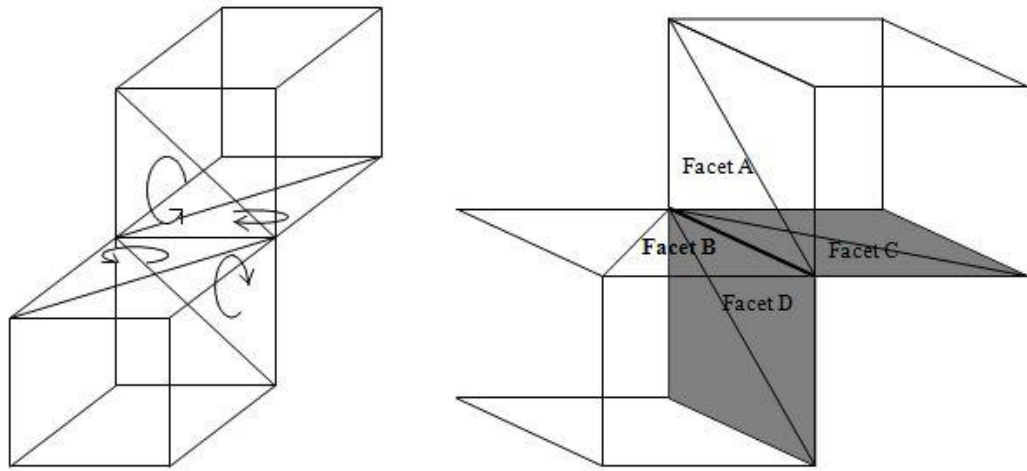


Fig 2.6 Non-manifold Edge

- Here, the non-manifold edge is actually shared by four different facets.
- A valid model would be one whose facets have only an adjacent facet each, that is; one edge is shared by two facets only.
- Hence the non-manifold edges must be resolved such that each facet has only one neighboring facet along each edge, that is, by reconstructing a topologically manifold surface.
- In below figure, two other types of non-manifold conditions are shown.

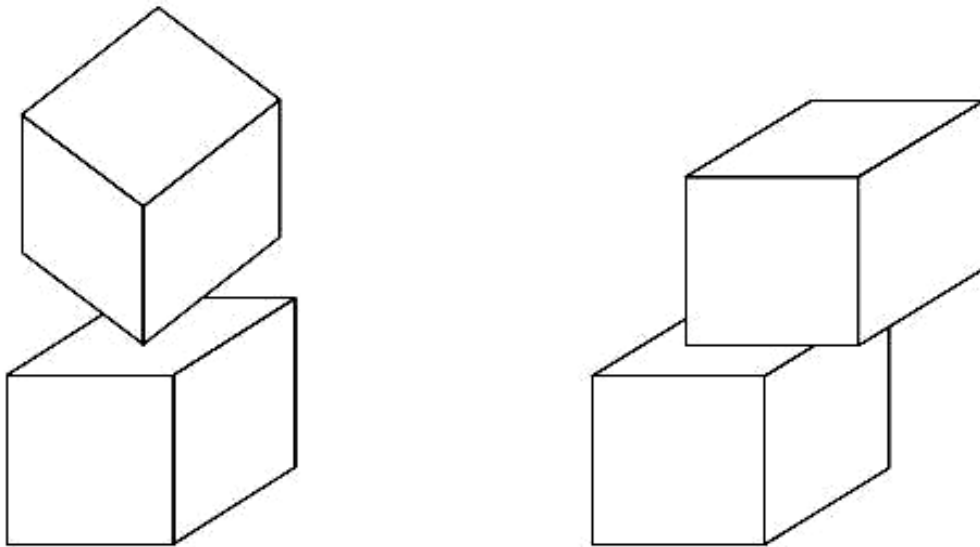


Fig 2.7 Non-manifold point and Non-manifold face

- All problems that have been mentioned previously are difficult for most slicing algorithms to handle and they do cause fabrication problems for RP processes which essentially require valid tessellated solids as input.
- Moreover, these problems arise because tessellation is a first-order approximation of more complex geometric entities.
- Thus, such problems have become almost inevitable as long as the representation of the solid model is done using the STL format which inherently has these limitations.

2.1.1.2 A Valid Model

- A tessellated model is said to be valid if there are no missing facets, degenerate facets, overlapping facets or any other abnormalities.
- When a valid tessellated model is used as an input, it will first be sliced into 2D layers, as shown in the below figure.
- Each layer would then be converted into unidirectional (or 1D) scan lines for the laser or other RP techniques to commence building the model as shown in the below figure.

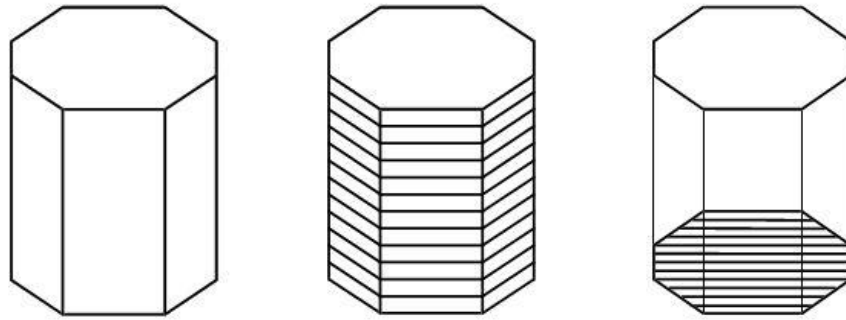


Fig 2.8 A Valid Model

- The scan lines would act as on/off points for the laser beam controller so that the part model can be built accordingly without any problems.

2.1.1.3 An Invalid Model

- However, if the tessellated model is invalid, a situation may develop as shown in the below figure.
- A solid model is tessellated non-robustly and results in a gap as shown in figure.

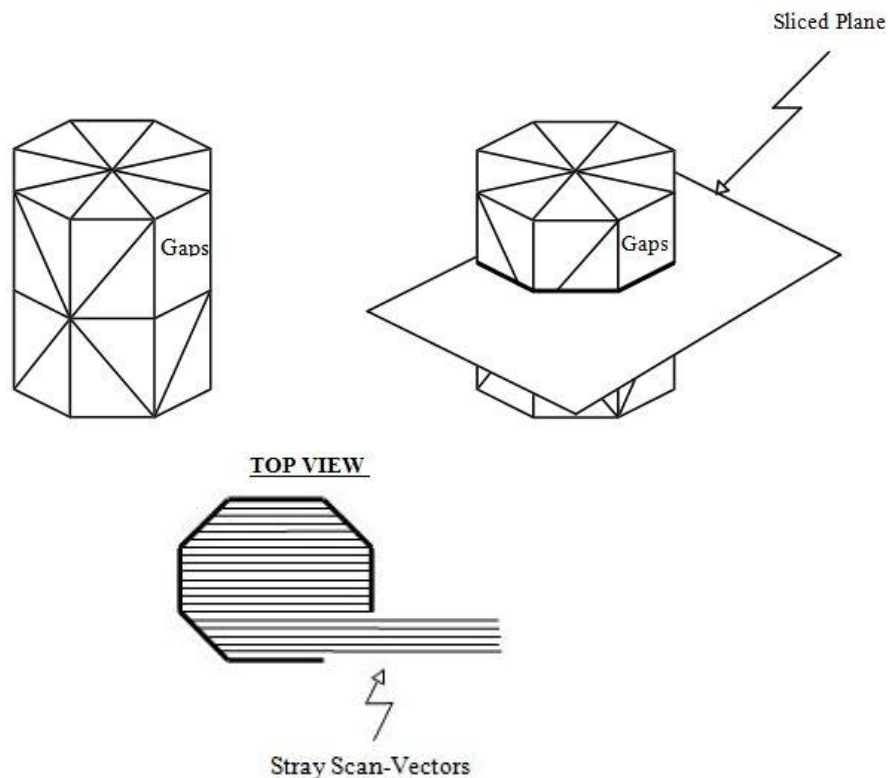


Fig 2.9 An invalid model being sliced, its tessellated model and top view of a layer of being scanned

- If this error is not corrected and the model is subsequently sliced, as shown in figure, in preparation for it to be built layer by layer, the missing facet in the geometrical model would cause the system to have no predefined stopping boundary on the particular slice, thus the building process would continue right to the physical limit of the RP machine, creating a stray physical solid line and ruining the part being produced, as illustrated in the figure.
- Therefore, it is of paramount importance that the model be “repaired” before it is sent for building.

2.1.2 IGES (Initial Graphics Exchange Specification)

- IGES (Initial Graphics Exchange Specification) is a standard used to exchange graphics information between commercial CAD systems.
- It was set up as an American National Standard in 1981. The IGES file can precisely represent CAD models.
- It includes not only the geometry information (Parameter Data Section) but also topological information (Directory Entry Section).
- In the IGES, surface modeling, constructive solid geometry (CSG) and boundary representation (B-rep) are introduced.
- Especially, the ways of representing the regularized operations for union, intersection, and difference have also been defined.
- The advantages of the IGES standard are its wide adoption and comprehensive coverage.
- Since IGES was set up as American National Standard, virtually every commercial CAD/CAM system has adopted IGES implementations.
- Furthermore, it provides the entities of points, lines, arcs, splines, NURBS surfaces and solid elements. Therefore, it can precisely represent CAD model.
- However, several disadvantages of the IGES standard in relation to its use as a RP format include the following objections:
 - Because IGES is the standard format to exchange data between CAD systems, it also includes much redundant information that is not needed for rapid prototyping systems.
 - The algorithms for slicing an IGES file are more complex than the algorithms slicing a STL file.
 - The support structures needed in RP systems such as the SLA cannot be created according to the IGES format.
- IGES is a generally used data transfer medium which interfaces with various CAD systems. It can precisely represent a CAD model.
- Advantages of using IGES over current approximate methods include precise geometry representations, few data conversions, smaller data files and simpler control strategies.
- However, the problems are the lack of transfer standards for a variety of CAD systems and system complexities.

2.1.3 HP/GL (Hewlett-Packard Graphics Language)

- HP/GL (Hewlett-Packard Graphics Language) is a standard data format for graphic plotters.
- Data types are all two-dimensional, including lines, circles, splines, texts, etc.
- The approach, as seen from a designer's point of view, would be to automate a slicing routine which generates a section slice, invoke the plotter routine to produce a plotter output file and then loop back to repeat the process.
- The advantages of the HP/GL format are that a lot of commercial CAD systems have the interface to output the HP/GL format and it is a 2D geometry data format which does not need to be sliced.
- However, there are two distinct disadvantages of the HP/GL format. First, because HP/GL is a 2D data format, the files would not be appended, potentially leaving hundreds of small files needing to be given logical names and then transferred.
- Second, all the support structures required must be generated in the CAD system and sliced in the same way.

2.1.4 CT (Computerized Tomography)

- CT (Computerized Tomography) scan data is a particular approach for medical imaging.
- This is not standardized data. Formats are proprietary and somewhat unique from one CT scan machine to another.
- The scan generates data as a grid of three-dimensional points, where each point has a varying shade of gray indicating the density of the body tissue found at that particular point.
- Data from CT scans have been used to build skull, femur, knee, and other bone models on Stereolithography systems.
- Some of the reproductions were used to generate implants, which have been successfully installed in patients.
- The CT data consist essentially of raster images of the physical objects being imaged. It is used to produce models of human temporal bones.
- There are three approaches to making models out of CT scan information:
(1) Via CAD Systems, (2) STL-interfacing and (3) Direct Interfacing
- The main advantage of using CT data as an interface of rapid prototyping is that it is possible to produce structures of the human body by the rapid prototyping systems.
- But, disadvantages of CT data include firstly, the increased difficulty in dealing with image data as compared with STL data and secondly, the need for a special interpreter to process CT data.

2.1.5 SLC (Stereolithography Contour)

- The SLC (Stereolithography Contour) file format is developed at 3D Systems, USA.
- It addresses a number of problems associated with the STL format.

- An STL file is a triangular surface representation of a CAD model. Since the CAD data must be translated to this faceted representation, the surface of the STL file is only an approximation of the real surface of an object.
- The facets created by STL translation are sometimes noticeable on rapid prototyping parts (such as the AutoCAD Designer part).
- When the number of STL triangles is increased to produce smoother part surfaces, STL files become very large and the time required for a rapid prototyping system to calculate the slices can increase.
- SLC attempts to solve these problems by taking two-dimensional slices directly from a CAD model instead of using an intermediate tessellated STL model.
- According to 3D Systems, these slices eliminate the facets associated with STL files because they approximate the contours of the actual geometry.
- Three problems may arise from this new approach. Firstly, in slicing a CAD model, it is not always necessarily more accurate as the contours of each slice are still approximations of the geometry.
- Secondly, slicing in this manner requires much more complicated calculations (and therefore, is very time-consuming) when compared to the relatively straightforward STL files.
- Thirdly, a feature of a CAD model which falls between two slices, but is just under the tolerances set for inclusion on either of the adjacent slices, may simply disappear.

SLC File Specification:

- The SLC file format is a “2.5 - D” contour representation of a CAD model.
- It consists of successive cross-sections taken at ascending Z intervals in which solid material is represented by interior and exterior boundary polylines.
- SLC data can be generated from various sources, either by conversion from CAD solid or surface models, or more directly from systems which produce data arranged in layers, such as CT-scanners.

Definition of Terms

- **Segment:** A segment is a straight line connecting two X/Y vertice points.
- **Polyline:** A polyline is an ordered list of X/Y vertice points connected continuously by each successive line segment. The polyline must be closed whereby the last point must equal the first point in the vertice list.
- **Contour boundary:** A boundary is a closed polyline representing interior or exterior solid material.
 - An exterior boundary has its polyline list in counter-clockwise order. The solid material is inside the polyline.
 - An interior boundary has its polyline list in clockwise order and solid material is outside the polyline.

Following figure shows a description of the contour boundary.

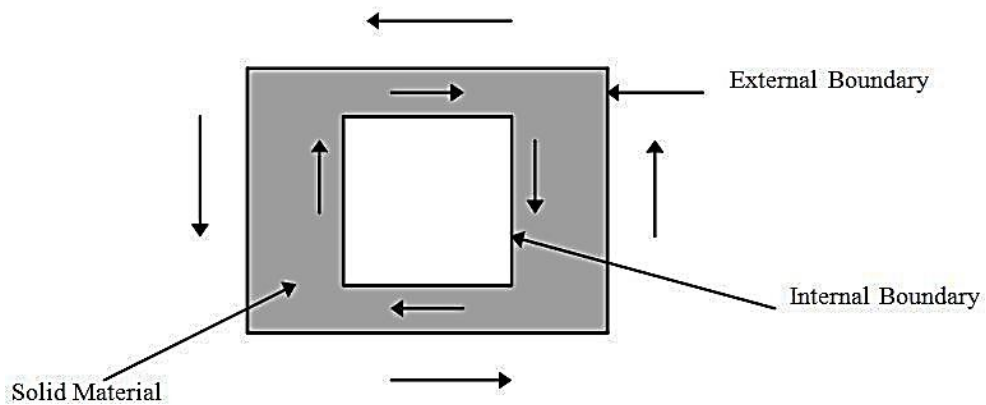


Fig 2.10 Contour boundary description

- **Contour layer:** A contour layer is a list of exterior and interior boundaries representing the solid material at a specified Z cross-section of the CAD model. The cross-section slice is taken parallel to the X-Y plane and has a specified layer thickness.

Overview of the SLC File Structure

- The SLC file is divided into a header section, a 3D reserved section, a sample table section, and the contour data section.

(i) Header section:

- The Header section is an ASCII character string containing global information about the part and how it was prepared.
- The header can be a maximum of 2048 bytes.
- The syntax of the header section is a keyword followed by its appropriate parameter.

Table 1.1 Header keywords

Header Keywords	Meaning	Example
"-SLCVER <X.X>"	SLC file format version number	The version number of this specification is 2.0
"-UNIT <INCH/MM>"	Indicates unit of the SLC data	Inch or mm
"-TYPE <PART/SUPPORT>"	Specifies the CAD model type	PART and SUPPORT must be closed contours.
"-EXTENTS <minx, maxx miny, maxy minz, maxz>"	Describes the X, Y and Z extents of the CAD model	
"-ARCRES <value in degrees>"	Specifies the arc resolution	
"-MAXGAPFOUND <value>"	Specifies the maximum gap size found	

(ii) 3D reserved section:

- This 256 byte section is reserved for future use.

(iii) Sampling table section:

- The sample table describes the sampling thicknesses (layer thickness or slice thickness) of the part.
- There can be up to 256 entries in the table.
- Each entry describes the Z start, the slice thickness, and what line width compensation is desired for that sampling range.
- The first sampling table entry Z start value must be the very first Z contour layer.
- For example, if the cross-sections were produced with a single thickness of 0.006 inches and the first Z level of the part is 0.4 inches and a line width compensation value of 0.005 is desired, then the sampling table will look like the following:

Sample Table Size : 1
Sample Table Entry : 0.4 0.006 0.005 0.0

- If for example, the part was sliced with two different layer thicknesses, the sample table could look like the following:

Sample Table Size : 2
Sample Table Entry 1 : 0.4 0.005 0.004 0.0
Sample Table Entry 2 : 2.0 0.010 0.005 0.0

- Slice thicknesses must be even multiples of one other to avoid processing problems.

(iv) Contour data section:

- The contour data section is a series of successive ascending Z cross-sections or layers with the accompanying contour data.
- Each contour layer contains the minimum Z layer value, number of boundaries followed by the list of individual boundary data.
- The boundary data contains the number of x, y vertices for that boundary, the number of gaps, and finally the list of floating point vertice points.
- The location of a gap can be determined when a vertice point repeats itself.
- To illustrate, consider the contour layer given in previous figure. The contour section could be as follows:

Z Layer : 0.4
Number of Boundaries : 2
Number of Vertices for the 1st Boundary : 5
Number of Gaps for the 1st Boundary : 0
Vertex List for 1st Boundary : 0.0, 0.0
1.0, 0.0
1.0, 1.0
0.0, 1.0
0.0, 0.0

Number of Vertices for the 2 nd Boundary	: 5
Number of Gaps for the 2 nd Boundary	: 0
Vertex List for 2 nd Boundary	: 0.2, 0.2 0.2, 0.8 0.8, 0.8 0.8, 0.2 0.2, 0.2

- Notice the direction of the vertex list for 1st boundary is counter-clockwise indicating that the solid material is inside the polyline. Also, notice that the polyline is closed because the last vertex is equal to the first vertex.
- Notice the direction of the vertex list for 2nd boundary is clockwise indicating the solid material is outside the polyline. Also, notice that the polyline is closed because the last vertex is equal to the first vertex.
- The contour layers are stacked in ascending order until the top of the part.
- The last layer or the top of the part is indicated by the Z level and a termination unsigned integer (0xFFFFFFFF).

2.1.6 CLI (Common Layer Interface):

- The CLI (Common Layer Interface) format is developed in a Brite Euram project with the support of major European car manufacturers.
- The CLI format is meant as a vendor-independent format for layer by layer manufacturing technologies.
- In this format, a part is built by a succession of layer descriptions.
- The CLI file can be in binary or ASCII format. The geometry part of the file is organized in layers in the ascending order.
- Every layer is started by a layer command, giving the height of the layer.
- The layers consist of series of geometric commands.
- The CLI format has two kinds of entities. One is the polyline. The polylines are closed, which means that they have a unique sense, either clockwise or anti-clockwise.
- This directional sense is used in the CLI format to state whether a polyline is on the outside of the part or surrounding a hole in the part.
- Counter-clockwise polylines surround the part, whereas clockwise polylines surround holes. This allows correct directions for beam offset.
- The other is the hatching to distinguish between the inside and outside of the part.
- As this information is already present in the direction of polyline, and hatching takes up considerable file space, hatches have not been included into output files.

- The advantages of the CLI format are given as follows:
 - (1) Since the CLI format only supports polyline entities, it is a simpler format compared to the HP/GL format.
 - (2) The slicing step can be avoided in some applications.
 - (3) The error in the layer information is much easier to be correct than that in the 3D information. Automated recovery procedures can be used and if required, editing is also not difficult.
- However, there exist several disadvantages of the CLI format. They are given as follows:
 - (1) The CLI format only has the capability of producing polylines of the outline of the slice.
 - (2) Although the real outline of the part is obtained, by reducing the curve to segments of straight lines, the advantage over the STL format is lost.
- The CLI format also includes the layer information like the HP/GL format.
- But, the CLI format only has polyline entities, while HP/GL supports arcs and lines.
- The CLI format is simpler than the HP/GL format and has been used by several rapid prototyping systems. It is hoped that the CLI format will become an industrial standard such as STL.

2.1.7 RPI (Rapid Prototyping Interface):

- The RPI (Rapid Prototyping Interface) format is designed by the Rensselaer Design Research Center, Rensselaer Polytechnic Institute.
- It can be derived from currently accepted STL format data.
- The RPI format is capable of representing facet solids, but it includes additional information about the facet topology.
- Topological information is maintained by representing each facet solid entity with indexed lists of vertices, edges, and faces.
- Instead of explicitly specifying the vertex coordinates for each facet, a facet can refer to them by index numbers.
- This contributes to the goal of overall redundant information reduction.
- The format is developed in ASCII to facilitate cross-platform data exchange and debugging.
- A RPI format file is composed of the collection of entities, each of which internally defines the data it contains.
- Each entity conforms to the syntax defined by the syntax diagram shown in the following figure.
- Each entity is composed of an entity name, a record count, a schema definition, schema termination symbol, and the corresponding data.
- The data is logically subdivided into records which are made up of fields. Each record corresponds to one variable type in the type definition.

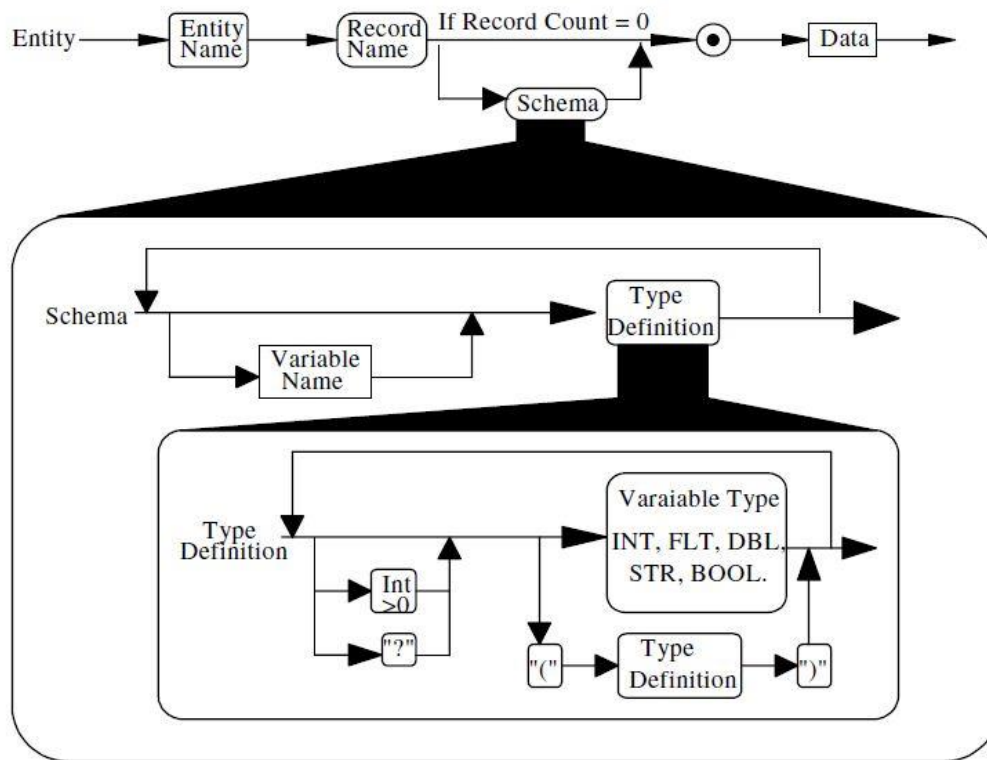


Fig 2.11 RPI format entity syntax diagram

- The RPI format includes the following four **advantages**:
 - (1) Topological information is added to the RPI format. As the result, flexibility is achieved. It allows users to balance storage and processing costs.
 - (2) Redundancy in the STL is removed and the size of file is compacted.
 - (3) Format extensibility is made possible by interleaving the format schema with data as shown in the figure.
 - (4) Representation of CSG primitives is provided, as capabilities to represent multiple instances of both facet and CSG solids.
- Two **disadvantages of the RPI** format are given as follows:
 - (1) An interpreter which processes a format as flexible and extensible as the RPI format is more complex than that for the STL format.
 - (2) Surface patches suitable for solid approximation cannot be identified in the RPI format.
- The RPI format offers a number of features unavailable in the STL format.
- The format can represent CSG primitive models as well as facet models.
- Both can be operated by the Boolean union, intersection, and difference operators.
- Provisions for solid translation and multiple instancing are also provided.
- Process parameters, such as process types, scan methods, materials, and even machine operator instructions, can be included in the file.
- Facet models are more efficiently represented as redundancy is reduced. The flexible format definition allows storage and processing cost to be balanced.

2.1.8 LEAF (Layer Exchange ASCII Format)

- The LEAF or Layer Exchange ASCII Format is generated by Helsinki University of Technology.
- To describe this data model, concepts from the object-oriented paradigm are borrowed.
- At the top level, there is an object called LMT-file (Layer Manufacture Technology file) that can contain parts which in turn are composed of other parts or by layers.
- Ultimately, layers are composed of 2D primitives and currently the only ones which are planned for implementation are polylines.
- For example, an object of a given class is created. The object classes are organized in a simple tree shown in the below figure.



Fig 2.12 The object tree

- Attached to each object class is a collection of properties. A particular instance of an object specifies the values for each property.

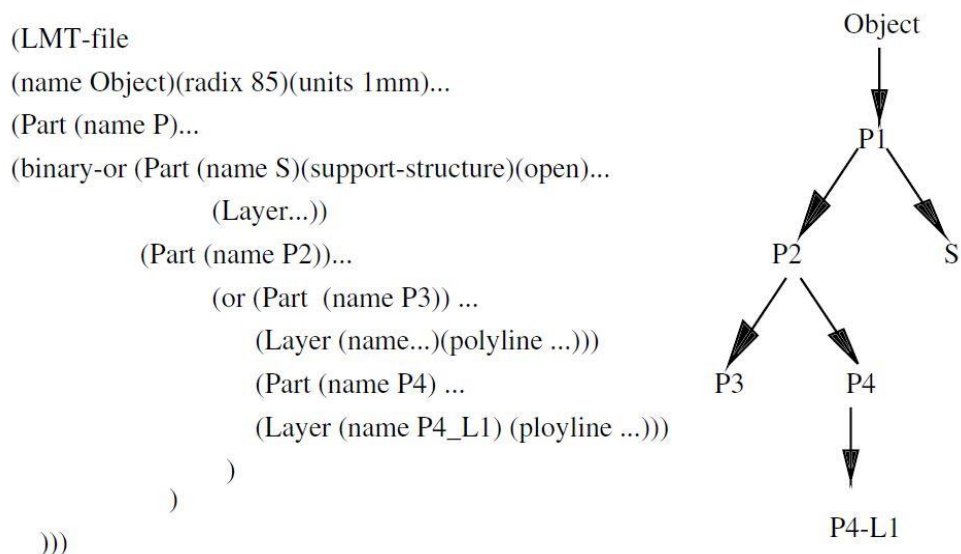


Fig 2.13 An instance tree

- Objects inherit properties from their parents. In LEAF, the geometry of an object is simply one among several other properties.
- In this example, the object is a LMT-file. It contains exactly one child, the object P1.
- P1 is the combination of two parts, one of which is the support structures and the other one is P2, again a combination of two others.

- The objects at leaves of the tree — P3, P4 and S — must have been, evidently, sliced with the same z-values so that the required operations, in this case or and binary-or, can be performed and the layers of P1 and P2 constructed.
- In LEAF, the properties support-structure and open can also be attached to layer or even polyline objects allowing the sender to represent the original model and the support structures as one single part.
- In Figure, all parts inherit the properties of object, their ultimate parent.
- Likewise, all layers of the object S inherit the open property indicating that the contours in the layers are always interpreted as open, even if they are geometrically closed.
- Amongst the many advantages of the LEAF format are:
 - (1) It is easy to implement and use.
 - (2) It is not ambiguous.
 - (3) It allows for data compression and for a human-readable representation.
 - (4) It is machine independent and LMT process independent.
 - (5) Slices of CSG models can be represented almost directly in LEAF.
 - (6) The part representing the support structures can be easily separated from the original part.
- The disadvantages of the LEAF format include the following items:
 - (1) The new interpreter is needed for connecting the rapid prototyping systems.
 - (2) The structure of the format is more complicated than that of the STL format.
 - (3) The STL format cannot be changed into this format.
- The LEAF format is described at several levels, mainly at a logical level using a data model based on object-oriented concepts, and at a physical level using a LISP-like syntax.
- At the physical level, the syntax rules are specified by several translation phases.
- Thus defined, it allows one to choose at which level, interaction with LEAF is desirable and at each level there is clear and easy-to-use interface.
- It is doubtful that LEAF currently supports the needs of all processes currently available but it is hoped it is a step forward in the direction.

2.2 CAD Model Preparation

- Rapid prototyping includes a class of fully automatic manufacturing technologies that are capable of producing prototype models of any shape provided a computer description of the object is available.
- With most of today's rapid prototyping systems, a valid STL model is required as input. To reliably produce a valid STL model, a non-ambiguous CAD solid model is often needed.

- The model surface must uniquely distinguish between 'inside' and the 'outside' of the object concerned.
- A solid model provides a complete, valid and unambiguous representation mostly suited for automatic processing, such as interference analysis between individual objects, mass property calculation, automatic mesh generation for finite element analysis, and rapid prototyping.
- A CAD surface model provides only geometric information. Surface representations are the main building blocks for solid modeling and a solid model is built upon surface representations.
- CAD surfaces created through reverse engineering techniques discussed in the previous chapter often need to be further processed and converted into a solid model for downstream applications, such as for rapid prototyping.
- To convert a CAD surface model into a solid model, one often needs to extend the CAD surfaces, find intersections between surfaces, apply chamfering and fillets, and finally form a closed watertight solid model.
- Constructive solid geometry (CSG) is one of the important schemes for solid modeling. CSG is built upon three key building blocks: solid primitives, transformation operations and Boolean operations.
- Solid primitives are standard solid features, such as a block, a cylinder, a sphere or a solid wedge. These primitives can be easily defined through just a few parameters. Boolean operations include union, intersection and subtraction.
- Starting from simple solid primitives and combining with transformation operations such as translation, rotation, shearing, scaling and their combinations, one can gradually progress to very complex engineering parts.
- Following figure highlights the idea of CSG solid modeling represented as a CSG tree.

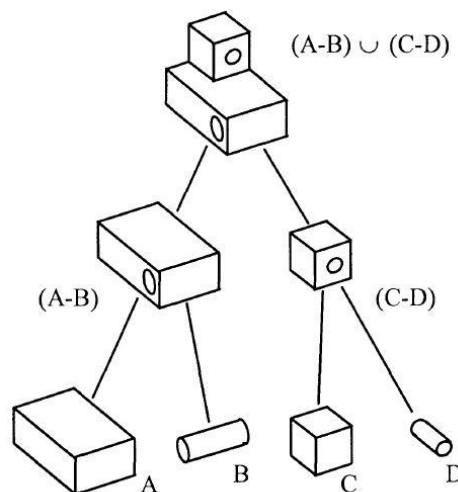


Fig 2.14 CSG solid modeling

- CSG is a very intuitive and user-friendly solid modeling scheme. However, depending on the particular CAD modeling system being used, the modeling capability might be limited owing to the limited availability of solid primitives.

- Boundary representation (B-rep) is an alternative solid modeling scheme that is entirely complimentary to CSG in solid modeling activities.
- B-rep is a very powerful and flexible scheme that can be used to model any object found in the physical world.
- As the name of the scheme implies, B-rep defines an object by a set of boundary faces that can be either planar or freeform surfaces.
- Topologically, each boundary face is enclosed by a loop of boundary curves, each of which can again be a simple line segment or a free form curve.
- Apart from geometric parameters, each boundary curve should have two end/boundary points. This leads to the well-known topological data structures of the B-rep solid modeling schemes shown in following figures.

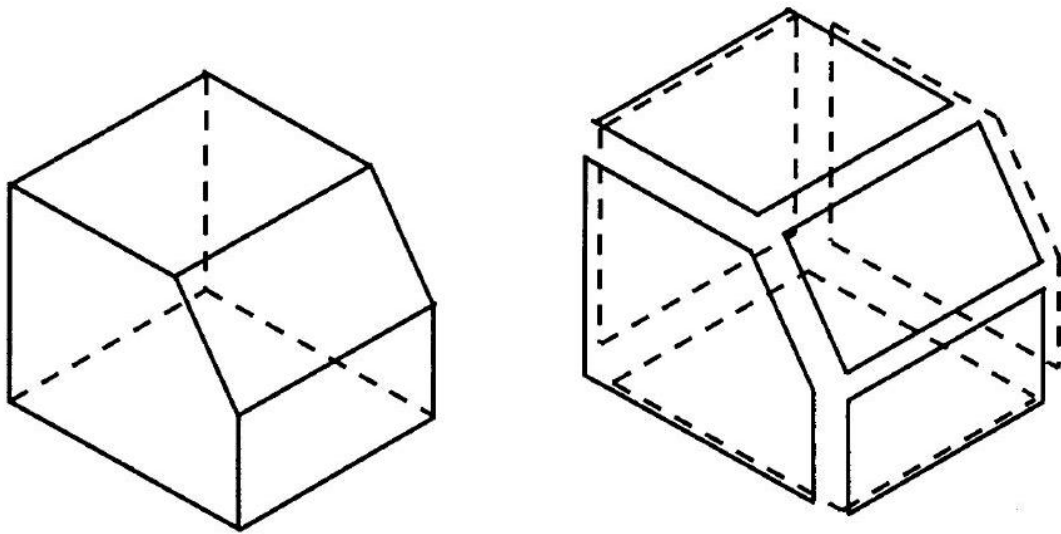


Fig 2.15 Boundary representation (B-rep) for solid modeling

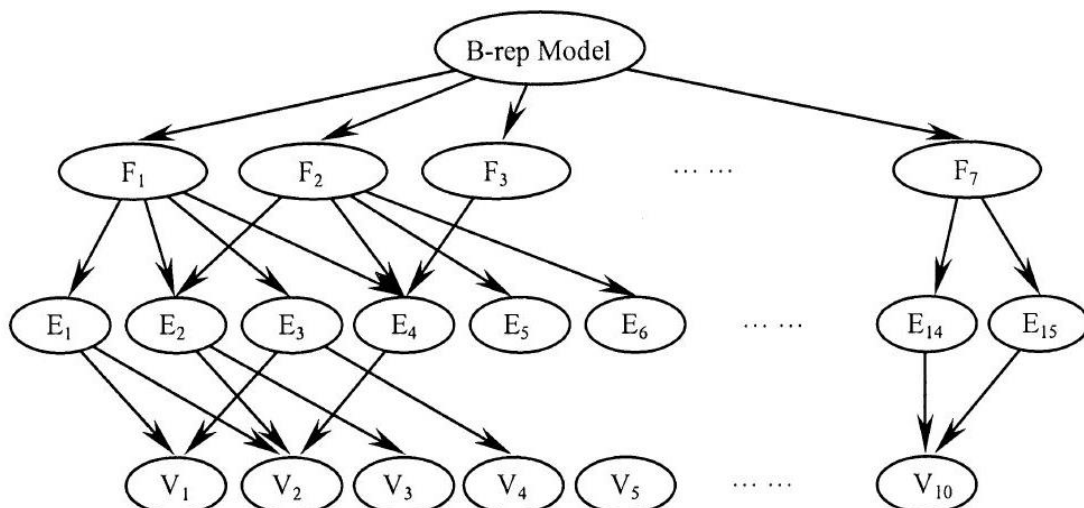


Fig 2.16 Topological data structure for B-rep solid modeling

- While B-rep is undoubtedly a powerful scheme for solid modeling, it may not be very convenient for the user if one always starts from surface definition even for regular primitive features.

- To provide users both a friendly and intuitive interface and a powerful database, most of the computer-aided design and manufacturing (CAD/CAM) systems use a hybrid solid modeling scheme with B-rep for flexible model representation and CSG for user interfacing.
- To the user, the CAD/ CAM system looks like a CSG solid modeling system with solid primitives and Boolean operations. However, for internal data representation, the B-rep data structure is used.
- Thus, all possible modeling operations applicable to a CSG solid modeler are available to the user.
- The user can also define any freeform features built upon surface modeling techniques.
- When equipped with other modeling operations such as sweep solid modeling, automatic filleting and chamfering, today's CAD/CAM systems offer powerful and sophisticated modeling tools for advanced solid modeling.
- In addition to CSG and B-rep solid modeling, there are also some voxel based modeling schemes, such as cell decomposition and octree encoding, often used for scientific and medical visualization.
- These modeling schemes could be very useful for rapid prototyping of colored models.

2.3 Part Orientation and Support Generation

- Part orientation and support generation are two closely related issues in layered manufacturing.
- By selecting an optimal part orientation for model prototyping, it is possible to shorten build time and minimize the overall prototyping cost.
- Part orientation has a significant effect on the final part quality and prototyping cost. The general part orientation characteristics are as follows:
 - Most of the important faces should be positioned either vertically or horizontally without support.
 - Ensure that the part is firmly supported during the entire prototyping process.
 - For processes that need supports structures, part orientations should also be optimized such that it would require minimal support.
 - Wherever the supports meet the part there will be small marks and reducing the amount of supports would reduce the amount of part cleanup and post process finishing.
 - The total support volume should also be minimized to save time and material(s) for building the support structures.
 - Parts that have thick walls may be designed to include hollow features if this does not reduce the part's functionality.
 - A honeycomb or truss-like internal structure can assist in providing support and strength within a part, while reducing its overall mass and volume.

- There are two key parameters to be optimized in this respect. While ensuring that the part is firmly supported during the entire prototyping process, the overall support contact area should be minimized. This helps in minimizing the influence of the support on the surface quality of the prototype. It also reduces further efforts during post-processing.
- We should also make good use of the allowable overhang angle that needs no further support.
- The external surfaces produced should be as smooth as possible.
- As RP models are built in a layered fashion, a staircase effect is unavoidable, but it should be minimized.
- This can be achieved by reducing the number and areas of inclined faces, i.e., by trying to position the part such that most of the faces or, at least, most of the important faces are positioned either vertically or horizontally without support, to the extent possible.

2.4 Support Structure Design

- Depending on the nature of a particular RP process, there will be a need for part supports while implementing the prototyping process.
- The **Functions of Part Supports** are as following:
 - **To separate parts from the platform:** The use of supports will make it easier to safely remove the part from the platform after model production. It will also be easier to control the layer thickness and surface quality of the bottom layers. Marks on the platform would not be printed on the final part.
 - **To provide support to hanging structures:** First of all, it provides support to hanging structures and prevents such structures from collapsing. In addition, it can also strengthen overhanging regions for the prevention of deformation and curling for stereolithography as well as other processes.
- Depending on the design and the application, a support structure may be decomposed into three functional areas with different building strategies for practical applications. For an area connecting to part surfaces, the support structure should be easily removable while providing sufficient support.
- The support structure for this area is often defined as sierras or needles with minimum contact with the part surface.
- The main support should be strong enough to withstand both the vertical weight and other horizontal disturbances.
- A different strategy may be applied for areas between the main support and the platform for easy removal while providing a stable base support.
- The structure should be designed such that its total weight is minimized. Thus, the three functional areas are:
 - **Sierras or Needles:** connections between the main support and the part
 - **Supports:** the main support structure
 - **Separators:** connections between the main support and the platform

- Following figure illustrates the three functional areas of a support structure.

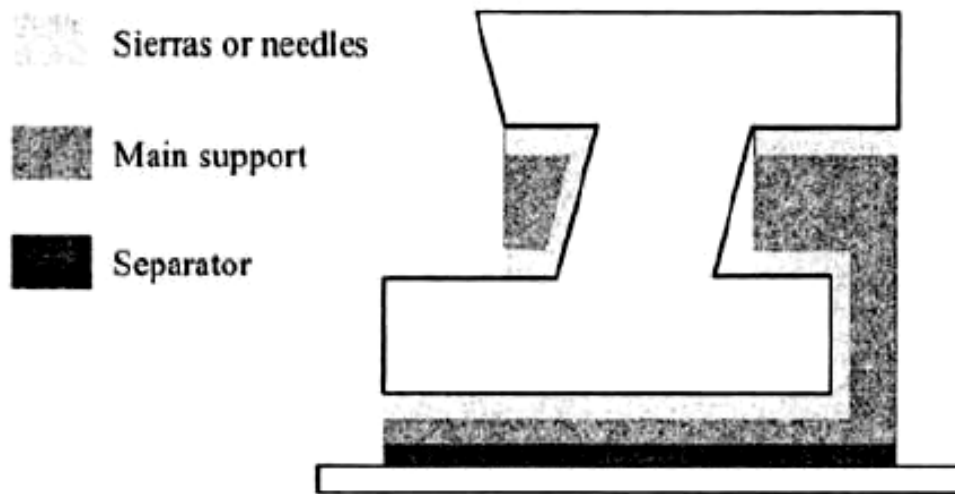


Fig 2.17 Illustration of support structures

- Following figure shows several cases where supports are required.

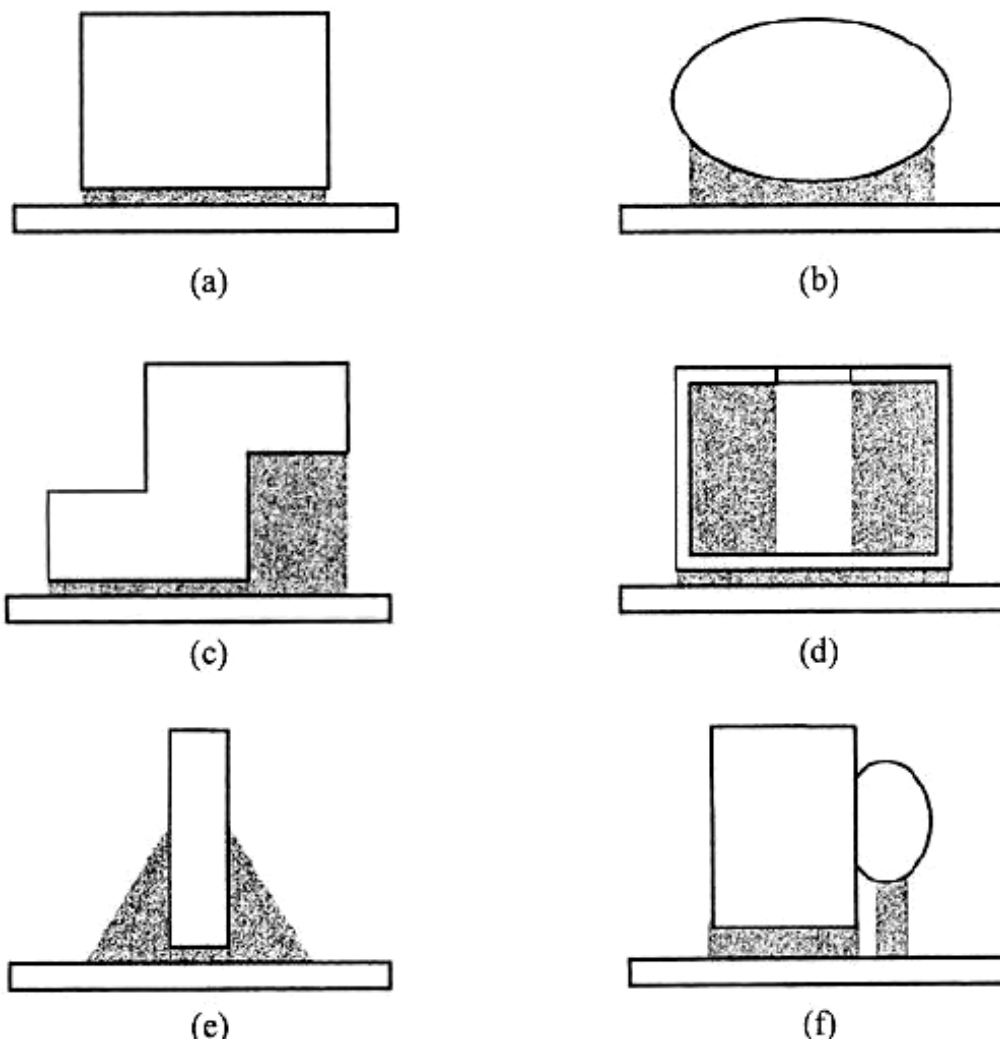


Fig 2.18 Incidences where supports are needed: (a) separation between part and platform; (b) down facing regions below the equator of the surface normal curvature; (c) supports for hanging structures; (d) internal supports; (e) support for part stability; and (f) supports for islands.

- There exist a variety of designs for the main support structure. Some of the approaches are illustrated in below figure.

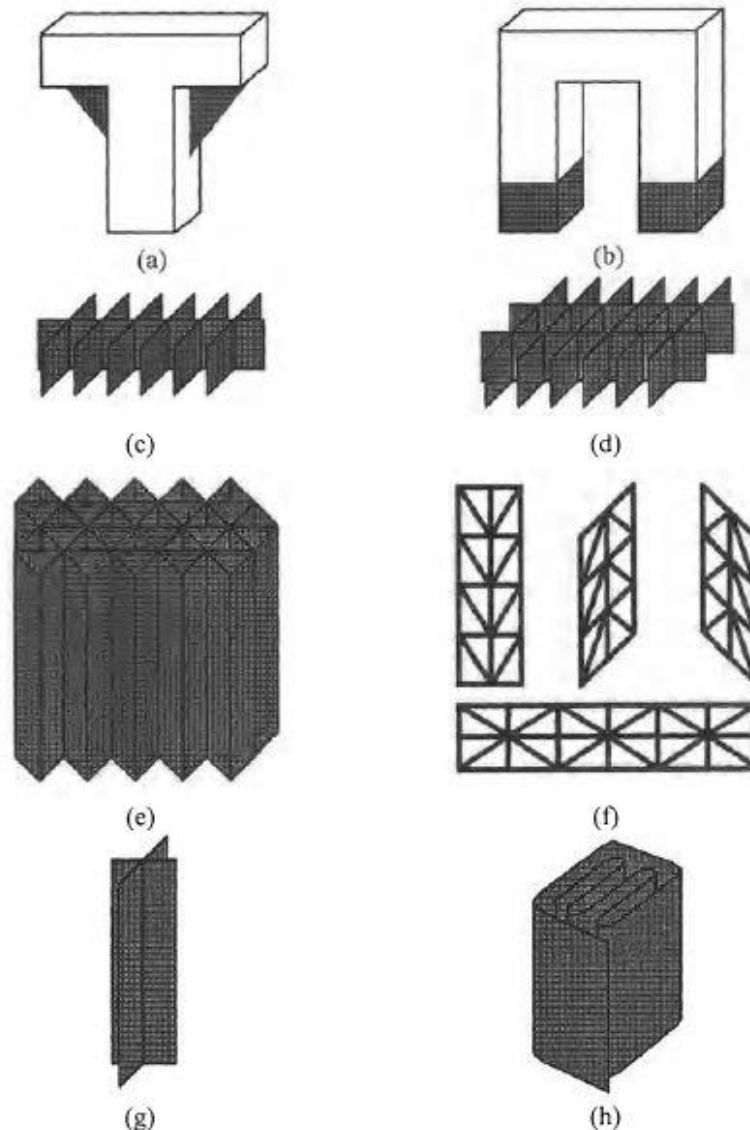


Fig 2.19 Support structure design : (a) gussets; (b) projected feature edges; (c) single webs; (d) webs; (e) triangle webs; (f) perforated wall structures for various web-based support design; (g) columns; and (h) zigzag and perimeter support

- The following are some commonly used support structures:
 - Gussets:** As illustrated in **Figure a**, gussets (a single one or a set) are used to support lightweight overhang areas during the part building process and attach to a vertical wall near the overhang areas. Gussets provide the optimal support for overhang areas while requiring minimal resources during the building process. The supports are also easily identified during cleanup.
 - Projected feature edges (Figure b):** The edges of unsupported lightweight areas where gussets cannot reach are projected downwards to provide support. Projected feature edges support the edges of the feature and provide excellent control against curling and warpage.

- 3) **Single webs (Figure c):** Thin walls can be supported by single webs produced by projecting the center-line along the narrow side of the thin walled feature. Cross members are added to provide stability of the support structure.
 - 4) **Webs (Figures d, e):** Large unsupported areas may be supported by various web structures, such as those shown in **Figures d and e**. Contact of such support structures with vertical part walls should be avoided to protect the final part surface. To minimize support material consumption, perforated walls may be used in the web structure as shown in **Figure f**.
 - 5) **Honeycomb:** Other sophisticated support structures similar to the honeycomb style for hollowing master prototype models initially developed may also be used as support structures.
 - 6) **Columns:** For isolated small islands, column type support structures can be used as shown in **Figure g**. For large islands, columns defined by other web structures may also be used.
 - 7) **Zigzag and perimeter support:** Delicate support structures are most suitable for processes such as stereolithography as the laser beam can be easily blocked anytime anywhere to prevent the resin from solidification. For processes such as FDM that use nozzles for material injection, a continuous path is preferred whether for support generation or for building the part. The zigzag and perimeter support structure shown in **Figure h** is most suited for FDM prototyping with a continuous path for each layer.
- For all the above mentioned support structures, the thickness of the thin webs can be just a single cured line (usually 0.18mm to 0.3mm thick) in the case of laser lithography or a single road width (often two times the layer thickness) in the case of fused deposition modeling.
 - Sierras or needles for connecting the part surface, if used, should penetrate into part surface by a few layer thicknesses. The intersection will ensure that the supports physically connect to the part features.

2.5 Model Slicing and Skin Contour Determination

- A STL facet model used for rapid prototyping applications contains a collection of planar faces. These faces define an approximate boundary representation for the object.
- During subsequent tool path generation, we need to slice the model based on either **uniform layer thickness or adaptively variable layer thickness**.
- In this section, we use uniform slicing to illustrate the **slicing algorithm**. As for adaptive slicing, one only needs to determine the corresponding adaptive layer thickness and the slicing algorithms are the same.
- Based on a user-entered layer thickness, a sequence of parallel slicing planes can be defined for model slicing.
- As a convention, we assume that the model has been properly oriented such that the z-axis will be the building direction.

- Let d be the layer thickness and n be the total number of slicing planes excluding the bottom plane with $Z = Z_{min}$ that are not used during the slicing procedure.
- Further, let Z_{max} and Z_{min} be the extreme z-coordinates of the STL model.
- The total number of layers (valid slicing planes) required is then defined by the following equation:

$$n = (Z_{max} - Z_{min}) / d$$

- The term $(Z_{max} - Z_{min})$ defines the dimension of the object along the z-axis.
- In this case, the slicing planes are defined as planes parallel to the x-y coordinate plane as follows:

$$Z_i = Z_{i+1} + d \quad \text{for } i = 1, 2, \dots, n$$

- For each of the slicing planes, a **slicing procedure** is performed.
- Following figure highlights a generalized procedure for slicing faceted models.
- To efficiently use this algorithm, contour points should be sorted first in the slicing direction, i.e., sorted following the z-coordinates.

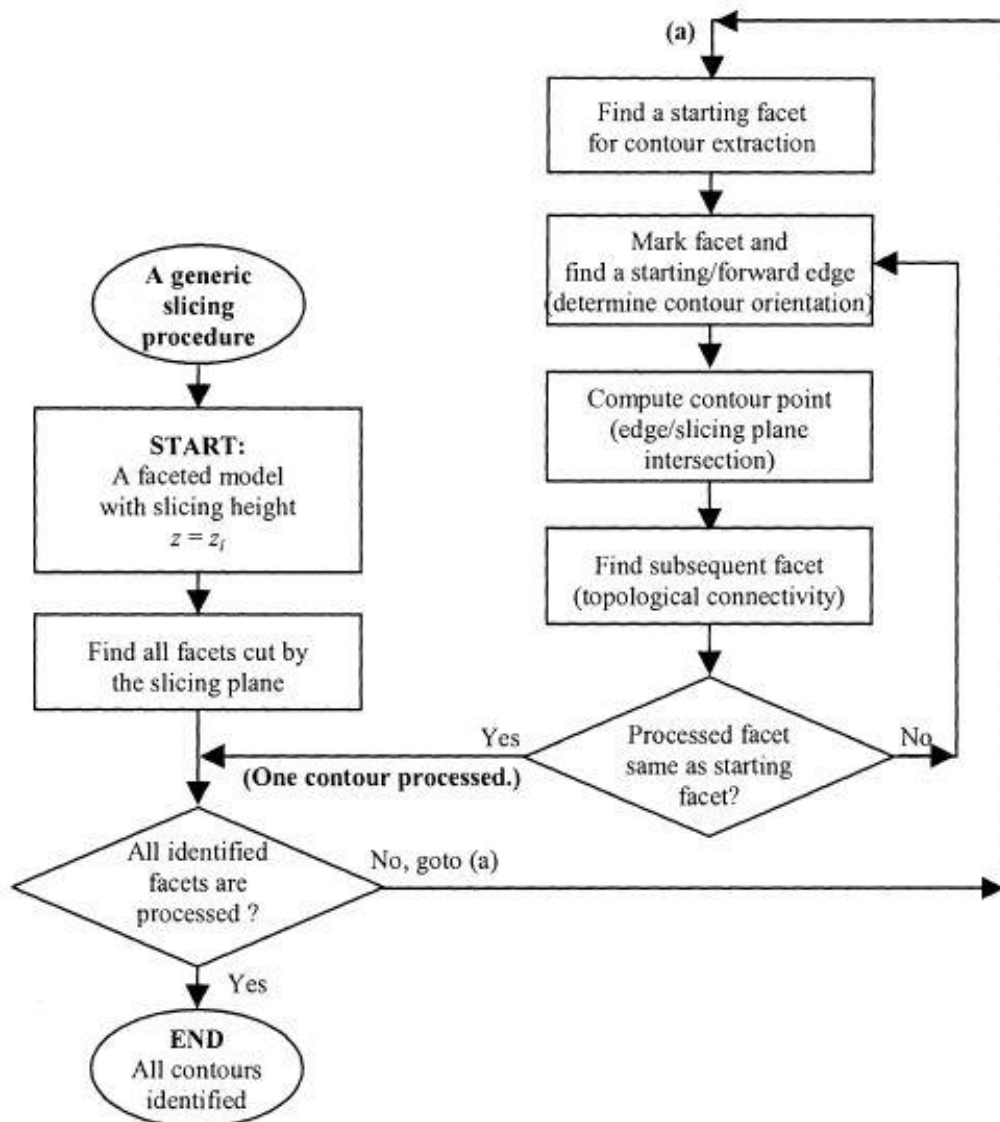


Fig 2.20 A general slicing procedure for STL models

- After completing model slicing and having determined the skin contours, we should have arrived at a list of skin contours.
- Each of the contours is defined by a list of chain contour points.
- One can use an arbitrary starting point and the direction of ordering, i.e. clockwise or counter clockwise, is also arbitrary at this point and will be decided later.
- Figure a shows an object being cut by a slicing plane and Figure b shows the individual triangles with cutting lines. Figures c and d show the surface contours (scaled) produced after model slicing with two alternative orientations.

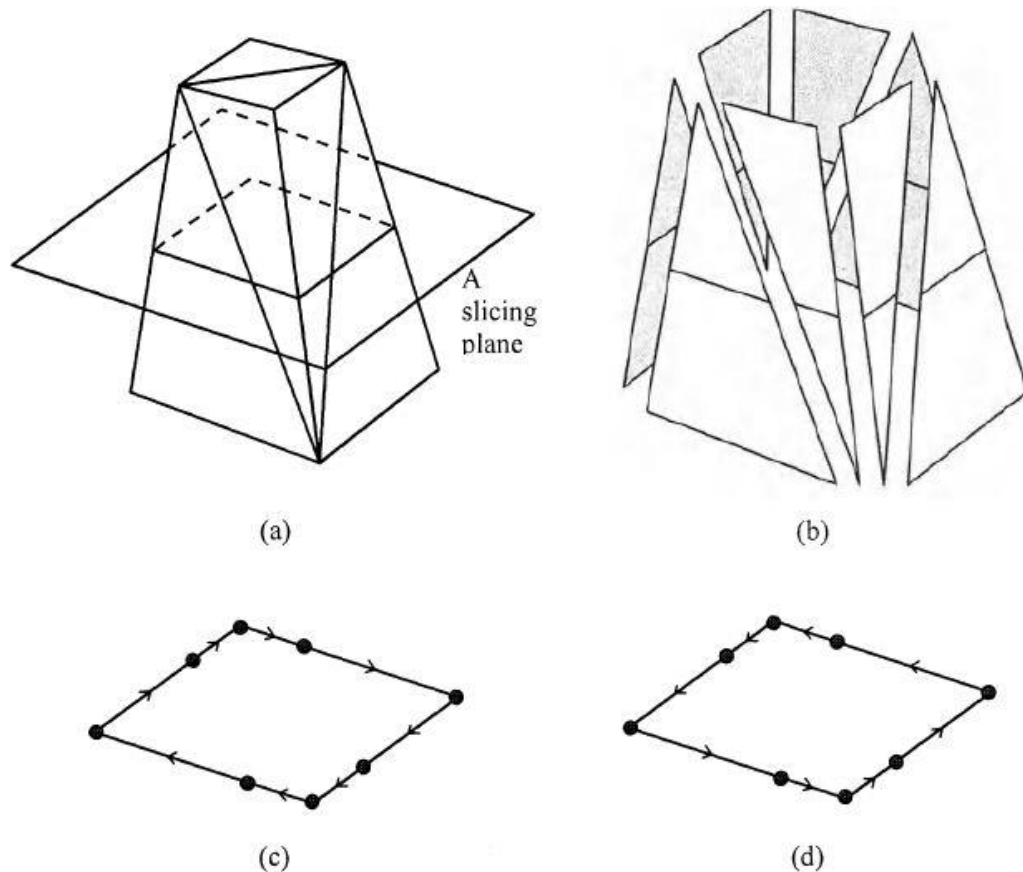


Fig 2.21 Facet model slicing and contour data initial sorting: (a) A STL model with a slicing plane; (b) related individual triangles cut by the slicing plane; (c)-(d) the identified contour (scaled) after initial contour points sorting with two possible orientations.

2.6 Identification of Internal and External Contours

- The contour data identified during the previous step include both external contours and internal contours as shown in following figure.
- Any continuous solid area is defined by one external contour and one or more immediate internal contours.
- The algorithm for the identification of the internal and external contours can be interpreted as follows.
- For each slice, a line located on the slicing plane is drawn across the contours as shown in figure. Since all slicing planes are parallel to the x-y coordinate plane, the line can either be parallel to the x-axis or they-axis.

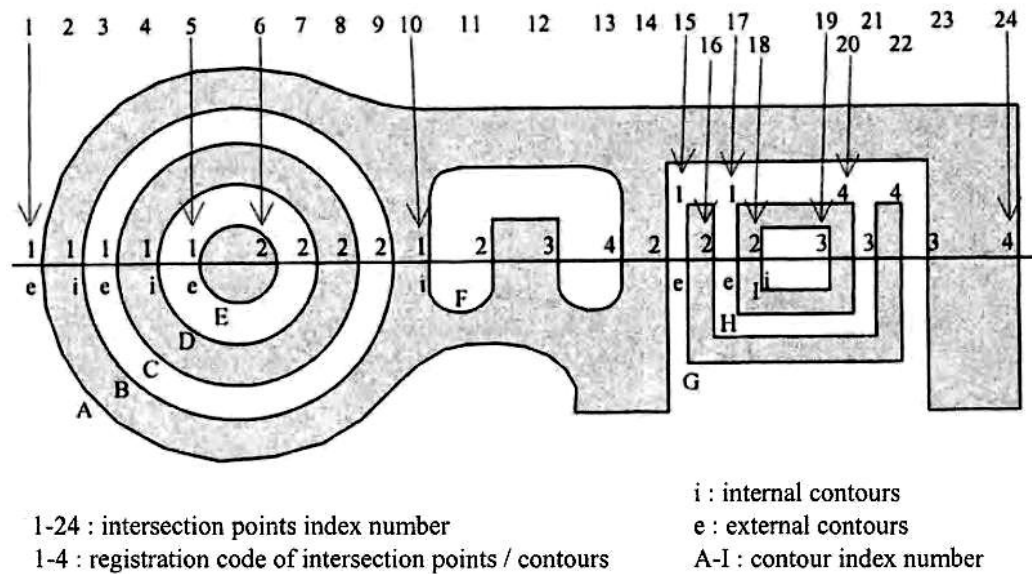


Fig 2.22 Contour type identification with a single horizontal line

- The intersection points between the line and the contours are then computed.
- If no single line satisfies the purpose, more lines should be constructed until intersection occurs for all contours as shown in the following figure.

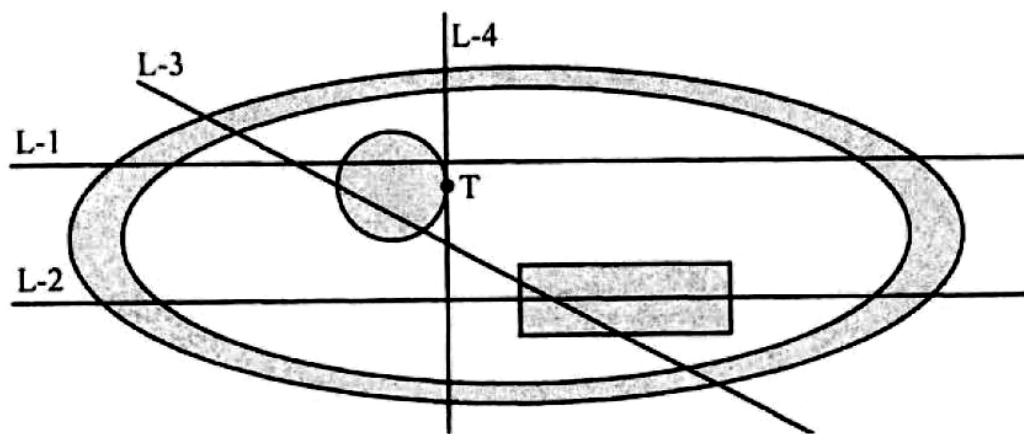


Fig 2.23 Contour type identification with two horizontal lines (L-1 and L-2) or with a single inclined line (L-3).

- If there is any contour with no intersection, one can simply add another line going through one of its contour points. In theory, one may also use inclined lines as shown in figure.
- For each of the casting lines, the intersections are sorted and registered from one side, such as from left to right for horizontal lines or downwards for vertical lines.
- For each of the contours, a **registration code** is reserved for indicating the status of a particular intersection, with an odd number indicating the '**in**' condition and an even number indicating the '**out**' condition.

- An initial registration code of **"0"** is assigned to all the intersecting contours before processing.
- The registration code of a contour will be incremented by one when the intersection line meets an intersection point of that contour during the identification process.
- Each of the intersection points will also have a unique registration code equaling the registration code of the corresponding contour at that intersection point.

2.7 Contour Data Organization

- A variety of contour data interfaces are being used by the RP community.
- One of the commonly used contour data interfaces is the Common Layer Interface (CLI) developed through a Brite Euram project.
- In addition, individual RP machine manufacturers also use their proprietary contour data interfaces.
- Typical examples include SLC from 3D Systems, Inc. and SSL (Stratasys Slicing Language) from Stratasys, Inc.
- Following figure illustrates a data structure adapted from the C LI interface for contour data organization.

```
// Contour data of the first layer
layer_index      : layer number
z_cord          : z coordinate of the current layer
n_contours      : number of contours of this layer

// Information of the first contour
contour_index    : contour number
contour_closed   : closed or open contour
contour_external : external or internal contour
father_contour   : contour pointer, 0 if outmost contour

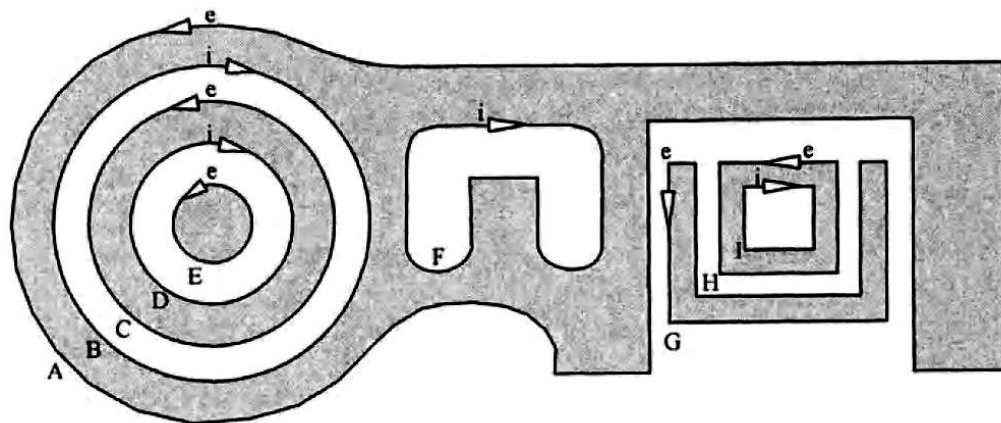
n                : number of contour points
x(1), y(1), z(1) : coordinates of the 1st contour point
x(2), y(2), z(2) : coordinates of the 2nd contour point
:
:
:
x(n), y(n), z(n) : coordinates of the last contour point

// Information of the second contour
:
:
:
// Information of the last contour

// Contour data of the second layer
:
:
:
// Contour data of the last layer
```

Fig 2.24 Parameters for contour data organization

- Following figure shows an example indicating how the directions of internal and external contours are defined in a CLI file.



i : internal contours
 e : external contours
 A-I : contour index number

Fig 2.25 Contour data organization: external contours - counter clockwise; internal contours – clockwise

- With the CLI contour data interface, all contours are organized layer by layer. Strictly speaking, contour formats only include closed contours.
- Sometimes, open contours also need to be supported in order to represent support structures or hatching.
- Closed contours could be either external or internal contours as discussed in the previous subsection.
- The internal and external contours are arranged clockwise and counter clockwise, respectively, in the direction of the slicing axis, i.e., in the direction of the z-axis if the slicing planes are parallel to the xy-plane.

2.8 Direct and Adaptive Slicing

- This section addresses adaptive slicing for obtaining a smooth surface finish while ensuring high building speed.
- Instead of working with a STL model, direct slicing algorithms are presented, i.e., the algorithms directly work with a CAD model.
- The procedure is subdivided into the following major steps.
 - **Peak feature point identification:** When producing prototype models with uniform layer thickness, there is no guarantee that important features of an object, such as horizontal features and other important feature points, are properly reproduced. With adaptive slicing, one can place a layer anywhere and hence all the peak features can be reproduced on the prototype model. In order to do so, all the peak features in a CAD model are first identified from the model surfaces as a set of feature points. These feature points subdivide the CAD model into slabs along the slicing direction, i.e., the z-direction. Feature points are sorted according to the slicing direction and will be used as inputs for the adaptive slicing algorithms.

- **Adaptive slicing with arbitrary tolerance control:** An adaptive slicing algorithm based on surface curvature along the vertical direction at the reference level/points is applied to each of the slabs with a pre-specified cusp height tolerance, and the minimum and maximum layer thickness. The skin contours on each layer are obtained from the allowable layer thickness, the local geometry information, and the given tolerance.
- The use of adaptive slicing with a variable layer thickness can yield the minimum number of layers along a given direction that satisfy the cusp height requirement or other tolerance criterion. The build time is thus reduced.
- At the same time, direct slicing of a CAD model can avoid potential problems related to the STL interface and thus improve the slicing accuracy.
- A major drawback with the use of direct slicing is the complexity of slicing algorithms, which could be a major reason why the STL interface is still the widely accepted standard of the RP industry.
- However, the algorithms presented here can also be extended to process models represented in STL format.

2.9 Tool Path Generation

- Once the slicing contour data are ready, one can start addressing process-dependent issues for tool path generation.
- In particular, as most of the RP processes are layer-based processes, one can produce the tool path layer-by-layer starting from the bottom layer.
- Following figure shows a sample part with one layer of sliced surface contours for illustrating various tool paths used for rapid prototyping applications.

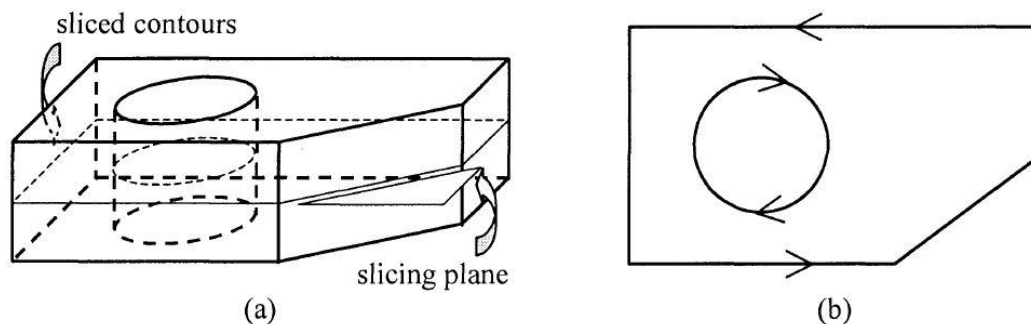


Fig 2.26 An example illustrating various types of tool paths for model prototyping: (a) the original part with a slicing plane and sliced contours; (b) the sliced contours on the xy-plane.

- In general, one can classify tool paths for all RP processes into the following basic categories:
 - 1) **Raster scanning:** Raster scanning refers to scanning along one coordinate axis for model solidification. This is the simplest tool path for layered manufacturing.
 - The scanning strategy can be applied to processes such as stereolithography (SL), selective laser sintering (SLS) and some other 3-D printing processes for internal hatching.

- **Figure a** illustrates a typical scanning pattern produced by two orthogonal raster scanning operations along the x and y-axis for internal area solidification.

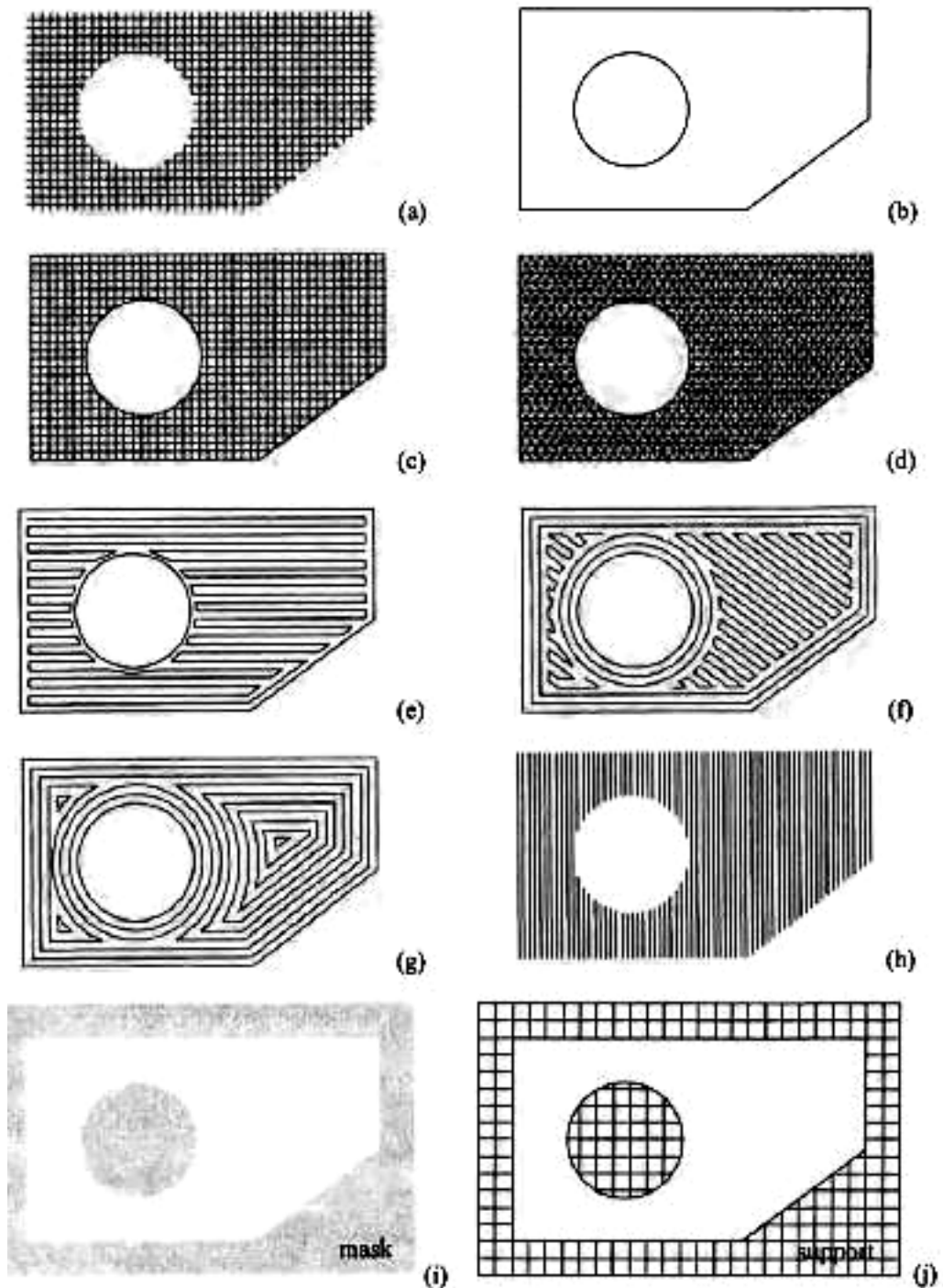


Fig 2.27 Typical tool paths for model prototyping: (a) x- and y-raster scanning for internal hatching (may be used separately); (b) perimeter scanning; (c) a typical tool path with a single perimeter surface scanning and orthogonal internal xy-hatching; (d) single perimeter surface scanning with internal directional hatching; (e) single perimeter with internal horizontal/vertical zigzag paths; (f) three perimeters with internal inclined zigzag paths; (g) contouring or equidistant paths; (h) line-by-line scanning; (i) area-based solidification using masks; and (j) boundary cutting with orthogonal cross-cutting for LOM

- 2) **Perimeter scanning:** The perimeter scanning approach shown in *Figure b* (illustrating only a single perimeter) is often used for producing external surfaces.
 - This approach can also be turned into a contouring approach with multiple perimeters and their offsetting contours.
 - The method is applicable to almost all RP processes involving skin region solidification.
 - It is also the main scanning strategy used for paper cutting in the LOM process.
 - *Figure c* shows a scanning pattern produced by single perimeter scanning plus orthogonal internal x and y hatchings.
 - This example illustrates the basic pattern of several scanning styles such as the **WEAVE** and the **STAR-WEAVE** patterns used on SLA machines of 3D Systems.
- 3) **Directional scanning:** Sometimes, raster scanning may produce a large number of scanning vectors and it might be advantageous to perform scanning along arbitrary paths, such as inclined linear and other contouring paths.
 - In certain other cases, we may also need to use directional scanning for improving the mechanical properties of the produced model prototype.
 - *Figure d* illustrates a scanning pattern with a single perimeter and three groups of scanning lines at 0°, 60° and 120° angles to the x-axis
 - This is the basic pattern used for the '**Tri-Hatch**' scanning style that was once used on stereolithography machines of 3D Systems.
- 4) **Zigzag tool path:** Zigzag tool path is often used for FDM prototyping, 3D welding and other extruding type RP systems.
 - It has also been used for some drop-on-demand and point-by-point 3D printing processes such as the 3D Printing (3DP) process developed by MIT and Ballistic Particle Manufacturing (BPM).
 - *Figure e* illustrates a zigzag tool path for internal solidification with a single perimeter for surface scanning.
 - *Figure f* shows an inclined zigzag path for internal filling with three perimeters for skin area solidification.
- 5) **Contouring and spiral paths:** Contouring and spiral tool paths can also be used for model prototyping.
 - For parts with certain geometries, these approaches may produce parts with improved mechanical properties.
 - *Figure g* illustrates a contouring tool path for the example part.
- 6) **Line by line scanning:** Line by line scanning is often used for some inkjet type printing processes, such as the process used by ThermoJet 3D printer of 3D Systems.
 - Each layer is produced through single sweeping of a line component along the principal scanning direction.
- 7) **Area by area solidification:** Some RP processes directly solidify the object area by area. Typical examples include photopolymer-based processes such as the Cubital's stereolithography process.
 - As shown in *Figure i*, a mask is first developed based on the sliced contours and a thin layer of photopolymeric resin is then selectively solidified by exposing to a flash of UV light.

8) **Boundary cutting tool paths (a variant of perimeter scanning):** In laminated object manufacturing (LOM), a boundary cutting strategy is used.

- For cutting waste and supporting materials during the LOM process, a basic orthogonal xy-hatching pattern is often used. Such an approach is illustrated in **Figure j**.
- In addition to the basic tool paths discussed above, there are also a variety of well-studied scanning strategies/styles capable of rapidly producing prototype models for various applications.
- In addition to TriHatch, WEAVE and STAR-WEAVE mentioned earlier, there are three scanning styles used for QuickCast, a popular scanning strategy for producing hollow stereolithography master models for quick tooling.
- The finally produced master model is a shell model with internal supports specially designed for easy drainage of residual resins after the building process and for easy bum out of the support structures during the tooling process. Following figure illustrates the pattern for QuickCast 1.0.

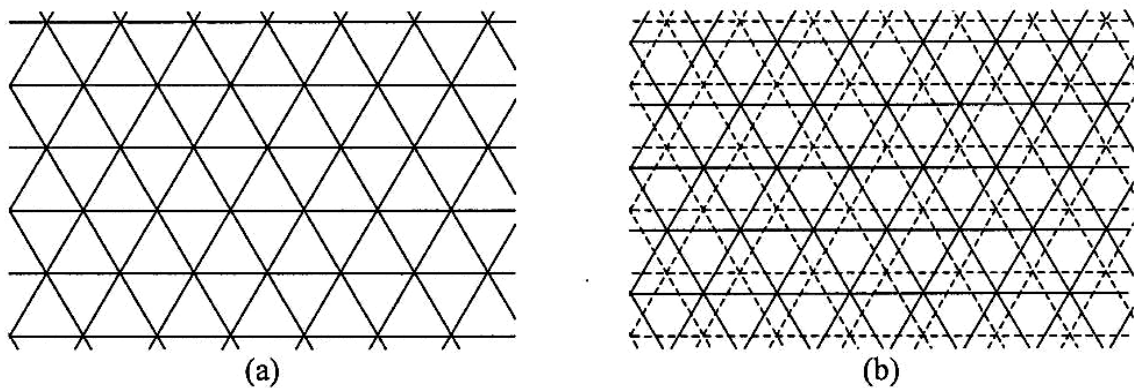


Fig 2.28 Special scanning patterns used for QuickCast 1.0: (a) first level scanning pattern; (b) top view of the scanning pattern after several levels with solid lines indicating odd levels and broken lines indicating even levels

- During the first level of the building process, the basic pattern of above **figure (a)** is used.
- During the second level of the building process, the pattern shown in above **figure (b)** that is produced by offsetting the pattern of figure (a) is used.
- The offsetting is produced such that the vertices of the pattern for the even levels will be located at the center of the triangles of the odd levels.
- The entire process is then repeated till the completion of the QuickCast master model.
- The entire internal volume is composed of interconnected triangular cells and hence the resin contained within can be easily released after the building process.
- A similar approach is used for QuickCast 1.1 with orthogonal grid cells as shown in following figure.

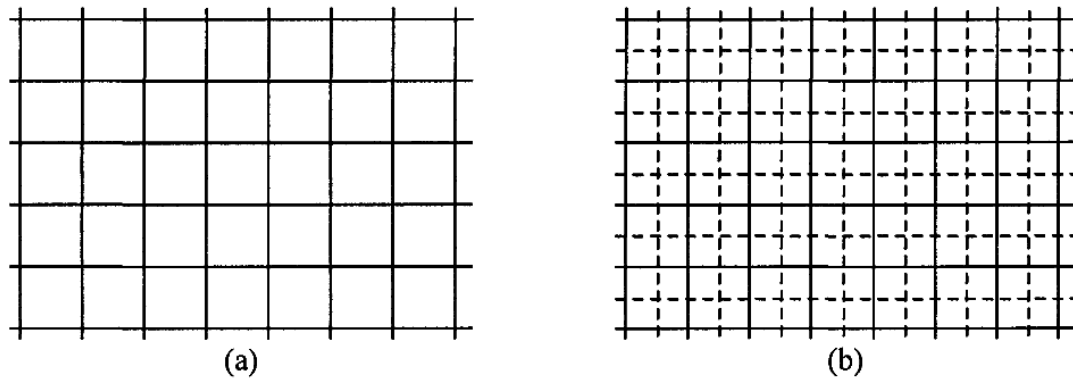


Fig 2.29 Special scanning patterns used for QuickCast 1.1: (a) first level scanning pattern; (b) top view of the scanning pattern after several levels with solid lines indicating odd levels and broken lines indicating even levels

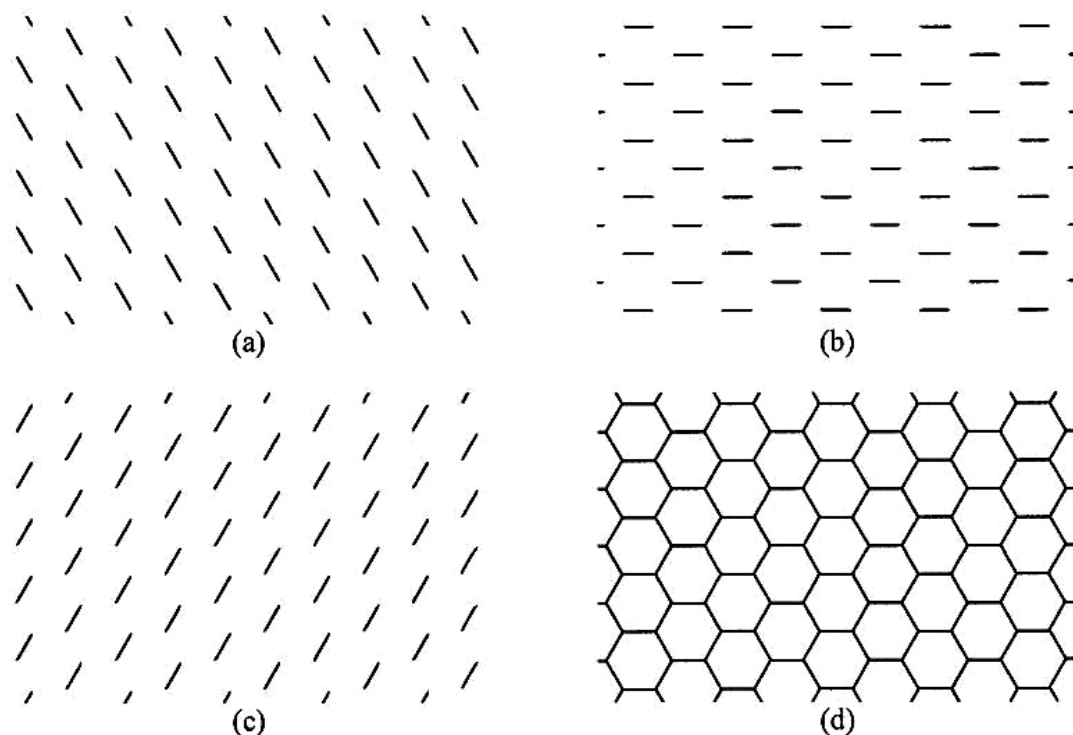
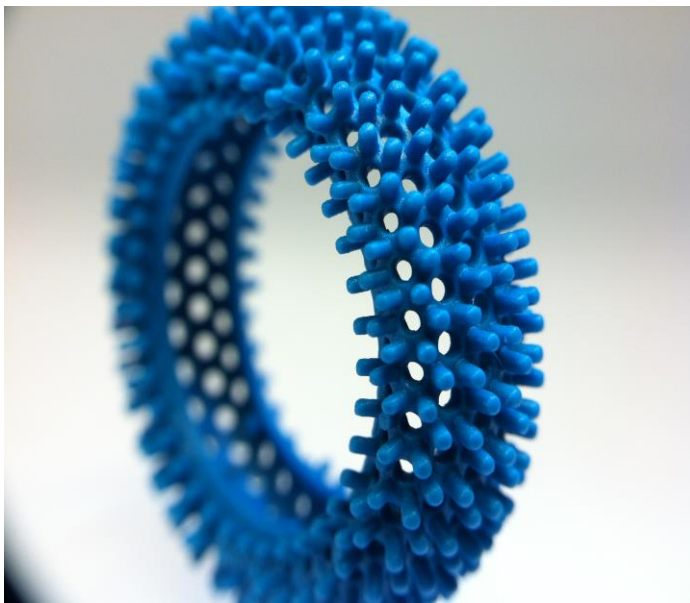


Fig 2.30 Special scanning patterns used for QuickCast 2.0: (a) first level scanning pattern; (b) second level scanning pattern; (c) third level scanning pattern; (d) top view of the scanning pattern after more than three levels

- The above figure illustrates the pattern used for QuickCast 2.0. The build style produces hexagons in three levels.
- The three levels of this structure use the same scanning pattern with a rotation of 120° as shown in Figures a-c.
- Together, the three levels produce a complete hexagon when seen from the top, often called a honeycomb structure.

3

RP Processes



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 - I. Selective laser Sintering (SLS)
 - II. Electron Beam melting (EBM)
- 3.12** Extrusion-Based RP Systems
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 - II. 3D Printing
 - III. Sheet Lamination Laminated Object Manufacturing (LOM)
 - IV. Ultrasonic Consolidation (UC)
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 - II. Direct Metal Deposition (DMD)

3.1 Introduction

The term Rapid Prototyping (RP) refers to a class of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data. The goal of Rapid Prototyping (RP) is to be able to quickly fabricate complex-shaped, three dimensional parts directly from CAD models

3.2 Principle of Rapid Prototyping

The principal of RP is illustrated in fig.1(a). The CAD model of the object shown is sliced by parallel planes. The edges of the slices thus obtained are squared. Thus, a complex 3D object is decomposed into several 2D objects or slices. In other words, a complex 3D manufacturing problem is converted into several simple 2D manufacturing problems. These slices are physically realized in one of several ways, stacked and pasted together as shown in fig, to obtain the physical prototype. The accuracy of these prototypes, due to the staircase effect, can be improved by decreasing the slice thickness. For even better finish, polishing can be applied.

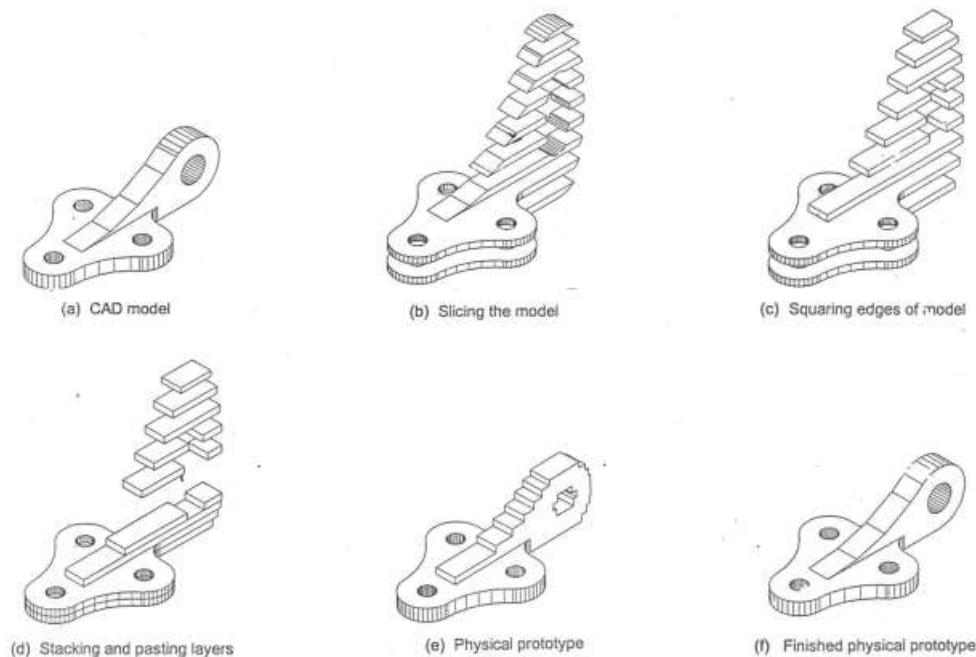


Figure 1: Principal of Rapid Prototyping

Each physical layer will be placed over the previous one. If the previous layer is smaller than the current one, then it will not be able to fully support the current layer. For this purpose, a complementary shaped sacrificial layer of a different material is deposited and fused to the previous layer using one of several available deposition and fusion technologies. The sacrificial material has two primary roles: first, it holds the part, analogous to a fixture in traditional fabrication techniques: second, it serves as a substrate upon which unconnected regions and overhanging features can be deposited. The unconnected regions require this support since they are not joined with the main body until subsequent layer are deposited. Another use of sacrificial material is to form blind cavities in the part. The collection of this sacrificial layer is called support structures.

3.3 Process Physics & Tooling

- **Rapid Prototyping Process Step**

Although several rapid prototyping techniques exist, all employ the same basic five-step process.

The steps are:

1. Create a CAD model of the design
2. Convert the CAD model to STL format
3. Slice the STL file into thin cross-sectional layers
4. Construct the model one layer atop another
5. Clean and finish the model

- **Rapid tooling**

A much-anticipated application of rapid prototyping is rapid tooling, the automatic fabrication of production quality machine tools. Tooling is one of the slowest and most expensive steps in the manufacturing process, because of the extremely high quality required. Tools often have a complex geometry, yet must be dimensionally accurate to within a hundredth of a millimeter. In addition, tools must be hard, wear-resistant, and have very low surface roughness (about 0.5 micrometers root mean square). To meet these requirements, molds and dies are traditionally made by CNC-machining, electro-discharge machining, or by hand. All are expensive and time consuming, so manufacturers would like to incorporate rapid prototyping techniques to speed the process. Peter Hilton, president of Technology Strategy Consulting in Concord, MA, believes that "tooling costs and development times can be reduced by 75 percent or more" by using rapid tooling and related technologies.

1. Indirect Tooling

Most rapid tooling today is indirect: RP parts are used as patterns for making molds and dies. RP models can be indirectly used in a number of manufacturing processes:

- **Vacuum Casting:** In the simplest and oldest rapid tooling technique, a RP positive pattern is suspended in a vat of liquid silicone or room temperature vulcanizing (RTV) rubber. When the rubber hardens, it is cut into two halves and the RP pattern is removed. The resulting rubber mold can be used to cast up to 20 polyurethane replicas of the original RP pattern.

A more useful variant, known as the Keltool powder metal sintering process, uses the rubber molds to produce metal tools. Developed by 3M and now owned by 3D Systems, the Keltool process involves filling the rubber molds with powdered tool steel and epoxy binder. When the binder cures, the "green" metal tool is removed from the rubber mold and then sintered. At this stage the metal is only 70% dense, so it is infiltrated with copper to bring it close to its theoretical

maximum density. The tools have fairly good accuracy, but are limited to less than 25 centimeters in size.

- **Sand Casting:** A RP model is used as the positive pattern around which the sand mold is built. LOM models, which resemble the wooden models traditionally used for this purpose, are often used. If sealed and finished, a LOM pattern can produce about 100 sand molds.

- **Investment Casting:** Some RP prototypes can be used as investment casting patterns. The pattern must not expand when heated, or it will crack the ceramic shell during autoclaving. Both Stratasys and Cubital make investment casting wax for their machines. Paper LOM prototypes may also be used, as they are dimensionally stable with temperature. The paper shells burn out, leaving some ash to be removed. To counter thermal expansion in stereo lithography parts, 3D Systems introduced Quick Cast, a build style featuring a solid outer skin and mostly hollow inner structure. The part collapses inward when heated. Likewise, DTM sells True form polymer, a porous substance that expands little with temperature rise, for use in its SLS machines.

- **Injection molding:** CEMCOM Research Associates, Inc. has developed the NCC Tooling System to make metal/ceramic composite molds for the injection molding of plastics. First, a stereo lithography machine is used to make a match-plate positive pattern of the desired molding. To form the mold, the SLA pattern is plated with nickel, which is then reinforced with a stiff ceramic material. The two mold halves are separated to remove the pattern, leaving a matched die set that can produce tens of thousands of injection moldings.

2. Direct Tooling: -

To directly make hard tooling from CAD data is the Holy Grail of rapid tooling. Realization of this objective is still several years away, but some strong strides are being made:

- **RapidTool:** A DTM process that selectively sinters polymer-coated steel pellets together to produce a metal mold. The mold is then placed in a furnace where the polymer binder is burned off and the part is infiltrated with copper (as in the Keltool process). The resulting mold can produce up to 50,000 injection moldings.

- **Laser-Engineered Net Shaping (LENS):** It is a process being developed at Sandia National Laboratories and Stanford University that will create metal tools from CAD data. Materials include 316 stainless steel, Inconel 625, H13 tool steel, tungsten, and titanium carbide cermets. A laser beam melts the top layer of the part in areas where material is to be added. Powder metal is injected into the molten pool, which then solidifies. Layer after layer is added until the part is complete. Unlike traditional powder metal processing, LENS produces fully dense parts, since the metal is melted, not merely sintered. The resulting parts have

exceptional mechanical properties, but the process currently works only for parts with simple, uniform cross sections. Commercialization is still several years away.

- **Direct AIM (ACES Injection Molding):** A technique from 3D Systems in which stereo lithography-produced cores are used with traditional metal molds for injection molding of high and low-density polyethylene, polystyrene, polypropylene and ABS plastic. Very good accuracy is achieved for fewer than 200 moldings. Long cycle times (five minutes) are required to allow the molding to cool enough that it will not stick to the SLA core.

In another variation, cores are made from thin SLA shells filled with epoxy and aluminum shot. Aluminum's high conductivity helps the molding cool faster, thus shortening cycle time. The outer surface can also be plated with metal to improve wear resistance. Production runs of 1000-5000 moldings are envisioned to make the process economically viable.

- **LOM Composite:** Helysis and the University of Dayton are working to develop ceramic composite materials for Laminated Object Manufacturing. LOM Composite parts would be very strong and durable, and could be used as tooling in a variety of manufacturing processes.

- **Sand Molding:** At least two RP techniques can construct sand molds directly from CAD data. DTM sells sand-like material that can be sintered into molds, while Soligen 3D Printing machines can produce ceramic molds as well.

3.4 Prototyping materials

- **Prototyping and material properties**

When selecting a material, material properties are critical since they are the link between basic material composition and service performance. Material processing is also critical since it determines part manufacturing processes. Prototyping materials often are different than the final product materials, especially for lower fidelity prototypes, due to the differences in project objectives and time constraints in prototyping. For quick prototyping purposes, there are several materials available.

1. **Modeling clay:** Modeling clay is easy to work with, is useful for visualization and airflow studies, always remains soft, and is available in hobby and craft shops. Each time Congress authorizes a new coin or medal, an artist sketches out ideas for the design. After one design has been approved, the U.S. Mint sculptor engraver.

2. **Machining wax:** Wax can be machined well and is useful for prototyping tooling patterns.

3. **Foam board:** Foam board has a good finish, is easily carved, useful for painting (aesthetic=appearance models), and machinable. Pressurized cans of insulating foam are available that harden quickly and may be cut and formed with a knife and sanding board.

4. Foam core: The foam core is made of sheets of hard paper with internal foam, is useful for mock-ups and layout of square objects, can be used with bondo/clay for more complex shapes, and is more durable and rigid than cardboard.

5. Rubber, elastomer: Rubber and elastomer are useful in energy absorption applications or seals, can be used as a removable mold for castings of other materials, and can be carved.

6. Cardboard, paper, cloth: Cloth and paper can serve as joints in mock-ups and are very cheap

.

EXAMPLES:

Metallic materials – Plain Carbon Steel, Tool Steel, Stainless steel, Aluminium, Copper, Titanium, Bronze, Nickel Aluminides

Polymers and Polymeric Composites - ABS, Nylon (Polyamide), Polycarbonate, PP, Epoxies, Glass filled polyamide, Windform, Polystyrene, Polyester, Polyphenylenesulfone

Others - Sand, Ceramics, Elastomers, Tungsten, Wax, Starch, Plaster

Bio Compatible Materials - Polycaprolactone (PCL), polypropylene-tricalcium phosphate, (PP-TCP), PCL-hydroxyapatite (HA), polyetheretherketone-hydroxyapatite, (PEEK-HA), tetracalcium phosphate (TTCP), beta – tricalcium phosphate (TCP), Polymethyl methacrylate (PMMA)

3.5 Material selection

- In the 21st century, one of the hallmarks of modern, industrialized society is the rising use of materials.
- Not only human beings are consuming materials more rapidly, but also they are using an increasing diversity of materials.
- Indeed, it has been postulated that assuming current trends in world production and population growth, the materials requirements for the next decade and a half could equal all the materials used throughout the history up to date.
- People interact with these vast numbers of materials mostly via products. The interaction involves a number of attributes.
- For instance, material of a product with its technical properties should fulfill the functional requirements for an intended use and with its sensorial properties it should appeal to the senses of its user.
- Therefore, product designers are responsible for selecting appropriate materials for their products by taking these technical and sensorial characteristics of materials into consideration.
- However, the competitive market rising from the increase in product and material consumption have made product designers consider some aspects besides the technical and sensorial ones.

- For instance, designers have started to make use of materials in order to attribute particular meanings to their products or support the existing meanings. There are plenty of examples that provide sufficient proof for this statement.
- For instance, metal appears cold and can connote precision, and it seems durable and robust; for this reason, designers can use metal to emphasize the technological superiority and high level engineering.
- Existing materials selection sources can serve a useful function in giving up to date information on the technical (physical, quantifiable) aspects of materials.
- However, as mentioned in the previous paragraph, product designers use also some intangible aspects, in order to express their intentions through the selected materials.
- Conversely, even though these intangible aspects in materials selection process are crucial for designers, the existing materials selection sources neither consider them, nor offer a systematic way for involving them into materials selection process.
- For engineering designers, it is easy to access to information they need- handbook, selection software, advisory services from material suppliers- and to analysis and optimization codes for safe, economical design.

Factors effective in materials selection in engineering design

- The selection of a material for a specific application is a thorough, lengthy and expensive process.
- Almost always more than one material is suited to an application, and the final selection is a compromise that brings some advantages as well as disadvantages.
- There are many factors or constraints to be considered in selecting materials. There are of course some situations that the certain criteria for a material are defined at the beginning of the design.
- Although at such situations the required criteria dominate the selection process, most of the time one material among a range of materials is selected depending on some factors.
- At different engineered based sources, the factors that affect the materials selection are grouped under various subtitles, which can be followed as shown in figure below.

Materials (1967)	Patton (1968)	Esin (1980)	Ashby (1992)	Lindbeck (1995)	Budinski (1996)	Mangonon (1999)	Ashby & Johnson (2002)	Ashby (2005)
Mechanical Properties	Service Requirements	Production Requirements	General Properties	Mechanical Properties	Chemical Properties	Physical Factor	General attributes	General properties
Cost	Fabrication Requirements	Economic Requirements	Mechanical Properties	Physical Properties	Physical Properties	Mechanical Factor	Technical attributes	Mechanical properties
	Economic Requirements	Maintenance	Thermal Properties	Chemical Properties	Mechanical Properties	Processing & Fabricability	Eco attributes	Thermal properties
			Wear	Thermal Properties	Dimensional Properties	Life of component factors	Aesthetic attributes	Electrical properties
			Corrosion/oxidation	Electrical Properties	Business Issues	Cost & Availability		Optical properties
				Acoustical Properties		Codes, Statutory and other		Eco properties
				Optical Properties		Processing profile		Environmental resistance
						Environmental Profile		

Fig 4.1 Review of different sources defining the effective material aspects for material selection process

- Although most of these sources define the design process as an entire process covering both technical and non-technical issues of design, they mostly concentrate on the technical side; which shape the content of the engineering based sources.
- When a designer selects a material, he must consider fulfilling the three basic requirements:
 - 1) Service requirements,
 - 2) Fabrication requirements and
 - 3) Economic requirements.
- According to him, the service requirements are supreme.
- The material must stand up to service demands which commonly include dimensional stability, corrosion resistance, adequate strength, hardness, toughness and heat resistance.
- The material must be possible to shape and join to other materials. Patton puts those properties of materials under 'fabrication requirements'.
- Finally, he states that, the objective of a designer is to minimize overall cost of the product and manufacturing.
- For example, a more expensive free machining metal may be substituted for a standard metal, since the savings in machining cost may overweigh the increased cost of the more expensive metal.

3.6 Material properties

- Basics of the mechanical properties of materials provide the development of material science and encourage designers to explore new use areas for new materials; because mechanical properties of materials define their usage and environment.
- Strength and rigidity, quality and durability of the surface are listed as the most important mechanical properties.
- Similarly, requirements related to the physical properties (material's melting point, density, moisture content, porosity, and surface texture); chemical properties (resistance to corrosion and dissolution); thermal properties (heat conductivity, heat resistance); electrical properties (materials' conductivity and resistance to electrical charges); acoustical properties (materials' reactions to sound), and optical properties (materials reactions to light), must be fulfilled through appropriate materials selection.
- Mechanical properties are especially important because they are indicators of strength, producibility, and durability.
- Knowledge of such forces and the ways in which materials react to them are valuable in determining which material to use in a specific application.
- The factors to be considered in materials selection into four major categories:
 - Chemical properties,
 - Physical properties,
 - Mechanical properties and
 - Dimensional properties
- The factors considered in materials selection under availability categories:
 - Production requirements,
 - Economic requirements, and
 - Maintenance requirements
- The material, which has been selected on the basis of its functional merits, must also be capably embodied. The designer, therefore, take into consideration of a much wider range of properties such as the ability of the material to be machined, shaped, formed, cast, welded, hardened etc.
- For most situations, the designer has to make some sort of comparative assessment to select the most favorable material.
- A well knowledgeable design engineer defines five factors having influence on materials selection:
 - Physical factors,
 - Mechanical factors,
 - Processing and fabricability,
 - Life of component factors,
 - Cost and availability and
 - Codes, statutory, and others.

- Life of component factors herein relate to the length of time the materials perform their intended function in the environment to which they are exposed.
- The properties in this group are the corrosion, oxidation, and wear resistance, creep, and the fatigue or corrosion fatigue life properties in dynamic loading.
- As it is seen, he combines cost and availability criteria, and explains that, in a market-driven economy, these two factors are inseparable.
- For the last category- codes, statutory, and other factors which had been called as 'business issues', Codes are sets of technical requirements that are imposed on the material or the component.
- These are usually set by the customer, or are based from those of technical organizations.
- Statutory factors relate to local, state, and federal regulations about materials and processes used or the disposal of the material.
- These are regarding to health, safety, and environmental requirements. Interestingly, at most of the sources, the environmental issues are placed at the bottom of the listed requirements for design engineers.
- Another classification for the current design engineers, and organizes the factors under three topics:
 - Property profile
 - Processing profile and
 - Environmental profile
- As indicated above, selection based on the environmental profile covers the impact of the material, its manufacture, its use and reuse, and its disposal on the environment topics.
- It adds that designers and companies feel that if the costs of incorporating them in design are prohibitive, the environmental aspects are usually laid aside, unless law mandates it.
- Designing for the environment is a good strategy because it can be a good marketing tool for environment-conscious consumers.
- The emphasis on:
 - General properties
 - Mechanical properties
 - Thermal properties
 - Wear and corrosion/ oxidation properties of materials
- The basic design limiting properties of materials also to be consider and these are as:
 - General properties of materials (density and price)
 - Mechanical properties
 - Thermal properties
 - Electrical properties
 - Optical properties
 - Eco- properties

- Environmental resistance properties of materials
- Aesthetic attributes of materials (which are the sensorial properties of materials, like warmth, softness, etc.) into their material properties list for designers.
- In addition to the aesthetic attributes of materials, also define the materials' two overlapping roles as: providing technical functionality and creating product personality.
- Accordingly it, redefine their list of requirements adding some intangible issues:
 - Technical
 - Economic
 - Sustainability (related with environmental issues)
 - Aesthetic
 - Perceptions and
 - Intentions
- Likewise, a few sources slightly touch upon similar kinds of intangible characteristics of materials but they do not propose to integrate these characteristics into their material requirements list.
- Names these characteristics of materials 'indefinable characteristics of materials', which are the appearance, odour, feel, and general impression that result from special uses and combinations of materials for aesthetic purposes.
- It also emphasize that these characteristics are directly related to the emotional approaches of the consumers and can easily be affected by the marketing strategies.
- Some of the issues are interesting to note the high value at which the market rates some properties and the low value applied to others.
- Relatively little economic value is attached to a high modulus of elasticity, for example the attractive appearance of the plastics vastly outweighs their poor dimensional stability.
- Consequently, if the concise evaluation of this section is done, it becomes apparent that: the existing engineering design based sources put more emphasis on the technical properties of materials.
- In more recent sources, the significance of sensorial properties and the intangible issues like perceptions, associations and emotions are underlined.
- Nowadays, some researchers in design and materials field explore this topic intensive and define the major design limiting materials characteristics based on product designers' needs and expectations.

3.7 Material economics

- It is important to consider costs and economics at every stage of design, product development, prototyping and manufacturing.
- A client / customer will have a significant view on costs and potential profits, which is usually emphasized at the beginning of the design process.

- Reducing costs, without a reduction in the quality of a product; should be the aim of every designer. Reducing costs can be beneficial to the environment.
- For instance, using cheaper recycled materials, which leads to a cheaper final product, is both an advantage to the manufacturer and customer.
- This approach also helps to reduce the environmental impact of manufacturing.
- Further to this, the economic necessity to reduce costs and customer pressure on manufacturers to protect the environment, often leads to innovation in design.

3.8 Material evaluation for selection

- The competitive market rising from the increase in product consumption makes product designers consider more about materials than before.
- Existing materials selection sources can serve as useful function in giving up to date information on technical (physical, quantifiable) characteristics of materials.
- However, designers also use some intangible aspects with the aim of expressing their intentions; attributing some meanings to their products through their appropriate choices of material.
- The main objective is to evaluate materials selection process in product design in order to find out what kinds of aspects of materials are significant for product designers in their selections.

3.8.1 Initial Screening of Materials

- In the first stages of development of a new product, such questions as the following are posed:
 - What is it?
 - What does it do?
 - How does it do it?
- After answering these questions it is possible to specify the performance requirements of the different parts involved in the design and to broadly outline the main materials performance and processing requirements.
- This is then followed by the initial screening of materials whereby certain classes of materials and manufacturing processes may be eliminated and others chosen as likely candidates.

3.8.2 Analysis of Material Performance Requirements

- The material performance requirements can be divided into five broad categories: functional requirements, processability requirements, cost consideration, reliability, and resistance to service conditions.

1. Functional Requirements

- Functional requirements are directly related to the required characteristics of the part or the product.
- For example, if the part carries a uniaxial tensile load, the yield strength of a candidate material can be directly related to the load-carrying capacity of the product.

- However, some characteristics of the part or product may not have simple correspondence with measurable material properties, as in the case of thermal shock resistance, wear resistance, reliability, etc.
- Under these conditions, the evaluation process can be quite - complex and may depend upon predictions based on simulated service tests or upon the most closely related mechanical, physical, or chemical properties.
- For example, thermal shock resistance can be related to the thermal expansion coefficient, thermal conductivity, modulus of elasticity, ductility; and tensile strength.
- On the other hand, resistance to stress-corrosion cracking can be related to tensile strength and electrochemical potential.

2. Processability Requirements

- The processability of a material is a measure of its ability to be worked and shaped into a finished part.
- With reference to a specific manufacturing method, processability can be defined as castability, weldability, machinability, etc.
- Ductility and hardenability can be relevant to processability if the material is to be deformed or hardened by heat treatment, respectively.
- The closeness of the stock form to the required product form can be taken as a measure of processability in some cases.
- It is important to remember that processing operations will almost always affect the material properties so that processability considerations are closely related to functional requirements.

3. Cost consideration

- Cost is usually an important factor in evaluating materials, because in many applications there is a cost limit for a given component.
- When the cost limit is exceeded, the design may have to be changed to allow for the use of a less expensive material or process.
- In some cases, a relatively more expensive material may eventually yield a less expensive component than a low-priced material that is more expensive to process.

4. Reliability Requirements

- Reliability of a material can be defined as the probability that it will perform the intended function for the expected life without failure.
- Material reliability is difficult to measure, because it is not only dependent upon the material's inherent properties, but it is also greatly affected by its production and processing history.
- Generally, new and nonstandard materials will tend to have lower reliability than established, standard materials.
- Despite difficulties of evaluating reliability, it is often an important selection factor that must be taken into account.

- Failure analysis techniques are usually used to predict the different ways in which a product can fail and can be considered as a systematic approach to reliability evaluation.
- The causes of failure of a part in service can usually be traced back to defects in materials and processing, faulty design, unexpected service conditions, or misuse of the product.

5. Resistance to Service Conditions

- The environment in which the product or part will operate plays an important role in determining the material performance requirements.
- Corrosive environments, as well as high or low temperatures, can adversely affect the performance of most materials in service.
- Whenever more than one material is involved in an application, compatibility becomes a selection consideration.
- In a thermal environment, for example, the coefficients of thermal expansion of all the materials involved may have to be similar in order to avoid thermal stresses.
- In wet environments, materials that will be in electrical contact should be chosen carefully to avoid galvanic corrosion.
- In applications where, relative movement exists between different parts, wear resistance of the materials involved should be considered.
- The design should provide access for lubrication; otherwise self-lubricating materials have to be used.

3.9 Advantages, Limitations and Applications of RP

3.9.1 Advantages of RP

- Customization
- Constant Prototyping and Increased Productivity – Affordability
- Storage
- Employment Opportunities
- Health Care

3.9.2 Limitations of RP

- Cost
- Accuracy
- Finish
- Strength
- Material Options

3.9.3 Applications of RP

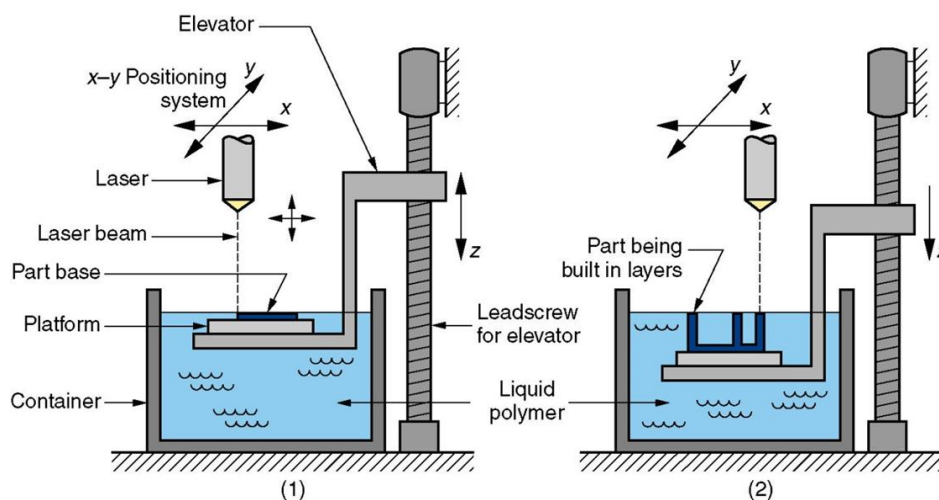
- Historical Developments
- Rapid Tooling

- To Support Medical Applications
- Surgical and Diagnostic Aids
- Prosthetics Development
- Manufacturing
- Tissue Engineering and Organ Printing
- Aerospace Applications
- Automotive Applications
- Reverse Engineering
- Direct Tooling
- Jewelry Design
- Patterns for Casting
- Molds for Casting
- Patterns for Casting
- Validation of Invention
- Wind Tunnel Testing

3.10 Photopolymerization (Stereolithography (SL))

When a light of appropriate wave length falls on liquid photopolymer, the energy absorbed causes polymerization. The polymerized photopolymer will be in solid state. Laser light is used. When it is scanned on the selected region over a layer of liquid polymer, that region become solid. The remaining liquid can be drained.

Laser beam is positioned using a small mirror capable of deflecting in two directions. Therefore, this has very low inertia and hence high speed and accuracy. The power of the laser decides the layer thickness. Explicit support structures are required. This is achieved by modifying the geometry of the prototype. Typically bristles and thin structures are added.



1. At the start of the process, in which the initial layer is added to the platform
2. After several layers have been added so that the part geometry gradually takes form.

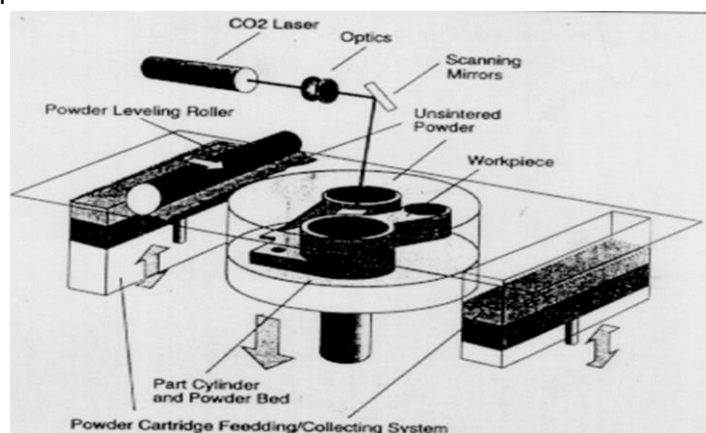
Steps

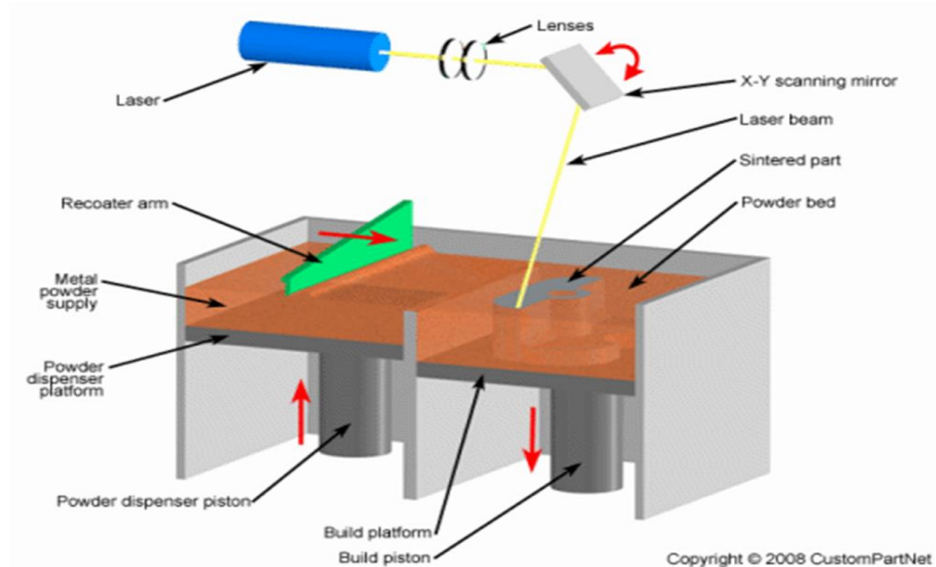
- Support structures are automatically added to the model wherever required.
- Slicing is done.
- Each slice or layer is realized using the following steps:
- The table (called vat) dips and comes up to the required Z level.
- A blade wipes off the excess liquid.
- The beam scans the liquid layer. For each loop, the border is made and then area filling is done. Area filling is not in zig-zag pattern but in grids .
- After all layers are made, the table rises completely revealing the part.
- After the liquid has drained, it is removed from the table and the support structure is carefully cut off.
- The part is kept in a post-cure apparatus where it is kept under UV radiation for an hour or so. This completes polymerization.
- The part is finished and painted as required

3.11 Powder Bed Fusion

I. Selective laser Sintering (SLS)

- It is developed by University of Texas, Austin.
- It is marketed by DTM, USA and EOS, Germany. Raw material is powder. Principle is similar to Powder Metallurgy but for the absence of compaction. Green part is prepared on the RP machine after partial sintering and sintering is completed inside another furnace.
- Just as SLA, here also laser light is used. When it is scanned on the selected region over a layer of powder, the particles in that region fuse together. The remaining powder acts as support as in the case of LOM.
- Laser beam is positioned using a small mirror capable of deflecting in two directions. Therefore, this has very low inertia and hence high speed and accuracy.
- The power of the laser decides the layer thickness.
- Explicit support structures are not required.
- A wide variety of powders can be used.





Steps

- When the slicing is done, The working volume is maintained with appropriate temperature so that laser supplies the energy required to cross the threshold sintering temperature. An inert environment is created using continuous supply of gas such as Nitrogen. This is to minimize fire hazards as the fine particles have high activation.
- Each slice or layer is realized using the following steps:
- The table dips by a layer thickness.
- A layer of powder is spread and leveled using a contra-rotating roller.
- The beam scans the layer of powder. Thus, the required region is “selectively sintered”.
- After all layers are made, the table rises completely revealing a block of cake with the part inside.
- The surrounding powder is soft and it is removed using suitable brushes. This powder is reusable.
- The part is kept in a suitable hot chamber to complete the sintering.
- The metallic prototypes require copper impregnation in another furnace to improve their polishability.
- The part is finished and painted as required.

Advantages

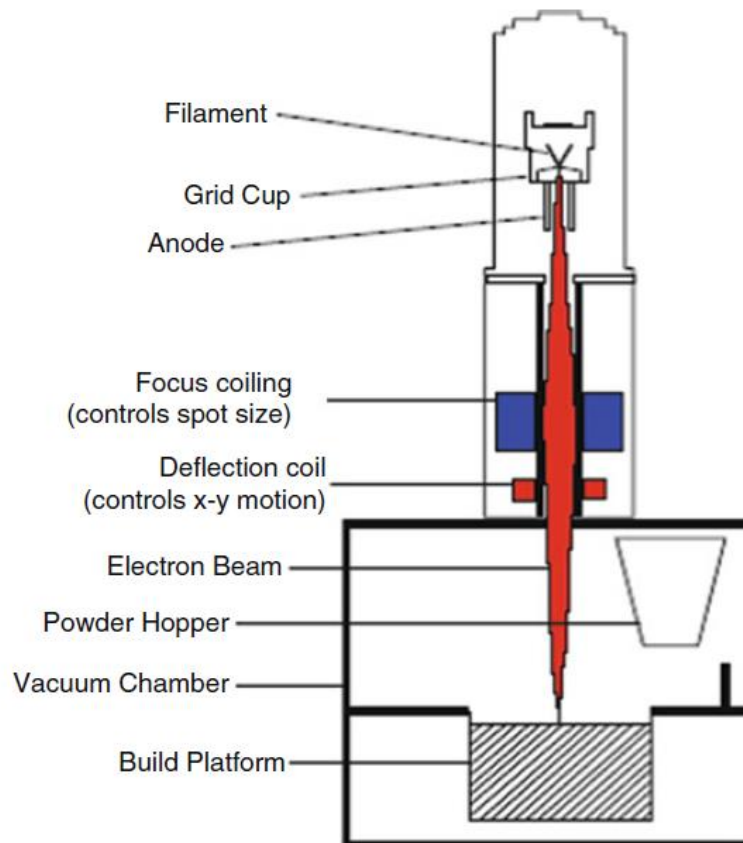
- A wide variety of powders can be used.
- Fast due to tiny moving mirror parts as in SLA.
- Metallic parts can be made.
- Suitable for making injection molding tools.

Limitations

- Surface finish is less and dictated by the particle size.
- Z accuracy is poor due to the absence of milling.

II. Electron Beam melting (EBM)

Electron beam melting (EBM) has become a successful approach to PBF (Powder Bed Fusion). In contrast to laser-based systems, EBM uses a high-energy electron beam to induce fusion between metal powder particles. This process was developed at Chalmers University of Technology, Sweden, and was commercialized by Arcam AB, Sweden, in 2001.



Laser beams heat the powder when photons are absorbed by powder particles. Electron beams, however, heat powder by transfer of kinetic energy from incoming electrons into powder particles. As powder particles absorb electrons they gain an increasingly negative charge. This has two potentially detrimental effects: (1) if the repulsive force of neighboring negatively charged particles overcomes the gravitational and frictional forces holding them in place, there will be a rapid expulsion of powder particles from the powder bed, creating a powder cloud (which is worse for fine powders than coarser powders) and (2) increasing negative charges in the powder particles will tend to repel the incoming negatively charged electrons, thus creating a more diffuse beam. There are no such complimentary phenomena with photons. As a result, the conductivity of the powder bed in EBM must be high enough that powder particles do not become highly negatively charged, and scan strategies must be used to avoid build-up of regions of negatively charged particles. In practice, electron beam energy is more diffuse, in part, so as not to build up too great a negative charge in any one location. As a result, the effective melt pool size increases, creating a larger heat-affected zone. Consequently,

the minimum feature size, median powder particle size, layer thickness, resolution, and surface finish of an EBM process are typically larger than for an mLS process.

As mentioned above, in EBM the powder bed must be conductive. Thus, EBM can only be used to process conductive materials (e.g., metals) whereas, lasers can be used with any material that absorbs energy at the laser wavelength (e.g., metals, polymers, and ceramics).

Electron beam generation is typically a much more efficient process than laser beam generation.

3.12 Extrusion-Based RP Systems

I. Fused Deposition Modelling (FDM)

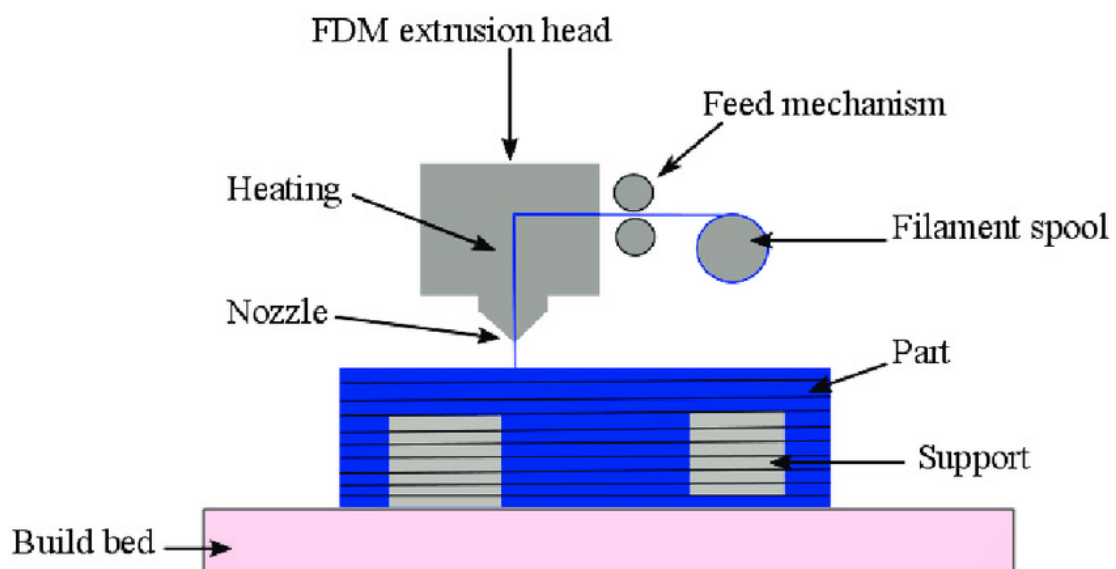
This is a very sophisticated version of ,Jilebi (in Hindi)' ,chakli (in Hindi)' or ,Murukku (in Tamil)' or ,vermicelli (in English?)' making process.

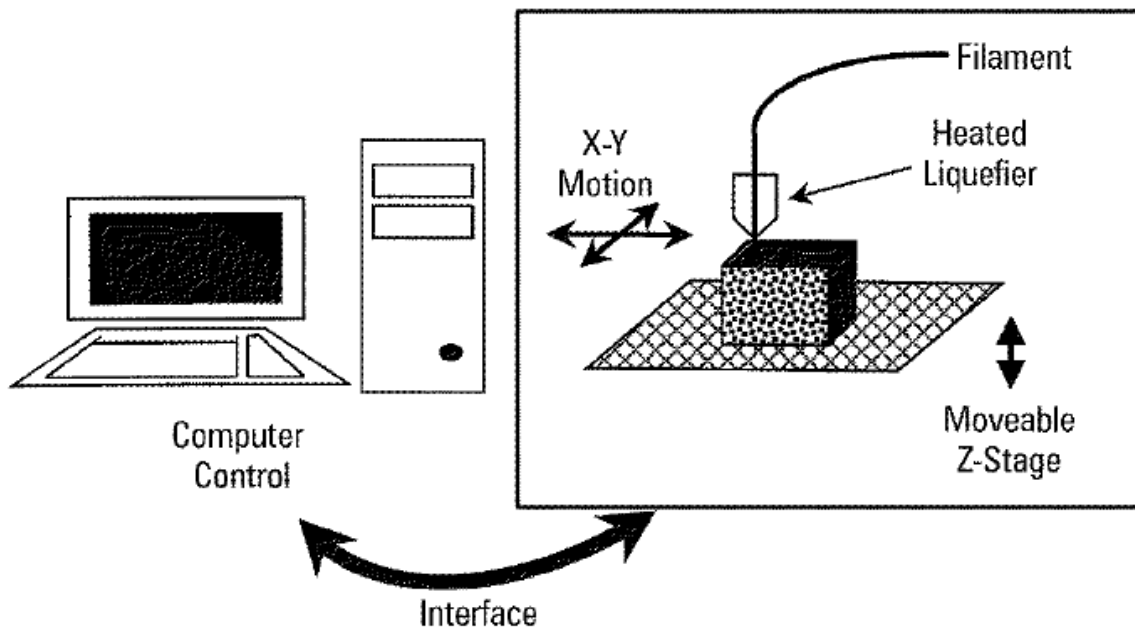
Molten material inside a hot chamber is extruded through a nozzle. Use of the raw material in wire form as a consumable piston is a great idea. The nozzle size alone does not decide the layer thickness and roadwidth. They together depend on speed of head and wire feed speed. Their relation can be obtained from the principle of conservation of mass. (Analogy: applying tooth paste on the brush.)

Explicit support structures are required. Therefore, twin heads are used, one for model and the other for support.

Steps

- Starting material is melted and small droplets are shot by a nozzle onto previously formed layer
- Droplets cold weld to surface to form a new layer
- Deposition for each layer controlled by a moving x-y nozzle whose path is based on a cross section of a CAD geometric model that is sliced into layers
- Work materials include wax and thermoplastics





Advantages

- Any thermoplastic material can be used as long as the appropriate head is available.
- It does not employ lasers and hence no safety related issues. It does not use liquid/powder raw materials and hence clean. It can be kept in an office environment as a 3D printer.
- Very easy to remove the support. This is probably the easiest of all RP processes.
- This is the cheapest machine. However, this is also due to their business policy since the costs of all RP machines are comparable.

Limitations

- As every point of the volume is addressed by a „mechanical device“, it is very slow.
- Not very accurate compared SLA, SGC etc.
- Not isotropic.

II. 3D Printing

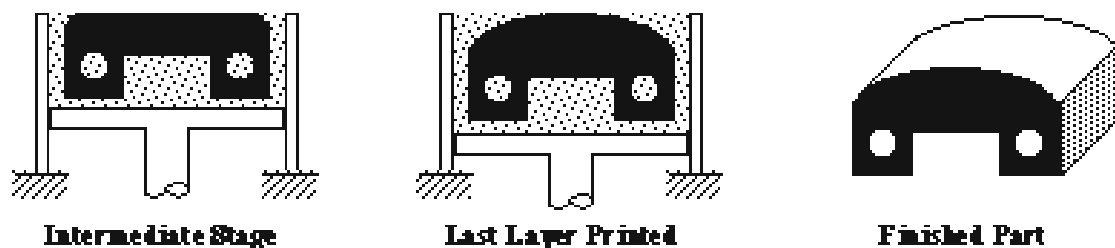
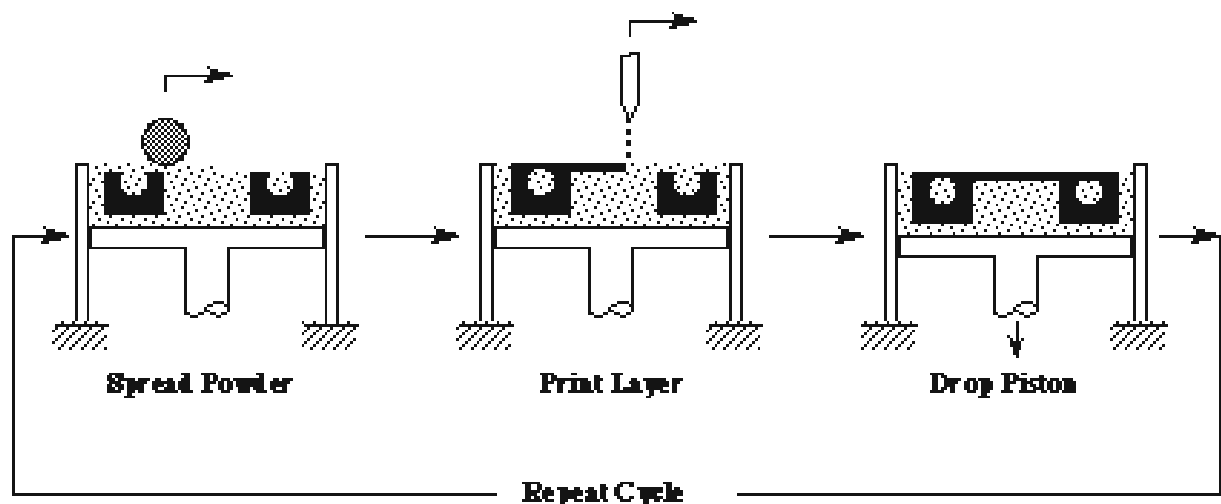
Very similar to SLS except that a binder liquid is sprayed in selected regions instead of laser. Raw material is powder. Concept models can be prepared rapidly using a multi-jet multi-color spray over starch (ZCorp). Green parts will require sintering inside another furnace.

When a binder is sprayed through thin nozzles on the selected region over a layer of powder, the particles in that region stick together. The remaining powder acts as support as in the case of LOM.

Binder spray makes use of mechanical movement. However, use of multiple jets make it faster. Explicit support structures are not required. A wide variety of powders can be used.

Steps

- Raw material is powder.
- The binder liquid is selectively deposited on the layer of powder.
- This is followed by a curing after which unbound powder is separated.



III. Sheet Lamination (Laminated Object Manufacturing (LOM))

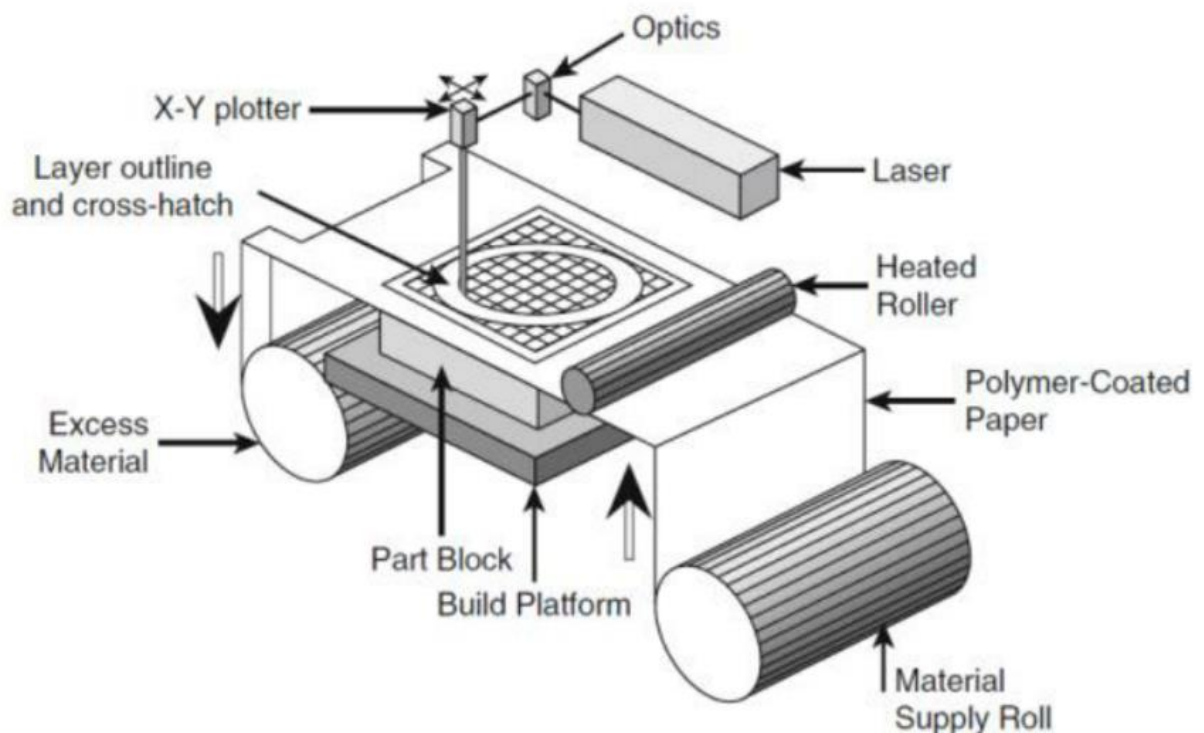
There are two approaches of LOM process.

I. Cut and then paste

- Handling the cut pieces is difficult if not impossible since
 - More than one piece may have to be handled for every layer
 - Such pieces may be odd-shaped
 - Paper being flexible further complicates handling
- A support mechanism will be required.
- Suitable for laminated tooling.

II. Paste and then cut

- Handling is easy – indexing of the reel is all that is required.
- The remaining stock acts as the support material.
- The only drawback is the time-consuming decubing operation.
- Suitable for paper-like flexible materials.



Steps

- If multiple parts are to be made, one has to arrive at a cluster of optimal packing (an automatic program for this is still not available!). It is preferable to pack as many pieces as possible in processes such as LOM, SLS, SGC and 3DPrinting.
- The object/ cluster is positioned and oriented in the desired place. Some users tilt it by 10 to 15 deg. to avoid any surface becoming horizontal (why?).
- Set the machine with the desired process parameters such as beam diameter, beam offset flag, grid sizes, number of dummy layers, bridging gap between two cuts etc.
- Load the paper roll of appropriate width.
- Identify the location for the build on the table and feed it to the machine. Paste a double-sided adhesive in that zone.
- Each slice or layer is realized using the following steps:
 - The paper reel indexes by a fixed distance. It has adhesive at the bottom surface.
 - The table rises to the required height.
 - A hot roller (laminating tool) rolls over it causing it to stick to the previous layer.
 - The height is measured and it is passed on to the slicing software.
 - The loops of the slice are cut by the laser. It is possible to offset the laser beam by beam radius in such a direction as to compensate for it.
 - This is followed by grid cutting around the bounding box of the stock. Note that the grids of all layers coincide.
 - Finally, a parting off cut is made.
 - The table lowers by a considerable distance so that the cut portion is stripped off from the reel.
- After all layers are made, the built volume is a rectangular block. This is parted off from the table using a thin wire rope.
- The unwanted material inside and surrounding are removed using hand tools. This is called 'decubing'. This operation takes several hours.
- The part is finished and painted as required. It can be given a lacquer coat to prevent it from absorbing moisture.

Advantages

- Only boundaries are to be addressed and not their interiors.
- It employs CO2 laser which is cheaper. No protective environment is required.
- Paper is very cheap.
- It gives strong wood-like parts. Ideal as patterns for casting

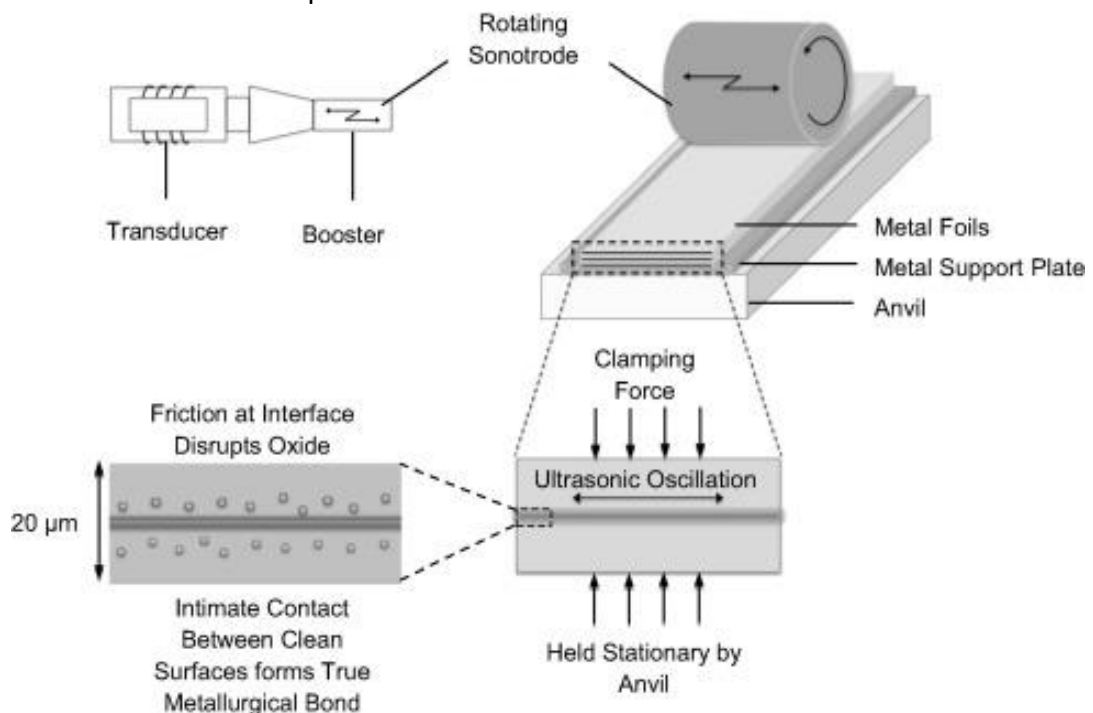
Limitations

- Grid cutting takes much more time than object cutting.
- Decubing also is time-consuming.
- Horizontal surfaces pose problems. Although it is solvable, it has not been done till date.

IV. Ultrasonic Consolidation (UC)

Ultrasonic Additive Manufacturing (UAM), also known as Ultrasonic Consolidation (UC), is a hybrid sheet lamination process combining ultrasonic metal seam welding and CNC milling, and commercialized by Solidica Inc., USA in 2000, and subsequently licensed to Fabrisonics (USA). In UAM, the object is built up on a rigidly held base plate bolted onto a heated platen, with temperatures ranging from room temperature to approximately 200 °C. Parts are built from bottom to top, and each layer is composed of several metal foils laid side by side and then trimmed using CNC milling.

During UAM, a rotating sonotrode travels along the length of a thin metal foil (typically 100–150 µm thick). The foil is held closely in contact with the base plate or previous layer by applying a normal force via the rotating sonotrode, as shown schematically in. The sonotrode oscillates transversely to the direction of motion, at a constant 20 kHz frequency and user-set oscillation amplitude. After depositing a foil, another foil is deposited adjacent to it. This procedure is repeated until a complete layer is placed. The next layer is bonded to the previously deposited layer using the same procedure. Typically, four layers of deposited metal foils are termed one level in UAM. After deposition of one level, the CNC milling head shapes the deposited foils/layers to their slice contour (the contour does not need to be vertical, but can be a curved or angled surface, based on the local part geometry). This additive-subtractive process continues until the final geometry of the part is achieved. Thus, UAM is a bond-then-form process, where the forming can occur after each layer or after a number of layers, depending on the settings chosen by the user. Additionally, each layer is typically deposited as a combination of foils laid side by side rather than a single large sheet, as is typically practiced in sheet lamination processes.

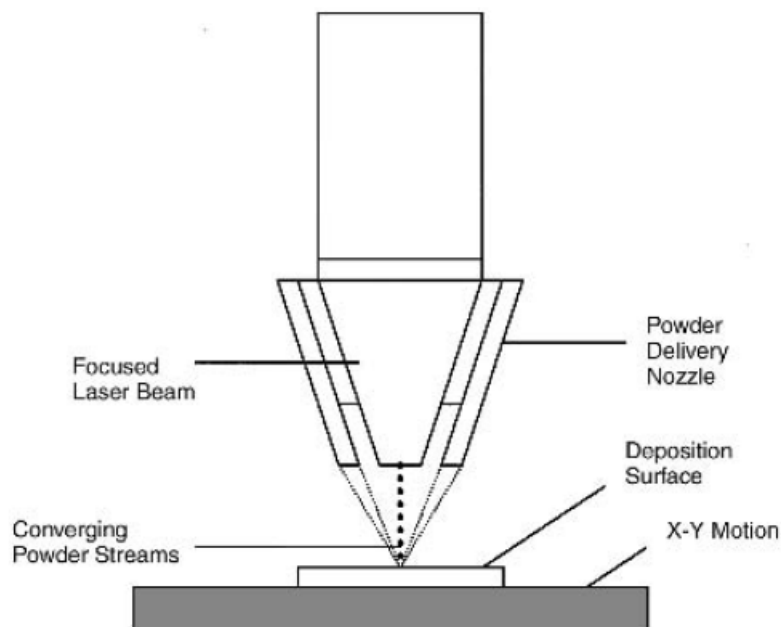


By the introduction of CNC machining, the dimensional accuracy and surface finish of UAM end products is not dependent on the foil thickness, but on the CNC milling approach that is used. This eliminates the stair-stepping effects and layerthickness- dependent accuracy aspects of other AM processes. Due to the combination of low-temperature ultrasonic bonding, and additive-plus-subtractive processing, the UAM process is capable of creating complex, multifunctional 3D parts, including objects with complex internal features, objects made up of multiple materials, and objects integrated with wiring, fiber optics, sensors, and instruments. The lack of an automated support material in commercial systems, however, means that many types of complex overhanging geometries cannot be built using UAM. However, on-going support material research for UAM will hopefully result in an automated support material approach in the future.

3.13 Beam Deposition

I. Laser Engineered Net Shaping (LENS)

The LENSTM process builds components in an additive manner from powdered metals using a Nd:YAG laser to fuse powder to a solid as shown in Figure 5.15. It is a freeform metal fabrication process in which a fully dense metal component is formed. The LENSTM process comprises of the following steps.



Steps

- A deposition head supplies metal powder to the focus of a high powered Nd:YAG laser beam to be melted. This laser is typically directed by fiber optics or precision angled mirrors.
- The laser is focused on a particular spot by a series of lenses, and a motion system underneath the platform moves horizontally and laterally as the laser beam traces the cross-section of the part being produced. The fabrication process takes place in a low-pressure argon chamber for oxygen-free operation in the melting zone, ensuring that good adhesion is accomplished.
- When a layer is completed, the deposition head moves up and continues with the next layer. The process is repeated layer by layer until the part is completed. The entire process is usually enclosed to isolate the process from the atmosphere. Generally, the prototypes need additional finishing, but are fully dense products with good grain formation.

Principle

The LENS process is based on the following two principles:

- A high powered Nd: YAG laser focused onto a metal substrate creates a molten puddle on the substrate surface. Powder is then injected into the molten puddle to increase material volume.
- A “printing” motion system moves a platform horizontally and laterally as the laser beam traces the cross-section of the part being produced. After formation of a layer of the part, the machine’s powder delivery nozzle moves upwards prior to building next layer.

Advantages

- Superior material properties. The LENS process is capable of producing fully dense metal parts. Metal parts produced can also include embedded structures and superior material properties. The microstructure produced is also relatively good.
- Complex parts. Functional metal parts with complex features are the forte of the LENS system.
- Reduced post-processing requirements. Post-processing is minimized, thus reducing cycle time.

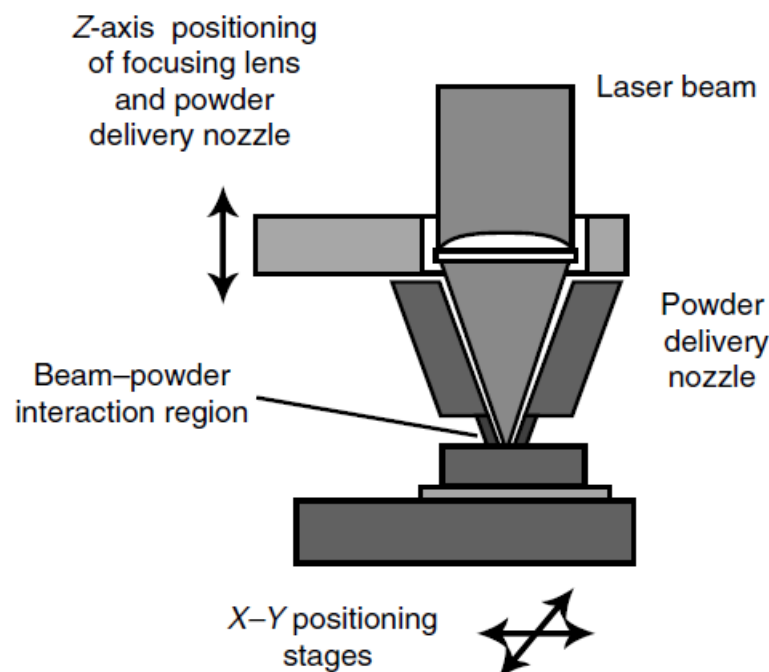
Disadvantages

- Limited materials. The process is currently narrowly focused to produce only metal parts.
- Large physical unit size. The unit requires a relatively large area to house.
- High power consumption. The laser system requires very high wattage.

3.14 Direct Metal Deposition (DMD)

A direct laser deposition (DLD) or direct metal deposition (DMD) process is a laser-assisted direct metal manufacturing process that uses computer controlled lasers that, in hours, weld air blown streams of metallic powders into custom parts and manufacturing molds. Some processes use wire instead of powder, but the concept is similar. A representative process is called the Laser Engineered Net Shaping (LENS) process. It uses CAD file cross-sections to control the forming process developed by Optomec Inc. The DLD process can be used throughout the entire product life-cycle for applications ranging from materials research to functional prototyping to volume manufacturing. An additional benefit is its unique ability to add material to existing components for service and repair applications. Powder-metal particles are delivered in a gas stream into the focus of a laser to form a molten pool of metal. It is a layer-by-layer additive rapid prototyping process. The DLD process allows the production of parts, molds, and dies that are made out of the actual end-material, such as aluminum or tool steel. In other words, this produces the high-temperature materials that are difficult to make using the traditional RP processes.

The laser beam is moved back and forth across the part and creates a molten pool of metal where a precise stream of metal powder is injected into the pool to increase its size. This process is the hybrid of several technologies: lasers, CAD, CAM, sensors, and powder metallurgy. This process also improves on other methods of metalworking in that there is no waste material or subtractive processes necessary. It can also mix metals to specific standards and specifications in a manner that has never been possible before.



Advantages

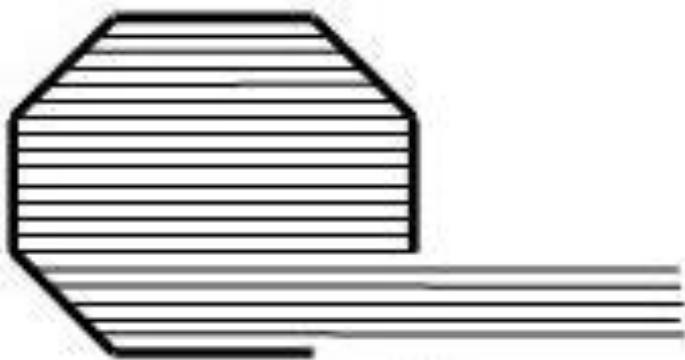
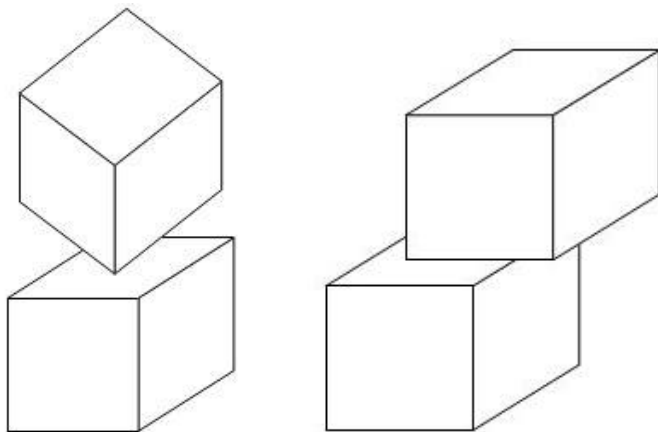
- The strength of DLD lies in the process' ability to fabricate fully dense metal parts with good metallurgical properties at reasonable speeds.
- DLD is an efficient approach that reduces production costs and speeds time to market for high-value components.
- The DLD systems enable the fabrication of novel shapes, hollow structures, and material gradients that are not otherwise feasible.

Disadvantages

- Since DLD is a freeform process, there is a limit to the overhang angle that can be built.
- The traditional DLD or RP processes are using three-axis tables, and thus support structures are very often needed in building overhang parts. These structures are not desirable in laser-based processes involving metals. One could use a high melting-point material to build the support structures and use other processes, such as chemical etching, to remove the support material afterward.

4

Errors in RP Processes



Course Contents

- 4.1** Problems with STL Files
- 4.2** Accuracy Problems in SLA Processes
- 4.3** STL File Repair
- 4.4** Solving the “Missing Facets” Problem
- 4.5** Solving the “Wrong Orientation of Facets” Problem

4.1 Problems with STL Files

- Although the STL format is quite simple, there can still be errors in files resulting from CAD conversion. The following are typical problems that can occur in bad STL files:

Unit changing:

- This is not strictly a result of a bad STL file.
- Since US machines still commonly use imperial measurements and most of the rest of the world uses metric, some files can appear scaled because there is no explicit mention of the units used in the STL format.
- If the person building the model is unaware of the purpose of the part then he may build it approximately 25 times too large or too small in one direction.
- Furthermore, units must correspond to the location of the origin within the machine to be used.
- This normally means that the physical origin of the machine lies in the bottom left-hand corner and so all triangle coordinates within an STL file must be positive.
- However, this may not be the case for a particular part made in the CAD system and so some adjustment offset of the STL file may be required.

Vertex to vertex rule:

- Each triangle must share two of its vertices with each of the triangles adjacent to it.
- This means that a vertex cannot intersect the side of another, like that shown in the below figure.

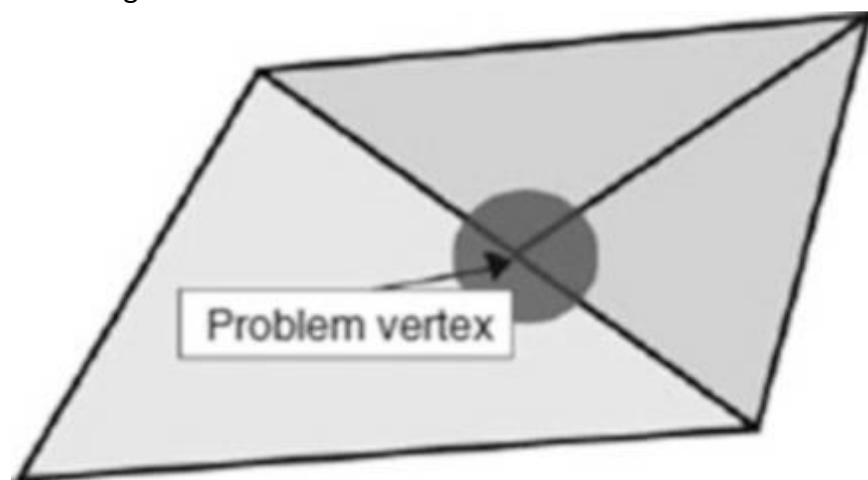


Fig 4.1 A case that violates the vertex to vertex rule

- This is not something that is explicitly stated in the STL file description and therefore STL file generation may not adhere to this rule.
- However, a number of checks can be made on the file to determine whether this rule has been violated.

- For example, the number of faces of a proper solid defined using STL must be an even number.
- Furthermore, the number of edges must be divisible by three and follow the equation:

$$\frac{\text{No. of faces}}{\text{No. of edges}} = \frac{3}{2}$$

Leaking STL files:

- STL files should describe fully enclosed surfaces that represent the solids generated within the originating CAD system. In other words, STL data files should construct one or more manifold entities according to Euler's Rule for solids:

$$\text{No. of faces} - \text{No. of edges} + \text{No. of vertices} = 2 \times \text{No. of bodies}$$

- If this rule does not hold then the STL file is said to be leaking and the file slices will not represent the actual model.
- There may be too few or too many vectors for a particular slice.
- Slicing software may add in extra vectors to close the outline or it may just ignore the extra vectors.
- Small defects can possibly be ignored in this way. Large leaks may result in unacceptable final models.
- Leaks can be generated by facets crossing each other in 3D space as shown in the below figure.

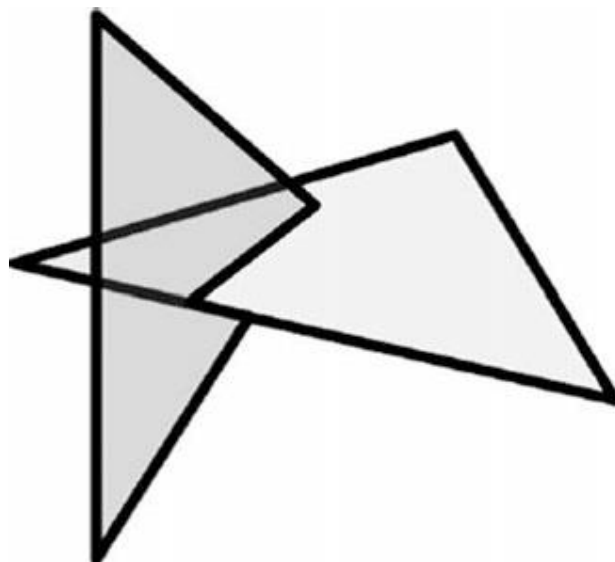


Fig 4.2 Two triangles intersecting each other in 3D space

- This can result from poorly generated CAD models, particularly those that do not use Boolean operations when generating solids.
- A CAD model may also be generated using a method which stitches together surface patches.
- If the triangulated edges of two surface patches do not match up with each other, then holes, like in the below figure, may occur.

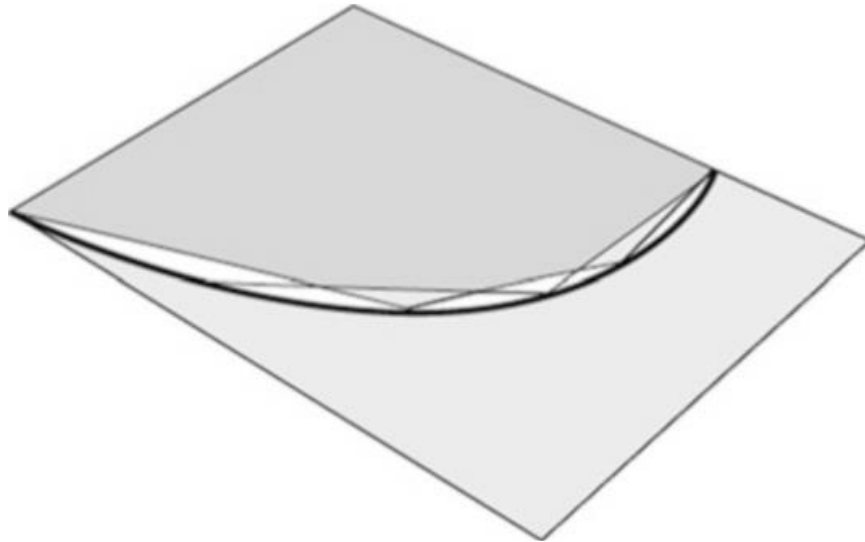


Fig 4.3 Two surface patches that do not match up with each other, resulting in holes

Degenerated facets:

- These facets normally result from numerical truncation. A triangle may be so small that all three points virtually coincide with each other.
 - After truncation, these points lay on top of each other causing a triangle with no area. This can also occur when a truncated triangle returns no height and all three vertices of the triangle lie on a single straight line.
 - While the resulting slicing algorithm will not cause incorrect slices, there may be some difficulties with any checking algorithms and so such triangles should really be removed from the STL file.
- It is worth mentioning that, while a few errors may creep into some STL files, most professional 3D CAD systems today produce high-quality and error-free results.
 - In the past, problems more commonly occurred from surface modeling systems, which are now becoming scarcer, even in fields outside of engineering CAD-like computer graphics and 3D gaming software.
 - Also, in earlier systems, STL generation was not properly checked and faults were not detected within the CAD system.
 - Nowadays, potential problems are better understood and there are well-known algorithms for detecting and correcting such problems.

4.2 Accuracy Problems in SLA Processes

- RP processes are integrated manufacturing processes that include CAD/CAM, control of laser devices, materials, manufacturing parameter setup, and post-processing.
 - Individual processes can introduce some errors one way or another, as explained below.
 - These errors severely reduce RP product accuracy and obstruct its further applications in rapid tooling and functional part fabrication.
- (i) **CAD/CAM induced error:** Most rapid prototyping systems use the de facto standard STL CAD file format of solid representation to define parts to be built. However, STL files pose the problems of dimension, form and surface errors resulting from

approximation of three-dimensional surfaces by triangular facets. Although a large number of facets can be used to reduce these errors, doing so will result in a giant data file and longer part build time.

- (ii) **Laser beam width induced error:** The laser beam used to create parts is of a finite width, though the file used to drive the machine represents the edges as zero-width lines. The width of this beam can be compensated for in the laser beam scan control software, but the beam width is not constant from machine to machine and not even the same on a single machine over time. This induces part errors.
- (iii) **Material shrinkage error:** SLA part accuracy is a direct result of the resin properties. Many researchers are striving to develop new resins that offer low shrinkage and high dimensional stability. The earlier resins available from 3D Systems Inc. are primarily limited to the acrylate base resins with relatively large shrinkage (5–7% in volume), causing severe distortions of the finished parts.
- (iv) **RP machine parameter setup:** Errors that occur during the building time are mainly in the manufacturing control factor setups, which are RP machine vendor defaulted and user selected parameters. Different parameter setups will generate different machining accuracy and build time.
- (v) **Post-processing error:** SL parts are designed to be post-cured as soon as they are built, otherwise green creep distortion, which results from the residual internal stress generated during the SLA building cycle, will occur.
- An accumulation of the above five errors usually causes 250–500 mm dimensional error and very unpleasant surface roughness, which make RP products unacceptable in many applications for a long time.

4.3 STL File Repair

- The STL file repair can be implemented using a generic solution and dedicated solutions for special cases.
- 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.
- The main problem of repairing the invalid tessellated model would be that of matching the solution to the designer's intent when it may have been lost in the overall process.

- Without the knowledge of the designer's intent, it would indeed be difficult to determine what the "right" solution should be. Hence, an "educated" guess is usually made when faced with ambiguities of the invalid model.
- The algorithm in this report aims to match, if not exceed, the quality of repair done manually by a skilled technician when information of the designer's intent is not available.
- The basic approach of the algorithm to solve the "missing facets" problem would be to detect and identify the boundaries of all the gaps in the model.
- Once the boundaries of the gap are identified, suitable facets would then be generated to repair and "patch up" these gaps.
- The size of the generated facets would be restricted by the gap's boundaries while the orientation of its normal would be controlled by comparing it with the rest of the shell.
- This is to ensure that the generated facets' orientation are correct and consistent throughout the gap closure process.
- The orientation of the shell's facets can be obtained from the STL file which lists its vertices in an ordered manner following Mobius' rule.
- The algorithm exploits this feature so that the repair carried out on the invalid model, using suitably created facets, would have the correct orientation.
- Thus, this generic algorithm can be said to have the ability to make an inference from the information contained in the STL file so that the following two conditions can be ensured:
 - (1) The orientation of the generated facet is correct and compatible with the rest of the model.
 - (2) Any contoured surface of the model would be followed closely by the generated facets due to the smaller facet generated. This is in contrast to manual repair whereby, in order to save time, fewer facets generated to close the gaps are desired, resulting in large generated facets that do not follow closely to the contoured surfaces.
- Finally, the basis for the working of the algorithm is due to the fact that in a valid tessellated model, there must only be two facets sharing every edge.
- If this condition is not fulfilled, then this indicates that there are some missing facets.
- With the detection and subsequent repair of these missing facets, the problems associated with the invalid model can then be eliminated.

4.4 Solving the "Missing Facets" Problem

- The following procedure illustrates the detection of gaps in the tessellated model and its subsequent repair. It is carried out in four steps.

Step 1: Checking for Approved Edges with Adjacent Facets

- The checking routine executes as follows for Facet A as seen in following figure:
 - (a) (i) Read in first edge {vertex 1-2} from the STL file.
 - (ii) Search file for a similar edge in the opposite direction {vertex 2-1}.

- (iii) If edge exists, store this under a temporary file (e.g., file B) for approved edges.
- (iv) Do the same for 2 and 3 below.

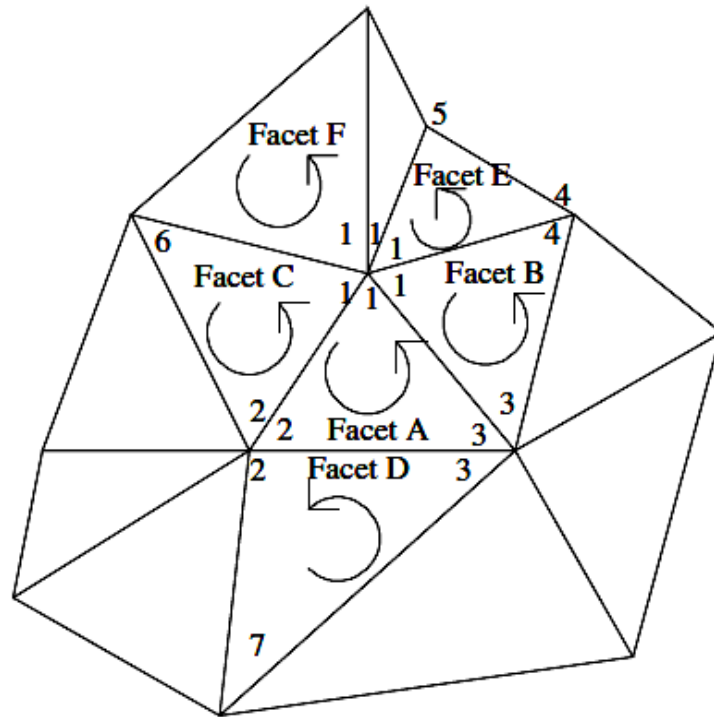


Fig 4.4 A representation of a portion of a tessellated surface without any gaps

- (b)
 - (i) Read in second edge {vertex 2-3} from the STL file.
 - (ii) Search file for a similar edge in the opposite direction {vertex 3-2}.
 - (iii) Perform as in (a) (iii) above.
- (c)
 - (i) Read in third {vertex 3-1} from the STL file.
 - (ii) Search file for a similar edge in the opposite direction {vertex 1-3}.
 - (iii) Perform as in (a) (iii) above.
- This process is repeated for the next facet until all the facets have been searched.

Step 2: Detection of Gaps in the Tessellated Model

- The detection routine executes as follows:
For Facet A (please refer to following figure):
 - (a)
 - (i) Read in edge {vertex 2-3} from the STL file.
 - (ii) Search file for a similar edge in the opposite direction {vertex 3-2}.
 - (iii) If edge does not exist, store edge {vertex 3-2} in another temporary file (e.g., file C) for suspected gap's bounding edges and store vertex 2-3 in file B1 for existing edges without adjacent facets (this would be used later for checking the generated facet orientation).
- For Facet B,
 - (b)
 - (i) Read in edge {vertex 5-2} from the STL file.
 - (ii) Search file for a similar edge in the opposite direction {vertex 2-5}.
 - (iii) If it does not exist, perform as in (a) (iii) above.

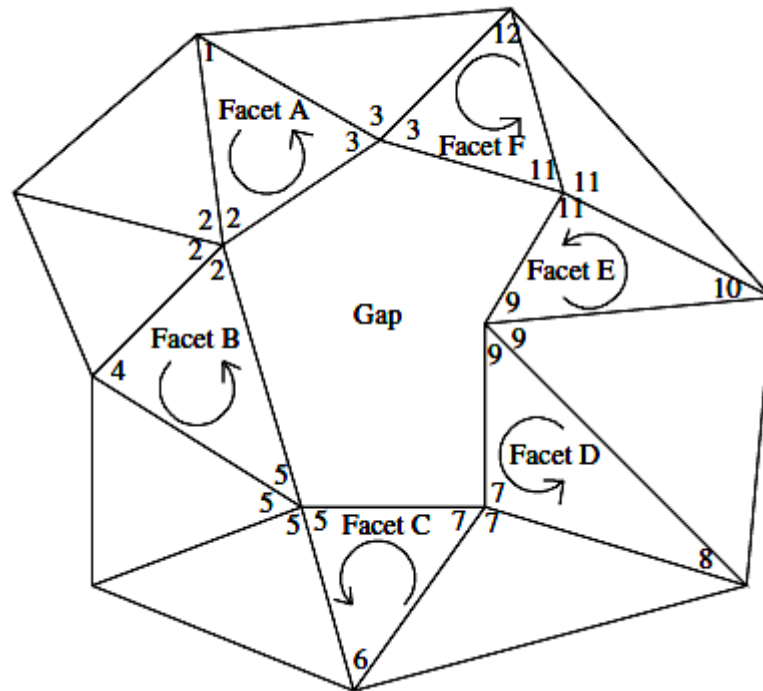


Fig 4.5 A representation of a portion of a tessellated surface with a gap present

- (c)
- (i) Repeat for edges: 5-2; 7-5; 9-7; 11-9; 3-11.
 - (ii) Search for edges: 2-5; 5-7; 7-9; 9-11; 11-3.
 - (iii) Store all the edges in that temporary file B1 for edges without any adjacent facet and store all the suspected bounding edges of the gap in temporary file C. File B1 can appear as in following table.

Table 4.1 File B1 contains existing edges without adjacent facets

Vertex	Edge					
	First	Second	Third	Fourth	Fifth	Sixth
First	2	7	3	5	9	11
Second	3	5	11	2	7	9

Step 3: Sorting of Erroneous Edges into a Closed Loop

- When the checking and storing of edges (both with and without adjacent facets) are completed, a sort would be carried out to group all the edges without adjacent facets to form a closed loop.
- This closed loop would represent the gap detected and be stored in another temporary file (e.g., file D) for further processing.
- The following is a simple illustration of what could be stored in file C for edges that do not have an adjacent edge.

- Assuming all the “erroneous” edges are stored according to the detection routine (see above figure for all the erroneous edges), then file C can appear as in the following table.

Table 4.2 File C containing all the “Erroneous” edges that would form the boundary of each gaps

Vertex	Edge								
	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Eighth	Ninth
First	3	5	*	11	2	7	*	9	*
Second	2	7	*	3	5	9	*	11	*

*Represent all the other edges that would form the boundaries of other gaps

- As can be seen in the above table, all the edges are unordered. Hence, a sort would have to be carried out to group all the edges into a closed loop.
- When the edges have been sorted, it would then be stored in a temporary file, say file D.
- Following table is an illustration of what could be stored in file D.

Table 4.3 File D containing sorted edges

	First edge	Second edge	Third edge	Fourth edge	Fifth edge	Sixth edge
First vertex	3	2	5	7	9	11
Second vertex	2	5	7	9	11	3

- Following figure is a representation of the gap, with all the edges forming a sorted closed loop.

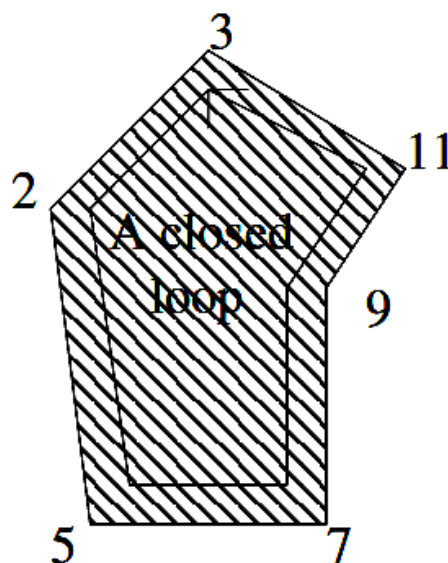


Fig 4.6 A representation of a gap bounded by all the sorted edges

Step 4: Generation of Facets for the Repair of the Gaps

- When the closed loop of the gap is established with its vertices known, facets are generated one at a time to fill up the gap. This process is summarized in following table and illustrated in following figure.

Table 4.4 Process of facet generation

		V3	V2	V5	V7	V9	V11
Generation of facets	F1	1	2	—	—	—	3
	F2	E	1	—	—	2	3
	F3	E	1	2	—	3	E
	F4	E	E	1	2	3	E

V = vertex, F = facet, E = eliminated from the process of facet generation

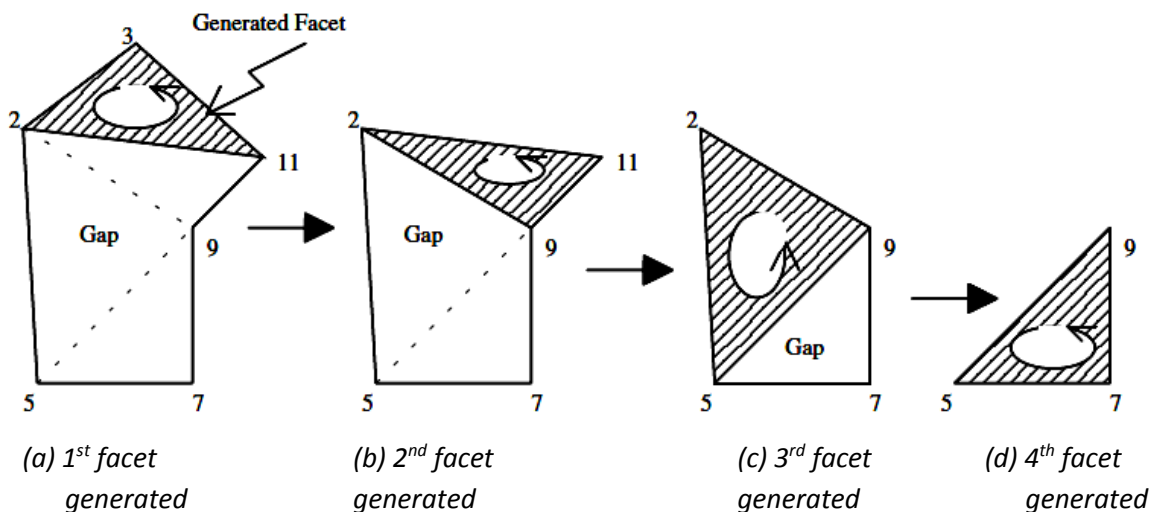


Fig 4.7 Generation of Facets

With reference to File D,

(a) Generating the first facet: First two vertices (V3 and V2) in the first two edges of file D will be connected to the first vertex in the last edge (V11) in file D and the facet is stored in a temporary file E (see the following table on how the first generated facet would be stored in file E).

- The facet is then checked for its orientation using the information stored in file B1. Once its orientation is determined to be correct, the first vertex (V3) from file D will be temporarily removed.

(b) Generating the second facet: Of the remaining vertices in file D, the previous second vertex (V2) will become the first edge of file D.

- The second facet is formed by connecting the first vertex (V2) of the first edge with that of the last two vertices in file D (V9, V11), and the facet is stored in temporary file E.
- It is then checked to confirm if its orientation is correct.
- Once it is determined to be correct, the vertex (V11) of the last edge in file D is then removed temporarily.

(c) Generating the third facet: The whole process is repeated as it was done in the generation of facets 1 and 2.

- The first vertex of the first two edges (V2, V5) is connected to the first vertex of the last edge (V9) and the facet is stored in temporary file E.
- Once its orientation is confirmed, the first vertex of the first edge (V2) will be removed from file D temporarily.

(d) Generating the fourth facet: The first vertex in the first edge will then be connected to the first vertices of the last two edges to form the fourth facet and it will again be stored in the temporary file E.

- Once the number of edges in file D is less than three, the process of facet generation will be terminated.
- After the last facet is generated, the data in file E will be written to file A and its content (file E's) will be subsequently deleted.
- Following table shows how file E may appear.

Table 4.5 Illustration of how data could be stored in File E

Generated facet	First edge		Second edge		Third edge	
	First vertex	Second vertex	First vertex	Second vertex	First vertex	Second vertex
First	V3	V2	V2	V5	V5	V3
Second	V2	V9	V9	V11	V11	V2
Third	V2	V5	V5	V9	V9	V2
Fourth	V5	V7	V7	V9	V9	V5

- The above procedures work for both types of gaps whose boundaries consist either of odd or even number of edges.
- Following figure and Table illustrate how the algorithm works for an even number of edges or vertices in file D.

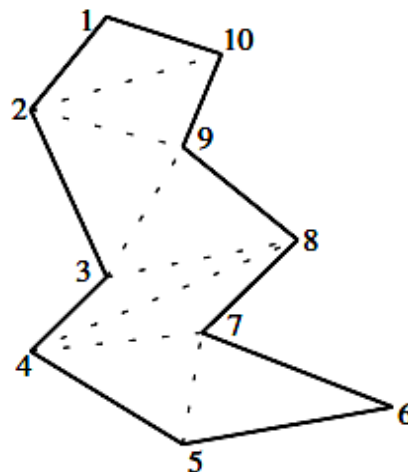


Fig 4.8 Gaps with even number of edges

Table 4.6 Process of facet generation for gaps with even number of edges

Facets	Vertices									
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
F1	1	2								3
F2	E	1							2	3
F3	E	1	2						3	E
F4	E	E	1					2	3	E
F5	E	E	1	2				3	E	E
F6	E	E	E	1			2	3	E	E
F7	E	E	E	1	2		3	E	E	E
F8	E	E	E	E	1	2	3	E	E	E

- With reference to above table,
First facet generated:
 Edge 1 → V1, V2
 Edge 2 → V2, V10
 Edge 3 → V10, V1
 and so on until the whole gap is covered.
- Similarly, following figure and Table illustrate how the algorithm works for an odd number of edges or vertices in file D.

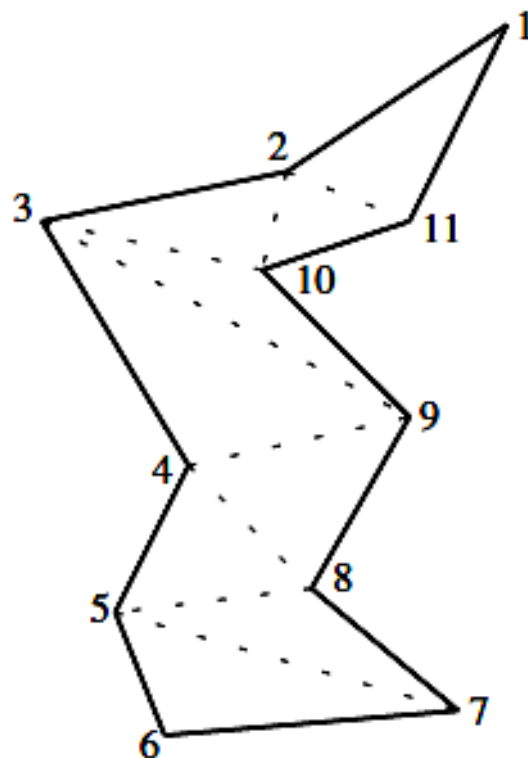


Fig 4.9 Gaps with odd number of edges

Table 4.7 Process of facet generation for gaps with odd number of edges

Facets	Vertices										
	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11
F1	1	2									3
F2	E	1								2	3
F3	E	1	2							3	E
F4	E	E	1						2	3	E
F5	E	E	1	2					3	E	E
F6	E	E	E	1				2	3	E	E
F7	E	E	E	1	2			3	E	E	E
F8	E	E	E	E	1		2	3	E	E	E
F9	E	E	E	E	1	2	3	E	E	E	E

- The process of facet generation for odd vertices are also done in the same way as even vertices. The process of facet generation has the following pattern:
 - F1 → First and second vertices are combined with the last vertex. Once completed, eliminate first vertex. The remainder is ten vertices.
 - F2 → First vertex is combined with the last two vertices. Once completed, eliminate the last vertex. The remainder is nine vertices.
 - F3 → First and second vertices are combined with the last vertex. Once completed, eliminate first vertex. The remainder is eight vertices.
 - F4 → First vertex is combined with last two vertices. Once completed, eliminate the last vertex. The remainder is seven vertices.
- This process is continued until all the gaps are patched.

4.5 Solving the “Wrong Orientation of Facets” Problem

- In the case when the generated facet’s orientation is wrong, the algorithm should be able to detect it and corrective action can be taken to rectify this error.
- Following figure shows how a generated facet with a wrong orientation can be corrected.
- It can be seen that facet Z (vertices 1, 2, 11) is oriented in a clockwise direction and this contradicts the right-hand rule adopted by the STL format. Thus, this is not acceptable and needs corrections.
- This can be done by shifting the last record in file D of following table to the position of the first edge in file D of next to the following table.
- All the edges, including the initial first one will be shifted one position to the right (assuming that the records are stored in the left to right structure).
- Once this is done, step 4 of facet generation can be implemented.

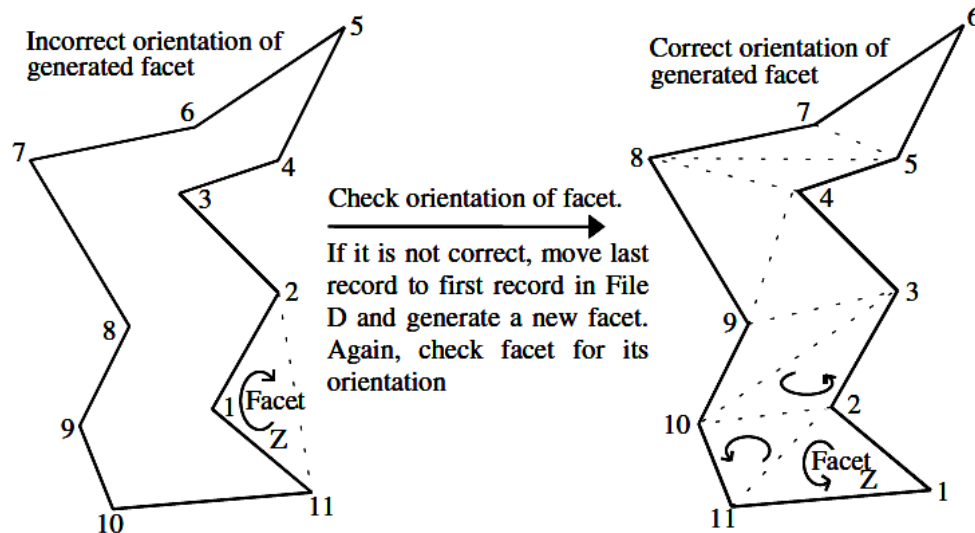


Fig 4.10 Incorrectly generated facet's orientation and its repair

- Before the shift:

Table 4.8 Illustration showing how file D is manipulated to solve orientation problems

Vertex	Edge										
	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Eighth	Ninth	Tenth	Eleventh
First	1	2	3	4	5	6	7	8	9	10	11
Second	2	3	4	5	6	7	8	9	10	11	1

- After the shift:

Table 4.9 Illustration showing the result of the shift to correct the facet orientation

Vertex	Edge										
	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Eighth	Ninth	Tenth	Eleventh
First	11	1	2	3	4	5	6	7	8	9	10
Second	1	2	3	4	5	6	7	8	9	10	11

- As can be seen from the above example, vertices 1 and 2 are used initially as the first edge to form a facet. However, this resulted in a facet having a clockwise direction. After the shift, vertices 11 and 1 are used as the first edge to form a facet.
- Facet Z, as shown on the right-hand-side in the above figure, is again generated (vertices 1, 2, 11) and checked for its orientation.
- When its orientation is correct (i.e., in the anti-clockwise direction), it is saved and stored in temporary file E.
- All subsequent facets are then generated and checked for its orientation.
- If any of its subsequently generated facets has an incorrect orientation, the whole process would be restarted using the initial temporary file D.
- If all the facets are in the right orientation, it will then be written to the original file A.