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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – I – INTRODUCTION – SPR1616

INTRODUCTION TO RAPID PROTOTYPING

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

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

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

Rapid Prototyping (RP) can be defined as a group of techniques used to quickly fabricate a scale model of a part or assembly using three-dimensional computer aided design (CAD) data. What is commonly considered to be the first RP technique, Stereolithography, was developed by 3D Systems of Valencia, CA, USA. The company was founded in 1986, and since then, a number of different RP techniques have become available.

Rapid Prototyping has also been referred to as solid free-form manufacturing, computer automated manufacturing, and layered manufacturing. RP has obvious use as a vehicle for visualization. In addition, RP models can be used for testing, such as when an air foil shape is put into a wind tunnel. RP models can be used to create male models for tooling, such as silicone rubber molds and investment casts. In some cases, the RP part can be the final part, but typically the RP material is not strong or accurate enough. When the RP material is suitable, highly convoluted shapes (including parts nested within parts) can be produced because of the nature of RP.

Definition:

Rapid Prototyping is basically a additive manufacturing process used to quickly fabricate a model of a part using 3-D CAM data. It can be defined as layer by layer fabrication of 3D physical models directly from CAD.

What is Rapid Prototyping?

Rapid Prototyping is the "process of quickly building and evaluating a series of prototypes" early and often throughout the design process. Prototypes are usually incomplete examples of what a final product may look like. Each time a prototype is used, a formative evaluation gathers information for the next, revised prototype. This cycle continues to refine the product until the final needs and objectives are met. The following diagram demonstrates the non-linear nature of Rapid Prototyping.

Why Rapid Prototyping?

The reasons of Rapid Prototyping are

- To increase effective communication.
- To decrease development time.
- To decrease costly mistakes.
- To minimize sustaining engineering changes.
- To extend product lifetime by adding necessary features and eliminating redundant features early in the design.

Rapid Prototyping decreases development time by allowing corrections to a product to be made early in the process. By giving engineering, manufacturing, marketing, and purchasing a look at the product early in the design process, mistakes can be corrected and changes can be made while they are still inexpensive. The trends in manufacturing industries continue to emphasize the following:

- Increasing number of variants of products.
- Increasing product complexity.
- Decreasing product lifetime before obsolescence.
- Decreasing delivery time.

Rapid Prototyping improves product development by enabling better communication in a concurrent engineering environment.

How does Rapid Prototyping Work?

Rapid Prototyping, also known as 3D printing, is an additive manufacturing technology. The process begins with taking a virtual design from modeling or computer aided design (CAD) software. The 3D printing machine reads the data from the CAD drawing and lays down successive layers of liquid, powder, or sheet material — building up the physical model from a series of cross sections. These layers, which correspond to the virtual cross section from the CAD model, are automatically joined together to create the final shape.

Rapid Prototyping uses a standard data interface, implemented as the STL file format, to translate from the CAD software to the 3D prototyping machine. The STL file approximates the shape of a part or assembly using triangular facets.

Typically, Rapid Prototyping systems can produce 3D models within a few hours. Yet, this can vary widely, depending on the type of machine being used and the size and number of models being produced.

NEED FOR THE COMPRESSION IN THE PRODUCT DEVELOPMENT

- To increase effective communication
- To decrease development time
- To decrease costly mistakes
- To minimize sustaining engineering changes
- To extend product life time by adding necessary features & eliminating redundant features early in the design.

TRENDS IN MANUFACTURING INDUSTRIES EMPHASIS THE FOLLOWING

- Increasing the no of variants of products
- Increase in product complexity
- Decrease in product lifetime before obsolescence
- Decrease in delivery time
- Product development by Rapid Prototyping by enabling better communication

HISTORICAL DEVELOPMENT

The development of Rapid Prototyping is closely tied in with the development of applications of computers in the industry. The declining cost of computers, especially of personal and mini computers, has changed the way a factory works. The increase in the use of computers has spurred the advancement in many computer-related areas including Computer-Aided Design (CAD), Computer-Aided

Manufacturing (CAM) and Computer Numerical Control (CNC) machine tools. In particular, the emergence of RP systems could not have been possible without the existence of CAD. However, from careful examinations of the numerous RP systems in existence today, it can be easily deduced that other than CAD, many other technologies and advancements in other fields such as manufacturing systems and materials have also been crucial in the development of RP systems. Table 1.1 traces the historical development of relevant technologies related to RP from the estimated date of inception.

Table: 1.1 Historical development of Rapid Prototyping and related technologies

Year of Inception	Technology
1770	Mechanization
1946	First Computer
1952	First Numerical Control (NC) Machine Tool
1960	First commercial Laser
1961	First commercial Robot
1963	First Interactive Graphics System
1988	First commercial Rapid Prototyping System

First Phase: Manual Prototyping

Prototyping had begun as early as humans began to develop tools to help them live. However, prototyping as applied to products in what is considered to be the first phase of prototype development began several centuries ago. In this early phase, prototypes typically are not very sophisticated and fabrication of prototypes takes on average about four weeks, depending on the level of complexity and representativeness. The techniques used in making these prototypes tend to be craft-based and are usually extremely labour intensive.

Second Phase: Soft or Virtual Prototyping

As application of CAD/CAE/CAM become more widespread, the early 1980s saw the evolution of the second phase of prototyping — *Soft or Virtual Prototyping*. Virtual prototyping takes on a new meaning as more computer tools become available — computer models can now be stressed, tested, analyzed and modified as if they were physical prototypes. For example, analysis of stress and strain can be accurately predicted on the product because of the ability to specify exact material attributes and properties. With such tools on the computer, several iterations of designs can be easily carried out by changing the parameters of the computer models.

Also, products and as such prototypes tend to become relatively more complex — about twice the complexity as before. Correspondingly, the time required to make the physical model tends to increase tremendously to about that of 16 weeks as building of physical prototypes is still dependent on craft-based methods though introduction of better precision machines like CNC machines helps.

Even with the advent of Rapid Prototyping in the third phase, there is still strong support for virtual prototyping. Lee argues that there are still unavoidable limitations with rapid prototyping. These include material limitations (either because of expense or through the use of materials dissimilar to that of the intended part), the inability to perform endless what-if scenarios and the likelihood that little or no reliable data can be gathered from the rapid prototype to perform finite element analysis (FEA). Specifically, in the application of kinematic/dynamic analysis, he described a program which can assign physical properties of many different materials, such as steel, ice, plastic, clay or any custom material imaginable and perform kinematics and motion analysis as if a working prototype existed. Despite such strengths of virtual prototyping, there is one inherent weakness that such soft prototypes cannot be tested for phenomena that is not anticipated or accounted for in the computer program. As such there is no guarantee that the virtual prototype is really problem free.

Third Phase: Rapid Prototyping

Rapid Prototyping of physical parts, or otherwise known as solid freeform fabrication or desktop manufacturing or layer manufacturing technology, represents the third phase in the evolution of prototyping. The invention of this series of rapid prototyping methodologies is described as a "watershed event" [11] because of the tremendous time savings, especially for complicated models. Though the parts (individual components) are relatively three times as complex as parts made in 1970s, the time required to make such a part now averages only three weeks [9]. Since 1988, more than twenty different rapid prototyping techniques have emerged.

FUNDAMENTALS OF RAPID PROTOTYPING

a) A model or component is modelled on a Computer-Aided Design/Computer-Aided Manufacturing (CAD/CAM) system. The model which represents the physical part to be built must be represented as closed surfaces which unambiguously define an enclosed volume. This mean that the data must specify the inside, outside and boundary of the model. This requirement will become redundant if the modelling technique used is solid modelling. This is by virtue of the technique used, as a valid solid model will automatically be enclosed volume. This requirement ensures that all horizontal cross sections that are essential to RP are enclosed curves to create the solid object.

b) The solid or surface model to be built is next converted into a format dubbed the “STL” (Stereolithography) file format which originates from 3D systems. The STL file format approximates the surfaces of ten model by polygons. Highly curved surfaces must employ many polygons, which means that STL files for curved parts can be very large. However, these are some rapid prototyping systems which also accept IGES (Initial Graphics Exchange Specifications) data, provided it is of the correct “flavour”.

c) A computer program analyzes a STL file that defines the model to be fabricated and “slices” the model into cross sections. The cross sections are systematically recreated through the solidification of either liquids or powders and then combined to form a 3D model. Another possibility is that the cross sections are already thin, solid laminations and these thin laminations are glued together with adhesives to form a 3D model. Other similar methods may also be employed to build the model.

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

INPUT

Input refers to the electronic information required to describe the physical object with 3D data. These are two possible starting points- a computer model or a physical model. The computer model created by a CAD system can be either a surface model or a solid model. On the other hand, 3D data from the physical model is not at all straight forward. It requires data acquisition through a method known as reverse engineering. In reverse engineering, a wide range of equipment can be used, such as CMM (coordinate measuring machine) or a laser digitizer, to capture data points of the physical model and “reconstruct” it in a CAD system.

METHOD

While they are currently more than 20 vendors for RP systems, the method employed by each vendor can be generally classified into the following categories: photo-curing, cutting and gluing/joining, melting and solidifying/fusing and joining/binding. Photo-curing can be further divided into categories of single beam, double laser beams and masked lamp.

MATERIAL

The initial state of material can come in either solid, liquid or powder state. In solid state, it can come in various forms such as pellets, wire or laminates. The current range materials include paper, nylon, wax, resins, metals and ceramics.

APPLICATION:

Most of the RP parts are finished or touched up before they are used for their intended applications. Applications can be grouped into 1. Design 2. Engineering, Analysis, and planning and 3. Tooling and Manufacturing. A wide range of industries can benefit from RP and these include, but are not limited to, aerospace, automotive, biomedical, consumer, electrical and electronics products.

Applications of Rapid Prototyping

RAPID TOOLING

- Patterns for Sand Casting
- Patterns for Investment Casting
- Pattern for Injection mouldings

RAPID MANUFACTURING

- Short productions run
- Custom made parts
- On-Demand Manufacturing
- Manufacturing of very complex shapes

AEROSPACE & MARINE

- Wind tunnel models
- Functional prototypes
- Boeing’s On-Demand-Manufacturing

AUTOMOTIVE RP SERVICES

- Needed from concept to production level
- Reduced time to market

- Functional testing
- Dies & Moulds

BIOMEDICAL APPLICATIONS - I

- Prosthetic parts
- Use of data from MRI and CT scan to build 3D parts
- 3D visualization for education and training

BIOMEDICAL APPLICATIONS - II

- Customized surgical implants
- Mechanical bone replicas
- Anthropology
- Forensics

ARCHITECTURE

- 3D visualization of design space
- Iterations of shape
- Sectioned models

FASHION & JEWELRY

- Shoe Design
- Jewellery
- Pattern for lost wax
- Other castings

Classification of Rapid Prototyping Systems

LIQUID-BASED

- Stereo lithography (SLA)
- Solid Ground Curing (SGA)

SOLID-BASED

- Fused deposition modeling (FDM)
- Laminated object manufacturing (LOM)

POWDER-BASED

- 3D Printing
- Selective laser sintering (SLS)
- Direct metal laser sintering (DMLS)

Classification of Rapid Prototyping Systems

The professional literature in RP contains different ways of classifying RP processes. However, one representation based on German standard of production processes classifies RP processes according to state of aggregation of their original material and is given in figure

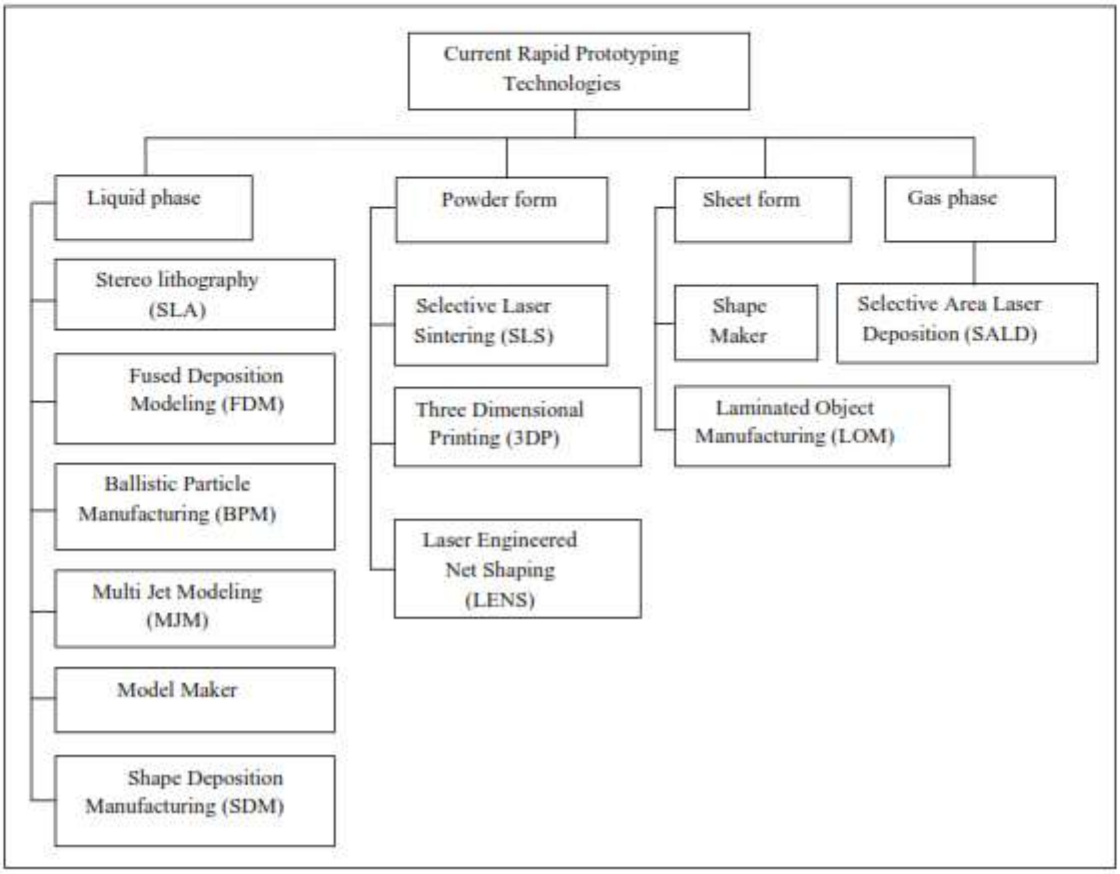

Fig 1.1: Classification of Rapid Prototyping Systems

a) Liquid-based
b) Solid-based
c) Powder-based

Liquid-Based

Liquid based RP systems have the initial form of its materials in liquid state. Through a process commonly known as curing, the liquid is converted into the solid state. The following RP systems fall into the following category

i) 3D systems' Stereolithography apparatus (SLA)
ii) Cubical's Solid Ground Curing (SGC)
iii) Sony's Solid reaction Systems (SCS)
iv) CMET's Solid Object Ultraviolet-Laser Printer (SOUP)
v) Autostrade's E-Darts
vi) Teijin Seiki's Soliform Systems
vii) Meiko's Rapid Prototyping systems for the jewellery Industry
viii) Denken's SLP
ix) Mitsui's COLAMN
x) Fockele & Schwarze's LMS
xi) Light Sculpting
xii) Aaroflex
xiii) Rapid Freeze
xiv) Two Laser Beams
xv) Microfabrication

Solid-Based

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:

i) Cubic Technologies' Laminated Object Manufacturing (LOM)
ii) Stratasys's Fused Deposition Modelling (FDM)
iii) Kira Corporation's Paper Laminated Technology (PLT)
iv) 3D Systems's Multi-Jet Modelling Systems (MJM)
v) Solidscape's Modelmaker and PatternMaster
vi) Beijing Yinhua's Slicing Solid Manufacturing (SSM), Melted Extrusion Modelling (MEM) and Multi-Functional RPM Systems (M-RPM)
vii) CAM-LEM's CL 100
viii) Ennex Corporation's Offset Fabbers

Powder-Based

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 the category

i) 3D Systems's Selective Laser Sintering (SLS)
ii) EOS's EOSINT Systems
iii) Z Corporation's Three-Dimensional Printing (3DP)
iv) Optomec's Laser Engineered Net Shaping (LENS)
v) Soligen's Direct Shell Production Casting (DSPC)
vi) Fraunhofer's Multiphase Jet Solidification (MJS)
vii) Acram's Electron Beam Melting (EBM)
viii) Aeromet Corporation's Lasform Technology
ix) Precision Optical Manufacturing;s Direct Metal Deposition (DMD)
x) Generi's RP Systems (GS)
xi) Therics Inc.'s Theriform Technology
xii) Extrude Hone's Prometal 3D Printing Process

All the above RP Ssytems employ the Joining/Binding method. The method of joining/binding differs for the above systems in that some employ a laser while others use a binder/glue to achieve the joining effect.

RPT Basic Process

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

1) **CAD Model Creation**

First, the object to be built is modelled using a Computer-Aided Design (CAD) software package. Solid modelers, such as Pro/ENGINEER, tend to represent 3-D objects more accurately than wire-frame modellers such as AutoCAD, and will therefore yield better results. The designer can use a pre-existing CAD file or may wish to create one expressly for prototyping purposes. This process is identical for all of the RP build techniques. The basic process is similar across the different additive type RP technologies. We will use a ball as an example here. It begins with using a CAD software such as Solidworks to design a 3D computer model. Figure 1.1 is a golf ball designed in Solidworks.

Fig 1.2: CAD model of a ball

2) **Conversion to STL Format**

The various CAD packages use a number of different algorithms to represent solid objects. To establish consistency, the STL (stereolithography, the first RP technique) format has been adopted as the standard of the rapid prototyping industry. The second step, therefore, is to convert the CAD file into STL format. This format represents a three-dimensional surface as an assembly of planar triangles, "like the facets of a cut jewel." 6 The file contains the coordinates of the vertices and the direction of the outward normal of each triangle. Because STL files use planar elements, they cannot represent curved surfaces exactly. Increasing the number of triangles improves the approximation, but at the cost of bigger file size. Large, complicated files require more time to pre-process and build, so the designer must balance accuracy with manageability to produce a useful STL file. Since the .stl format is universal, this process is identical for all of the RP build techniques.

This 3D CAD model is next converted into a Stereolithography or Standard Tessellation Language (STL) file format. The STL file format only describes the surface geometry of a 3D CAD model. It does not contain any information on the color, texture or material. STL file format can be saved in either ASCII or binary versions, with the latter as the more compact version. The surface geometry is described with triangular facets. Each triangle facets uses a set of Cartesian coordinates to describe its three vertices and the surface normal vector using a right-hand rule for ordering. An example of how an ASCII STL file format is show in Fig. 1.2.

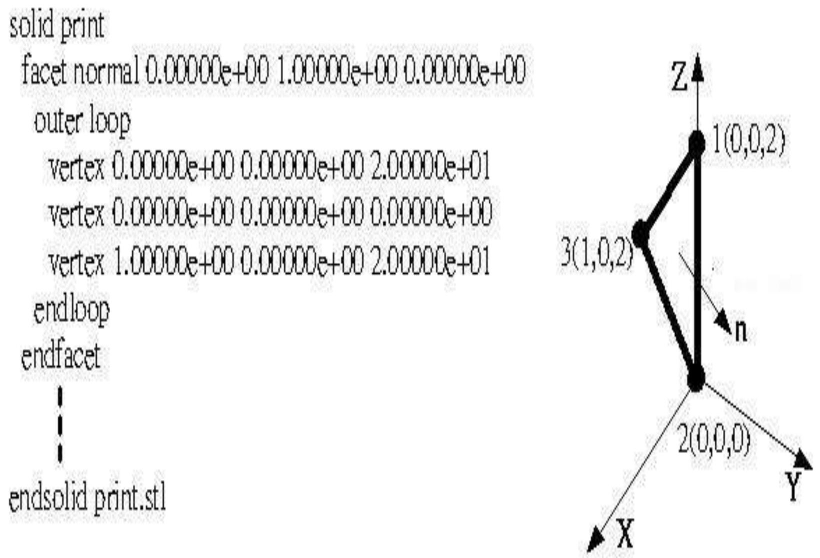

Figure 1.3: ASCII STL file format

To convert a CAD model to STL in Solidworks, File >Save as>Change ‘Save as type’ to .STL Select ‘Options’ for more advance export options. Figure 1.4 shows a print screen of the STL export option. As shown in Fig. 1.4, one can select to export the STL as Binary or ASCII file format in millimetre, centimetre, meter, inches or feet depending on the unit used in the CAD model.

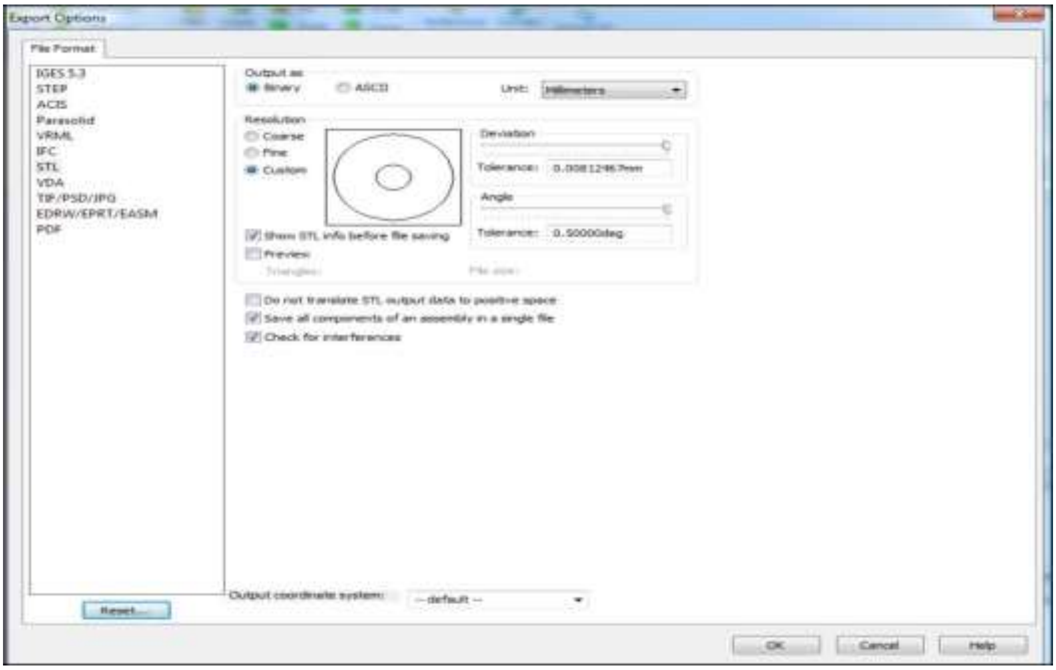

Figure 1.4: Solidworks STL export option

3) **Slice the STL File**

In the third step, a pre-processing program prepares the STL file to be built. Several programs are available, and most allow the user to adjust the size, location and orientation of the model. Build orientation is important for several reasons. First, properties of rapid prototypes vary from one coordinate direction to another. For example, prototypes are usually weaker and less accurate in the z (vertical) direction than in the x-y plane. In addition, part orientation partially determines the amount of time required to build the model. Placing the shortest dimension in the z direction reduces the number of layers, thereby shortening build time. The pre-processing software slices the STL model into a number of layers from 0.01 mm to 0.7 mm thick, depending on the build technique.

The program may also generate an auxiliary structure to support the model during the build. Supports are useful for delicate features such as overhangs, internal cavities, and thin-walled sections. Each PR machine manufacturer supplies their own proprietary pre-processing software.

The resolution options allow a user to control the tessellation of non-planar surfaces. There are two preset resolutions of ‘Coarse’ and ‘Fine’. The ‘Custom’ setting allows one to adjust the deviation and angle tolerances. Lower deviation tolerance sets tighter accuracy to the tessellation whereas smaller angle deviation sets smaller detail tessellation. The caveat is that tighter tolerances create more triangle facets to describe the 3D CAD model’s surface more finely which causes the file size to be large.

Figure 1.4 shows a CAD model exported to a coarse resolution STL (114KB), fine resolution STL (300 KB), and a very fine resolution STL file (1.51 MB). A more complicated design with complicated features would also result in a large STL file size. Figure 1.5 shows an exaggerated view of how the export STL tolerance option affects how the 3D CAD model’s surface is described. Furthermore, depending on how fine the tolerances are set, computation power to export the CAD model and process the file for fabrication could be an issue. Once the appropriate STL file has been generated, this is then loaded into the individual RP company’s proprietary software to be processed into 2D slices for fabrication.

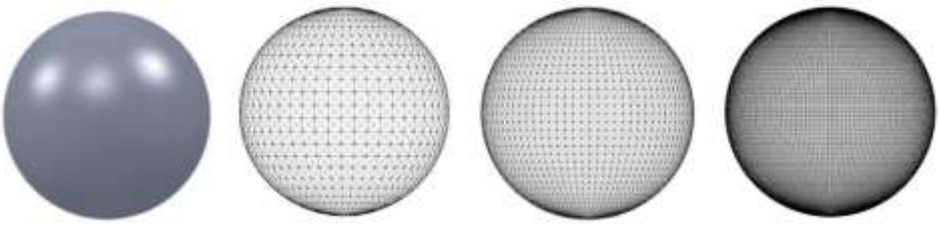

Figure 1.5: CAD model to a coarse STL, fine STL, and a very fine STL file.

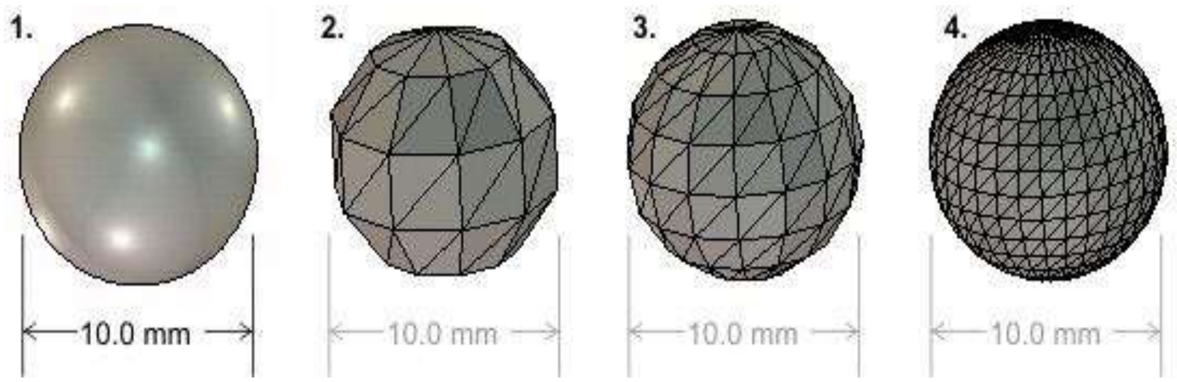

Figure 1.6: Exaggerated view of different STL tolerances

4) **Layer by Layer Construction**

The fourth step is the actual construction of the part. Using one of several techniques (described in the next section) RP machines build one layer at a time from polymers, paper, or powdered metal. Most machines are fairly autonomous, needing little human intervention.

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

5) **Clean and Finish**

The final step is post-processing. This involves removing the prototype from the machine and detaching any supports. Some photosensitive materials need to be fully cured before use. Prototypes may also require minor cleaning and surface treatment. Sanding, sealing, and/or painting the model will improve its appearance and durability.

Advantages and disadvantages of rapid prototyping

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

Advantage of Rapid Prototyping

- Fast and inexpensive method of prototyping design ideas
- Multiple design iterations
- Physical validation of design
- Reduced product development time
- It encourages and requires active student participation the design process.
- Iteration and change are natural consequences of instructional systems development. Clients tend to change their minds.
- Clients don't know their requirements until they see them implemented.
- An approved prototype is the equivalent of a paper specification & dash with one exception. Errors can be detected earlier.
- Prototyping can increase creativity through quicker user feedback. (But see below.)
- Prototyping accelerates the development cycle.

Disadvantages of Rapid Prototyping

- The main disadvantage of prototyping can be summed up in one complaint that is easy to imagine: it has a tendency to encourage informal design methods which may introduce more problems than they eliminate.
- Resolution not as fine as traditional machining (millimeter to sub-millimeter resolution)
- Surface flatness is rough (dependant of material and type of RP)
- This failure can be avoided if the following issues are kept in mind: (Tripp and Bichelmeyer)
- Prototyping can lead to a design-by-repair philosophy, which is only an excuse for lack of discipline.
- Prototyping does not eliminate the need for front-end analysis. It cannot help if the situation is not amenable to instructional design.
- A prototype cannot substitute completely for a paper analysis.
- There may be many instructional design problems which are not addressed by prototyping.
- Prototyping may lead to premature commitment to a design if it is not remembered that a design is only a hypothesis.
- When prototyping an instructional package, creeping featurism (the adding of bells and whistles) may lead to designs that get out of control."

OVERVIEW OF EXISTING TECHNOLOGIES OF PROTOTYPING AND TOOLING

Prototype

- A prototype is an early sample or model built to test a concept or process or to act as a thing to be replicated or learned from.

Design and modeling

In many fields, there is great uncertainty as to whether a new design will actually do what is desired. New designs often have unexpected problems. A prototype is often used as part of the product design process to allow engineers and designers the ability to explore design alternatives, test theories and confirm performance prior to starting production of a new product. Engineers use their experience to tailor the prototype according to the specific unknowns still present in the intended design. For example, some prototypes are used to confirm and verify consumer interest in a proposed design whereas other prototypes will attempt to verify the performance or suitability of a specific design approach.

In general, an iterative series of prototypes will be designed, constructed and tested as the final design emerges and is prepared for production. With rare exceptions, multiple iterations of prototypes are used to progressively refine the design. A common strategy is to design, test, evaluate and then modify the design based on analysis of the prototype.

In many products it is common to assign the prototype iterations Greek letters. For example, a first iteration prototype may be called an "Alpha" prototype. Often this iteration is not expected to perform as intended and some amount of failures or issues are anticipated. Subsequent prototyping iterations (Beta, Gamma, etc.) will be expected to resolve issues and perform closer to the final production intent.

In many product development organizations, prototyping specialists are employed - individuals with specialized skills and training in general fabrication techniques that can help bridge between theoretical designs and the fabrication of prototypes.

Basic prototype categories

There is no general agreement on what constitutes a "prototype" and the word is often used interchangeably with the word "model" which can cause confusion. In general, "prototypes" fall into five basic categories:

Proof-of-Principle Prototype (Model) (in electronics sometimes built on a breadboard). A Proof of concept prototype is used to test some aspect of the intended design without attempting to exactly simulate the visual appearance, choice of materials or intended manufacturing process. Such prototypes can be used to "prove" out a potential design approach such as range of motion, mechanics, sensors, architecture, etc. These types of models are often used to identify which design options will not work, or where further development and testing is necessary.

Form Study Prototype (Model). This type of prototype will allow designers to explore the basic size, look and feel of a product without simulating the actual function or exact visual appearance of the product. They can help assess ergonomic factors and provide insight into visual aspects of the product's final form. Form Study Prototypes are often hand-carved or machined models from easily sculpted, inexpensive materials (e.g., urethane foam), without representing the intended color, finish, or texture. Due to the materials used, these models are intended for internal decision making and are generally not durable enough or suitable for use by representative users or consumers.

User Experience Prototype (Model). A User Experience Model invites active human interaction and is primarily used to support user focused research. While intentionally not addressing possible aesthetic treatments, this type of model does more accurately represent the overall size, proportions, interfaces, and articulation of a promising concept. This type of model allows early assessment of how a potential user interacts with various elements, motions, and actions of a concept which define the initial use scenario and overall user experience. As these models are fully intended to be used and handled, more robust construction is key. Materials typically include plywood, REN shape, RP processes and CNC machined components. Construction of user experience models is typically driven by preliminary CAID/CAD which may be constructed from scratch or with methods such as industrial CT scanning.

Visual Prototype (Model) will capture the intended design aesthetic and simulate the appearance, color and surface textures of the intended product but will not actually embody the function(s) of the final product. These models will be suitable for use in market research, executive reviews and approval, packaging mock-ups, and photo shoots for sales literature.

Functional Prototype (Model) (also called a working prototype) will, to the greatest extent practical, attempt to simulate the final design, aesthetics, materials and functionality of the intended design. The functional prototype may be reduced in size (scaled down) in order to reduce costs. The construction of a fully working full-scale prototype and the ultimate test of concept, is the engineers' final check for design flaws and allows last-minute improvements to be made before larger production runs are ordered.

Differences between a prototype and a production design

In general, prototypes will differ from the final production variant in three fundamental ways:

Materials. Production materials may require manufacturing processes involving higher capital costs than what is practical for prototyping. Instead, engineers or prototyping specialists will attempt to substitute materials with properties that simulate the intended final material.

Processes. Often expensive and time-consuming unique tooling is required to fabricate a custom design. Prototypes will often compromise by using more flexible processes.

Lower fidelity. Final production designs often require extensive effort to capture high volume manufacturing detail. Such detail is generally unwarranted for prototypes as some refinement to the design is to be expected. Often prototypes are built using very limited engineering detail as compared to final production intent.

Characteristics and limitations of prototypes

Engineers and prototyping specialists seek to understand the limitations of prototypes to exactly simulate the characteristics of their intended design. A degree of skill and experience is necessary to effectively use prototyping as a design verification tool.

It is important to realize that by their very definition, prototypes will represent some compromise from the final production design. Due to differences in materials, processes and design fidelity, it is possible that a prototype may fail to perform acceptably whereas the production design may have been sound. A counter-intuitive idea is that prototypes may actually perform acceptably whereas the production design may be flawed since prototyping materials and processes may occasionally outperform their production counterparts.

In general, it can be expected that individual prototype costs will be substantially greater than the final production costs due to inefficiencies in materials and processes. Prototypes are also used to revise the design for the purposes of reducing costs through optimization and refinement.

It is possible to use prototype testing to reduce the risk that a design may not perform acceptably, however prototypes generally cannot eliminate all risk. There are pragmatic and practical limitations to the ability of a prototype to match the intended final performance of the product and some allowances and engineering judgment are often required before moving forward with a production design.

Building the full design is often expensive and can be time-consuming, especially when repeated several times—building the full design, figuring out what the problems are and how to solve them, then building another full design. As an alternative, "rapid-prototyping" or "rapid application development" techniques are used for the initial prototypes, which implement part, but not all, of the complete design. This allows designers and manufacturers to rapidly and inexpensively test the parts of the design that are most likely to have problems, solve those problems, and then build the full design.

Modern trends

With the recent advances in computer modeling it is becoming practical to eliminate the creation of a physical prototype, instead modeling all aspects of the final product as a computer model. An example of such a development can be seen in the Boeing 787 Dreamliner, in which the first full sized physical realization is made on the series production line.

Mechanical and electrical engineering

The most common use of the word prototype is a functional, although experimental, version of a non-military machine (e.g., automobiles, domestic appliances, consumer electronics) whose designers would like to have built by mass production means, as opposed to a mockup, which is an inert representation of a machine's appearance, often made of some non-durable substance. Figure 1.6 shows the A prototype of the Polish economy hatchback car Beskid 106 designed in the 1980s.

Fig. 1.7: A prototype of the Polish economy hatchback car Beskids 106 designed in the 1980s.

An electronics designer often builds the first prototype from breadboard or strip board or per board, typically using "DIP" packages. However, more and more often the first functional prototype is built on a "prototype PCB" almost identical to the production PCB, as PCB manufacturing prices fall and as many components are not available in DIP packages, but only available in SMT packages optimized for placing on a PCB. Builders of military machines and aviation prefer the terms "experimental" and "service test".

NEED FOR SPEED DESIGN TO MARKET OPERATIONS

Speed is crucial in industrial management. Manufacturers continually explore ways of shortening the time between the definition of a product and its availability in the market (time-to-market) to gain competitive advantage. Industrial managers are also pressured to maintain a steady flow of new products into the market as the product offerings of competitors continue to change. Speed-to-market is the goal of time-sensitive competitors. There is increased emphasis on speed in all aspects of manufacturing, particularly in engineering, production, sales response, and customer service, in an effort to make short product life cycles even shorter. Speed-to-market requires the proper technology, as well as policies and procedures relating all development operations.

Faster, faster, faster! We're in a world obsessed with speed. "Time" has become our most valued resource--from the food we eat, to computers, airplanes, automobiles, pharmaceuticals, and even written information. No longer is ordinary mail sufficient, we now have electronic mail. Why waste time typing?

Manufacturers, too, have come to grips with the competitive nature of speed. Executives have long known that "time is money," but only recently has that concept been widely accepted as a competitive advantage across all markets and product lines. Markets based on style, fashion, or fads have always felt this pressure, but today producers of semiconductors, industrial vehicles and equipment, and chemicals, to name a few, a feel the same effects.

Change and Time to Market

The emphasis in manufacturing companies during the 1990s will be "Time-to-market." The term is generally defined as the elapsed time between product definition and product availability. Time-to-market is doubly important when one considers another current trend: the pervasive nature of change. New products, improved products, new and improved products, extensions and expansions of product lines, revisions and enhancements of products, all are evidence of the requirement to keep a steady stream of new products going into the market. Product designers are having a field day.

The combination of continuous change and pressure to minimize time-to-market puts new challenges before today's managers. Led by the success of Japanese competitors, the electronics/computer industry, and select niches in the aerospace and automotive industries, U.S. firms are feeling the need to shorten product life cycles, minimize lead times, and adopt a new mentality toward the process of launching new products.

These time-sensitive competitors don't adhere to the old rules. Traditional management practice was based on having plenty of time: weigh the options, generate and evaluate several alternatives, play out the scenarios, product staff reports justifying decisions and directions. Heroes were the ones who operated within budget and on low-risk projects. The results of such a cautious and conservative approach were predictable: sluggish organizations, disgruntled employees, customer dissatisfaction, and eventual erosion of market share.

Accelerators

The new competitors are time-to-market "accelerators." Their focus is on speed: in engineering, production, sales response, and customer service. They talk in terms of speed-to-market. Their product life cycles frequently look more like spikes than smooth flowing curves. To them, the marketplace is global and so is the competition. Niche marketing is crucial to understand customer requirements and concentrate resources on pertinent products

Who are these accelerators? The bad news is that there a few corporations whose total enterprise can be categorized as accelerating.

Ford Motor Company created "Team Taurus" to develop the Taurus and Sable lines of automobiles. Team members included designers, engineers, and production specialists. Even customers were asked what they wanted in the car. The team addressed profitability and competitiveness in both the design stage and production cycle. In their effort to rationalize the car's mechanical components and the way in which it would be built, they replaced sequential engineering activities with simultaneous input from the diverse members of the group. Before the first clay model was built, they knew how the car would be assembled. Under the previous system, manufacturing managers never saw the cars they would build until eight or nine months before production started. The success of Team Taurus is cited as a significant factor in the

The Ballistic Systems Division of Boeing Aerospace Corporation has implemented a program called "Developmental Operations." The goal is to simplify developmental practices. A multi-functional team is formed to develop a specific product and, in so doing, utilize process simplification techniques to speed the development effort, among other noteworthy goals. Design analysis was reduced from two weeks to 38 minutes (their goal is four minutes), the average number of engineering changes per drawing dropped from a high of 15 to 20 to a low of one. To accelerate production, critical inspection features were identified directly on the drawing.

The development effort is paid off during the Stage II phase of the traditional life cycle. In the 1990s, however, the product life cycle is in transition. The emphasis is on innovation -- avoiding becoming a commodity. The cycle is shorter, so short that the accelerators refer to product life cycle "spikes." Much of the shortness is in reaction to, or in anticipation of, stiffer competition. The reduced life cycle means less time to pay back the development effort. To maintain profit margins the accelerators are extending the product life cycle forward

Becoming an Accelerator

Becomes readily apparent, then, that speed-to-market creates opportunities in market share, market leadership, and profits. So how can one become an accelerator? What propels products to market? With so many functions and activities involved in the time-to-market process, a clear target and a concentrated action plan are needed. A useful starting point might be to eliminate some strategies that appear to be practical, but in actuality can be counterproductive. For example, we can't just "step on the gas," an approach that normally appeals to descendants of Attila the Hun. Not only must proper tools be in place, but the policies and procedures which tie various development functions together need to be established. No amount of intimidation can overcome these requirements.

Even when a change in operations is recognized as a necessary element in reducing time-to-market, managers have to appreciate the difference between incremental versus total change. Incremental changes are indeed useful in the early activities of tool building. Organizations should be given the proper resources to optimize departmental productivity, e.g., design engineers should be using computer-aided-design (CAD) systems, which have already proven their worth in engineering productivity. But on an interdepartmental basis, incremental change is inefficient to affect the development cycle. This safe, easily managed, easily reversed, slow approach makes people feel like something is being accomplished. However, only the symptoms are being treated. Speed-to-market requires a major or total change in traditional operations.

To the surprise of very few people, the time-to-market bottleneck in manufacturing firms is in the combined design engineering manufacturing activity. Here we should look to apply our two premises. Within that sphere of activity, the design engineering functions wields more influence than might be evidence at first glance. Exhibit 3 shows the inverse effect of design engineering on time-to-market.

The influence of the design function does not arise from the intrinsic nature of the creative process. As mentioned earlier, productivity aids such as CAD have long ago solved that problem

The organizational environment needed to minimize downstream product changes has been explained to us numerous times in many sources. Peters and Waterman, in their classic, In Search of Excellence, describe the innovation that comes from "skunk-works" development groups. Keep these developers away from the administrative nightmare of large, bureaucratic organizations and let genius prevail. Waterman follows up with "Adhocracy" organizations which react dynamically to changing conditions. "Entrepreneurship" has not been lost as a philosophy underlying these various structures, although to date the reviews of this technique are mixed.

There is nothing wrong with the judicious application of novel organizational structures to improve creativity and productivity. Most managers continually seek to simplify business units and eliminate organizational layers and middlemen where practical. Basically, the new innovation-oriented organizations are designed to enhance flexibility: static flexibility to adjust to changing market conditions, and dynamic flexibility for steadily increasing productivity through improved production processes and innovation.

The accelerators-to-market groups have such an organizational environment in place that they are able to consistently produce manufactural products. Key to their success is the ability to remove the artificial barrier between the design engineers and manufacturing. Known primarily as concurrent engineering, but also as simultaneous engineering and reducibility engineering, the goal of tightening this innovative team is to produce a manufactural (and maintainable) product.

Concurrent engineering is not new. Toyota and Honda have been using it in Japan for years. The well-known Japanese team approach and consensus orientation is the basis for concurrent engineering. On the home front, GM and Ford have been at concurrent engineering for about four years now. Even the U.S. Air Force has jumped on the concept. At the Wright Research and Development Centre they established a concurrent Engineering Office with the stated goal of increasing the productivity of the aerospace-related work force. Furthermore, concurrent engineering will be a Department of Defence mandate in the acquisition of future weapons systems.

The lesson learned thus far in concurrent engineering is that the more intelligence put into the design process, the less intelligence needed on the shop floor. In most U.S. manufacturing firms, today's process and quality are severely limited by existing product design. Designing a product for manufacturability doesn't necessarily reduce the number of engineering changes that occur throughout the product's life cycle. Most likely there will be fewer changes, but more important, they will be earlier in the development cycle. Exhibit 6 contrasts the timing of design changes in concurrent engineering versus traditional product development

Accelerating-to-market

Means that engineering and manufacturing, as disciplines, share in the design process. It is more than an organizational interface: a new organizational entity is created so that a multi-disciplinary team produces the design. Products cannot be "forced" through the factory. Material travels no faster than the information needed to produce the product. Therefore, time-to-market, with its inherent product and process design, is a function of the speed of information. All members have input to the concurrent design criteria.

Integrating these systems is essential to ensure that all team members know what is happening in the product development cycle. Networks that tie various computer systems together enhance the speed and accuracy of communications within the group. Moreover, ancillary and immediate benefits can occur as redundant information is eliminated and more pertinent data relationships are established. "Open systems," a term designating a seamless flow of information throughout a computer network, ensures that all software packages are available for team audit.

If anything is needed in an environment that is rife with change and speed, it's flexibility. A Just-in-time manufacturing philosophy means more than the name implies--it means the elimination of waste. Waste adds time, as well as cost and complexity. Flexibility allows for reduced lot sizes, quick changeover equipment, minimal inventories, and simplicity. Process planners and manufacturing engineers have a key goal to gain valuable flexibility while maintaining efficiency.

The ever-increasing time pressure on concurrent engineering teams motivates them to use high technology capabilities whenever possible. Engineering drawings are initiated in computer-aided-design (CAD) systems and quickly passed to more useful imaging systems. Imaging technology is a more efficient method of distributing the engineering design or drawing and allows reviewers to red-line, or mark and comment on the drawings without disturbing the original design. Alternative sketches can easily be entered by any team reviewer to enhance manufacturability. Artificial intelligence (AI) systems are also helping in the evaluation of manufacturable designs, although usually in a narrow and well-defined segment of the process

Top Management

As in most successful major business changes, top management must be supportive (at the least) and, preferably, actively involved. The top-line executive must commit to a speed-to-market operating philosophy. What is commitment? Relating it to the proverbial American breakfast of bacon and eggs, the chicken is involved, but the pig is totally committed. Top management provides a vision of the future and a time-to-market goal that product developers continually strive to meet and exceed. Inter-departmental processes must be put in place to fit the new concurrent engineering direction. Top management also provides the tools, in this case the computer systems and other high technology capabilities necessary for rapid communication Lastly, top management never accepts the status quo. Change, innovation, and improvement are continual. The "accelerators" of tomorrow will, by definition, emerge from nowhere. The competitors and the market will be taken by surprise; market shares and profitability will be affected. Time-to-market is tomorrow's competitive issue.

STEREOLITHOGRAPHY APPARATUS (SLA)

It is the first RP system developed by 3D systems of varencia in California, USA in 1996. First Model developed ewas 250/50 followed by 250/30,3500,5000 and 7000.

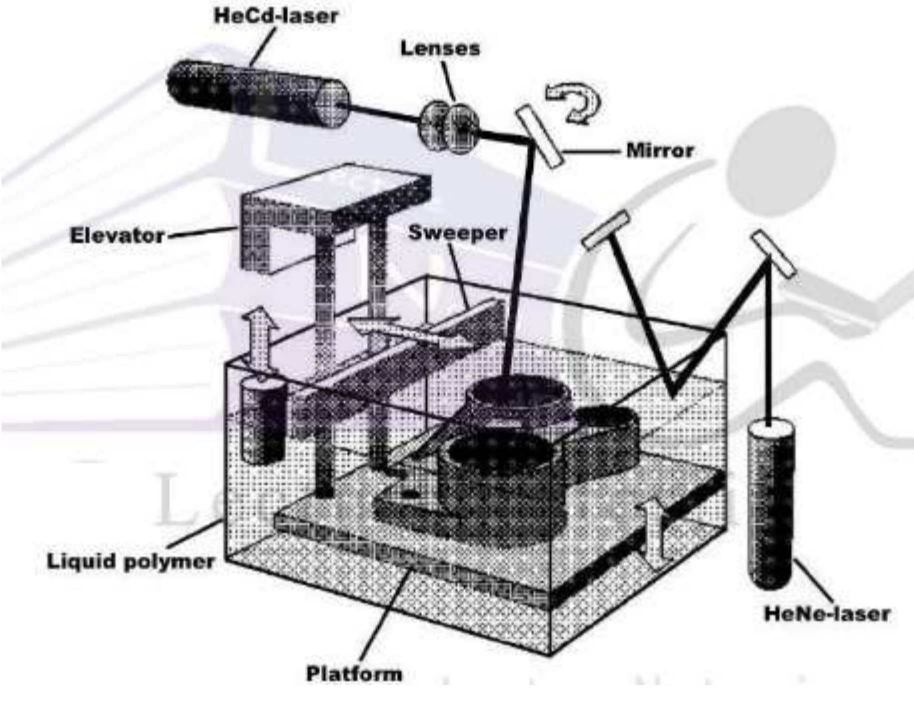

Fig: 1.8: Stereolithography Apparatus

Company

3D Systems was founded in 1986 by inventor Charles W. Hull and entrepreneur Raymond S. Freed. Amongst all the commercial RP systems, the Stereolithography Apparatus, or SLA® as it is commonly called, is the pioneer with its first commercial system marketed in 1988. It has been awarded more than 40 United States patents and 20 international patents, with additional patents filed or pending inter-nationally. 3D Systems Inc. is currently headquartered in 26801 Avenue Hall, Valencia, CA 91355, USA.

Products

Models and Specifications

3D Systems produces a wide range of machines to cater to various part sizes and throughput. There are several models available, including those in the series of SLA 250/30A, SLA 250/50, SLA-250/50HR, SLA 3500, SLA 5000, SLA 7000 and Viper si2. The SLA 250/30A is an economical and versatile SLA starter system that uses a Helium Cadmium (He–Cd) laser. The SLA 250/50 is a supercharged system with a higher-powered laser, interchangeable vats and Zephyr recoater system, whereas the SLA 250/50HR adds a special feature of a small spot laser for high-resolution application. All SLA 250 type systems have a maximum build envelope of 250* 250 *250 mm and use a He–Cd laser. For bigger build envelopes, the SLA 3500, SLA 5000 and SLA 7000 are available. These three machines use a different laser from the SLA 250 (solid-state Nd:YVO_4). The SLA 7000 (see Figure 1.8: below) is the top of the series. It can build parts up to four times faster than the SLA 5000 with the capacity of building thinner layers (minimum layer thickness 0.025 mm) for finer surface finish. Its faster speed is largely due to its dual spot laser's ability.

Figure 1.9: 3D Systems' SLA 7000 (Courtesy 3D Systems)

This means that a smaller beam spot is used for the border for accuracy, whereas the bigger beam spot is used for internal cross-hatching for speed. 3D Systems' new Viper si2 SLA system is their first solid imaging system to combine standard and high-resolution part building in the same system. The Viper si2 system lets you choose between standard resolution, for the best balance of build speed and part resolution, and high resolution (HR mode) for ultra-detailed small parts and features. All these are made possible by a carefully integrated digital signal processor (DSP) controlled high speed scanning system with a single, solid-state laser that delivers a constant 100 mW of available power throughout its 7500-hour warranty life. The Viper si2 system builds parts with a smooth surface finish, excellent optical clarity, high accuracy, and thin, straight vertical walls. It is ideal for a myriad of solid imaging applications, from rapid modelling and prototyping to injection moulding and investment casting.

Principle

SLA is a laser based Rapid Prototyping process which builds parts directly from CAD by curing or hardening a photosensitive resin with a relatively low power laser.

Stereolithography (SL) is the best known rapid prototyping system. The technique builds three-dimensional models from liquid photosensitive polymers that solidify when exposed to laser beam. The model is built upon a platform in a vat of photo sensitive liquid. A focussed UV laser traces out the first layer, solidifying the model cross section while leaving excess areas liquid. In the next step, an elevator lowers the platform into the liquid polymer by an amount equal to layer thickness. A sweeper recoats the solidified layer with liquid, and the laser traces the second layer on the first. This process is repeated until the prototype is complete. Afterwards, the solid part is removed from the vat and rinsed clean of excess liquids. Supports are broken off and the model is then placed in an ultraviolet oven for complete curing.

The SLA process is based fundamentally on the following principles:

(1) Parts are built from a photo-curable liquid resin that cures when exposed to a laser beam (basically, undergoing the photo polymerization process) which scans across the surface of the resin.
(2) The building is done layer by layer, each layer being scanned by the optical scanning system and controlled by an elevation mechanism which lowers at the completion of each layer.
These two principles will be briefly discussed in this section to lay the foundation to the understanding of RP processes. They are mostly applicable to the liquid-based RP systems described in this chapter. This first principle deals mostly with photo-curable liquid resins, which are essentially photopolymers and the photo polymerization process. The second principle deals mainly with CAD data, the laser, and the control of the optical scanning system as well as the elevation mechanism.

In this process photosensitive liquid resin which forms a solid polymer when exposed to ultraviolet light is used as a fundamental concept. Due to the absorption and scattering of beam, the reaction only takes place near the surface and voxels of solid polymeric resin are formed. A SL machine consists of a build platform (substrate), which is mounted in a vat of resin and a UV Helium-Cadmium or Argon ion laser. The laser scans the first layer and platform is then lowered equal to one slice thickness and left for short time (dip-delay) so that liquid polymer settles to a flat and even surface and inhibit bubble formation. The new slice is then scanned. Schematic diagram of a typical Stereolithography apparatus is shown in figure 1.9.

Process

3D Systems' stereolithography process creates three-dimensional plastic objects directly from CAD data.

The process begins with the vat filled with the photo-curable liquid resin and the elevator table set just below the surface of the liquid resin (see Figure 1.9: below).

The operator loads a three-dimensional CAD solid model file into the system. Supports are designed to stabilize the part during building.

The translator converts the CAD data into a STL file. The control unit slices the model and support into a series of cross sections from 0.025 to 0.5 mm (0.001 to 0.020 in) thick.

The computer-controlled optical scanning system then directs and focuses the laser beam so that it solidifies a two-dimensional cross-section corresponding to the slice

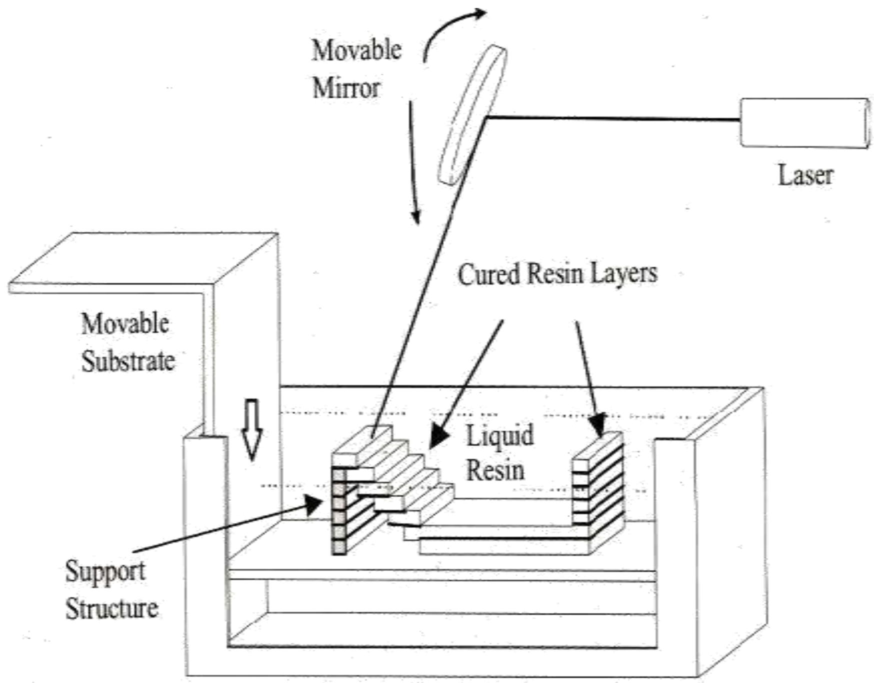

Fig. 1.10: Stereolithography Apparatus (SLA)

The computer-controlled optical scanning system then directs and focuses the laser beam so that it solidifies a two-dimensional cross-section corresponding to the slice on the surface of the photo-curable liquid resin to a depth greater than one-layer thickness. The elevator table then drops enough to cover the solid polymer with another layer of the liquid resin. A levelling wiper or vacuum blade (for Zephyr™ recoating system) moves across the surfaces to recoat the next layer of resin on the surface. The laser then draws the next layer. This process continues building the part from bottom up, until the system completes the part. The part is then raised out of the vat and cleaned of excess polymer.

The main components of the SLA system are a control computer, a control panel, a laser, an optical system and a process chamber. The workstation software used by the SLA system, known as 3D Light year exploits the full power of the Windows NT operating system, and delivers far richer functionality than the UNIX-based Maestro software. Maestro includes the following software modules:

(1) dverify™ *Module.* This module can be accessed to confirm the integrity and/or provide limited repair to stereolithography (STL)

files before part building without having to return to the original CAD software. Gaps between triangles, overlapping or redundant triangles and incorrect normal directions are some examples of the flaws that can be identified and corrected.

(2) *View*™ *Module*. This module can display the STL files and slice file (SLI) in graphical form. The viewing function is used for visual inspection and for the orientation of these files so as to achieve optimal building.

(3) *MERGE Module.* By using MERGE, several SLI files can be merged into a group which can be used together in future process.

(4) *Vista*™ *Module.* This module is a powerful software tool that automatically generates support structures for the part files. Support structures are an integral part to successful part building, as they help to anchor parts to the platform when the part is free floating or there is an overhang.

(5) *Part Manager*™ *Module*. This software module is the first stage of preparing a part for building. It utilizes a spreadsheet format into which the STL file is loaded and set-up with the appropriate build and recoat style parameters.

(6) *Slice*™ *Module.* This is the second stage of preparing a part for building. It converts the spreadsheet information from the *Part*

(7) *Manager*™ module to a model of three-dimensional cross sections or layers.

(8) *Converge*™ *Module.* This is the third and last stage of preparing a part for building. This is the module which creates the final build files used by the SLA.

Table: 1.2: Summary specifications of SLA-250 machines (Source from 3D Systems)

Model	SLA 250/30A	SLA 250/50	SLA 250/50HR
SYSTEM CHARACTERISTICS			
	SmartStart. An economical and versatile SLA starter system.	A supercharged system with higher powered laser, interchangeable vats, and Zephyr recoating system.	A specialty system with small spot laser for high-resolution applications.
VAT CAPACITY			
Maximum Build Envelope	$250 \times 250 \times 250$ mm^3 $10 \times 10 \times 10$ in^3	$250 \times 250 \times 250$ mm^3 $10 \times 10 \times 10$ in^3	$250 \times 250 \times 250$ mm^3 $10 \times 10 \times 10$ in^3
VOLUME			
L (U.S. gal)	29.4 (7.8)	32.2 (8.5)	32.2 (8.5)
LASER			
Type	Helium Cadmium (He–Cd)	Helium Cadmium (He–Cd)	Helium Cadmium (He–Cd)
Wavelength	325 nm	325 nm	325 nm
Power at Vat @ hrs	@ 2000/hrs 12 mW	@ 2000/hrs 25 mW	@ 2000/hrs 6 mW
Warranty	2000 hrs	2000 hrs	2000 hrs
OPTICAL & SCANNING			
Dual Spot	No	No	No
Beam Diameter; Border @ I/e^2	0.24 +/– 0.04 mm (0.0095 +/– 0.0015 in)	0.24 +/– 0.04 mm (0.0095 +/– 0.0015 in)	0.07 +/– 0.01 mm (0.003 +/– 0.0005 in)
Beam Diameter; Hatch @ I/e^2	0.24 +/– 0.04 mm (0.0095 +/– 0.0015 in)	0.24 +/– 0.04 mm (0.0095 +/– 0.0015 in)	0.07 +/– 0.01 mm (0.003 +/– 0.0005 in)
RECOATING SYSTEM			
	Doctor	Zephyr	Zephyr

Model	SLA 250/30A	SLA 250/50	SLA 250/50HR
FEATURES			
Interchangeable Vat	Available Option	Yes	Yes
SmartSweep	No	No	No
Auto Resin Refill	No	No	No
SOFTWARE			
3D Lghtyear / Windows NT	With Build-station 3.8.4	With Build-station 3.8.4	With Build-station 3.8.4
Buildstation O/S	MS DOS	MS DOS	MS DOS
RESINS			
General Purpose	SL 5149, SL 5170, SL 5220	SL 5149, SL 5170, SL 5220	SL 5149, SL 5170, SL 5220
Durable	N/A	N/A	N/A
High Temperature	SL 5210	SL 5210	SL 5210
WARRANTY			
	1 yr from installation date	1 yr from installation date	1 yr from installation date

Table 1.3: Summary specifications of the rest of the SLA machines (Source from 3D Systems

Model	SLA 3500	SLA 5000	SLA 7000	Viper si2
SYSTEM CHARACTERISTICS				
	A mid-sized system up to 2.5 times faster than SLA 250 with productivity enhancements like auto resin refill and SmartSweep.	A large-frame system with three times the build volume of SLA 3500.	A supercharged large-frame system two times faster than SLA 5000 with the capability of building thinner layers for finer surface finish.	A dual-resolution, constant power, longer-life laser.
VAT CAPACITY				
Maximum Build Envelope	$350 \times 350 \times 400$ mm^3 $13.8 \times 13.8 \times 15.7$ in^3	$508 \times 508 \times 584$ mm^3 $20 \times 20 \times 23$ in^3	$508 \times 508 \times 600$ mm^3 $20 \times 20 \times 23.6$ in^3	$250 \times 250 \times 250$ mm^3 $10 \times 10 \times 10$ in^3
VOLUME				
L (U.S. gal)	99.3 (25.6)	253.6 (67)		32.2 (8.5l)
LASER				
Type	Solid-State (Nd:YVO_4)			
Wavelength	354.7 nm			
Power at Vat @ hrs	@ 5000/hrs 160 mW	@ 5000/hrs 216 mW	@ 5000/hrs 800 mW	@ 7500/hrs 100 mW
Warranty	5000 hrs			7500 hrs
OPTICAL & SCANNING				
Dual Spot	No		Yes	
Beam Diameter; Border @ $1/e^2$	0.25 +/– 0.025 mm (0.010 +/– 0.001 in)			0.25 +/– 0.025 mm (0.010 +/– 0.001 in)
Beam Diameter; Hatch @ $1/e^2$	0.25 +/– 0.025 mm (0.010 +/– 0.001 in)		0.7615 +/– 0.0765 mm (0.03 +/– 0.003 in)	0.075 +/– 0.015 mm (0.0030 +/– 0.0006 in)
RECOATING SYSTEM				
	Zephyr			

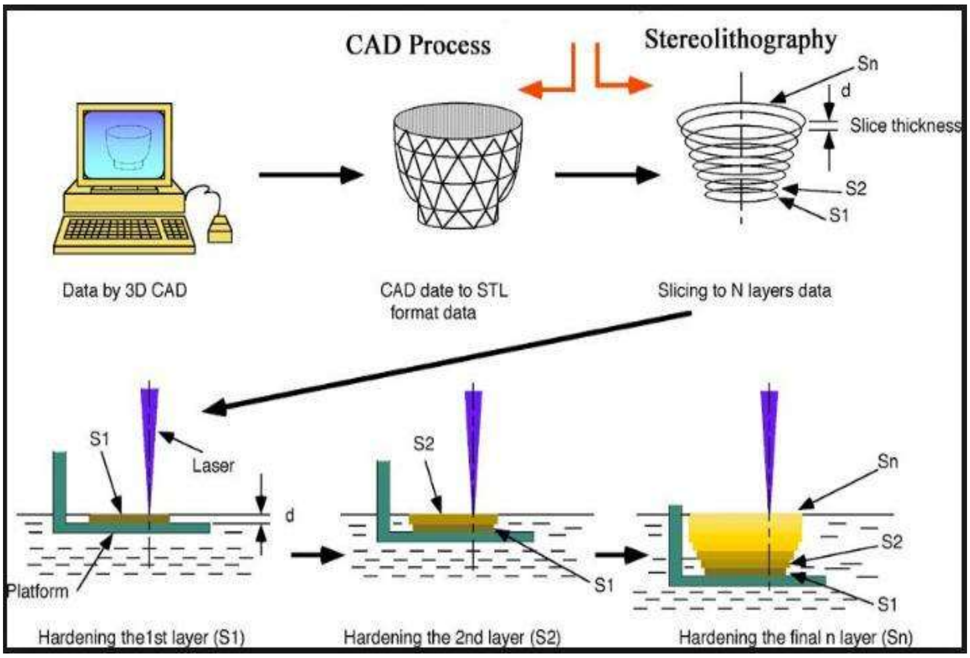

Fig.1.11: Stage wise SLA Process

In new SL systems, a blade spreads resin on the part as the blade traverses the vat. This ensures smoother surface and reduced recoating time. It also reduces trapped volumes which are sometimes formed due to excessive polymerization at the ends of the slices and an island of liquid resin having thickness more than slice thickness is formed. Once the complete part is deposited, it is removed from the vat and then excess resin is drained. It may take long time due to high viscosity of liquid resin. The green part is then post-cured in an UV oven after removing support structures. Overhangs or cantilever walls need support structures as a green layer has relatively low stability and strength. These overhangs etc. are supported if they exceed a certain size or angle, i.e., build orientation. The main functions of these structures are to support projecting parts and also to pull other parts down which due to shrinkage tends to curl up. These support structures are generated during data processing and due to these data grows heavily specially with STL files, as cuboid shaped support element need information about at least twelve triangles. A solid support is very difficult to remove later and may damage the model. Therefore a new support structure called fine point was developed by 3D Systems (figure 1.10) and is company s trademark. Build strategies have been developed to increase build speed and to decrease amount of resin by depositing the parts with a higher proportion of hollow volume. These strategies are devised as these models are used for making cavities for precision castings. Here walls are designed hollow connected by rod-type bridging elements and skin is introduced that close the model at the top and the bottom. These models require openings to drain out uncured resin.

OPERATIONS

i) The process begins with the solid model in various CAD formats.

ii) The solid model must consist of enclosed volumes before it is translated form CAD formats into .STL FILE

iii) The solid model is oriented into the positive octant of Cartesian coordinate system and then translate out Z axis by at least inches to allow for building of supports.

iv) The solid model is also oriented for optimum build which involves placing complex curvature in XY plane where possible and rotating for least Z heights as well as to where least amount of supports are required.

v) The .STL FILE is verified.

vi) The final .STL FILE one which supports in addition to original file are then sliced into horizontal cross section and saved as slice file.

vii) The slice file are then mashed to create four separates files that control SLA machine ending with extension L,R,V and PRM.

viii) Improvement one is V file.Le. Vector file. The V file contains actual line data that the laser will follow to cure the shape of the part.

ix) R file is the range file which contains data for solid or open fields as well as re-coater blade parameters.

The four build files are downloaded to SLA which begins building supports with platen adjust above the surface level. The first few support layers are actually cured into perforations into platen, thus providing a solid anchor for the rest of the part.

By building SLA uses laser to scan the cross section and fill across the surface of resin which is cured or hardened into the cross-sectional shape. The platen is lowered as the slices are completed so that more resin is available in the upper surface of the part to be cured. Final step is post processing.

POST PROCESSING

i) Ultraviolet Oven (Post Curing Apparatus)

ii) An Alcohol Bath

Clean the part in the alcohol bath and then go for final curing.

SLA Software

i) SLA CONTROL AND SET UP SOFTWARE: It operates on SLA and SLA machines. It has got three packages.

   a) SLA VIEW: UNIX based system for viewing and positioning.
   b) BRIDGE WORKS: UNIX based software for generating support structures.
   c) SLA SLICE: slicing and system operation software.

ii) MAESTRO: UNIX based software.

iii) MS WINDOWS NT SOFTWARE (SD LIGHT YEAR): It is used for viewing, positioning, support generation and slicing, build station for operating SLA machine.

The SLA control and setup software has gone through various changes since the inception of the original MS-DOS version, which still operates on many SLA250 and SLA500 machines today. For a while, there were three packages required: a UNIX-based system **T\/f** for viewing and positioning (SLA View). another UNIX-based third-party software for generating support structures (Bridge-Works); and finally, the slicing and system operation software

(SLA Slice) located on the PC attached to the SLA machine. The next generation of software combined the view/positioning and the support generation into a more powerful UNIX-based software deemed Maestro™, but still maintained the same DOS software for operation of the system. The latest systems have Microsoft.

Windows NT® software for all operations: 3D Light year for viewing and positioning, support generation, and slicing; and Build station for operating the SLA machine. Fortunately, the newer software can still write code for the old DOS-operated machines as well.

Build Materials

Epoxy resin, Acrylate Resin

Epoxy resin has better material properties and less hazardous but require large exposure time for curing.

The SLA is a liquid-based RP process, which builds parts directly from CAD by selectively curing, or hardening, a photosensitive resin with a relatively low-powered laser. Polymerization is the process of curing a plastic or polymer by introducing a catalyst. In other words, polymerization links small molecules (monomers) to create larger chain molecules (polymers), this finally develops into a fully cross-linked solid polymer. Photo polymerization is essentially the same effect, only that the catalyst introduced is light energy.

The light energy kicks off a free-radical polymerization, where the liquid photopolymer is phased from liquid to gel to solid. The solid obtained is, however a thermo-set, so it can only be used one time after it has been cured (non-recyclable). In the SLA process, the light energy is introduced by a focused laser, which selectively cures the resin in a desired shape following a CAD file. The original SLA build materials were acrylate based. They were improved upon by epoxy-based materials, also known as the ACES (Acrylic Clear Epoxy System) build style. The epoxy materials provide advantages over the acrylate resins in that they have better materials properties and are less hazardous. The integration of the epoxies did require, though, longer exposure time for cure as well as higher-powered lasers. There are now a wide variety of resins available not only from the vendor but also from third-party vendors as well. The competitive market continues to open up with higher-performance build materials at slightly lower costs. Resins can be purchased to improve resolution, temperature capacity, or even speed of the build.

The SLA Hardware

The build chamber of SLA contains

a) A removable VAT that holds the buld resins.
b) A detachable perforated build platen on a Z axis elevator frame
c) An automated resin level checking apparatus
d) VAT has a small amount of Z movement capability which allows computer to maintain a exact height per layer.
e) A recoated blade rides along the track at the top of the rack and serves to smooth the liquid across the part surfaces to prevent any rounding off edges due to cohesion effects.
f) Some systems have Zaphyrrecoater blade which actually softens up resin and delivers it evenly across the past surface.
g) Behind the build chamber resides the laser and optics required to cure resin.
h) Laser unit is long rectangular about feet long and remains stationary.

The build chamber of the SLA contains a removable vat that holds the build resin, a detachable, perforated build platen on a –z axis elevator frame, and an automated resin-level checking apparatus. The vat has a small amount of -z movement capability, which allows the computer to maintain the exact height per layer. A recoated blade rides along a track at the top of the vat, and serves to "smooth" the liquid across the part surface to prevent a rounding of edges due to cohesion effects. Some systems now have a Zephyr recoated blade, which actually siphons up resin and delivers it evenly across the part surface. In an enclosed area above and behind the build chamber, resides the laser and optics required to cure the resin. The laser unit is long and rectangular, about 4 feet long, and remains stationary. The laser beam is transferred to the part surface below by a series of optics, the final of which moves to scan the cross section of the part being built. Also required, however, are the post processing units; an ultraviolet oven call the Post Curing Apparatus (PCA); and an alcohol bath large enough to hold entire build platens with parts attached. Parts are washed in the alcohol or a similar solvent immediately after being removed from the machine (while still attached to the build platen). This step removes any extra resin that clings to the surfaces of the part. After the final supports are removed, with some build styles the parts are required to be placed in the PCA to finish fully curing.

- **The main advantages of using SLA are:**
- Parts have best surface quality
- High accuracy
- High speed
- Finely detailed features like thin vertical walls, sharp corners & fall columns can be fabricated with ease.

(1) *Round the clock operation.* The SLA can be used continuously and unattended round the clock.

(2) *Good user support.* The computerized process serves as a good user support.

(3) *Build volumes.* The different SLA machines have built volumes ranging from small to large to suit the needs of different users.

(4) *Good accuracy.* The SLA has good accuracy and can thus be used for many application areas.

(5) *Surface finish.* The SLA can obtain one of the best surface finishes amongst RP technologies.

(6) *Wide range of materials.* There is a wide range of materials, from general-purpose materials to specialty materials for specific applications.

The main disadvantages of using SLA are:

- It requires post processing i.e.post curing
- Careful handling of raw materials required
- High cost of Photo Curable Resin

(1) *Requires support structures*. Structures that have overhangs and undercuts must have supports that are designed and fabricated together with the main structure.

(2) *Requires post-processing.* Post-processing includes removal of supports and other unwanted materials, which is tedious, time consuming and can damage the model.

(3) *Requires post-curing.* Post-curing may be needed to cure the object completely and ensure the integrity of the structure.

Applications of SLA

- Investment casting
- Wind and tunnel modelling
- Tooling
- Injection mould tools

The SLA technology provides manufacturers with cost justifiable methods for reducing time to market, lowering product development costs, gaining greater control of their design process and improving product design. The range of applications includes:

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

Software developed to support these applications include QuickCastTM, a software tool which is used in the investment casting industry. QuickCast enables highly accurate resin patterns that are specifically used as an expendable pattern to form a ceramic mold to be created. The expendable pattern is subsequently burnt out. The standard process uses an expendable wax pattern which must be cast in a tool. QuickCast eliminates the need for the tooling used to make the expendable patterns. QuickCast produces parts which have a hard thin outer shell and contain a honeycomb like structure inside, allowing the pattern to collapse when heated instead of expanding, which would crack the shell.

FUSED DEPOSITION MODELING (FDM)

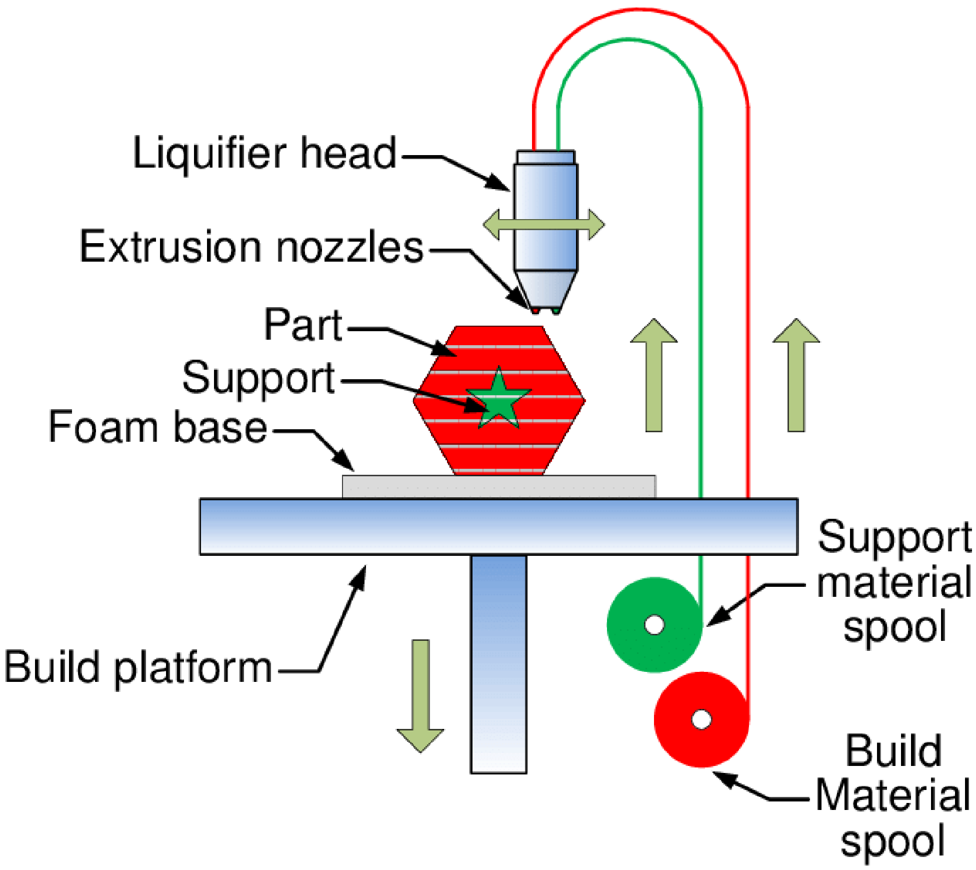

Fig.1.12: FDM Process Layout

Stratasys Inc. was founded in 1989 and has developed most of the company's products based on the Fused Deposition Modeling (FDM) technology. The technology was first developed by Scott Cramp in 1988 and the patent was awarded in the U.S. in 1992. FDM uses the extrusion process to build 3D models. Stratasys introduced its first rapid prototyping machine, the 3D modeler® in early 1992 and started shipping the units later that year. Over the past decade, Stratasys has grown progressively, seeing her rapid prototyping machines' sales increase from six units in the beginning to a total of 1582 units in the year 2000 [9]. The company's address is Stratasys Inc., 14950 Martin Drive, Eden Prairie, MN 55344-202, USA.

Principle

The principle of the FDM is based on surface chemistry, thermal energy, and layer manufacturing technology. The material in filament (spool) form is melted in a specially designed head, which extrudes on the model. As it is extruded, it is cooled and thus solidifies to form the model. The model is built layer by layer, like the other RP systems. Parameters which affect performance and functionalities of the system are material column strength, material flexural modulus, material viscosity, positioning accuracy, road widths, deposition speed, volumetric flow rate, tip diameter, envelope temperature, and part geometry.

Fused Deposition Modeling is an additive manufacturing process that can quickly produce geometrically complex parts through the melting, depositing, and solidifying of thermoplastics, layer by layer. Due primarily to its many cost -effective applications, Fused Deposition Modeling has emerged the most popular 3D Printing method since its creation in the 1980s. On top of being affordable and widely applicable, its lead times are extremely short when compared to traditional manufacturers. Thus, the FDM technology has since been patented by Stratasys, a leading company in the world of Additive Manufacturing.

As stated by Stratasys, ―Fused Deposition Modeling is a 3D Printing method that makes durable objects under the same plastics used in every-day products. The affordable and industrial-grade thermoplastics used within this process have created several beneficial parts, including concept models, functional prototypes, and even production -grade components. The following sections describe exactly how Fused Deposition Modeling achieves these incomparable fabrications.

Fused Deposition Modeling revolves around a simple manufacturing process, called extrusion. The FDM technology utilizes this old-age process under specific conditions with specialized components. These components are:

Build Material

The build material is the polymer used to build the part. This material is usually a thermoplastic, meaning it can retain its mechanical microstructure through thermal manipulation. In other words, this plastic material can easily be melted and solidified without losing its structural integrity. The build material is stored as a filament wrapped around a spool and it is pulled to the extrusion head before depositing onto the build platform.

Support Material

The support material is the removable polymer used to support the build material, especially when complex geometries are being built. This support material is used to create support structures on the build platform, essentially acting as scaffolding for the build material. These structures are broken away from the final part during post-processing. The support material is also stored as a filament wrapped around a spool, and it is pulled to the extrusion head before depositing onto the build platform.

Extrusion Head

The extrusion head is essential to the FDM process in that it performs three of the most important functions. The extrusion head, pulls the materials from the spools, melts them, and accurately places them onto the build platform within a two-dimensional plane. This extrusion head uses two gripping drive wheels per material, pinching the filament and pulling it to the head. A heating element melts the filament as it is leaving the extrusion head and entering the build chamber. Finally, this nozzle assembly moves along the x and y of the build chamber by sliding along a two-axis rail system. These pre-programmed movements are known as the tool paths.

Build Chamber / Build Platform

The build chamber consists of the x-y-z manufacturing boundaries of the FDM machines. This temperature-controlled area instantly solidifies the melted thermoplastics as they are being laid onto the build platform. The build platform is the stage upon which the build and support materials are deposited it is where the part is being build. This platform moves vertically, in the z-direction, starting close to the extrusion head and slowly moving downward as the FDM process progresses

Often times, the build platforms are also temperature-controlled to prevent warping of the build part.

Proprietary Software

The proprietary software manipulates the CAD file for use by the FDM machines. This software slices the 3D models into hundreds/thousands of layers and it creates tool paths for each of these layers. These tool paths tell the extrusion head where and when to move in the x-y plane, as well as how much filament to deposit into the build chamber. The tool paths also tell the build platform where and when to move in the z-direction. This software also determines the temperature of the build chamber based on the specific material's critical thermal points.

The FDM Process

After the key components have been identified, the overall process can be broken down into just a few steps.

1. **Pre-processing**
   The pre-processing represents the very first steps in any additive manufacturing. This includes readying the CAD file for ―printing,‖ or building.

The proprietary software performs as described above, creating a code that translates into mechanical movements and thermal adjustments performed by the FDM machines.

2. **Building**

With the build chamber and build platform clean and empty, the building begins. The extrusion head heats up to the appropriate temperature. When thermally stable, the head pulls the build material and support material from their perspective storage Spools. These thermoplastic filaments melt at the extrusion head and deposit as a bead being laid onto the build platform. Simultaneously, the extrusion head moves along the tool paths that were pre-programmed for each layer. As the tool path of that specific layer is completed, the build platform descends vertically in a very small incriminate. This vertically aligns the extrusion head with the next layer.

The thermoplastics solidify almost instantly upon entering the temperature-controlled build chamber, which builds the part layer by layer, from bottom to top. Support materials are built under overhanging sections of the part. These are visible in below the Figure shows FDM Process – Building a part. This stage can take a couple minutes to several hours, depending on the geometrical size and complexity of the build part.

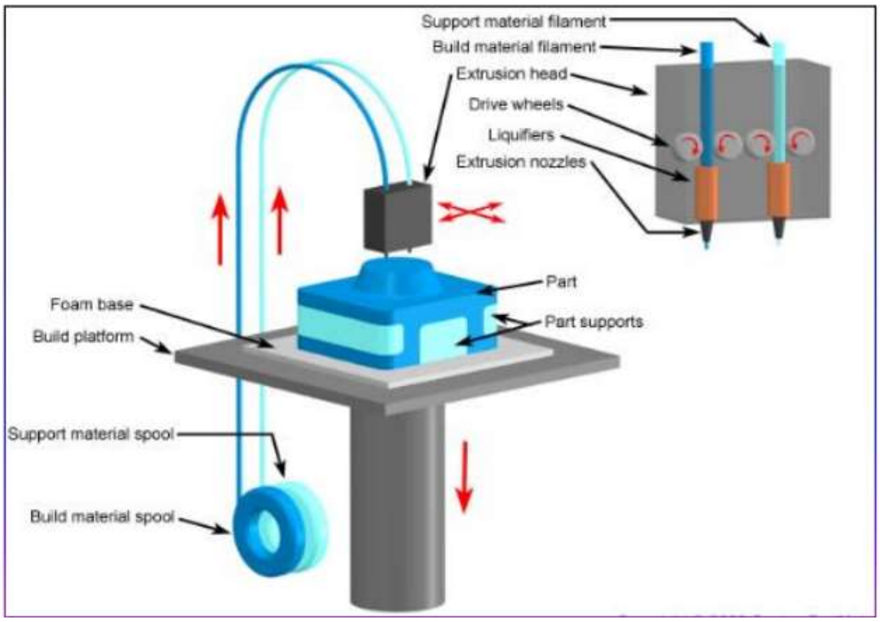

Fig.1.13: Stage wise SLA Process.

3. Post-processing

As the extrusion head finishes depositing material, the build chamber and build platform remain mechanically and thermally stable. This allows the build part and support structures to settle and cure with proper microstructures. After this cooling stage, the support structures are broken away and the final build part is cleaned. Thus, the fused deposition modeling process has come to a finish.

Detailed FDM Process (For making tea shape cup components)

The figure shows FDM process for making tea shaped cup component. In this patented process, a geometric model of a conceptual design is created on a CAD software which uses IGES or STL formatted files. It can then imported into the workstation where it is processed through the QuickSlice® and SupportWork™

Propriety software before loading to FDM 3000 or similar systems. For FDM Maxum and Titan, a newer software known as Insight is used. The basic function of Insight is similar to that of QuickSlice® and the only difference is that Insight does not need another software to auto-generate the supports. The function is incorporated into the software itself. Within this software, the CAD file is sliced into horizontal layers after the part is oriented for the optimum build position, and any necessary support structures are automatically detected and generated. The slice thickness can be set manually to anywhere between 0.172 to 0.356 mm (0.005 to 0.014 in) depending on the needs of the models. Tool paths of the build process are then generated which are downloaded to the FDM machine.

The modeling material is in spools — very much like a fishing line. The filament on the spools is fed into an extrusion head and heated to a semi-liquid state. The semi-liquid material is extruded through the head and then deposited in ultra thin layers from the FDM head, one layer at a time. Since the air surrounding the head is maintained at a temperature below the materials' melting point, the exiting material quickly solidifies. Moving on the *X–Y* plane, the head follows the tool path generated by QuickSlice® or Insight generating the desired layer. When the layer is completed, the head moves on to create the next layer. The horizontal width of the extruded material can vary between 0.250 to 0.965 mm depending on model. This feature, called ―road width‖, can vary from slice to slice. Two modeler materials are dispensed through a dual tip mechanism in the FDM machine. A primary modeler material is used to produce the model geometry and a secondary material, or release material, is used to produce the support structures. The release material forms a bond with the primary modeler material and can be washed away upon completion of the 3D models.

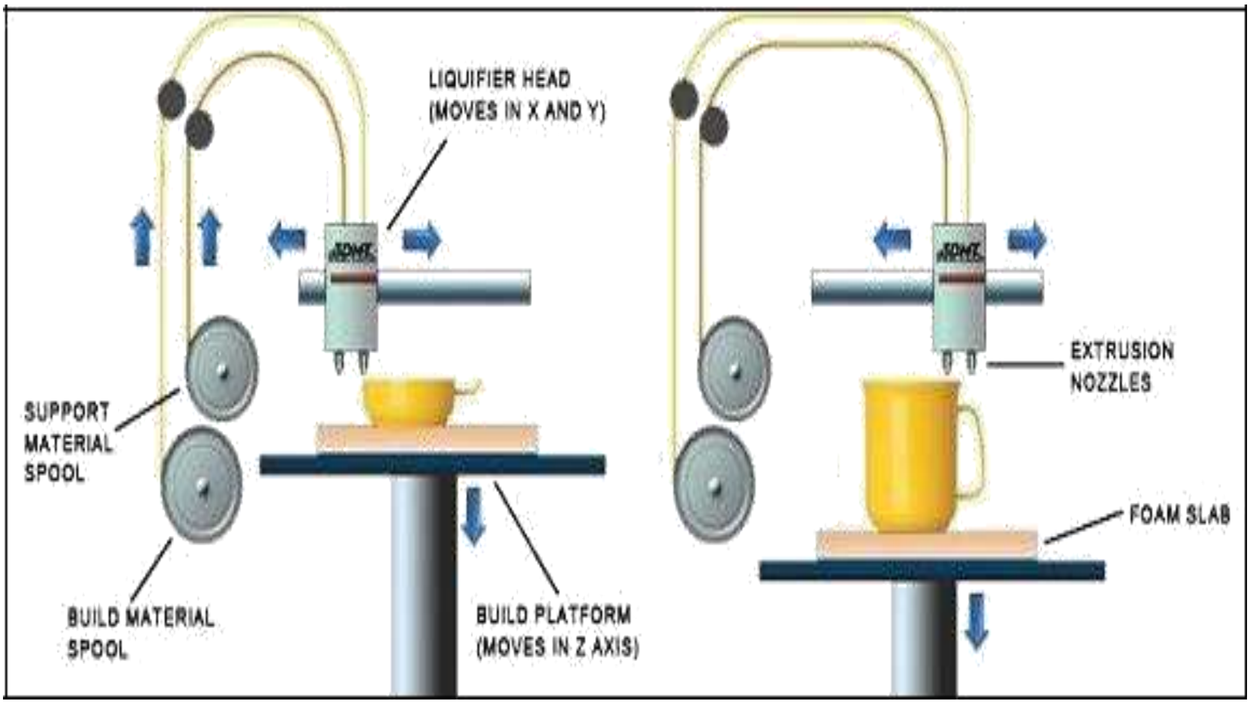

Fig 1.14: Fused Deposition Modelling for making tea cup shape product.

Table 1.4: FDM Material Properties

Material	Tensile Strength (Mpa)	Tensile Modulus (Mpa)	Flexural Strength (Mpa)	Flexural Modulus (Mpa)
ABDP	35.2	1535	66.9	2626
Medical Grade ABSP 500	38	2014	58.9	1810
Investment casting wax (ICWo6)	3.6	282	49.6	282
Elastometer	6.55	282	49.6	141

Advantages and Disadvantages

The main advantages of using FDM technology are as follows:

(1) *Fabrication of functional parts*. FDM process is able to fabricate prototypes with materials that are similar to that of the actual molded product. With ABS, it is able to fabricate fully functional parts that have 85% of the strength of the actual molded part. This is especially useful in developing products that require quick prototypes for functional testing.

(2) *Minimal wastage*. The FDM process build parts directly by extruding semi-liquid melt onto the model. Thus, only those material needed to build the part and its support are needed, and material wastages are kept to a minimum. There is also little need for cleaning up the model after it has been built.

(3) *Ease of support removal*. With the use of Break Away Support System (BASS) and Water Works Soluble Support System, support structures generated during the FDM building process can be easily broken off or simply washed away. This makes it very convenient for users to get to their prototypes very quickly and there is very little or no post-processing necessary.

(4) *Ease of material change*. Build materials, supplied in spool form (or cartridge form in the case of the Dimension or Prodigy Plus), are easy to handle and can be changed readily when the materials in the system are running low. This keeps the operation of the machine simple and the maintenance relatively easy.

The main disadvantages of using FDM technology are as follows:

(1) *Restricted accuracy*. Parts built with the FDM process usually have restricted accuracy due to the shape of the material used, i.e., the filament form. Typically, the filament used has a diameter of 1.27 mm and this tends to set a limit on how accurately the part can be built.

(2) *Slow process*. The building process is slow, as the whole cross-sectional area needs to be filled with building materials. Building speed is restricted by the extrusion rate or the flow rate of the build material from the extrusion head. As the build material used are plastics and their viscosities are relatively high, the build process cannot be easily speeded up.

(3) *Unpredictable shrinkage*. As the FDM process extrudes the build material from its extrusion head and cools them rapidly on deposition, stresses induced by such rapid cooling invariably are introduced into the model. As such, shrinkages and distortions caused to the model built are a common occurrence and are usually difficult to predict, though with experience, users may be able to compensate for these by adjusting the process parameters of the machine.

FDM Applications

FDM models can be used in the following general applications areas:

(1) *Models for conceptualization and presentation*. Models can be marked, sanded, painted and drilled and thus can be finished to be almost like the actual product.

(2) *Prototypes for design, analysis and functional testing*. The system can produce a fully functional prototype in ABS. The resulting ABS parts have 85% of the strength of the actual molded part. Thus actual testing can be carried out, especially with consumer products.

(3) *Patterns and masters for tooling*. Models can be used as patterns for investment casting, sand casting and molding.

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DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – II – RAPID PROTOTYPING TECHNIQUES – SPR1616

Selective Laser Sintering (SLS)

Selective Laser Sintering is a rapid prototyping process that builds models from a wide variety of materials using an additive fabrication method. SLS was developed by University of Texas Austin in 1987. The build media for SLS comes in powder form which is fused together by a powerful carbon dioxide laser to form the final products. DTM sinter station 2500 is the machine used for the process. SLS begins like other rapid prototyping processes with a standard.

.STL CAD file format. DTM view software uses the .STL files. This software do the required orientation and scaling of parts. This machine has auto nesting capabilities which will place multiple part optimally in the build chamber for best processing speed and results. Once the .STL file is placed and parameters are set the model is directly built from the sile. Figure 2.1 shows Selective laser sintering process

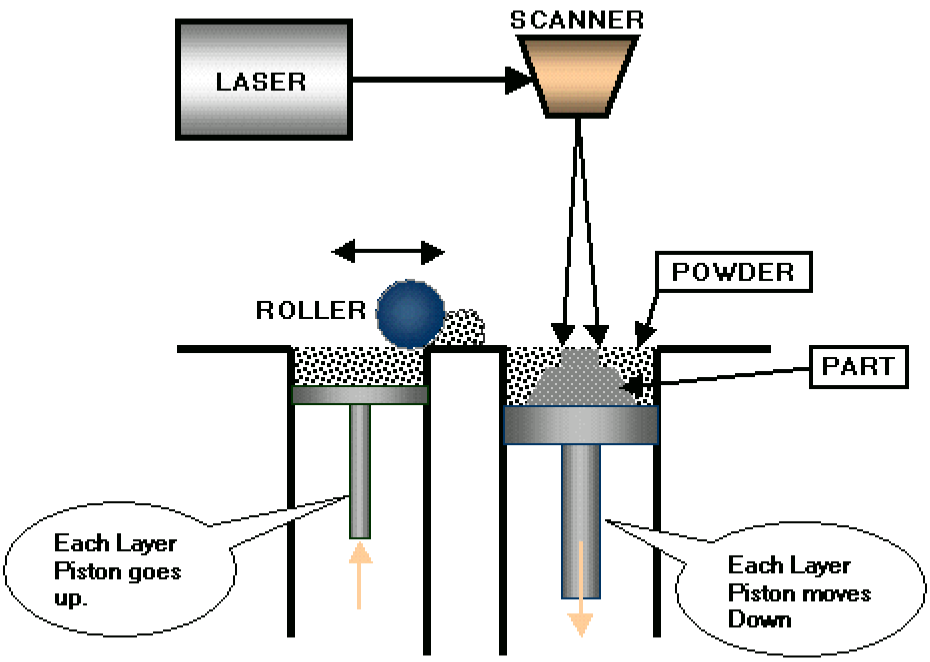

Fig 2.1: Selective laser sintering process

The sinter station has built piston at the center and feed piston on the either side. The model is build layer by layer like other rapid prototyping process so that the build piston will begin at the top of its range and will lower in increments of the set layer size as parts are built. With the build piston at the top a thin layer of powder is spread across the build area by the roller from one of the feed piston. The laser then cures in a raster sweeps motion across the area of the parts being built. The part piston lowers and more powder is deposited and the process is continued until all of the part is built. The build media is removed from the machine. It is a cake of powder. This cake is taken to the breakout station where excess powder is removed from the part manually with brushes the excess powder that has been removed can be kept for recycling and can be reused. Some material needs additional finishing. Some of the finishing techniques include grid blasting, sanding, polishing, drilling, toping and coating.

PURPOSE OF SELECTIVE LASER SINTERING

To avoid a prototyping tool.

To decrease the time and cost of design to product cycle.

It can use wide variety of materials to accommodate multiple application throughout the manufacturing process.

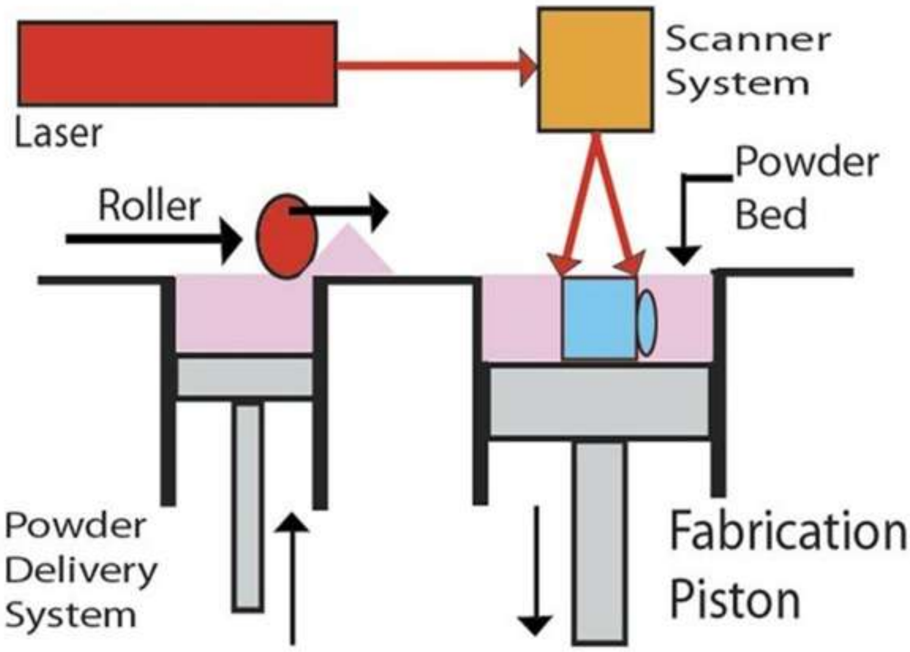

Fig 2.2: Selective laser sintering process

APPLICATIONS

- As conceptual models
- Functional prototypes
- As pattern masters

ADVANTAGES

- Wide range of build material
- High throughput capabilities
- Self-supporting build envelop
- Parts are completed faster
- Damage is less
- Less wastage of material

DISADVANTAGES

- Initial cost of system is high
- High operational and maintenance cost
- Peripheral and facility requirement

In Selective Laser Sintering (SLS) process, fine polymeric powder like polystyrene, polycarbonate or polyamide etc. (20 to 100 micrometer diameter) is spread on the substrate using a roller. Before starting CO2 laser scanning for sintering of a slice the temperature of the entire bed is raised just below its melting point by infrared heating in order to minimize thermal distortion (curling) and facilitate fusion to the previous layer. The laser is modulated in such away that only those grains, which are in direct contact with the beam, are affected. Once laser scanning cures a slice, bed is lowered and powder feed chamber is raised so that a covering of powder can be spread evenly over the build area by counter rotating roller. In this process support structures are not required as the unsintered powder remains at the places of support structure. It is cleaned away and can be recycled once the model is complete. The schematic diagram of a typical SLS apparatus is given

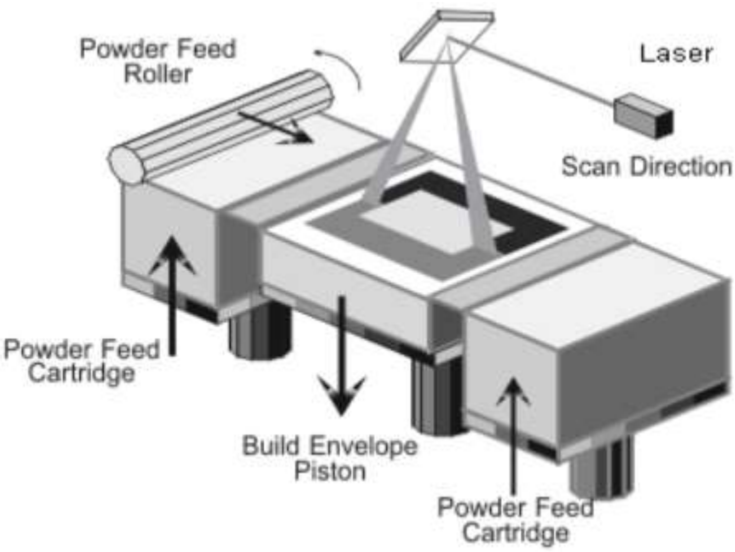

Fig 2.3: Selective Laser Sintering 3D view

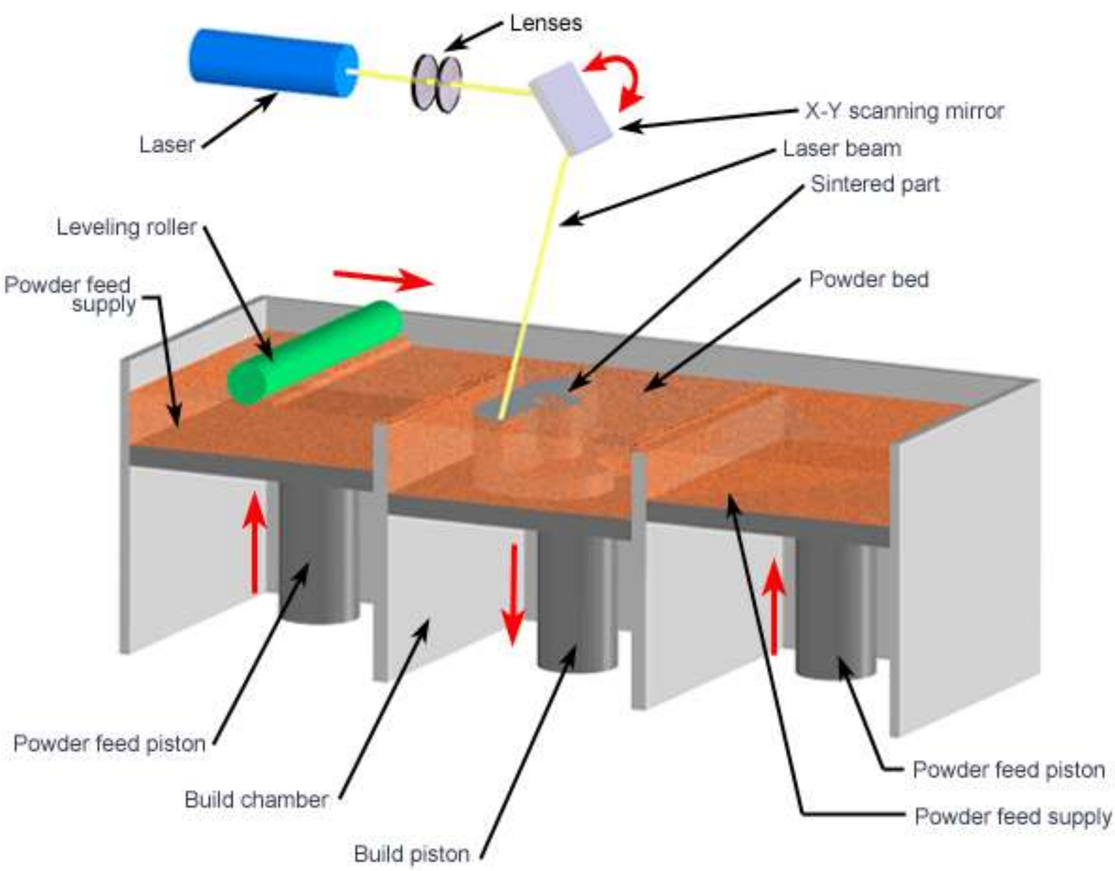

Fig 2.4: Selective laser sintering process

Company

3D Systems Corporation was founded by Charles W. Hull and Raymond S. Freed in 1986. The founding company, DTM Corporation, was established in 1987 to commercialize the SLS® technology. With the financial support from the BF Goodrich Company, and based on the technology that was developed and patented at the University of Texas at Austin, the company shipped its first commercial machine in 1992. DTM had worldwide exclusive license to commercialize the SLS® technology until they were bought over by 3D Systems in August 2001. 3D Systems' head office address is 26081 Avenue Hall, Valencia, CA91355, USA.

Products

Model and Specifications

In the last decade, the SLS® system has gone through three generations of products: the Sinter station 2000, Sinterstation 2500 and the Sinterstation 2500^{plus} (see Figure 2.3). The latest and fourth generation SLS® system is the Vanguard^{TM}. The system is capable of producing objects measuring up to 380 mm (15 inches) length by 330 mm (13 inches) width by 380 mm (15 inches) in height, accommodating most rapid prototyping applications. The new Vanguard™ system offers several significant improvements over the previous generation systems such as improved part accuracy, higher speed, smoother surface finish and finer resolution. A summary of the specifications for the Vanguard™ si2™ is found in Table 5.1. The SLS® process is the only technology with the capability to directly process a variety of engineering thermoplastic materials, metallic materials, ceramic materials, and thermoplastic composites.

Advantages

(1) *Good part stability*. Parts are created within a precise controlled environment. The process and materials provide for directly produced functional parts to be built.

(2) *Wide range of processing materials*. A wide range of materials including nylon, polycarbonates, metals and ceramics are available, thus providing flexibility and a wide scope of functional applications.

(3) *No part supports required*. The system does not require CAD-developed support structures. This saves the time required for support structure building and removal.

(4) *Little post-processing required*. The finishing of the part is reasonably fine and requires only minimal post-processing such as particle blasting and sanding.

(5) *No post-curing required*. The completed laser sintered part is generally solid enough and does not require further curing.

(6) *Advanced software support*. The New Version 2.0 software uses a Windows® NT-style graphical user interface (GUI). Apart from the basic features, it allows for streamlined parts scaling, advanced nonlinear parts scaling, in-progress part changes, build report utilities and is available in foreign languages.

Disadvantages

(1) *Large physical size of the unit*. The system requires a relatively large space to house it. Apart from this, additional storage space is required to house the inert gas tanks used for each build.

(2) *High power consumption*. The system requires high power consumption due to the high wattage of the laser required to sinter the powder particles together.

(3) *Poor surface finish*. The as-produced parts tend to have poorer surface finish due to the relatively large particle sizes of the powders used.

Table 2.1: Summary specifications of 3D Systems' Vanguard™ si2™ SLS® system

Model	Vanguard™ si2™ SLS®
Process	Selective Laser Sintering
Laser type	CO_2
Laser power (W)	25 or 100
Spot size (mm)	0.47
Maximum scan speed (mm/s)	7500 (standard beam delivery system) 10 000 (Celerity™ BDS)
XY resolution (mm)	0.178
Work volume, *XYZ (*mm)	370 x 320 x 445
Minimum layer thickness (mm)	0.076
Size of unit, *XYZ* (m)	2.1 x 1.3 x 1.9
Layering time per layer (s)	10 s
Data control unit	933 MHz Pentium III Windows 2000 OS
Power supply	240 V_{AC}, 12.5 kVA, 50/60 Hz, 3-phase

Process

The SLS® Process

The SLS® process creates three-dimensional objects, layer by layer, from CAD-data generated in a CAD software using powdered materials with heat generated by a CO_2 laser within the Vanguard™ system. CAD data files in the STL file format are first transferred to the Vanguard™ system where they are sliced. From this point, the SLS® process starts and operates as follows:

(1) A thin layer of heat-fusible powder is deposited onto the part-building chamber.

(2) The bottom-most cross-sectional slice of the CAD part under fabrication is selectively "drawn" (or scanned) on the layer of powder by a heat-generating CO_2 laser. The interaction of the laser beam with the powder elevates the temperature to the point of melting, fusing the powder particles to form a solid mass. The intensity of the laser beam is modulated to melt the powder only in areas defined by the part's geometry. Surrounding powder remain a loose compact and serve as supports.

(3) When the cross-section is completely drawn, an additional layer of powder is deposited via a roller mechanism on top of the previously scanned layer. This prepares the next layer for scanning.
(4) Steps 2 and 3 are repeated, with each layer fusing to the layer below it. Successive layers of powder are deposited and the process is repeated until the part is completed.

As SLS® materials are in powdered form, the powder not melted or fused during processing serves as a customized, built-in support structure. There is no need to create support structures within the CAD design prior to or during processing and thus no support structure to remove when the part is completed.

After the SLS® process, the part is removed from the build chamber and the loose powder simply falls away. SLS® parts may then require some post-processing or secondary finishing, such as sanding, lacquering and painting, depending upon the application of the prototype built.

The SLS® system contains the following hardware components:

(1) Build chamber dimensions (381 x 330 x 457 mm)
(2) Process station (2100 x 1300 x 1900 mm)
(3) Computer cabinet (600 x 600 x 1828 mm)
(4) Chiller (500 x 800 x 900 mm)

The software that comes with the Vanguard™ si2™ SLS® System includes the Windows 2000 operating system and other proprietary application software such as the slicing module, automatic part distribution module, and part modification application software.

Materials

In theory, a wide range of thermoplastics, composites, metals and ceramics can be used in this process, thus providing an extensive range of functional parts to be built. The main types of materials used in the Vanguard™ si2™ SLS® System are safe and non-toxic, easy to use, and can be easily stored, recycled, and disposed off. These are as follows [2]:

- *Polyamide*. Trade named "DuraForm™", this material is used to create rigid and rugged plastic parts for functional engineering environments. This material is durable, can be machined or even welded where required. A variation of this material is the polyamide-based composite system, incorporating glass-filled powders, to produce even more rugged engineering parts. This composite material improves the resistance to heat and chemicals.
- *Thermoplastic elastomer*. Flexible, rubber-like parts can be prototyped using the SLS. Trade named, "SOMOS® 201", the material produces parts with high elongation. Yet, it is able to resist abrasion

and provides good part stability. The material is impermeable to water and ideal for sports shoe applications and engineering seals.

- *Polycarbonate*. An industry-standard engineering thermoplastic. These are suitable for creating concept and functional models and prototypes, investment casting patterns for metal prototypes and cast tooling (with the RapidCasting^{TM} process), masters for duplication processes, and sand casting patterns. These materials only require a 10–20 W laser to work and are useful for visualizing parts and working prototypes that do not carry heavy loads. These parts can be built quickly and are excellent for prototypes and patterns with fine features.
- *Nylon*. Another industry-standard engineering thermoplastic. This material is suitable for creating models and prototypes that can withstand and perform in demanding environment. It is one of the most durable rapid prototyping materials currently available in the industry, and it offers substantial heat and chemical resistance. A variation of this is the *Fine Nylon* and is used to create fine-featured parts for working prototypes. It is durable, resistant to heat and chemicals, and is excellent when fine detail is required.
- *Metal*. This is a material where polymer coated stainless steel powder is infiltrated with bronze. Trade named "LaserForm ST-100", the material is excellent for producing core inserts and pre-production tools for injection molding prototype polymer parts. The material exhibits high durability and thermal conductivity and can be used for relatively large-scale production tools. An alternative material is the copper polyamide metal–polymer composite system which can be applied to tooling for injection molding small batch production of plastic parts.
- *Ceramics*. Trade named "SandForm^{TM} Zr" and "Sandform^{TM} Si", these use zircon and silica coated with phenolic binder to produce complex sand cores and molds for prototype sand castings of metal parts.

Principle

The SLS® process is based on the following two principles:

(1) Parts are built by sintering when a CO_2 laser beam hits a thin layer of powdered material. The interaction of the laser beam with the powder raises the temperature to the point of melting, resulting in particle bonding, fusing the particles to themselves and the previous layer to form a solid.

(2) The building of the part is done layer by layer. Each layer of the building process contains the cross-sections of one or many parts. The next layer is then built directly on top of the sintered layer after an additional layer of powder is deposited via a roller mechanism on top of the previously

formed layer.

The packing density of particles during sintering affects the part density. In studies of particle packing with uniform sized particles [3] and particles used in commercial sinter bonding [4], packing densities were found to range typically from 50% to 62%. Generally, the higher the packing density, the better would be the expected mechanical properties. However, it must be noted that scan pattern and exposure parameters are also the major factors in determining the mechanical properties of the part.

Applications

The Vanguard™ si2™ SLS® system can produce a wide range of parts in a broad variety of applications, including the following:

(1) *Concept models*. Physical representations of designs used to review design ideas, form and style.

Functional models and working prototypes. Parts that can withstand limited functional testing, or fit and operate within an assembly

(3) *Polycarbonate (RapidCasting™) patterns*. Patterns produced using polycarbonate, then cast in the metal of choice through the standard investment casting process. These build faster than wax patterns and are ideally suited for designs with thin walls and fine features. These patterns are also durable and heat resistant.

(4) *Metal tools (RapidTool™)*. Direct rapid prototype of tools of molds for small or short production runs.

LAMINATED OBJECT MANUFACTURING (LOM)

Introduction

Laminated Object Manufacturing is a rapid prototyping technique that produces 3D models with paper, plastics or composites. LOM was developed by Helices Corporation, Torrance, California. LOM is actually more of a hybrid between subtractive and additive process. In that models are built up with layers of cross section of the part. Hence as layers are been added, the excess material is not required for that cross section is being cut away. LOM is one of the fastest RP processes for parts with longer cross sectional areas which make it ideal producing large parts.

System Hardware

1. LOM system is available in two sizes.

- LOM 1015 produces parts up to 10×15×14 inches
- LOM 2030 produces parts up to 20×30×24 inches

2. Common build material is paper
3. Build material has pressure and heat sensitive additive on the banking
4. Material thickness ranges from 0.0038 – 0.005 inches.

Softwares

LOM SLICES SOFTWARE

It provides interface between operator and the system. LOM does not require a pre slice of STL FILE i.e. once the parameters are loaded into LOM SLICE, the STL file slices as the part builds. The process of continuous slicing is called slice on the fly. The LOM has a feed spindle and a take up spindle for the build material. The feed spindle holds the roll of virgin material whereas the take up spindle serves to store the excess material after the layer is cut. A heated roller travels across the face of the part being after each layer to activate adhesive and bond the part layer together.

An invisible 25Watts CO_2 laser is housed on the back of the LOM and reflected off three mirrors before finally passing through a focusing lens on the carriage. The carriage moves in the X firection and the lens moves in the Y direction on the carriage, thus allowing focal cutting point of laser to be moved like a plotter pen while cutting through build material in the shape desired.

This X and Y movements allows for two degrees of freedom or essentially a 2-D sketch of part cross section. The part being built is adhered to a removable metal plate which holds the part stationary until it is completed. The plate is bolted to the platen with brackets and moves in the Z direction by means of a large threaded shaft to allow the parts to be built up. This provides the third degree of freedom where in the LOM is able to build 3D models.

Some smoke and other vapors are created since the LOM functions by essentially burning through the sheets of materials with a laser, therefore LOM must be ventilated either to the outside air or through a large filtering device at rates around 500 cubic feet per minute.

LOM OPERATION

The way the LOM constructs the parts is by consecutively adhering layers of build material while cutting the cross section of the parts with a laser. The LOM SLICE software that comes with LOM machine controls all these. The following description of operation is described with paper as build material.

SOFTWARE

1. As with all RP systems, the LOM must begin with the standard RP computer file or STL file
2. The STL file is loaded into the LOM SLICE which graphically represents the model on the screen.
3. Upon loading the STL file, LOM SLICE creates initializing files in the background for controlling the LOM machine. Now there are several parameters the user must consider and enter before building the part.

PART ORIENTATION

The designed shape of the parts to be built in LOM must be evaluated for determining the orientation in which to build the parts.

FIRST CONSIDERATION

Accuracy Desired for Curved Surfaces

Parts with curved surfaces tend to have a better finish if the curvatures of the cross sections are cut in the XY plane. This is true due to the fact that the controlled motion of the laser cutting than the layered effects of XY and YZ planes.

If a part contains curvatures in more than one plane, one alternative is to build the Part at an angle to the axis. The benefits here are too full as the part will not only have more accurate curvatures but will also tend to have better laminar strength across the length of the part.

SECOND CONSIDERATION

Time taken to fabricate a part

The slowest aspect of build process for LOM is movement in Z direction or time between the layers. This is mainly because after laser cuts across the surface of the beam material, the LOM must bring more paper across the top face of the part and then adhere to the previous layer before the laser can begin cutting again.

For this reason, a general rule has come for orientation long narrow parts is to place the lengthiest sections in the XY plane. This way the slowest part of the process the actual laser cutting is minimized to a smaller number of layers.

These are some third-party software renders that have automatic testing functions that will strategically place parts in optimum orientations for the selected sections.

Cross hatching

Cross Hatching is necessary to get rid of excess paper on the individual layers. Cross hatch is set in LOM SLICE by the operator and can vary throughout the part. Basically, the operator puts in a range of layers for which we want a certain cross hatch pattern for sections of the part that do not have integrate features or cavities, a larger cross hatch can be set to make a part build faster but for thin walled sections and hollowed out areas, a finer cross hatch will be easier to remove. The cross-hatch size is given in values of X and Y. Therefore, the hatch pattern can vary from square to long thin rectangles.

The two main considerations for cross hatching are

- Ease of part removed
- Resulting build time

A very small hatch size will make for easy part removal. However, if the part is rather large or has large void area it can really slow down the build time. This is the reason for having varying cross hatch sizes throughout the part.

The LOM operator can either judge where and how the part should be cross hatched visually or use long slice to run a simulation build on the computer screen to determine layer ranges for the needed hatch sizes.

Also since the LOM SLICE creates slices as the part build parameters can be changed during a build simply by pausing a LOM machine and typing in new cross hatch values.

System Parameters

There are various controlling parameters such as laser powder, heater speed, and material advance margin and support wall thickness and heater compression.

Laser Power

It is the percentage of total laser output wattage.

For e.g. LOM 1015 is operated at a laser power of about 9% of maximum 25W laser or approximately 2.25 W. This value will be different for various materials or machines but essentially it is set to cut through only one sheet of build material.

Heater Speed

It is the rate at which hot roller passes across the top of the part. The rate given in inches/second. It is usually 6”/sec for initial pass and 3”/sec for returning pass of heater. The heater speed effects the lamination of the sheet so it must be set low enough to get a good bond between layers.

Material Advance

It is the distance the paper is advanced in addition to length of the part.

Support Wall Thickness.

It controls the outer support box walls throughout a part. The support wall thickness is generally set 0.25” in the Margin X and Y direction, although this value can be changed by operator.

Compression

It is used to set the pressure that the heater roller exerts on the layer. It is measured in inches which are basically the distance the roller is lifted from its initial track by the top surface of part. Values for compression will vary for different machines and materials, but are typically 0.015”-0.025”.

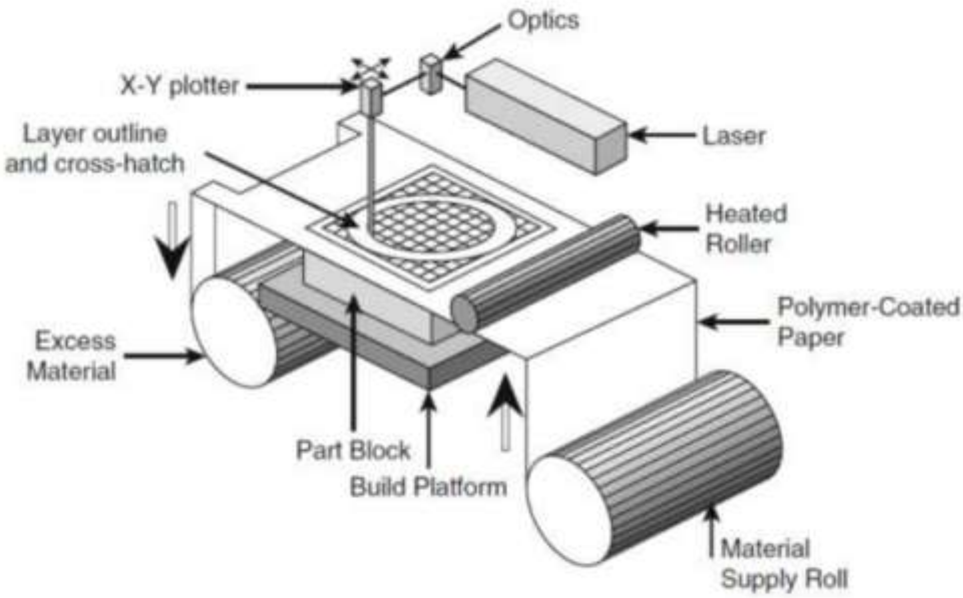

Fig 2.5: Laminated Object Manufacturing

Company

Cubic Technologies was established in December 2000 by Michael Feygin, the inventor who developed Laminated Object Manufacturing® (LOM™). In 1985, Feygin set up the original company, Helisys Inc., to market the LOM™ rapid prototyping machines. However, sales figures did not meet up to expectations [1] and the company ran into financial difficulties. Helisys Inc. subsequently ceased operation in November 2000. Currently, Cubic Technologies, the successor to Helisys Inc., is the exclusive manufacturer of the LOM™ rapid prototyping machine. The company's address is Cubic Technologies Inc., 100E, Domingnez Streets, Carson, California 90746-3608, USA.

Products

Models and Specifications

Cubic Technologies offers two models of LOM™ rapid prototyping systems, the LOM-1015Plus™ and LOM-2030H™. Both these systems use the CO_2 laser, with the LOM-1015Plus™ operating a 25 W laser and the LOM-2030H™ operating a 50 W laser. The optical system, which delivers a laser beam to the top surface of the work, consists of three mirrors that reflect the CO_2 laser beam and a focal lens that focuses the laser beam to about 0.25 mm (0.010"). The control of the laser during cutting is by means of a *XY* positioning table that is servo-based as opposed to the galvanometer mirror system. The LOM-2030H™ is a larger machine and produces larger prototypes. The work volume of the LOM-2030H™ is 810 mm x 550 mm x 500 mm (32" x 22" x 20") and that of the LOM-1015Plus™ is 380 mm x 250 mm x 350 mm (15" x 10" x 14"). Detailed specifications of the two machines are summarized in Table

Process

The patented Laminated Object Manufacturing® (LOM™) process [2–4] is an automated fabrication method in which a 3D object is constructed from a solid CAD representation by sequentially laminating the part. cross-sections. The process consists of three phases: pre-processing; building; post-processing.

Pre-processing

The pre-processing phase comprises several operations. The initial steps include generating an image from a CAD-derived STL file of the part to be manufactured, sorting input data, and creating secondary data structures. These are fully automated by LOMSlice™, the LOM™ system software, which calculates and controls the slicing functions. Orienting and merging the part on the LOM™ system are done manually. These tasks are aided by LOMSlice™, which provides a menu-driven interface to perform transformations (e.g., translation, scaling, and mirroring) as well as merges.

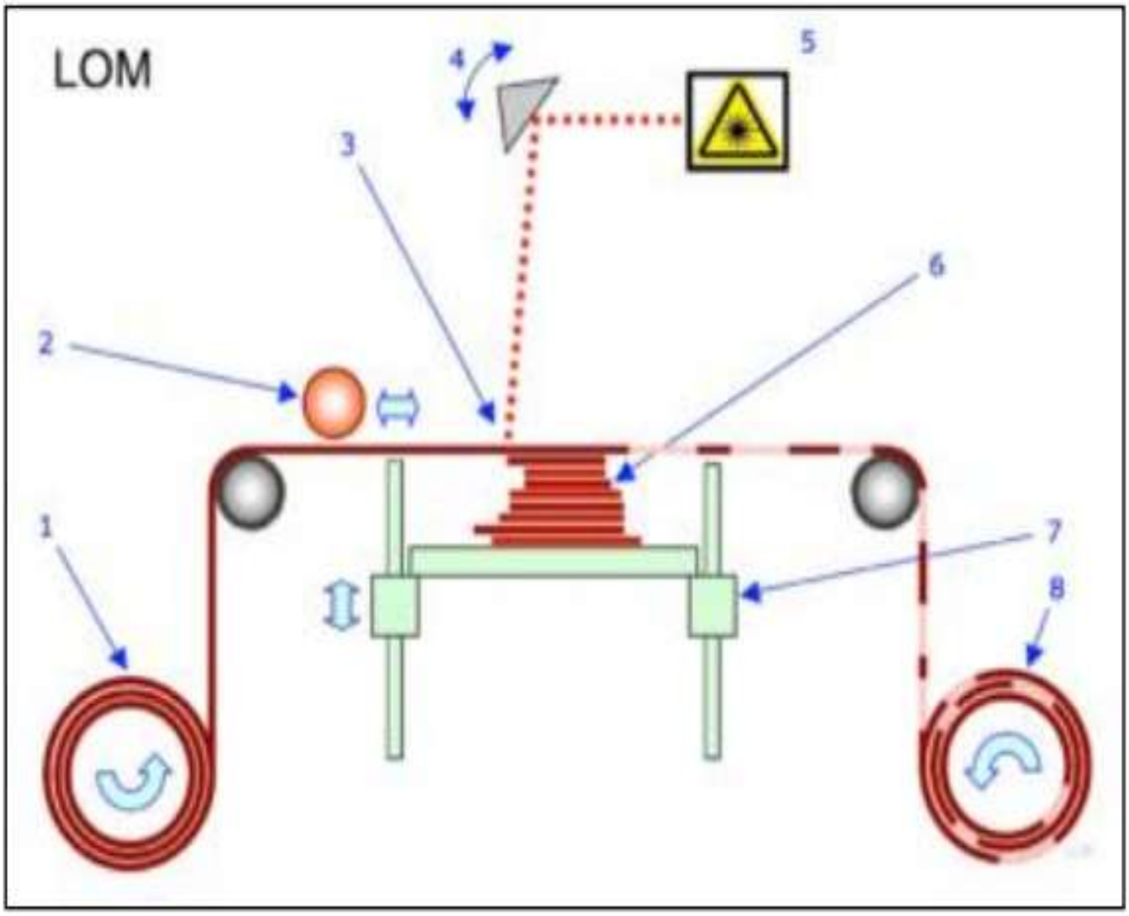

Fig 2.6: Laminated Object Manufacturing

Table 2.2: Specifications of LOM-1015Plus™ and LOM-2030H

Model	LOM-1015Plus™	LOM-2030H™
Max. part envelope	L381 x W254 x H356	L813 □ W559 □ H508
size, mm (in)	(L15 x W10 x H14)	(L32 □ W22 □ H20)
Max. part weight, kg (lbs)	32 (70)	204 (405)
Laser, power and type	Sealed 25 W, CO_2 Laser	Sealed 50 W, CO_2 Laser

Laser beam diameter, mm (in)	0.20–0.25 (0.008–0.010)	0.203–0.254 (0.008–0.010)
	Servo-based *X–Y* motion	Brushless servo-based *X–Y*
	systems with a speed up to	motion dystems with a speed
Motion control	457 mm/sec (18"/sec);	up to 457 mm/sec (18"/sec);
	Typical *Z*-platform	Typical *Z*-platform feedback
	feedback for motion system	for motion system
Part accuracy *XYZ* directions, mm (in)	±0.127 mm (±0.005 in)	±0.127 mm (±0.005 in)
Material thickness, mm (in)	0.08–0.25,	0.076–0.254,
Material size	Up to 356 mm (14") roll	Up to 711 mm (28") roll
Floor space, m (ft)	3.66 x 3.66 (12 x 12)	4.88 x 3.66 (16 x 12)
Power	Two (2) 110VAC, 50/60Hz, 20 Amp, single phase Two (2) 220VAC, 50/60 Hz, 15 Amp, single phase	220VAC, 50/60 Hz, 30 Amp,single phase
	LOMPaper® LPH series,	LOMPaper® LPH series,
Materials	LPS series LOMPlastics® LPX series	LPS series LOMPlastics® LPX series, LOMComposite® LGF series

Building

In the building phase, thin layers of adhesive-coated material are sequentially bonded to each other and individually cut by a CO_2 laser beam. The build cycle has the following steps:

(1) LOMSlice™ creates a cross-section of the 3D model measuring the exact height of the model and slices the horizontal plane accordingly. The software then images crosshatches which define the outer perimeter and convert these excess materials into a support structure.

(2) The computer generates precise calculations, which guide the focused laser beam to cut the cross-sectional outline, the cross-hatches, and the model's perimeter. The laser beam power is designed

to cut exactly the thickness of one layer of material at a time. After the perimeter is burned, everything within the model's boundary is "freed" from the remaining sheet.

(3) The platform with the stack of previously formed layers descends and a new section of material advances. The platform ascends and the heated roller laminates the material to the stack with a single reciprocal motion, thereby bonding it to the previous layer.

(4) The vertical encoder measures the height of the stack and relays the new height to LOMSlice^{TM}, which calculates the cross section for the next layer as the laser cuts the model's current layer.

This sequence continues until all the layers are built. The product emerges from the LOM^{TM} machine as a completely enclosed rectangular block containing the part.

Materials

Potentially, any sheet material with adhesive backing can be utilized in Laminated Object Manufacturing. It has been demonstrated that plastics, metals, and even ceramic tapes can be used. However, the most popular material has been Kraft paper with a polyethylene-based heat seal adhesive system because it is widely available, cost-effective, and environmentally benign [

In order to maintain uniform lamination across the entire working envelope it is critical that the temperature remain constant. A temperature control system, with closed-loop feedback, ensures the system's temperature remains constant, regardless of its surrounding environment.

Principle

The LOM^{TM} process is based on the following principles:

(1) Parts are built, layer-by-layer, by laminating each layer of paper or other sheet-form materials and the contour of the part on that layer is cut by a CO_2 laser.

(2) Each layer of the building process contains the cross-sections of one or many parts. The next layer is then laminated and built directly on top of the laser-cut layer.

(3) The *Z*-control is activated by an elevation platform, which lowers when each layer is completed, and the next layer is then laminated and ready for cutting. The *Z*-height is then measured for the exact height so that the corresponding cross sectional data can be calculated for that layer.

(4) No additional support structures are necessary as the "excess" material, which are cross-hatched for later removal, act as the support.

Advantages and Disadvantages

The main advantages of using LOM technology are as follows:

(1) *Wide variety of materials*. In principle, any material in sheet form can be used in the LOM^{TM} systems. These include a wide variety of organic and inorganic materials such as paper, plastics, metals, composites and ceramics. Commercial availability of these materials allows users to vary the type and thickness of manufacturing materials to meet their functional requirements and specific applications of the prototype.

(2) *Fast build time*. The laser in the LOM^{TM} process does not scan the entire surface area of each cross-section, rather it only outlines its periphery. Therefore, parts with thick sections are produced just as quickly as those with thin sections, making the LOM^{TM} process especially advantageous for the production of large and bulky parts.

(3) *High precision*. The feature to feature accuracy that can be achieved with LOM^{TM} machines is usually better than 0.127 mm (0.005"). Through design and selection of application specific parameters, higher accuracy levels in the X–Y and Z dimensions can be achieved. If the layer does shrink horizontally during lamination, there is no actual distortion as the contours are cut post-lamination, and laser cutting itself does not cause shrinkage. If the layers shrink in the transverse direction, a closed-loop feedback system gives the true cumulative part height upon each lamination to the software, which then slices the 3D model with a horizontal plane at the appropriate location.

The LOM^{TM} system uses a precise X–Y positioning table to guide the laser beam; it is monitored throughout the build process by the closed-loop, real-time motion control system, resulting in an accuracy of ±0.127 mm regardless of the part size. The Z-axis is also controlled using a real-time, closed-loop feedback system. It measures the cumulative part height at every layer and then slices the CAD geometry at the exact Z location. Also, as the laser cuts only the perimeter of a slice there is no need to translate vector data into raster form, therefore the accuracy of the cutting depends only on the resolution of the CAD model triangulation.

(4) *Support structure*. There is no need for additional support structure as the part is supported by its own material that is outside the periphery of the part built. These are not removed during the LOM^{TM} process and therefore automatically act as supports for its delicate or overhang features.

(5) *Post-curing*. The LOM^{TM} process does not need to convert expensive, and in some cases toxic, liquid polymers to solid plastics or plastic powders into sintered objects. Because sheet materials are not subjected to either physical or chemical phase changes, the finished LOM^{TM} parts do not experience warpage, internal residual stress, or other deformations.

The main disadvantages of using LOM are as follows:

(1) *Precise power adjustment*. The power of the laser used for cutting the perimeter (and the crosshatches) of the prototype needs to be precisely controlled so that the laser cuts only the current layer of lamination and not penetrate into the previously cut layers. Poor control of the cutting laser beam may cause distortion to the entire prototype.

(2) *Fabrication of thin walls*. The LOM^{TM} process is not well suited for building parts with delicate thin walls, especially in the *Z*-direction. This is because such walls usually are not sufficiently rigid to withstand the post-processing process when the cross-hatched outer perimeter portion of the block is being removed. such delicate parts are located in the model and take sufficient precautions so as not to damage these parts.

(3) *Integrity of prototypes*. The part built by the LOM^{TM} process is essentially held together by the heat sealed adhesives. The integrity of the part is therefore entirely dependent on the adhesive strength of the glue used, and as such is limited to this strength. Therefore, parts built may not be able to withstand the vigorous mechanical loading that the functional prototypes may require.

(4) *Removal of supports*. The most labor-intensive part of the LOM^{TM} process is its last phase of post-processing when the part has to be separated from its support material within the rectangular block of laminated material. This is usually done with wood carving tools and can be tedious and time consuming. The person working during this phase needs to be careful and aware of the presence of any delicate parts within the model so as not to damage it.

Applications

(1) *Visualization*. Many companies utilize LOM^{TM}'s ability to produce exact dimensions of a potential product purely for visualization. LOM^{TM} part's wood-like composition allows it to be painted or finished as a true replica of the product. As the LOM^{TM} procedure is inexpensive several models can be created, giving sales and marketing executives opportunities to utilize these prototypes for consumer testing, marketing product introductions, packaging samples, and samples for vendor quotations.

(2) *Form, fit and function*. LOM^{TM} parts lend themselves well for design verification and performance evaluation. In low-stress environments LOM^{TM} parts can withstand basic tests, giving manufacturers the opportunity to make changes as well as evaluate the aesthetic property of the prototype in its total environment.

(3) *Manufacturing*. The LOM^{TM} part's composition is such that, based on the sealant or finishing products used, it can be further tooled for use as a pattern or mold for most secondary tooling

techniques including: investment casting, casting, sanding casting, injection molding, silicon rubber mold, vacuum forming and spray metal molding. LOM^{TM} parts offer several advantages important for the secondary tooling process, namely: predictable level of accuracy across the entire part; stability and resistance to shrinkage, warpage and deformity; and the flexibility to create a master or a mold. In many industries the master created through secondary tooling, or even when the LOM^{TM} part serves as the master (e.g., vacuum forming), withstands enough injections, wax shootings or vacuum pressure to produce a low production run from 5 to 1000 pieces.

(4) *Rapid tooling*. Two part negative tooling is easily created with LOM^{TM} systems. Since the material is solid and inexpensive, bulk complicated tools are cost effective to produce. These wood-like molds can be used for injection of wax, polyurethane, epoxy or other low pressure and low temperature materials. Also, the tooling can be converted to aluminum or steel via the investment casting process for use in high temperature molding processes.

SOLID GROUND CURING (SGC) OR CUBITAL'S SOLID GROUND CURING (SGC)

The early versions of the system weighted several tons and required a sealed room. Size was made more manageable and the system sealed to prevent exposure to photopolymers, but it was still very large. Instead of using a laser to expose and harden photopolymer element by element within a layer as is done in stereolithography, SCG uses a mask to expose the entire object layer at once with a burst of intense UV light. The method of generating the masks is based on electrophotography (xerography)

Highlights

- Large parts of 500×500×350mm can be fabricated quickly
- High speed allows production of amny parts
- Masks are created
- No post curing required.
- Milling step ensures flatness of subsequent layers.
- Wax supports model, hence no extra support is required.
- Create a lot waste.
- Not as prevalent as SLA and SLS but gaining ground because of high throughout and large parts.

PROCESS

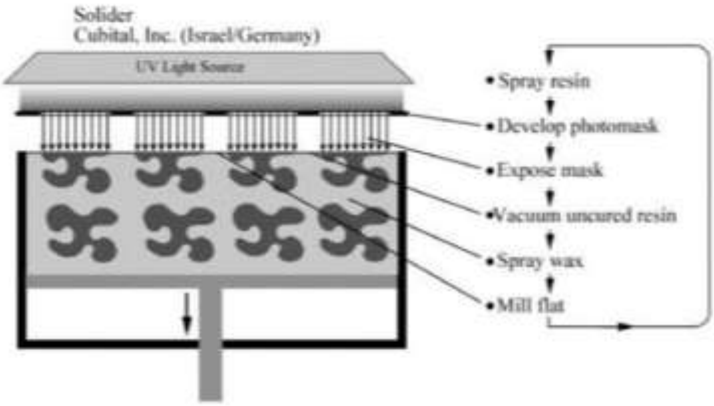

Fig 2.7: Solid ground curing process

1. **Spray Photosensitive resin**

   At the beginning of a layer creation step the flat work surface is sprayed with photosensitive resin**.**

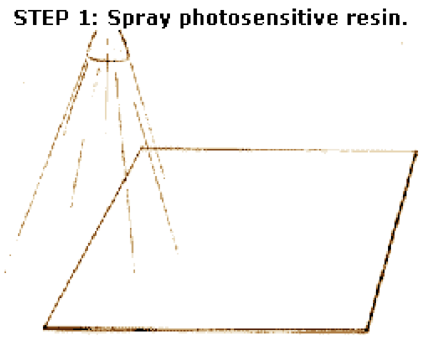

Fig 2.8: Solid ground curing process - Spray Photosensitive resin

2. **Development of Photo mask**

For each layer a photo mask is produced using cubital's proprietary ionographic printing technique.

Fig 2.9: Solid ground curing process - Development of Photo mask

3. **Expose photo mask**

   The photo mask is positioned over the work surface a powerful UV lamp hardens the exposed photosensitive resin.

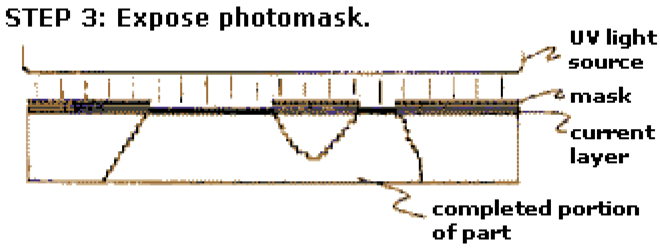

Fig 2.10: Solid ground curing process - Expose photo mask

4. **Vacuum uncured resin and solidify the remnants**

   After the layer is cured all the uncured resin is vacuumed for recycling leaving the hardened area intact the cured is passed beneath a strong linear UV lamp to fullycure in and solidify any remnants particles as shown in fig:

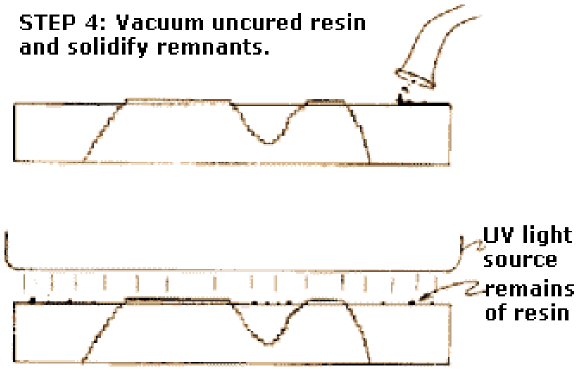

Fig 2.11: Solid ground curing process - Vacuum uncured resin and solidify the remnants

5. **Wax is applied to replace uncured resin area**

   Wax replaces the cavities left by vacuuming the liquid resin. The wax is hardened by cooling to provide continuous solid support for the model as it is fabricated extra support are not needed.

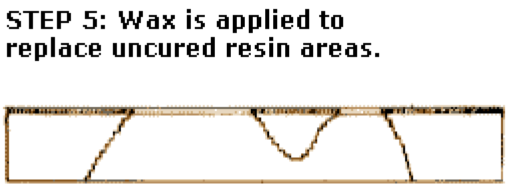

Fig 2.12: Solid ground curing process - Wax is applied to replace uncured resin area

6. **The top surface is milled flat**

   In the final step before the next layer, the wax resin surface is milled flat to an accurate reliable finish for next layer.

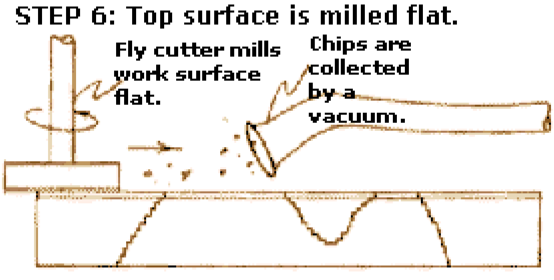

Fig 2.13: Solid ground curing process - The top surface is milled flat

Once all layers are completed the wax is removed and any finishing operations such as sanding etc can be performed no post curing is necessary.

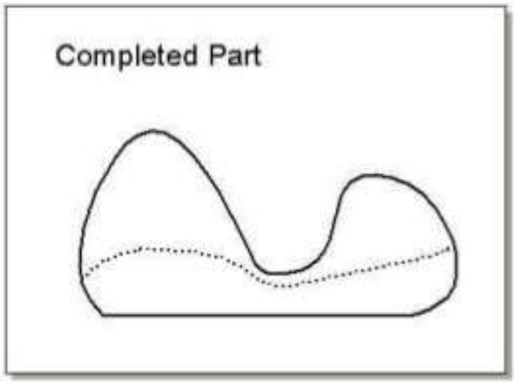

Fig 2.13: Solid ground curing process – Completed part

ADVANTAGES

- The entire layer is solidified at once
- Reduction in the part build time for multipart builds
- Larger prototypes can be nested to utilize the build volume fully
- No post curing is required.

DISADVANTAGES

- The system is large, noisy and heavy
- It wastes a large amount of wax which cannot be recycled
- SCG systems are prone to breakdowns

The resin models of SCG are not suitable for investment casting because coefficient of thermal expansion is more than ceramics in resin which may lead to cracks in casting.

Company

The Solid Ground Curing (SGC) System is produced by Cubital Ltd. and its address is Cubital Ltd., 13 Hasadna St., P.O.B. 2375, Industrial Zone North Raanana, 43650 Israel. Outside Israel, Cubital America Inc. is located at 1307F Allen Drive Troy, MI 48083, USA and Cubital GmbH, at Ringstrasse 132 55543 Bad-Kreuznach, Germany. Cubital Ltd.'s operations began in 1987 as a spin-off from Scitex Corporation and commercial sales began in 1991.

Products

Models and Specifications

Cubital's products include the Solider 4600 and Solider 5600. The Solider 4600 is Cubital's entry level three-dimensional model making system based on Solid Ground Curing. The Solider 5600, Cubital's sophisticated high-end system, provides a wider range and options for the varied modeling demands of Solid Ground Curing. Table 2.1 summarizes the specifications of the two machines.

Cubital's system uses several kinds of resins, including liquid resin and cured resin as materials to create parts, water soluble wax as support material and ionographic solid toner for creating an erasable image of the cross-section on a glass mask.

Process

The Cubital's Solid Ground Curing process includes three main steps: data preparation, mask generation and model making [14].

Data Preparation

In this first step, the CAD model of the job to be prototyped is prepared and the cross-sections are generated digitally and transferred to the mask generator. The software used, Cubital's Solider DFE (Data Front End) software, is a motif-based special-purpose CAD application pack-age that processes solid model CAD files prior to sending them to Cubital Solider system. DFE can search and correct flaws in the CAD files and render files on-screen for visualization purposes. Solider DFE accepts CAD files in the STL format and other widely used formats exported by most commercial CAD systems.

Mask Generation

After data are received, the mask plate is charged through an "image-wise" ionographic process. The charged image is then developed with electrostatic toner.

Table 2.3: Cubital Inc.'s Solider 4600 and 5600 (Source from Cubital Inc.)

Model	**Solider 4600**	**Solider 5600**
Irradiation medium	High power UV lamp	
XY resolution (mm)	Better than 0.1	
Surface definition (mm)	0.15	0.15
Elevator vertical resolution (mm)	0.15	0.1–0.2
Minimum feature size (mm)	0.4 (horizontal, *X*–*Y*) 0.15 (vertical, *Z*)	0.4 (horizontal, *X*–*Y*) 0.15 (vertical, *Z*)
Work volume, *XYZ* (mm *x* mm x mm)	350 x 350 x 350	500 x 350 x 500
Production rate (cm^3/hr)	550	1311
Minimum layer thickness (mm)	0.06	0.06
Dimensional accuracy	0.1%	0.1%
Size of unit, *XYZ* (m x m x m)	1.8 x 4.2 x 2.9	1.8 x 4.2 x 2.9
Data control unit	Data Front End (DFE) workstation	
Power supply	380 –415 V_{AC} , 3 phase, 50 kW	380 –415 V_{AC} , 3 phase, 50 kW

Model Making

In this step, a thin layer of photopolymer resin is spread on the work surface. The photo mask from the mask generator is placed in close proximity above the workpiece, and aligned under a collimated UV lamp (item 3). The UV light is turned on for a few seconds (item 4). The part of the resin layer which is exposed to the UV light through the photo mask is hardened. Note that the layers laid down for exposure to the lamp are actually thicker than the desired thickness. This is to allow for the final milling process. The un-solidified resin is then collected from the workpiece (item 5). This is done by vacuum suction. Following that, melted wax is spread into the cavities created after collecting the liquid resin (item 6). Consequently, the wax in the cavities is cooled to produce a wholly solid layer. Finally, the layer is milled to its exact thickness, producing a flat solid surface ready to receive the next layer (item 7).

In the SGC 5600, an additional step (item 8) is provided for final curing of the layer whereby the workpiece travels under a powerful longitudinal UV lamp. The cycle repeats itself until the final layer is completed.

The main components of the Solider system are:

(1) Data Front End (DFE) workstation.

(2) Model Production Machine (MPM). It includes:

  (i) Process engine,

  (ii) Operator's console,

  (iii) Vacuum generator.

(3) Automatic Dewaxing Machine (optional).

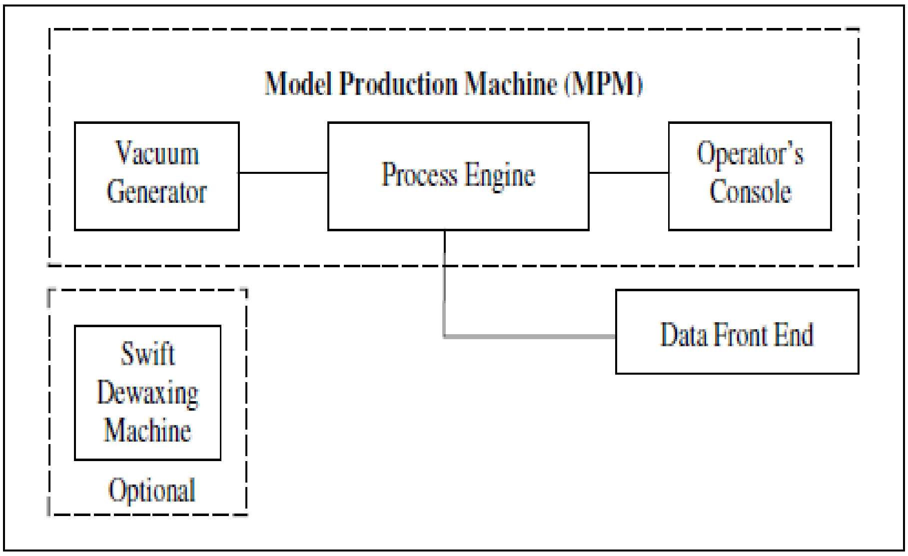

Fig 2.14: Solider system block diagram

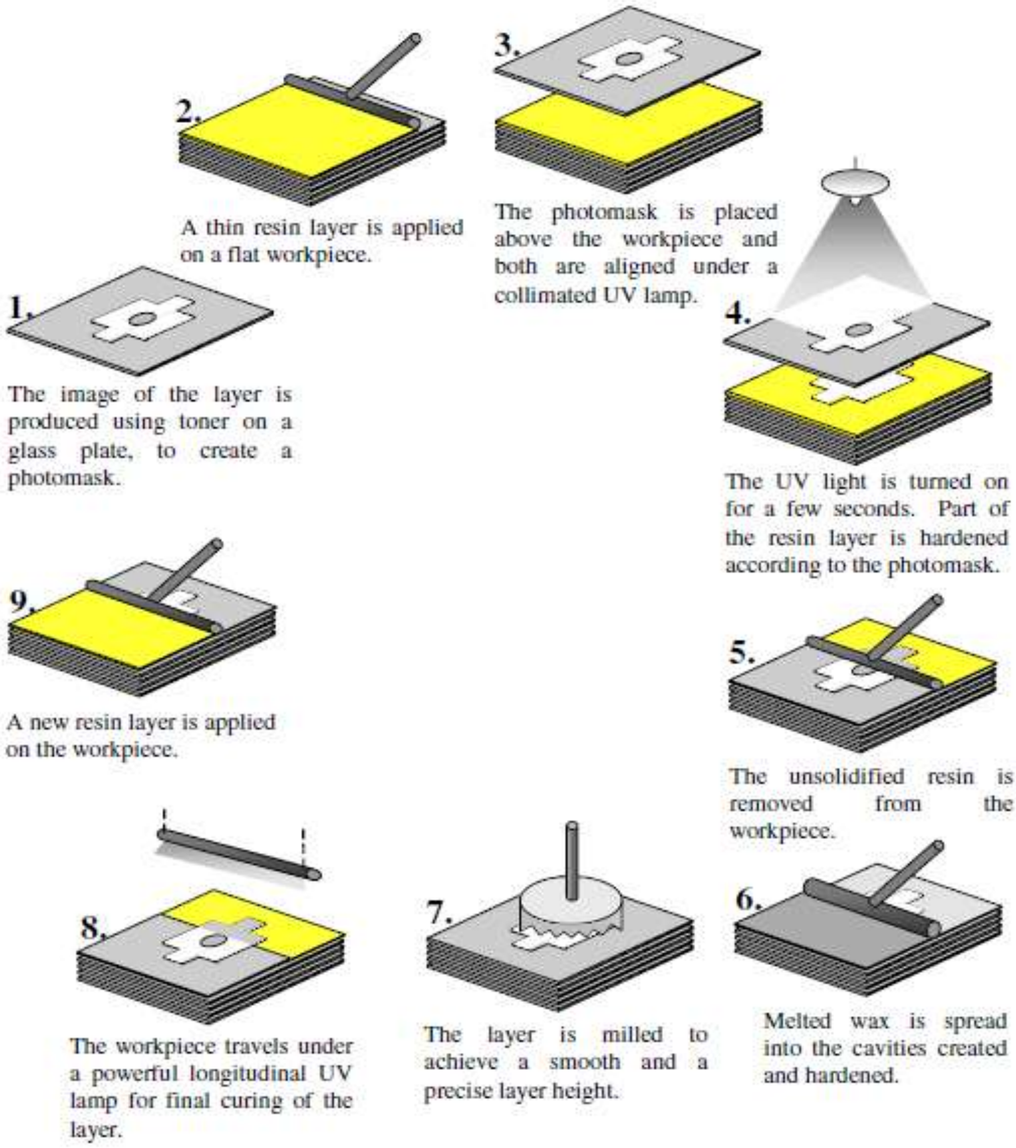

Fig 2.15 Solid Ground Curing process

Principle

Cubital's RP technology creates highly physical models directly from computerized three-dimensional data files. Parts of any geometric complexity can be produced without tools, dies or moulds by Cubital's RP technology.

The process is based on the following principles:

(1) Parts are built, layer by layer, from a liquid photopolymer resin that solidifies when exposed to UV light. The photopolymerization process is similar to that described in Section 3.1.4, except that the irradiation source is a high-power collimated UV lamp and the image of the layer is generated by masked illumination instead of optical scanning of a laser beam. The mask is created from the

CAD data input and “printed” on a transparent substrate (the mask plate) by an nonimpact ionographic printing process, a process similar to the Xerography process used in photocopiers and laser printers [15]. The image is formed by depositing black powder, a toner which adheres to the substrate electrostatically. This is used to mask the uniform illumination of the UV lamp. After exposure, the electrostatic toner is removed from the substrate for reuse and the pattern for the next layer is similarly “printed” on the substrate.

(2) Multiple parts may be processed and built in parallel by grouping them into batches (runs) using Cubital’s proprietary software.

(3) Each layer of a multiple layer run contains cross-sectional slices of one or many parts. Therefore, all slices in one layer are created simultaneously. Layers are created thicker than desired. This is to allow the layer to be milled precisely to its exact thickness, thus giving overall control of the vertical accuracy. This step also produces a roughened surface of cured photopolymer, assisting adhesion of the next layer to it. The next layer is then built immediately on the top of the created layer.

The process is self-supporting and does not require the addition of external support structures to emerging parts since continuous structural support for the parts is provided by the use of wax, acting as a solid support material.

Advantages and Disadvantages

The Solider system has the following advantages:

(1) *Parallel processing*. The process is based on instant, simultaneous curing of a whole cross-sectional layer area (rather than point-by-point curing). It has a high-speed throughput that is about eight times faster than its competitors. Its production costs can be 25% to 50% lower. It is a time and cost saving process.

(2) *Self-supporting*. It is user-friendly, fast, and simple to use. It has a solid modeling environment with unlimited geometry. The solid wax supports the part in all dimensions and therefore a support structure is not required.

(3) *Fault tolerance*. It has good fault tolerances. Removable trays allow job changing during a run and layers are erasable.

(4) *Unique part properties.* The part that the Solider system produces is reliable, accurate, sturdy, machinable, and can be mechanically finished.

(5) *CAD to RP software*. Cubital’s RP software, Data Front End (DFE), processes solid model CAD files before they are transferred to the Cubital’s machines. The DFE is an interactive and user-

friendly software.

(6) *Minimum shrinkage effect.* This is due to the full curing of every layer.

(7) *High structural strength and stability.* This is due to the curing process that minimizes the development of internal stresses in the structure. As a result, they are much less brittle.

(8) *No hazardous odors are generated.* The resin stays in a liquid state for a very short time, and the uncured liquid is wiped off immediately. Thus safety is considerably higher.

The Solider system has the following disadvantages:

(1) *Requires large physical space.* The size of the system is much larger than other systems with a similar build volume size.

(2) *Wax gets stuck in corners and crevices.* It is difficult to remove wax from parts with intricate geometry. Thus, some wax may be left behind.

(3) *Waste material produced.* The milling process creates shavings, which have to be cleaned from the machine.

(4) *Noisy.* The Solider system generates a high level of noise as compared to other systems.

Applications

The applications of Cubital's system can be divided into four areas:

(1) *General applications.* Conceptual design presentation, design proofing, engineering testing, integration and fitting, functional analysis, exhibitions and pre-production sales, market research, and inter-professional communication.

(2) *Tooling and casting applications.* Investment casting, sand casting, and rapid, tool-free manufacturing of plastic parts.

(3) *Mold and tooling*. Silicon rubber tooling, epoxy tooling, spray metal tooling, acrylic tooling, and plaster mold casting.

(4) *Medical imaging*. Diagnostic, surgical, operation and reconstruc-tion planning and custom prosthesis design.

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – III – CONCEPT MODELERS – SPR1616

CONCEPT MODELLER

Concept modelers, often called office modelers, are a class of rapid prototyping (RP) system designed specifically to made models quickly and inexpensively, without a great deal of effort. The system are usually small, inexpensive, quiet, and require very little or no training to operate. For these reasons, the systems are targeted to reside in design office environments, where they can ideally be operated much like a standard printer, only the prints from these are in three dimensions.

THERMAL INK JET PRINTER

Ink jet printing comes from the printer and plotter industry where the technique involves shooting tiny droplets of ink on paper to produce graphic images. RP ink jet techniques utilize ink jet technology to shoot droplets of liquid-to-solid compound and form a layer of an RP model. The additive fabrication technique of inkjet printing is based on the 2D printer technique of using a jet to deposit tiny drops of ink onto paper. In the additive process, the ink is replaced with thermoplastic and wax materials, which are held in a melted state. When printed, liquid drops of these materials instantly cool and solidify to form a layer of the part. For this reason, the process if often referred to as thermal phase change inkjet printing. Inkjet printing offers the advantages of excellent accuracy and surface finishes. However, the limitations include slow build speeds, few material options, and fragile parts. As a result, the most common application of inkjet printing is prototypes used for form and fit testing. Other applications include jewellery, medical devices, and high-precisions products. Several manufactures have developed different inkjet printing devices that use the basic technique described above. Inkjet printers from Solidscape Inc., such as the ModelMaker (MM), use a single jet for the build material and another jet for support material. 3D Systems has implemented their MultiJet Modelling (MJM) technology into their ThermoJet Modeller machines that utilize several hundred nozzles to enable faster build times. The inkjet printing process, as implemented by Solidscape Inc., begins with the build material (thermoplastic) and support material (wax) being held in a melted state inside two heated reservoirs. These materials are each fed to an inkjet print head which moves in the X-Y plane and shoots tiny droplets to the required locations to form one layer of the part. Both the build material and support material instantly cool and solidify. After a layer has been completed, a milling head moves across the layer to smooth the surface. The particles resulting from this cutting operation are vacuumed away by the particle collector. The elevator then lowers the build platform and part so that the next layer can be built. After this process is repeated for each layer and the part is complete, the part can be removed and the wax support material can be melted away.

- ❖ Several manufactures have developed different inkjet printing devices that use the basic technique described above.
- ❖ Inkjet printers from Solidscape Inc., such as the ModelMaker (MM), use a single jet for the build material and another jet for support material.
- ❖ 3D Systems has implemented their MultiJet Moldeling (MJM) technology into their ThermoJet Modeler machines that utilize several hundred nozzles to enable faster build times

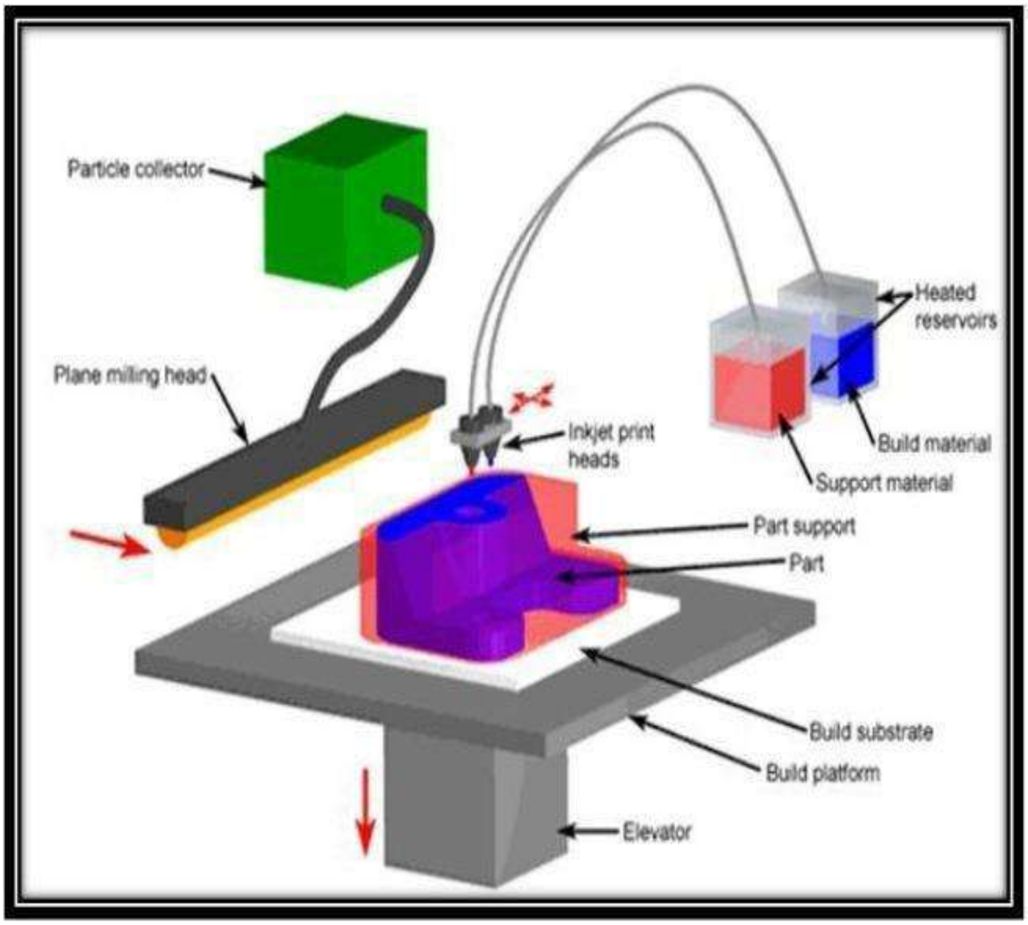

Fig 3.1: A schematic of Ink jet printer

Common ink jet printing techniques, such as

a) Sanders Model Maker.
b) Multi-Jet Modelling.
c) Z402 Ink Jet System.
d) Three-Dimensional Printing.
e) Genisys Xs printer.
f) Object Quadra systems.
g) Genisys Xs printer.

SANDER'S MODEL MAKER (MM)

The Sanders Model Maker (MM) series captures the essence of the ink-jet printing technology, and builds in a layer-by-layer fashion, similar to other rapid prototyping (RP) systems. The MM uses several different types of data file formats but has only one base type for the build and support materials, wax. The MM was developed by Sanders Prototype, Inc. (SPI), a subsidiary of Sanders Design in Wilton, NH, in the early 1990s with the intention of revolutionizing the industry as it pertains to accuracy and precision.

MODEL MAKER SYSTEM HARDWARE:

The MM system has evolved through three "models," Model Maker (original model), Model Maker II (MMII, second generation), and recently Rapid Tool Maker (RTM). The original modeller has a build envelope of 7" x 7" and the MMII has an envelope size of 13" x 7",

Whereas the RTM has a 12" x 12" working area. While both MMs are desktop models, the RTM is a self-contained unit with an on-board computer. Figure 3.2 shows an MM unit.

Fig 3.2: Hardware of MM

Software:

Both modelers utilize MW (MW) software, manufactured by SPI, to prepare and manipulate the incoming file for use in the MM machine. The software can be operated through a variety of workstations, from UNIX to PC, and the current modeller has an on-board computer that can function alone after it receives the prepared file from a "dummy" PC whose sole purpose is for file slicing and preparation.

Build Materials:

Both models use a build and support material to produce a 3-D model. These materials are wax based with the support having a lower melting point than the build. This insures that during postprocessing, the support material will melt away leaving only the part, made of build material. Each material has its own heated reservoir and is very sensitive to contamination, which means handling should not occur.

The Print-head:

The print-head assembly consists of the print-head; print-head cap, purge spout, purge spout cap, cable, and saddle (see Figure 3.3). There are two print-heads, one for building the part and the other for generating the necessary support. This support depends on the geometry of the part and can be produced around the entire part or just on certain areas. The jets sit on a carriage that enables them to move in the X and Y direction (left to right), while the stage moves in the Z direction (up and down). There are two processes that enable the materials to be transported to the print-heads.

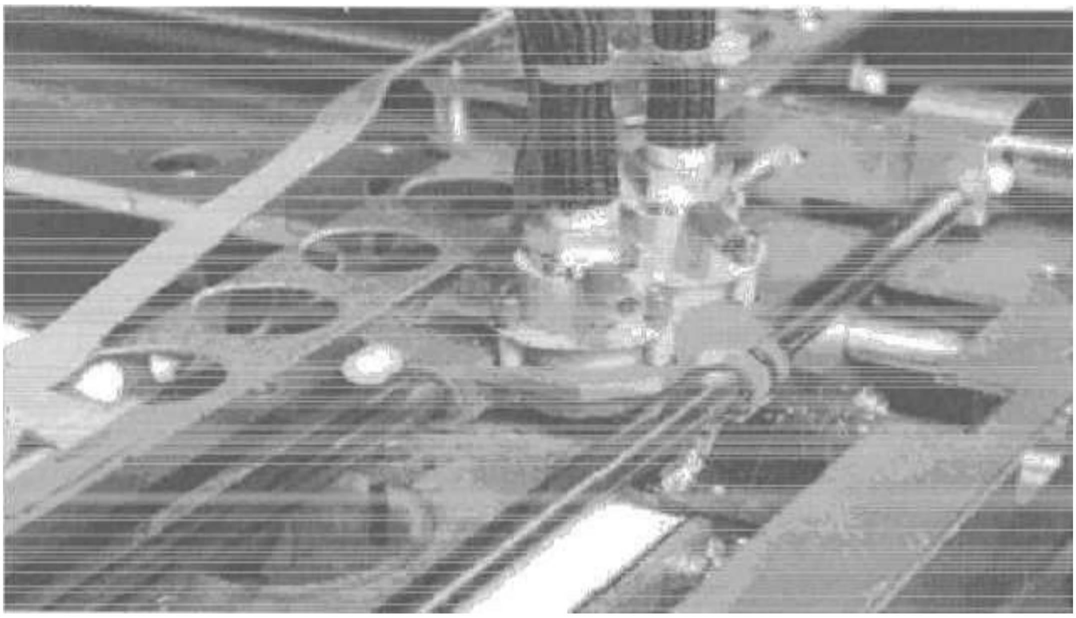

Fig 3.3: Print-head assembly of the MM

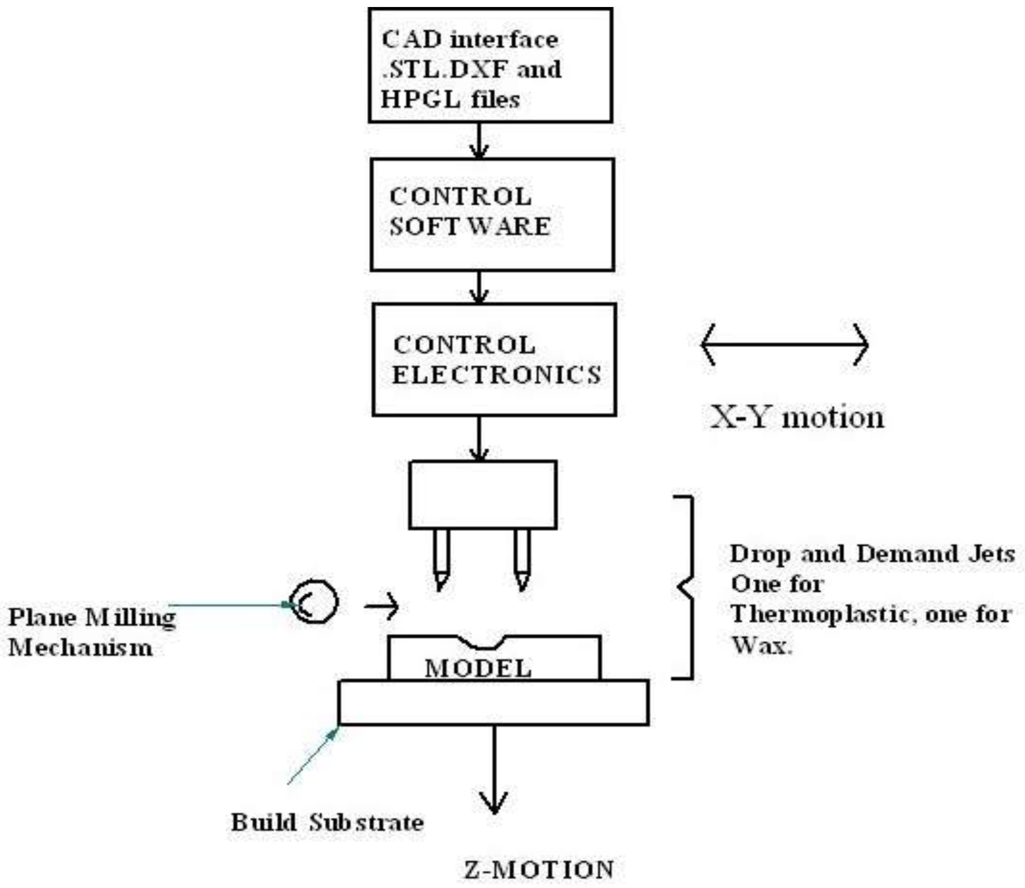

Fig 3.4: Flow chart representing Sanders Model Maker

1) Material is pumped to the feed lines by compressed air within the reservoir during the purge operation.

2) There is an actual siphon that is conducted from the reservoir to the feed lines, to the print head during the model build. The feed lines are heated, as are the print-heads. This heating of reservoirs, feed lines, and print heads is necessary to have a continual flow of material.

MODEL MAKER OPERATION

CAD File Preparation:

Prior to actually building the part, the STL file must be translated into the software language used by the MM. This software is MW and is used for the purpose of preparing and manipulating the file so that the MM can build it.

The file, after being read into MW, produces a picture of the file on screen in the Cartesian coordinate system (-x , -y , and -z). A box appears around this grid with a bar that has many functions that allow the user to put the part in its desired orientation. From this box you can perform slicing functions, zoom functions, layer thickness alterations, part positioning, part sizing and other build parameters. The MW software is very useful and gives the user ultimate control over the end product. Figure 3.5 shows an STL file as viewed by MW

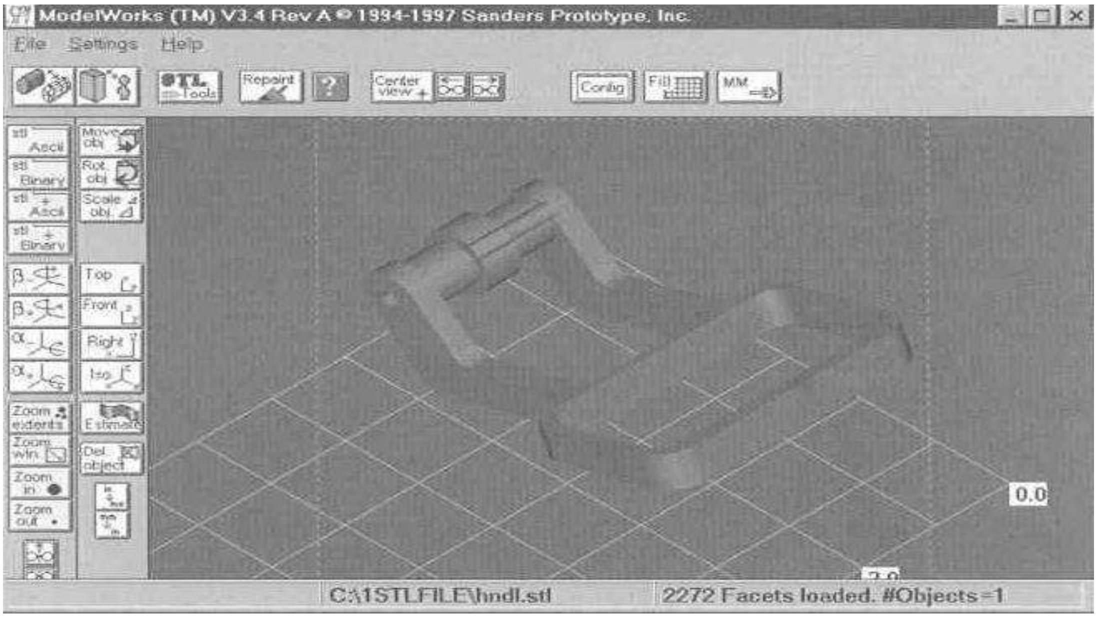

Fig 3.5: The STL file is viewed with MW before preparation to run

Positioning the Model:

There are several factors to consider when positioning the part. Among them are the distance the cutter travels, special features, detailing, opening edges, time to build, and the quality of the model. All of these can be changed as it pertains to the specific characteristics desired for the part. The fundamental rule for positioning is to have the longest length of the part parallel to the cutter.

Configuration Selection:

This is a very important factor prior to building a part. This particular feature is accessed through the Config button on the MW window. This notebook contains the database of settings that determine how the model is built. Different parameters can be set with five tabs on the screen. These tabs are: Configuration, Units, Machine, Memory, and Build.

Slicing:

The MM utilizes view as a viewer of the .MM2 and .BIN files generated by MW. This viewer displays slice cross sections and their respective fill patterns. A digital readout at the bottom of the screen gives the ability to extract measurements from this file. This information is helpful in determining the files integrity and getting a view of slice-by-slice formation.

This slice-by-slice file is the code the machine will use to generate a layer-by-layer creation of the model. To access this function you must select the Bview button from the menu. There are several different functions that you can implement to render the model and file exactly how you desire it to be prior to building. The Navigation buttons allow you to view the model slice by slice or at 10 percent increments, the Automated Control button gives you a real time build slice by slice, the Zoom buttons allow you to adjust the view of the model on the screen, and the Pan buttons allows you to adjust the -x and -y plane views of the model. Together, all of these functions give the modeller complete control over not only how the machine will build the part, but the customization of the part prior to the build.

Building a Part:

Once the part has been delivered to the MMII it is time to prepare the machine for building. Initially, you can check the material reservoirs to determine if you need to add any build or support materials. You can get a graphical representation by selecting <1> on your opening screen. The computer will tell you if additional material is needed and how much to add. Once you have added the material(s), allow 45 minutes for the material to

be liquefied in the reservoir before use. But while you are waiting you can check the optical tape receptacle to make sure it is empty and you can mill the substrate. To do so, select <3> from the initial screen (Run MM), select <I>, and then <N>, this will allow you to choose the mill command and level your substrate. Mill the original surface (dull finish) of the substrate until it has a clean, bright finish. This ensures that the surface is level. The next and most important step is to check the jet-firing status. Before each use, perform a manual purge to refill the jet reservoir with material and make sure that the proper amount of air is within the reservoir also. Cut a 3-inch piece of plastic tubing, remove the purge cap, and place the tube on the purge spout. Hold the cylindrical tube over the tube and under <M> choose the respective jet you are purging (build or support). Once the jet has been selected, another menu will appear that will prompt your actions, from this menu, choose the purge command. Allow the jet to purge until you get an even flow of material into the tube container and allow it to flow for 2 to 3 seconds, and then press any key to stop the purge. Immediately remove the tube from the spout and reapply the cap. After making sure that the jets are firing properly, go back into new build, select the file you want, and build.

Post-processing:

The post-processing procedure is a process that must be monitored very carefully. When setting your initial temperatures, you must be careful because the support material has a lower melting point than the build material. Either you can use a porcelain bowl like container, a hot plate, and a thermometer, or you can purchase a sonicator with heat control and a built-in digital thermometer. If you purchase the latter, remember that the sonication produces its own heat, so additional heat may or may not be necessary depending on the part size. Post-processing is a hands-on process that involves time and attention. Allow the part to sit in the recommended VSO solvent solution at 35° C for 30-minute increments. Depending on part size you may want to play with the temperature settings and the time you allow it to soak in VSO. You want the support material to be mushy so that you can easily remove it with a tool of your preference (be careful not to destroy part surface). When all the support (red) material has been removed, you may refinish your surface, paint it, or leave it as is. Remember, this process takes time, if you rush it you could sacrifice the integrity of your part.

Advantages and disadvantages

- ❖ The power of the MM family of systems lies primarily with the production of small, intricately detailed wax patterns
- ❖ The jewellery and medical industries have capitalized on this advantage due to their needs for highly accurate, small parts
- ❖ Perhaps the most apparent drawback of these systems are the slow build speed when it comes to fabricating parts larger than a 3- inch working cube

3-D printers:

Binder printing methods were developed in the early 1990s, primarily at MIT. They developed the 3D printing (3DP) process in which a binder is printed onto a powder bed to form part cross sections. Contrast this concept with SLS, where a laser melts powder particles to define a part cross section. A recoating system similar to SLS machines then deposits another layer of powder, enabling the machine to print binder to define the next cross section. Three-dimensional printing, or 3DP, is an MIT-licensed process, whereby liquid binder is jetted onto a powder media using ink jets to "print" a physical part from computer aided design (CAD) data. Z Corporation (Z Corp) incorporates the 3DP process into the Z402 system. The relatively inexpensive Z402 is directed toward building concept-verification models primarily, as the dimensional accuracy and surface roughness of the parts are less than higher end systems. The initial powder used was starch based and the binder was water based, however now the most commonly used powder is a new gypsum based material with a new binder system as well.

Models are built up from bottom to top with layers of the starch powder and binder printed in the shape of the cross sections of the part. The resulting porous model is then infiltrated with wax or another hardener to give the part dexterity. The Z402 is the fastest modeller on the market, with speeds 5 to 10 times faster than other current rapid prototyping (RP) systems. A wide range of polymer, metal, and ceramic materials have been processed in this manner.

Z402 System Hardware:

The Z402 is currently available in only one size, which can build models up to 8" x 11" x 8". The overall size of the modeller is approximately 3' X 4', so it can fit in a fairly confined area. Parts built with the starch material can be hardened to fit the application necessary. Wax infiltration gives the parts some strength but also leaves them usable as investment casting patterns. Stronger infiltrants, such as cyanoacrylate, can be used to provide a durable part that can survive significant handling. Since the starting point of this writing, Z Corp has advanced their 3DP system in several ways. First, they released updated print cartridges (Type 3) that last longer along with stronger infiltrants for durable parts. Secondly, a new material and binder system called ZP100 Microstone was released that provides stronger models directly from the machine with little or no postprocessing or infiltrant. Finally, an automated waxer was released that helps control the wax infiltration process if necessary. The modeler has several important components, including the following:

Build and Feed Pistons: These pistons provide the build area and supply material for constructing parts. The build piston lowers as part layers are printed, while the feed piston raises to provide a layer-by-layer supply of new material. This provides the z motion of the part build.

Printer Gantry: The printer gantry provides the XY motion of the part building process. It houses the print head, the printer cleaning station, and the wiper/roller for powder landscaping.

Powder Overflow System: The powder overflow system is an opening opposite the feed piston where excess powder scraped across the build piston is collected. The excess powder is pulled down into a disposable vacuum bag both by gravity and an onboard vacuum system.

Binder Feed/Take-up System: The liquid binder is fed from the container to the printer head by siphon technique, and excess pulled through the printer cleaning station is drained into a separate container. Sensors near the containers warn when the binder is low or the take up is too full.

The Z402 is operated through the COM port of a PC Workstation (not included), although the system has an onboard computer that can be used for diagnostics if necessary. The Z Corp slicing software is provided with the purchase of a Z402 system, and is compatible with Windows 98 and Windows NT.

Z Corp also sells a postprocessing package necessary for detail finishing and strengthening of the parts produced by 3DP. The package includes a glove box with air compressor and air brushes for excess powder removal, a heating oven to raise the temperature of the parts above that of the wax infiltrant and a wax-dipping unit that melts the wax and provides a dipping area for the parts.

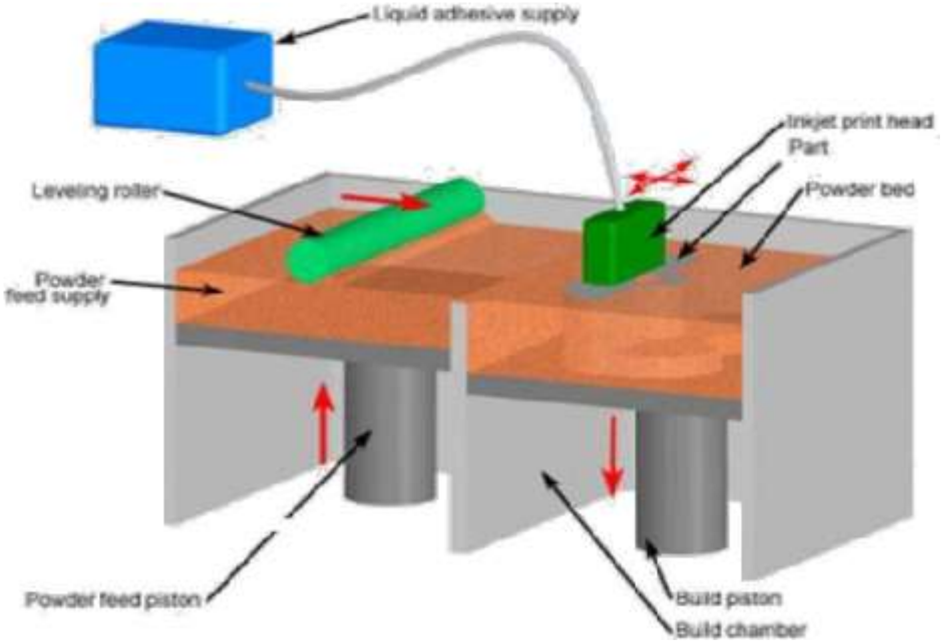

Fig 3.6: A Schematic of 3D printing

Z402 Operation:

The Z402 has a very user-friendly interface, where very few commands are necessary to build a part. Since the parts are built in a powder bed, no support structures are necessary for overhanging surfaces, unlike most other RP systems.

Software:

The Z402 starts with the standard STL file format, which is imported into the Z Corp software where it is automatically sliced and can be saved as a BLD (build) file. When a file is first imported into the software, it is automatically placed in an orientation with the shortest -z height. This is done as the fastest build capability, like other RP systems, is in the -x, -y direction. The part can be manually reoriented if necessary for best-part appearance. Multiple STL files can be imported to build various parts at the same time for maximum efficiency.

The default slice thickness is 0.008", however the value can be varied to fit the needs for particular parts. Objects can be copied, scaled, rotated or moved for optimum part build. Moving/translating a part can either be done by a simple drag-and-drop method, or else by entering coordinates. Parts can also be justified to either side of the build envelope, be it front, back, left, right, top, or bottom, with a simple menu command. Parts are copied simply by highlighting the part and clicking one copy command. The new part is automatically placed beside the current part if there is room in the build envelope; otherwise it is placed above it. Since the build envelope is a powder bed, three-dimensional nesting can be accomplished so that parts can be built in floating space to make room for others. This 3D nesting capability is only available in a few other RP systems, and provides for a higher throughput of parts to be accomplished. After the STL is imported and placed, a "3D Print" command is issued and the part file is sent to the machine to build. During the build, a progress bar shows the percentage of the part building, as well as the starting time and the estimated completion time. When a build is complete, a dialog box is displayed with the final build time of the part, along with the volume of material used and the average droplet size of the binder used.

(1) The parts are built in layer-by-layer fashion
(2) First, blank layers of powder are spread as a starting point for building upon.
(3) This is called ―landscaping‖
(4) This landscaping is done manually
(5) The remaining steps are carried out after this landscaping automatically
(6) When the first layer of the powder is spread, the liquid binder is called for binder spray
(7) The binder jet moves as per our virtual design (CAD model)
(8) After spraying the binder, the next layer of powder is spread and rolled for bonding
(9) The powder and binder spray depends upon the thickness of the product

The parts that are made using 3D printing, not as strong as SLS products. Because the material is adhesive bonded, where in SLS, the material is taken to fusion bonding.

Postprocessing:

Other than the Z402 system itself, there are several components needed for postprocessing of the part. For a concept model, the starch parts are generally infiltrated with paraffin wax, although more durable materials are available, from plastics to cyanoacrylate. Before infiltration, starch parts are fragile and must be handled with care. The following are the postprocessing steps for a part to be infiltrated with wax, with a total process time of about 15 to 20 minutes.

Powder Removal: After the parts are taken from the machine, the excess powder must be removed. With the system comes a small glove box with an airbrush system inside. The airbrush is used to easily and gently blow the powder off the part, and a vacuum cleaner is hooked to the glove box to remove the powder as it is blown from the part. (5 *Minutes)*

Heat for Infiltration: Once the powder is removed from the part surfaces, the part is placed in a small oven and heated to a temperature just above that of the infiltrant wax, to provide a wicking characteristic as opposed to coating. The part temperature for paraffin infiltrant is approximately 200°F. (10 Minutes).

Infiltration: Immediately after the part is heated, it is dipped for a few seconds into a vat of molten wax, then removed and placed on a sheet to dry. After drying the part is complete. *(5* Minutes) The actual postprocessing time will depend on the complexity of the part, the skill of the user, and the infiltrant used. Nonetheless, it is still minimal compared to some other RP processes.

Typical Uses of Z402 Parts

Parts built with the Z402 system are directly intended for use as concept-verification models in a design environment. The nontoxic materials allow for the models to be safely handled in meetings or the office, directly after fabrication. Another application that is beginning to be explored, not unlike other RP systems, is the use of Z402 parts for investment or sandcast patterns. The starch-based material burns out of an investment shell readily, therefore providing a quick way to produce metal hardware for testing or analysis.

Advantages and Disadvantages of 3D Printing

Ultimately, the speed is the most desirable trait of the Z402. With an average build time of one vertical inch per hour, even a part several inches tall can be built within a normal work day. This is extremely advantageous to any company where time is a factor in sales or production. The key disadvantages of the system include rough part surfaces, which can be remedied with sanding, and the cleanliness problems faced when dealing with any system that uses a powder as a build material or operating medium. Also, the ink-jet cartridges must be replaced quite frequently, on the order of every 100 hours of operation, so users must understand that the jets are expendable items just as the build powder itself. Finally, these concept models aren't fabricated to high dimensional tolerances, which may hinder the building of complex assembly prototypes.

Genisys Xs 3D Printer

The Genisys (and Genisys Xs) system, produced by Stratasys, Inc. is an office-friendly modeling system that builds parts with a durable polyester material. The current lines of Genisys system are small, compact table-top rapid material capability, and interoffice network queues for operation much like a printer.

HISTORY OF THE SYSTEM

Not unlike most newly developed technologies, the original Genisys machines has small quirks and technicalities that prevented it from really being a true “trouble free” office modeler.

However, after analyzing and working with customers, most of the systems were recalled and refurbished to correct the problems. The new line of Genisys, the Xs, apparently has printer-like reliability and operation, environment as intended.

SYSTEM OPERATION

SOFTWARE

The software of the Genisys Systems, which is compatible on both Unix and NT platforms, is designed for ease of operation. With simple point-and –click part-building features, the software automatically places, slices, generates supports, and then downloads the part file to the network queue to be fabricated. Parts can be set to be scaled automatically as well, although there is a manual scaling feature. Multiple parts may be nested in the –x, -y plane, again with single-click operability.

BUILD MATERIAL

The current material is quoted as a “durable polyester”. Since the systems have only one extrusion tip, the support structure are built of the same material, requiring mechanical removal upon completion of the part.

HARDWARE

The Genisys has a maximum build capacity of 12”×8”×8”, whereas the entire system occupies a space of only 36”×32”×29”. The unit weighs in at about 210 pounds and can operate an standard house current of wafers, which are loaded into a bank of cartridges within the machine. One wafer is loaded into the deposition head, where it is melted and deposited in thin layers through a single extrusion tip while tracing the cross section of the part being built. Once the wafer in the head is spent, it is replaced by another automatically and the build resumes. The build chamber is operated at ambient temperature, and fabricated parts can maintain dimensional accuracy in the range of +0.013 inches.

Fig 3.7: A schematic of Genisys Xs printer HP system

Typical Uses of Genisys Parts

The intended application of the Genisys’s product was mainly concept modeling and verification. However, as with all RP devices, various users have progressed the use of Genisys models into analysis, direct use, even low-impact wind-tunnel modeling. The material is said to be suitable for painting, drilling, and bonding to create the necessary appearance for an applications.

Advantage and Disadvantages of Genisys

The advantage is as follows

Ease of use

Network operability

Since the preprocessing is kept to a minimum, and the system can be networked much like printers, the Genisys lends itself to the office modeling envireonment.

Disadvantage

Single material capacity, results in more difficult support removal on complex parts.

This situation may well be addressed in the future, similar to what was done in the progression of its sister technology of fused deposition modeling, however the vendor has no plans released at the time of this writing.

Part 1: Preparing the Model

1. Start the AutoGen application from the QuickFind/Start menu on your computer.

2. Under the File menu, click "Open STL…" and select the desired file. Note that AutoGen may have issues with space characters in pathnames and filenames.

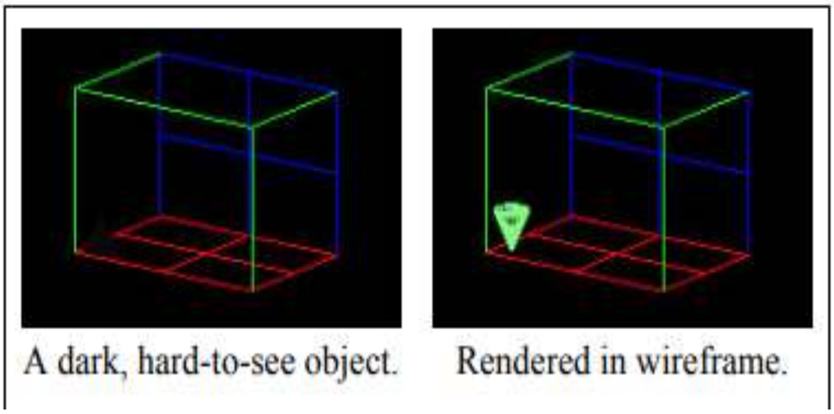

Fig 3.8: A schematic of Genisys Xs printer HP system

3. The model should now appear in the window. The red, green, and blue borders correspond to the available build volume of the printer.

4. You can zoom in or out or rotate the view of the build volume by adjusting the "thumbwheels".

5. If the model appears dark, or is hard to see, under the View menu, select Draw Style: Wireframe. The model will now be rendered without surface shading. The problem may also be corrected by reversing the orientation of the surface normals on the model prior to loading into AutoGen.

6. Resize your model if necessary using the Scale or Fit settings. The Fit menu allows you to specify a cube size to which the size of the printout should be constrained.

7. As the model is built, it may need to have supports attached to it to keep it from toppling over. Rotate the model to achieve the best orientation so as to minimize the complexity of the support structure. Rotation values must be typed into the three fields labeled Rotation, which represent X-, Y-, and Z-axis rotation angles in degrees.

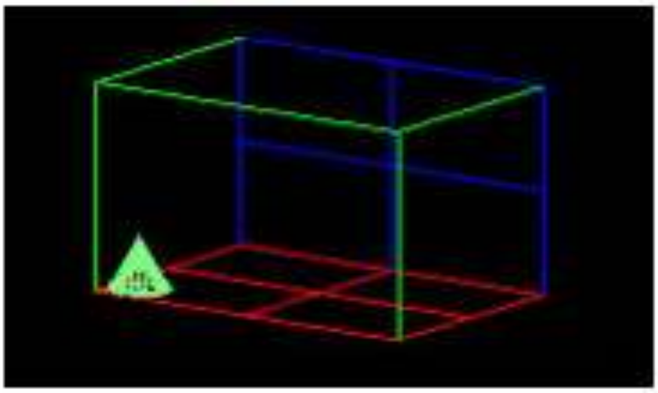

Fig 3.9: A schematic of Genisys Xs printer HP system

8. Use the "Fill" menu to determine whether to print a solid model (Normal), or to allow the printer to create a honeycomb support structure (Sparse). The normal model offers increased strength. The sparse model offers faster printing and cost efficiency as it requires less material.

Part 2: Pre-processing

1. Under the main menu select File:Print. When prompted, click the checkbox for "Pre-processing Only", and then click OK. If pre-processing fails, try rotating the model to a different orientation (even if it means adding supports), changing the fill type, or the part scaling. If this does not remedy the problem, it may be necessary to change some aspect of the model's design.

2. Once pre-processing is done; the model can be "packed". This is necessary only if multiple models or multiple copies of a model are to be printed in a single print job. To pack the model, select File: Print, and select "Pack" from the pull-down menu. Click OK and wait for the packing process to complete. Additional models can now be loaded, sized, and pre-processed.

3. Once the model(s) are pre-processed and packed, select File: Print and select "Print Alone" from the pull-down menu. Click OK to send your job to the Genesis Xs printer.

Part 3: Printing

1. Once the job is sent, the printer will queue it and begin warming up. While warming up, open the glass door and, using the yellow spatula on the shelf next to the printer, scrape any residual plastic from the metal plate. In particular, there will likely be a "test strip" from the last print job on the right hand side. Close the glass door when done. Once the metal plate heats up to a given temperature, the door will be locked until the print job is complete.

2. While the printer is rendering, consult the LCD display to monitor its progress. Use the percent-

complete and time-elapsed values to estimate a completion time.

3. If the model has an obvious flaw, or if the printer has screwed up by producing a seriously defective part, cancel the job from the console by following the prompts on the LCD display.

4. After the printing is done, use the menu, enter, escape, and arrow buttons to bring the printer offline and check the materials status. Press the menu button and select “put printer offline”. Press menu again, and using the arrow keys select “status menu”, and then “material status”. Record the values for each of the ten wafer cartridges in the log book sitting on the shelf next to the printer. Note the total difference from the previous entry and record it in the “wafers used” column.

5. Using the spatula, carefully remove the model from the platen, and clean the platen of any scraps of plastic. The platen remains hot, so take care not to touch it.

6. If support structures were added to the model, they can now be snapped off easily with fingers, and any defects lightly sanded out.

Object Quadra systems

The Quadra process is based on state-of-the-art ink-jet printing technology. The printer, which uses 1536 nozzles, jets a proprietary photopolymer developed in-house by Objet. Because it requires no post cure or postprocessing, Quadra touts the fastest start-to-finish process of any (RP) machine currently on the market. Object will initially offer one grade of material with properties similar to multipurpose resins currently offered with competitive RP systems. Additional materials with varying properties are under development. Material is delivered by a sealed cartridge that is easily installed and replaced. Jetting of different resins, once they become available, will not require costly investments in materials or hardware upgrades.

A new cartridge is dropped into place without any complicated procedures or specially trained staff. Quadra deposits a second material that is jetted to support models containing complicated geometry, such as overhangs and undercuts. The support material is easily removed by hand after building the model. The support material separates easily from the model body without leaving any contact points or blemishes to the model. No special staff or training are required. Furthermore, models built on the system do not require sanding or smoothing where the supports are attached.

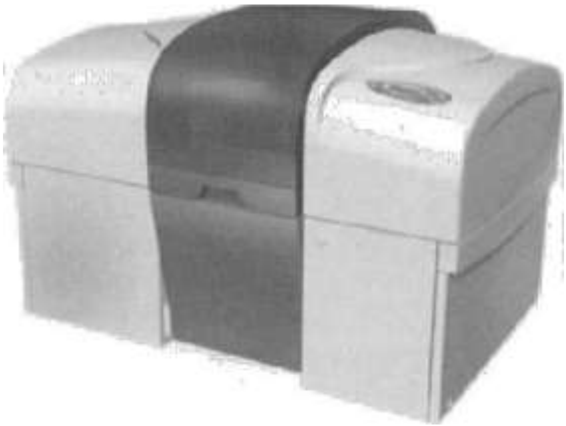

Fig 3.10: A Object Quadra system

Object Quadra offers significant advantages over previous technologies in the field. The material properties of items printed on Quadra are unmatched by machines in its class and price category, and are equalled only by industrial systems that cost an order of magnitude more. The Quadra prints in a resolution of 600 dpi, with a layer thickness of 20 microns, and builds parts up to a maximum size of 11" x 12" x 8". The introduction of Quadra marks the start of a revolution in the area of three-dimensional imaging. An intuitive user interface aids user in setting up the build, scaling, and positioning single and multiple models. Maintenance costs for Quadra are expected to be low. The UV lamps are a standard off-the-shelf item, priced below $75 each, with a life of 1,000 hours. Users can easily replace the lamps themselves.

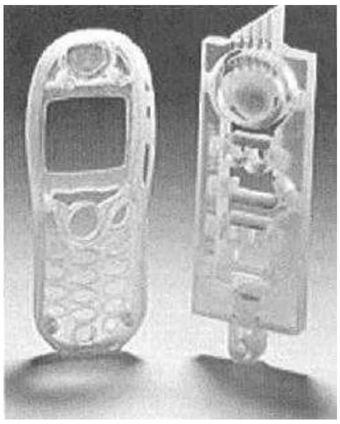

Fig 3.11: Parts from the Quadra

LASER ENGINEERED NET SHAPING (LENS)

Company

Optomec Inc. was incorporated in 1992. Since 1997, Optomec has focused on commercializing a direct fabrication process, the Laser Engineered Net Shaping (LENS^{TM}) process originally developed by Sandia National Laboratories. Optomec delivered its first commercial system to Ohio State University. The address of Optomec Inc. is 3911 Singer Boulevard, N.E., Albuquerque, NM 87109, USA.

Products

Model and Specifications

The latest Optomec's products are the LENS^{TM} 750 and LENS^{TM} 850 systems. These two systems feature the Laser Engineered Net Shaping (LENS) process, a technology that builds or repairs parts using metal powders to form fully dense objects to give excellent material properties. This technique can be used with a wide variety of metals including titanium, tool steels, stainless steels, copper and aluminum. The LENS^{TM} 750 and LENS^{TM} 850 systems contains the following hardware components as in Table 3.1.

Table 3.2 shows a summary of the models and specifications of the LENS systems.

Advantages

(1) *Superior material properties*. The LENS process is capable of producing fully dense metal parts [17]. Metal parts produced can also include embedded structures and superior material properties. The microstructure produced is also relatively good.

(2) *Complex parts*. Functional metal parts with complex features are the forte of the LENS system. *Reduced post-processing requirements*. Post-processing is

Table 3.1: Hardware components of the LENS systems

LENS^{TM} 750	**LENS^{TM} 850**
Argon recirculation unit	Argon recirculation unit
Laser power supply	Laser power supply
Ante-chamber	Ante-chamber
Workstation	Workstation
Process chamber and dri-train	Glove box

Table 3.2: Summary specifications of Optomec's LENS^{TM} systems

Model	**LENS^{TM} 750**	**LENS^{TM} 850**
Process	LENS	LENS
Build volume, *XYZ* (mm x mm x mm)	300 x 300 x 300	460 x 460 x 1070
Laser type	Nd:YAG single head laser	Nd:YAG dual head laser
Laser power (W)	600	1000
Laser wavelength (mm)	1064	1064
XY resolution (mm)	0.5	0.5
Z resolution (mm)	5	5
Size of unit, *XYZ* (mm x mm x mm)	1830 x 1040 x 2080	1170 x 1245 x 2080
Machine size (kg)	2540–2858	2540–2858
Power supply	208 or 240 V_{AC}, 3-phase, 75 A	460 V_{AC}, 3-phase, 75 A
Workstation	Pentium III Windows NT	Pentium III Windows NT
Materials	Stainless steels, H13 tool steel, titanium, super alloys such as inconel, tungsten, copper and aluminium	

Disadvantages

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

Process

The LENS^{TM} 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. It is a freeform metal fabrication process in which a fully dense metal component is formed. The LENS^{TM} process comprises of the following steps:

(1) 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.

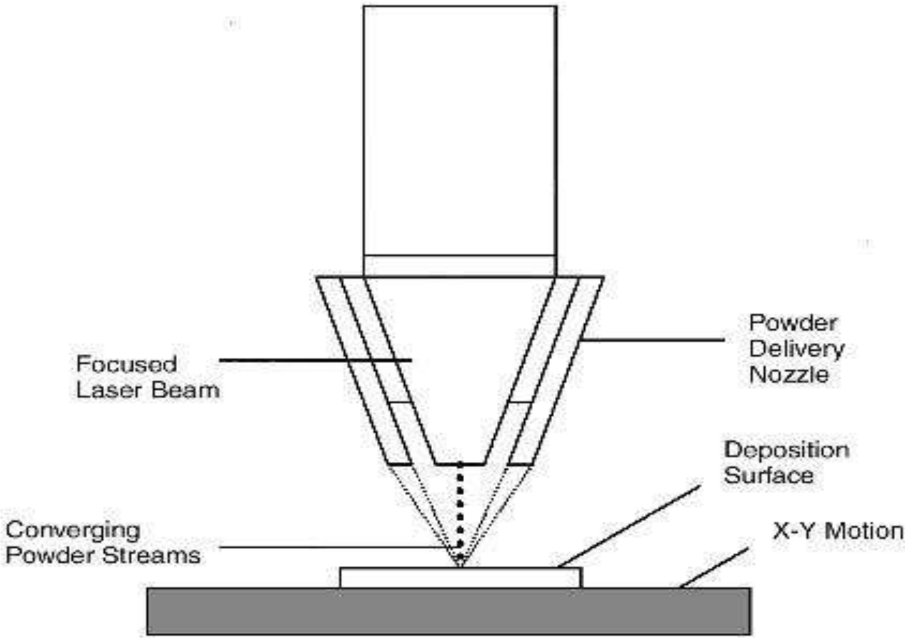

Fig 3.12: Optomec's LENS process

(2) 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.

(3) 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:

(1) 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.

(2) 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.

Applications

The LENS technology can be used in the following areas:

(1) Build mold and die inserts
(2) Producing titanium parts in racing industry
(3) Fabricate titanium components for biological implants
(4) Produce functionally gradient structures
(5)Figure shows a photograph of a metallic hip implant produced using LENS.

Fig 3.13: Medical LENS produced metal part Research and Development

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DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – IV – RAPID TOOLING – SPR1616

RAPID TOOLING

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

Rapid tooling can be classified into soft or hard, and direct or indirect tooling, as schematically shown in Figure 4.1.

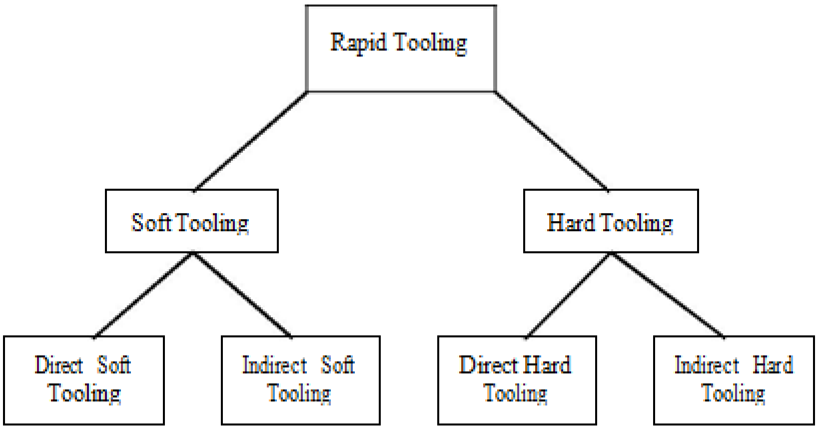


Fig 4.1: Classification of rapid tooling

Soft tooling, typically made of silicon rubber, epoxy resins, low melting point alloys and foundry sands, generally allows for only single casts or for small batch production runs. Hard tooling, on the other hand, usually made from tool steels, generally allows for longer production runs.

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

Soft Tooling:

It can be used to intake multiple wax or plastic parts using conventional injection moulding techniques. It produces short term production patterns. Injected wax patterns can be used to produce castings. Soft tools can usually be fabricated for ten times less than a machine tool.

Hard Tooling:

Patterns are fabricated by machining either tool steel or aluminum into the negative shape of the desired component. Steel tools are very expensive yet typically last indefinitely building millions of parts in a mass production environment. Aluminum tools are less expensive than steel and are used for lower production quantities.

Indirect Rapid Tooling:

As RP is becoming more mature, material properties, accuracy, cost and lead time are improving to permitting to be employed for production of tools. Indirect RT methods are called indirect because they use RP pattern obtained by appropriate RP technique as a model for mould and die making.

Role of Indirect methods in tool production:

RP technologies offer the capabilities of rapid production of 3D solid objects directly from CAD. Instead of several weeks, a prototype can be completed in a few days or even a few hours. Unfortunately, with RP techniques, there is only a limited range of materials from which prototypes can be made. Consequently, although visualization and dimensional verification are possible, functional testing of prototypes often is not due to different mechanical and thermal properties of prototype compared to production part.

All this leads to the next step which is for RP industry to target tooling as a natural way to capitalize on 3D CAD modeling and RP technology. With increase in accuracy of RP techniques, numerous processes have been developed for producing tooling from RP masters. The most widely used indirect RT methods are to use RP masters to make silicon room temperature vulcanizing moulds for plastic parts and as sacrificial models or investment casting of metal parts. These processes are usually known as Soft Tooling Techniques.

Indirect Soft Tooling

In this rapid tooling method, a master pattern is first produced using RP. From the master pattern, a mold tooling can be built out of an array of materials such as silicon rubber, epoxy resin, low melting point metals, and ceramics.

Direct Tooling:

Indirect methods for tool production necessitate a minimum of one intermediate replication process. This might result in a loss of accuracy and to increase the time for building the tool. To overcome some of the drawbacks of indirect method, new rapid tooling methods have come into existence that allow injection molding and die casting inserts to be built directly from 3D CAD models.

Classification of Direct Rapid Tooling methods:

Direct Rapid Tooling Processes can be divided into two main groups

1st group:

It includes less expensive methods with shorter lead times.

Direct RT methods that satisfy these requirements are called methods for firm tooling or bridge tooling.

RP processes for firm tooling fill the gap between soft and hard tooling

2nd group:

Solutions for hard tooling are based on fabrication of sintered metal steel, iron copper powder inserts infiltrated with copper or bronze.

It includes RT methods that allow inserts for pre-production and production tools to be built.

These methods come under hard tooling.

Classification of Direct RT methods:

1) Firm Tooling Methods

- Direct AIM
- DTM Copper PA Tooling
- DTM Sandform Tooling
- electro optical system direct chroning process LOM Tooling in Polymer
- 3DP Ceramic Shells

2) Hard Tooling Methods

- EOS Direct Tool
- DTM Rapid Tool Process
- LOM Tooling in Ceramic
- 3DP Direct Metal Tooling

SILICON RUBBER TOOLING

It is a soft tooling technique. It is an indirect rapid tooling method. Another root for soft tooling is to use RP model as a pattern which can then in turn be injected several times. Room temperature Vulcanization silicones are preferable as they do not require special curing equipment. This rubber moulding technique is a flexible mould that can be peeled away from more implacable patterns as supposed to former mould material. These are as many or more techniques for silicon moulding as there are RP processes but the following is the general description for making simple two-piece moulds.

First an RP process is used to fabricate the pattern. Next the pattern is fixture into a holding cell or box and coated with a special release agent (a wax based cerosal or a petroleum jelly mixture) to prevent it from sticking to the silicon. The silicon rubber typically in a two-part mix is then blended, vacuumed to remove air packets and poured into the box around the pattern until the pattern is completely encapsulated. After the rubber is fully cured which usually takes 12 to 24 hours the box is removed and the mould is cut into two (not necessarily in halves) along a pre-determined parting line. At this point, the original pattern is pulled from the silicon mould which can be placed back together and repeatedly filled with hot wax or plastic to fabricate multiple patterns. These tools are generally not injected due to the soft nature of the material. Therefore, the final part materials must be poured into the mould each cycle.

WIRE ARC SPRAYS

These are the thermal metal deposition techniques such as wire arc spray and vaccum plasma deposition. These are been developed to coat low temperature substrate with metallic materials. This results in a range of low-cost tools that can provide varying degrees of durability under injection pressures.

The concept is to first deploy a high temperature, high hardness shell material to an RP pattern and then backfill the remainder of the two shell with inexpensive low strength, low temperature materials on tooling channels. This provides a hard-durable face that will endure the forces on the temperature of injection moulding and a soft banking that can be worked for optimal thermal conductivity and heat transfer from the body.

In Wire Arc Spray, the metal to be deposited comes in filament form. Two filaments are fed into the device, one is positively charged and the other is negatively charged until they meet and create an electric arc. This arc melts the metal filaments while simultaneously a high velocity gas flows through the arc zone and propels the atomized metal particles on to the RP pattern. The spray pattern is either controlled manually or automatically by robotic control. Metal can be applied in successive thin coats to verify low temperature of RP patterns without deformation of geometry. Current wire arc technologies are limited to low temperature materials, however wire as well as to metals available in filament form.

Vacuum plasma spray technologies are more suited in higher melting temperature metals. The deposition material in this case comes in powder form which is then melted, accelerated and deposited by plasma generated under vacuum.

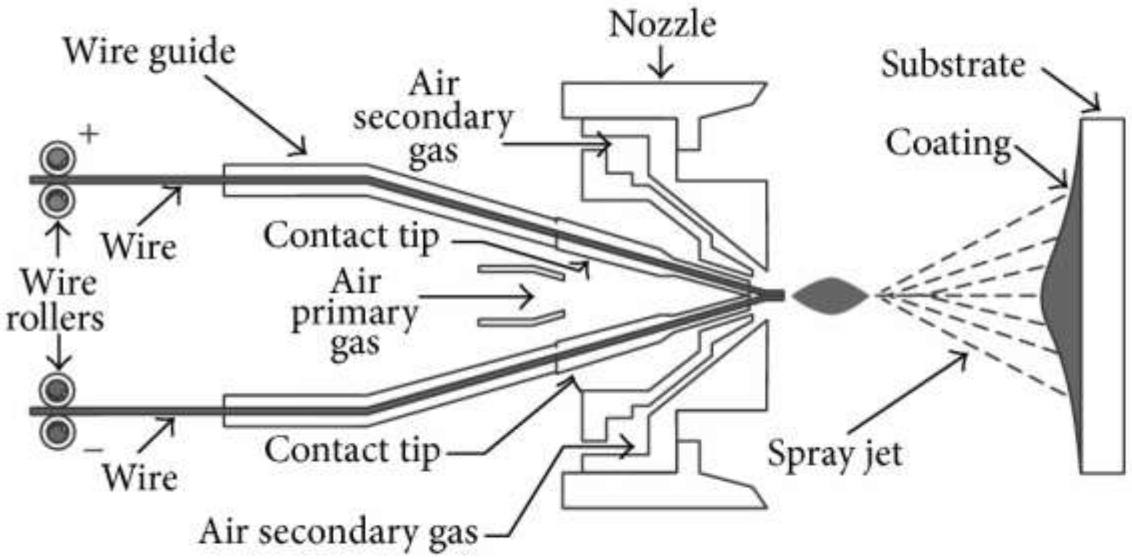


Fig 4.2: Wire Arc Spray

EPOXY TOOLS

Epoxy tools are used to manufacture prototype parts or limited runs of production parts.

Epoxy tools are used as

- Moulds for prototype injection plastic
- Moulds for casting
- Compression moulds
- Reaction injection Moulds

The fabrication of moulds begins with the construction of a simple frame around the parting line of RP model. Screw gauges and runners can be added or cut later on once moulds is finished. The exposed surface of the model is coated with a release agent and epoxy is poured over the model. Aluminium powder is usually added to epoxy resin and copper cooling lines can also be placed at this stage to increase the thermal conductivity of the mould. Once the epoxy is cured the assembly is inverted and the parting line block is removed leaving the pattern embedded in the side of the tool is cured. The two halves of the tool are separated and the pattern is removed. Another approach known as soft surface rapid tool involves machining an oversized cavity in an aluminium plate. The offset allows for introduction of casting material which may be poured into the cavity after suspending the model in its desired position and orientation. Some machining is required for this method and the thermal conductivity is better than for all epoxy models.

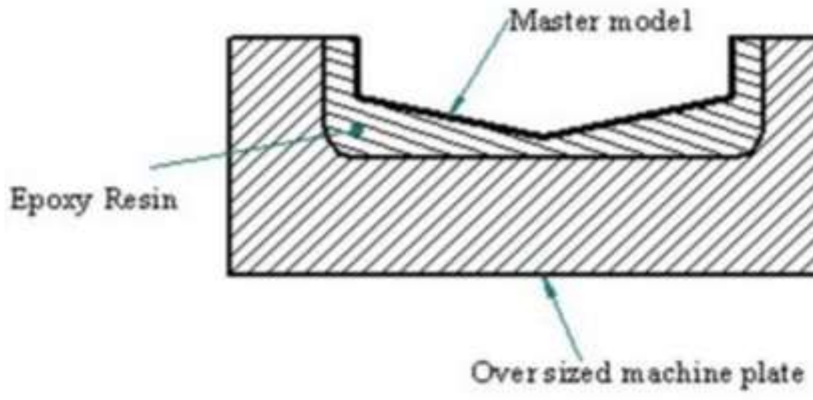


Fig 4.3: RP Model

Unfortunately epoxy curing is an exothermic reaction and it is not always possible directly to cast epoxy around a RP model without damaging it. In this case a silicon RTV mould is cast from RP pattern for aluminium fill deposited. A loss of accuracy occurs during this succession of reproduction steps. An alternative process is to build an RP mould as a master so that only a single silicon RTV reproduction step is needed because epoxy tooling requires no special skill or equipment. It is one of the cheapest techniques available. It is also one of the quickest. Several hundreds parts can be moulded in almost any common casting plastic material.

Epoxy tools have the following limitations.

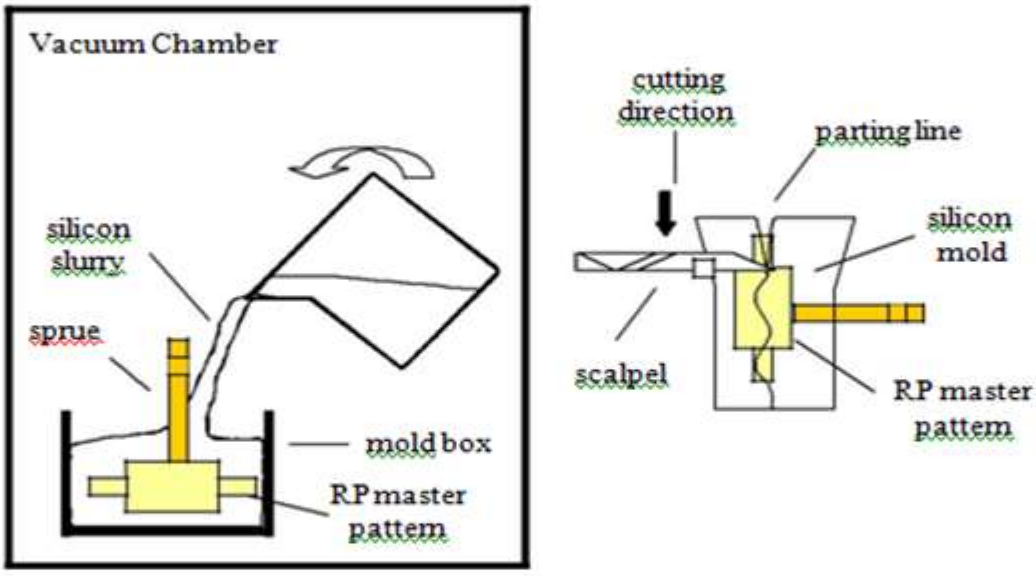
- Limited tool life
- Poor thermal transfer
- Tolerance dependent on master patterns
- Aluminium filled epoxy has low tensile strength

In manufacturing functional plastic, metal and ceramic components, vacuum casting with the silicon rubber mold has been the most flexible rapid tooling process and the most used to date. They have the following advantages:

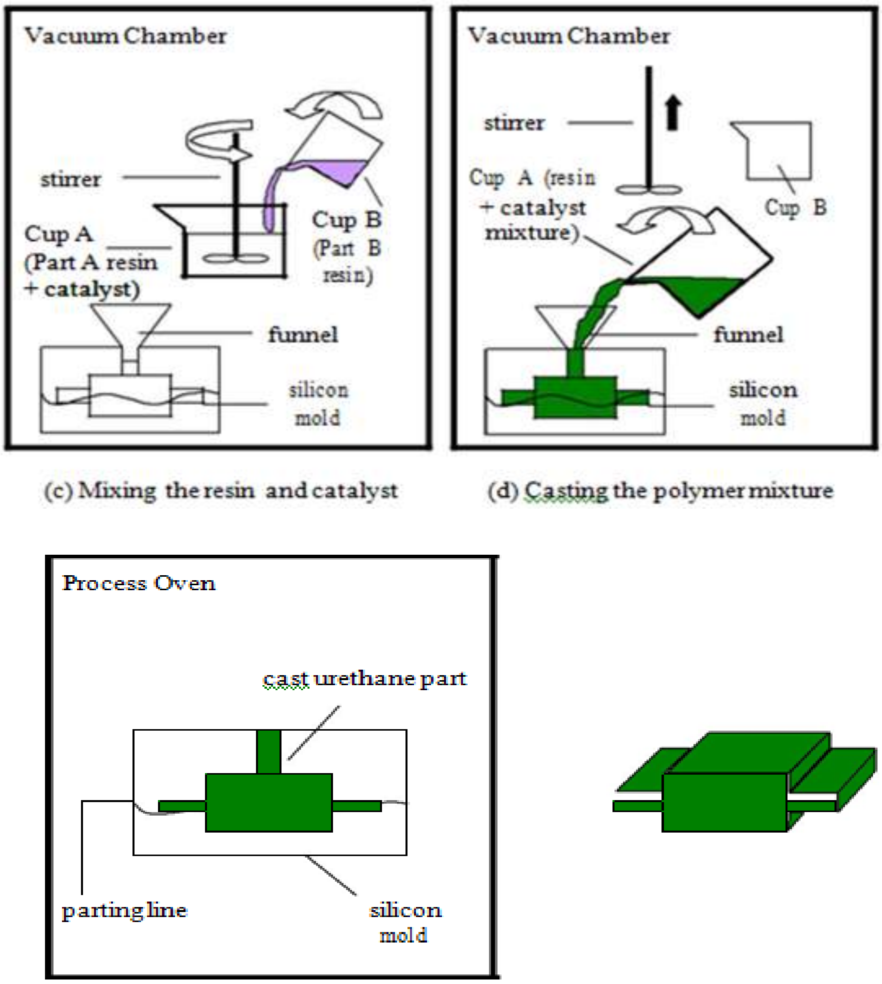
Extremely high resolution of master model details can be easily copied to the silicon cavity mold Gross reduction of back draft problems (i.e., die lock, or the inability to release the part from the mold cavity because some of the geometry is not within the same draw direction as for the rest of the part).

The master pattern, attached with a system of sprue, runner, gating and air vents, is suspended in a container. Silicon rubber slurry is poured into the container engulfing the master pattern. The silicon rubber slurry is baked at 70°C for three hours and upon solidification, a parting line is cut with a scalpel. The master pattern is removed from the mold thus forming the tool cavity. The halves of the mold are then firmly taped together. Materials, such as polyurethane, are poured into the silicon tool cavity under vacuum to avoid asperities caused by entrapped air. Further baking at 70°C for four hours is carried out to cure the cast polymer part. The vacuum casting process is generally used with such molds. Each silicon rubber mold can produce up to 20 polyurethane parts before it begins to break apart. These problems are commonly encountered when using hard molds, making it necessary to have expensive inserts and slides. They can be cumbersome and take a longer time to produce. These are virtually eliminated when the silicon molding process is used.

RP models can be used as master patterns for creating these silicon rubber molds. Figures 4.4 (a) - (f) describe the typical process of creating a silicon rubber mold and the subsequent urethane-based A variant of this is a process developed by Shonan Design Co. Ltd. This process, referred to as the "Temp-less" (temperature-less) process, makes use of similar principles in preparing the silicon mold and casting the liquid polymer except that no baking is necessary to cure the materials. Instead, ultraviolet rays are used for curing of the silicon mold and urethane parts. The advantages this gives is a higher accuracy in replicating the master model because no heat is used, less equipment is required, and it takes only about 30% of the time to produce the parts as compared to the standard silicon molding processes.



(a) Producing the silicon mold (b) Removing the RP master pattern



(c) Mixing the resin and catalyst

(d) Casting the polymer mixture

(e) Cast urethane part cured in a baking oven

(f) The final rapid tooled urethane part

Fig.4.4:(a-f) Silicon rubber molds

ALUMINUM FILLED EPOXY TOOLING

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- ❖ plastic Moulds for casting
- ❖ Compression moulds
- ❖ Reaction Injection Moulds

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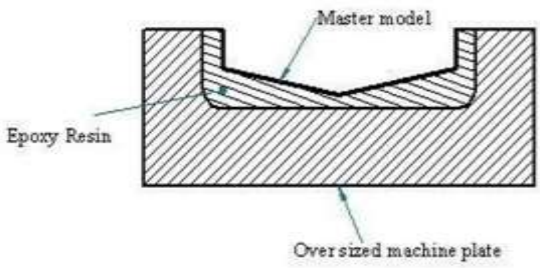

Fig 4.4: Soft Surface

Unfortunately epoxy curing is an exothermic reaction and it is not always possible directly to cast epoxy around a RP model without damaging it. In this case a Silicon RTV Mould is cast from RP pattern and silicon RTV model is made from the mould and is used as pattern for aluminum fill deposited. A loss of accuracy occurs during this succession of reproduction steps. An alternative process is to build an RP mould as a master so that only a single silicon RTV reproduction step is needed because epoxy tooling requires no special skill or equipment. It is one of the cheapest techniques available. It is also one of the quickest. Several hundred parts can be moulded in almost any common casting plastic material.

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- Tolerance dependent on master patterns
- Aluminum filled epoxy has low tensile strength

SPRAY METAL TOOLING

Using metal spraying on the RP model, it is possible to create very quickly an injection mold that can be used to mold a limited number of prototype parts. The metal spraying process is operated manually, with a hand-held gun. An electric arc is introduced between two wires, which melts the wires into tiny droplets. Compressed air blows out the droplets in small layers of approximately 0.5 mm of metal.

The master pattern produced by any RP process is mounted onto a base and bolster, which are then layered with a release agent. A coating of metal particles using the arc spray is then applied to the master pattern to produce the female form cavity of the desired tool. Depending on the type of tooling application, a reinforcement backing is selected and applied to the shell. Types of backing materials include filled epoxy resins, low-melting point metal alloys and ceramics. This method of producing soft tooling is cost and lead-time saving. A typical metal spray process for creating an injection mold is shown in Figure 4.5.

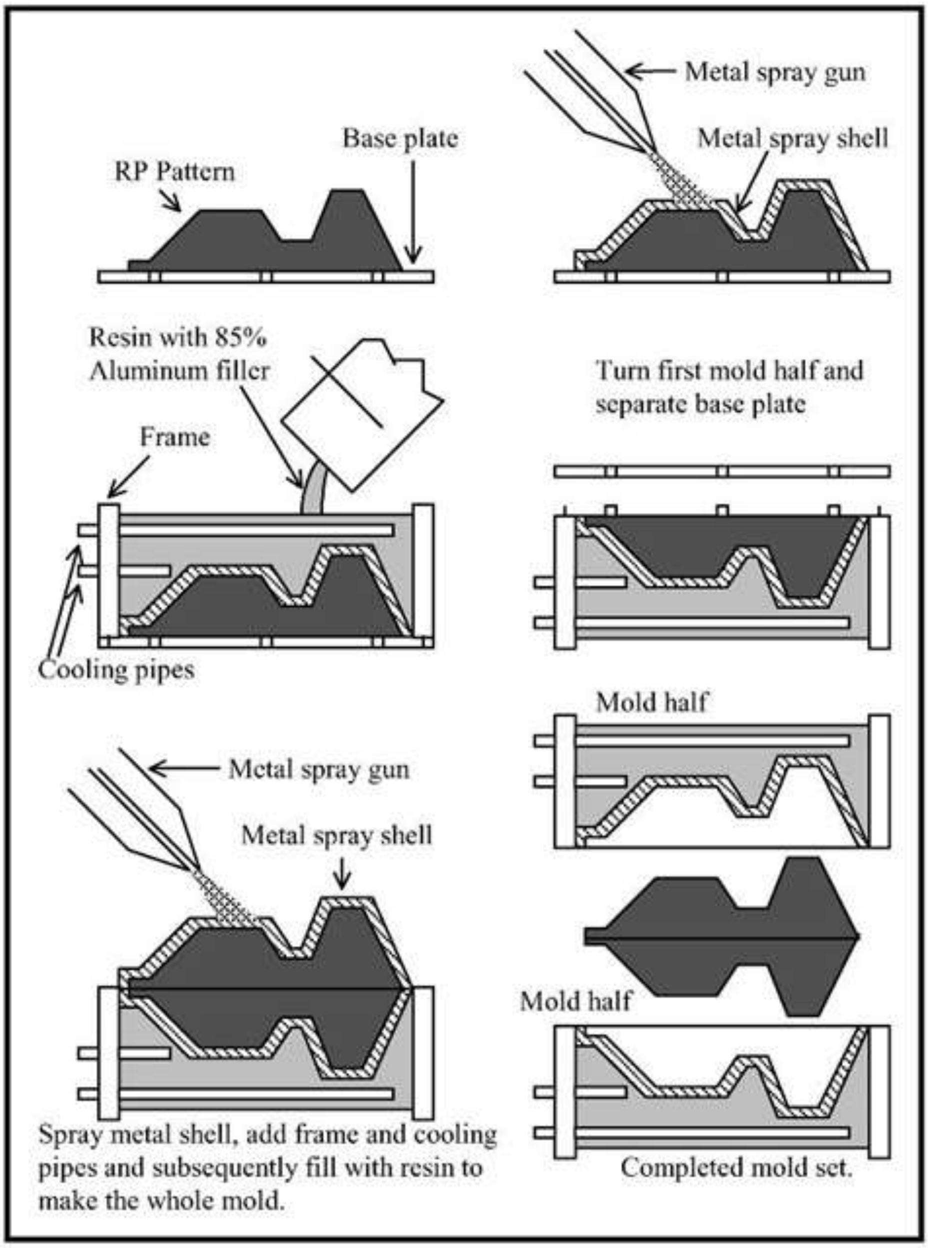


Fig 4.5: A metal arc spray system

QUICK CAST PROCESS

- Quick Cast is a process that allows for the creation of direct shell investment castings using "Quick Cast" Stereolithography (SLA) patterns.
- The Quick Cast method allows you to rapidly build highly accurate resin patterns in Stereolithography, bypassing the expensive and time-consuming step of tooling.
- Quick Cast facilitates rapid production of small quantities of metal parts in much less time than traditional methods.
- Instead of the SLA part being completely solid, Quick Cast eliminates 95% of the internal mass of the part.
- This is achieved by curing only external surfaces and an internal lattice structure. Holes in the bottom of the part allow uncured resin to drain from the part.
- The result is a 65-80% hollow part with an internal beehive or Honeycomb type lattice structure, which gives the part tremendous structural integrity.

Beehive or honeycomb structure avoids expansion during burning, provides high structural integrity.

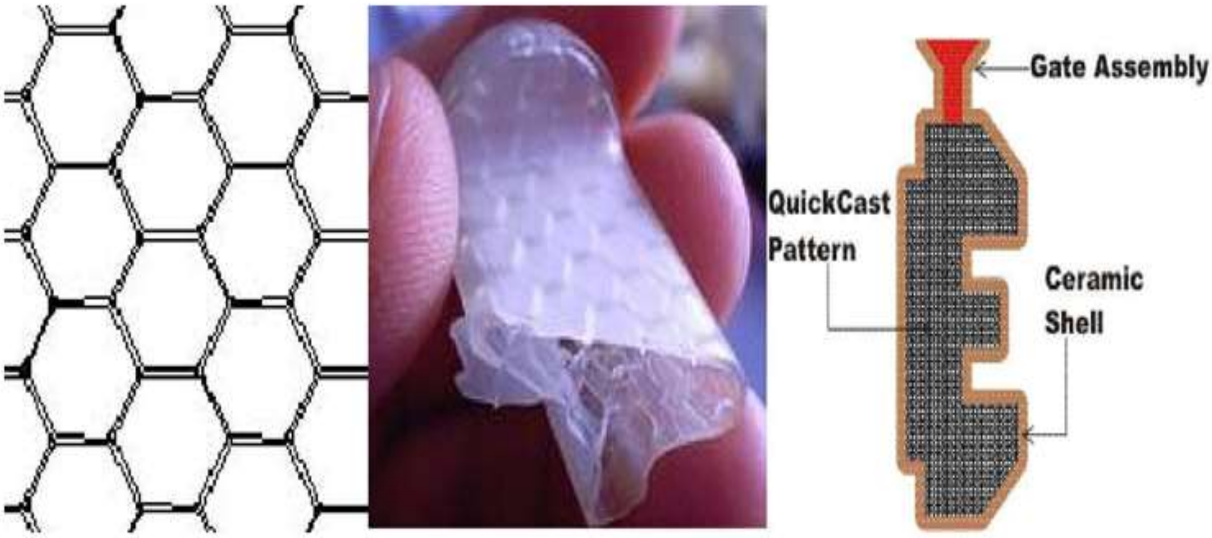


Fig 4.6: Honeycomb or beehive structure

Quick Cast, a 3D Systems proprietary process, replaces traditional wax patterns for investment casting with stereolithography (SLA) patterns created in a robust, durable material, without tooling and without delay. The net result is Quick Cast patterns in as little as 2 to 4 days and quality metal castings in 1 to 4 weeks.

The Quick Cast part resembles a beehive hatch pattern and ends up being about 80% hollow. It will burn out in the investment casting process with very little residue.

PROCESS DESCRIPTION:

A Stereolithography Quick Cast pattern is created from an STL file. The pattern is leak tested to make sure it is air tight. An investment caster is chosen (based on experience & material required). Quick Cast pattern is given to the caster. Caster puts part through ceramic coating process and performs firing procedure to burn out SLA pattern. Metal is poured into the fired ceramic shell. Ceramic shell is broken off to reveal metal part

POINTS TO BE CONSIDERED FOR QUICK CAST

- They must be reliable and repeatable.
- The pattern must be sufficiently accurate to accommodate normal investment casting problem.
- The resulting casting must be metallurgically sound.
- Quick Cast patterns must be fully sealed to ensure no ceramic slurry leaks into the hollow structure.
- Since humidity and temperature can have an adverse impact on Quick Cast patterns, special care must be taken in shipment.

SAND CASTING TOOLING

In the metal casting process, a metal, usually an alloy, is heated until it is in a molten state, whereupon it is poured into a mold or die that contains a cavity. The cavity will contain the shape of the component or casting to be produced. Although there are numerous casting techniques available, three main processes are discussed here: the conventional sand casting, investment casting, and evaporative casting processes. RP models render themselves well to be the master patterns for the creation of these metal dies.

Sand casting molds are similarly created using RP master patterns. RP patterns are first created and placed appropriately in the sand box. Casting sand is then poured and packed very compactly over the pattern. The box (cope and drag) is then separated and the pattern carefully removed leaving behind the cavity. The box is assembled together again and molten metal is cast into the sand mold. Sand casting is the cheapest and most practical method for the casting of large parts. Figure 4.7. shows a cast metal mold resulting from a RP pattern.

Fig 4.7: Cast metal (left) and RP pattern for sand casting

Casting process discussed in the evaporative pattern casting. As its names implies, it uses an evaporative pattern, such as polystyrene foam, as the master pattern. This pattern can be produced using the selective laser sintering (SLS) process along with the CastForm^{TM} polystyrene material. The master pattern is attached to sprue, riser and gating systems to form a “tree”. This polystyrene “tree” is then surrounded by foundry sand in a container and vacuum compacted to form a mold. Molten steel is then poured into the container through the sprue. As the metal fills the cavity, the polystyrene evaporates with a very low ash content. The part is cooled before the casting is removed. A variety of metals, such as titanium, steel, aluminum, magnesium and zinc can be cast using this method. Figure shows schematically how an RP master pattern is used with the evaporative pattern casting process

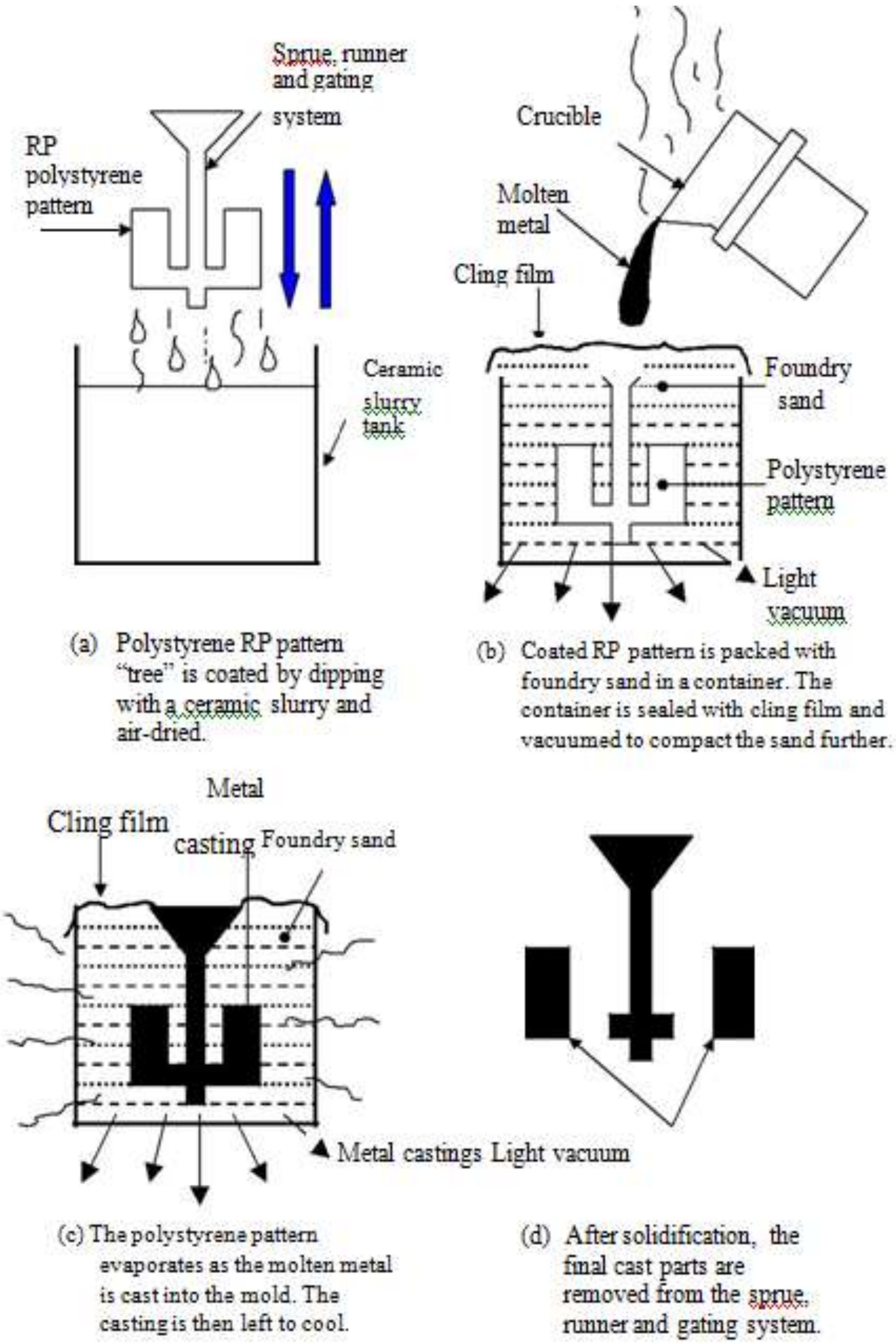


Fig 4.8: Evaporation pattern casting process

SOFTWARE FOR RP

STL File:

STL (Standard Tessellation Language) is a file format native to the stereolithography CAD software created by 3D Systems. This file format is supported by many other software packages; it is widely used for rapid prototyping and computer-aided manufacturing. STL files describe only the surface geometry of a three-dimensional object without any representation of colour, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations. Binary files are more common, since they are more compact.

An STL file describes a raw unstructured triangulated surface by the unit normal and vertices (ordered by the right-hand rule) of the triangles using a three-dimensional Cartesian coordinate system.This format has long been the industry standard in rapid prototyping. Let‘s look into the process of approximating surfaces with triangles: Each 3D form is made out of polygons. A polygon is defined as a flat shape which is bounded by a closed circuit. Each polygon with n sides can be represented using n-2 triangles.

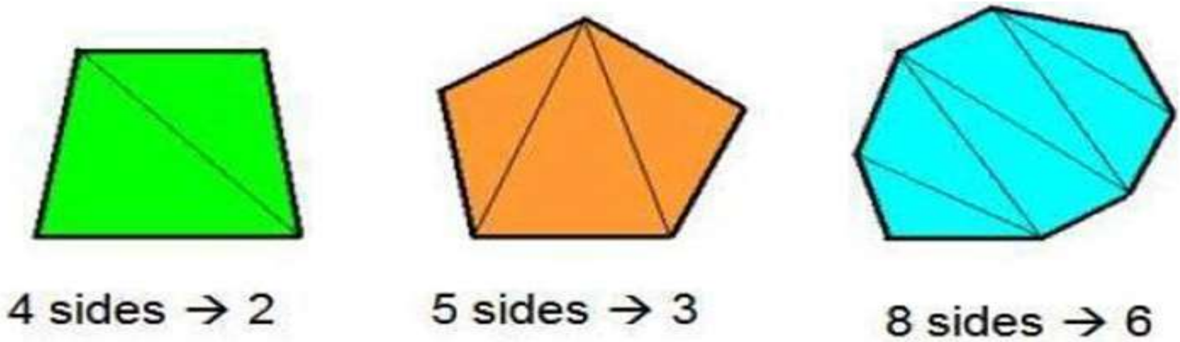


Fig.4.9: STL File

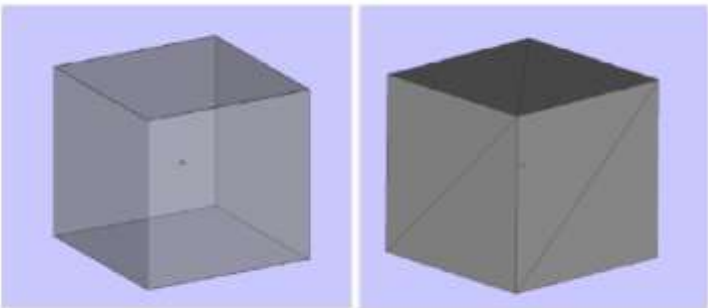
,


Fig 4.10: STL File

If we look at a box, for example: It is easy to see the box has 6 sides- each one is a polygon.Each one of those sides is a square, meaning it can be represented using 12 triangles.

Since we are dealing with 3-dimensional shapes, each triangle has a direction. This direction is expressed by the normal of the triangle. (The outward direction is represented by the normal)

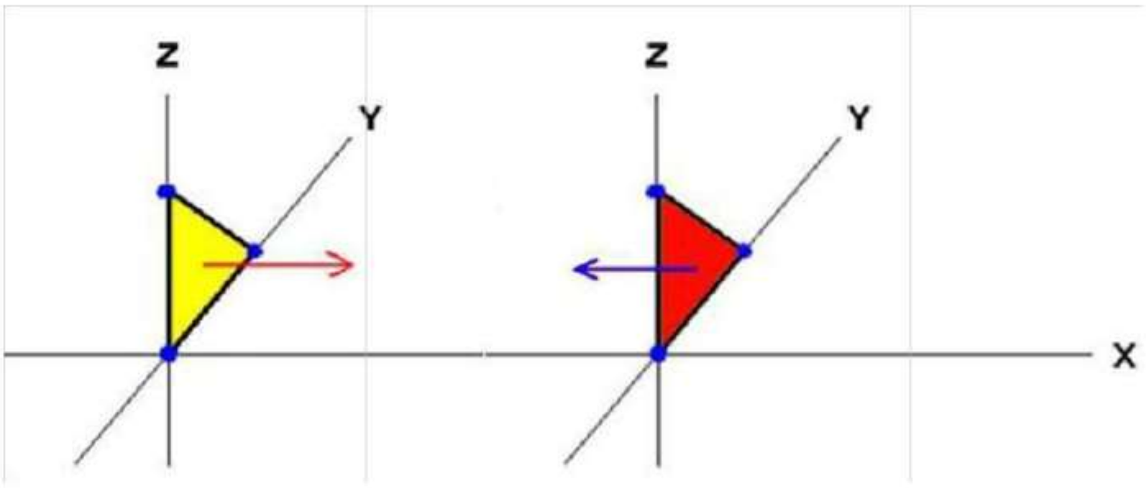


Fig 4.11: The two triangles above, though they are identical, are facing in opposite directions

STL MANIPULATION SOFTWARE

While all CAD software allows the creation of STL files, not always this process ends with a printable file. STL manipulation solutions allow:

1. Fixing those models in order to produce watertight models (see below for explanation)
2. Performing several simple actions to change the model (such as cutting and labelling)
    - Magics RP is the most extensive solution available
    - Meshlab is satisfactory as a free tool, although not very easy to use and lacking some functionality

Pricing is not specified, as this greatly varies from region to region. Additionally, most vendors offer several packages. Please consult your local distributor for pricing.

ONLINE FIXING SERVICES

As an alternative to purchasing an STL fixing software, where the user can upload the file and receive a fixed file, usually within a few minutes. Some vendors offer free automatic service, while some will have a specialist look into more complex issues. Pricing (if applicable) is typically per use, greatly reducing the initial cost. Some examples are:

- Netfabb cloud service: http://cloud.netfabb.com/ (free)
- STL fix by Materialise: http://www.stlfix.com/ (free automatic fixing, 15 EUR per file attended fixing)

DATA REPRENTATION (DATA CONVERSION AND TRANSMISSION)

The solid or surface model to be built is next converted into a format dubbed the STL file format. This format originates from 3D Systems which pioneers the **ST**ereo**L**ithography system. The STL file format approximates the surfaces of the model using tiny triangles. Highly curved surfaces must employ many more triangles, which mean that STL files for curved parts can be very large.

Almost, if not all, major CAD/CAM vendors supply the CAD-STL interface. Since 1990, almost all major CAD/CAM vendors have developed and integrated this interface into their systems. This conversion step is probably the simplest and shortest of the entire process chain. However, for a highly complex model coupled with an extremely low performance workstation or PC, the conversion can take several hours. Otherwise, the conversion to STL file should take only several minutes. Where necessary, supports are also converted to a separate STL file. Supports can alternatively be created or modified in the next step by third party software which allows verification and modifications of models and supports. The transmission step is also fairly straightforward. The purpose of this step is to transfer the STL files which reside in the workstation to the RP system's computer. It is typical that the workstation and the RP system are situated in different locations. The workstation, being a design tool, is typically located in a design office. The RP system, on the other hand, is a process or production machine, and is usually located on the shopfloor. Data transmission via agreed data formats such as STL or IGES may be carried out through a diskette, email (electronic mail) or LAN (local area network). No validation of the quality of the STL files is carried out at this stage.

STL FILE

1. IGES File

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 [12, 13]. 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:

(1) 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.
(2) The algorithms for slicing an IGES file are more complex than the algorithms slicing a STL file.
(3) 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. HP/GL File

HP/GL (Hewlett-Packard Graphics Language) is a standard data format for graphic plotters [1, 2]. 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.

3. CT Data

CT (Computerized Tomography) scan data is a particular approach for medical imaging [1, 14]. 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.

NEWLY PROPOSED DATA FORMATS

As seen above, the STL file — a collection of coordinate values of triangles is not ideal and has inherent problems in this format. As a result, researchers including the inventor of STL, 3D Systems Inc. USA, have in recent years proposed several new formats and these are discussed in the following sections. However, none of these has been accepted yet as a replacement of STL. STL files are still widely used today.

4. SLC File

The SLC (**S**tereo**L**ithography **C**ontour) 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.

5. CLI File

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 anticlockwise. 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 exists 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.

6. RPI File

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 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.

The RPI format includes the following four advantages:

(8) Topological information is added to the RPI format. As the result, flexibility is achieved. It allows users to balance storage and processing costs.

(9) Redundancy in the STL is removed and the size of file is compacted.

(10) Format extensibility is made possible by interleaving the format schema with data as shown in Figure below.

(11) 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.

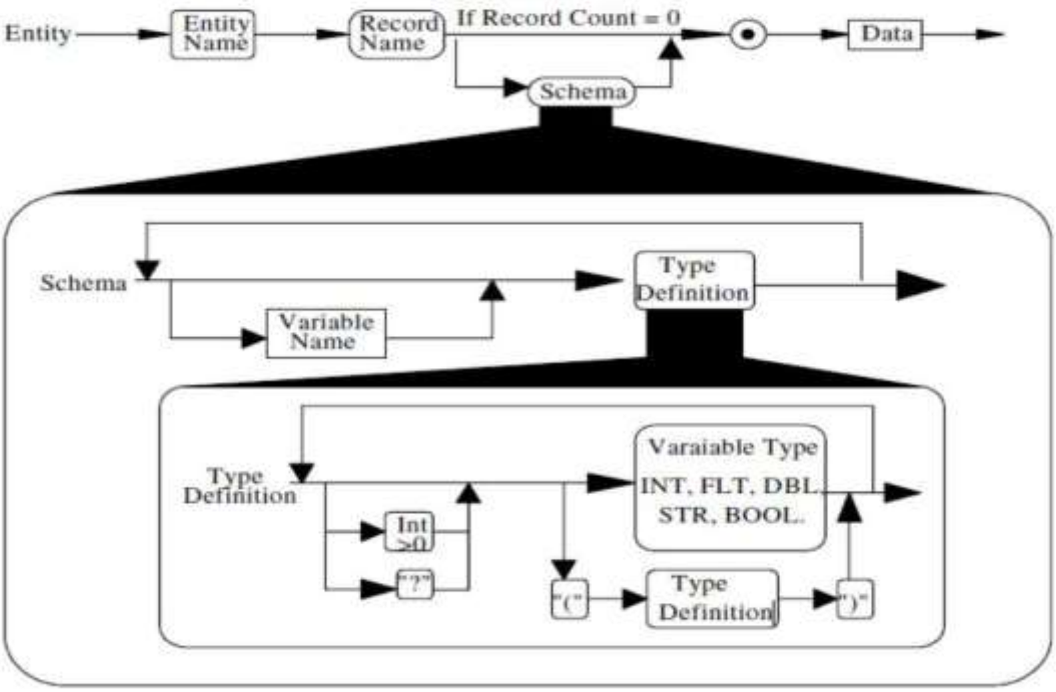


Fig 4.12: RPI format entity syntax diagram

LEAF File

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

Fig 4.13: The object tree

```
(LMT-file
(name Object)(radix 85)(units 1mm)...
(Part (name P)...
(binary-or (Part (name S)(support-structure)(open)...
                    (Layer...))
            (Part (name P2))...
                    (or (Part  (name P3)) ...
                        (Layer (name...)(polyline ...)))
                        (Part (name P4) ...
                        (Layer (name P4_L1) (ployline ...)))
                    )
              )
  )))
```

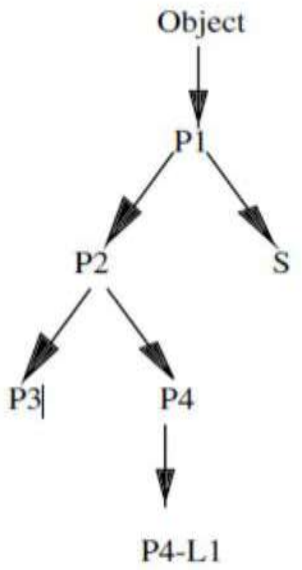


Fig 4.14: An instance tree

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:

(2) The new interpreter is needed for connecting the rapid prototyping systems.

(3) The structure of the format is more complicated than that of the STL format.

(4) 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.

Summary of STL File

- STL is the standard file format used in 3D printing
- An STL file appears as a triangular mesh of the CAD model and determines the resolution of the print
- It is possible to generate an STL file with nearly every CAD software
- In order to obtain a good STL file is important to observe the following conditions:
- Angle deviation and chord height: adjust the size and the number of triangle to increase or decrease the resolution of the STL
- Surfaces have to be “water tight” and geometries have to be solid. Do not forget holes or “naked edges”
- Give a wall thickness to every feature. STL do not work for single surfaces
- Make sure there are not overlapping surfaces on the design. That leads to inversed normal which is always good to avoid. (check and correct the inversed normals with Netfabb “STL VALIDATION” section)
- Save every component of the design in a separate file. Do not print STL made from an assembly mode. If you have embedded mechanics consult a technician
- The resolution of the STL file has to be made according to the resolution of the machine as well. Having a file with a higher resolution than the machine used is pointless
- When modeling make sure that the part does not exceed the overall printing dimensions of the machine
- Always save a copy of the CAD file and a copy of the STL. Once made the STL cannot be modified. Therefore, if there are some mistake to correct you will have to build again the model from scratch.
- Mac users on Solidworks. Set the output on ASCII instead of Binary. Otherwise Cura will fail slicing.
- Always make sure that the units used for modeling are the same used for the exporting. This is critical especially in Inventor.

SOLID VIEW & MIMICS Software Tools

SOLID VIEW

SolidView software allows non-CAD users to easily view, measure, translate and markup CAD data, opening up communication to all who need to be involved in the design process.

SolidView is used across the world by those needing access to CAD data but not trained in using CAD systems. It‘s a low-cost solution to access CAD data for manufacturing engineers, scientists, structural engineers, technical illustrators, managers, product managers and sales people.

MIMICS

Mimics are software specially developed by Materialize for medical image processing. Use Mimics for the segmentation of 3D medical images (coming from CT, MRI, micro-CT, CBCT, 3D Ultrasound, Confocal Microscopy) and the result will be highly accurate 3D models of your MAGIC patient’s anatomy. You can then use these patient-specific models for a variety of engineering applications directly in Mimics or 3-matic, or export the 3D models and anatomical landmark points to 3rd party software, like statistical, CAD, or FEA packages.

Mimics Z

For the first time, doctors, nurses, and technicians who have no previous experience with 3D modelling or 3D printing can create 3D anatomical models from MRI and CT scan images quickly and easily.

Developed by Materialise (creator of Mimics, the leading medical imaging software for the rapid prototyping industry), Mimics Z™ is optimized for output on 3D Systems high definition, 3D printers that produce full-colour models in only hours. Healthcare organizations worldwide increasingly rely on 3D anatomical models for pre-operative planning, specialist consultation, implant fit and design, patient counselling and medical education.

Use Mimics to:

- ❖ Easily and quickly create accurate 3D models from imaging data
- ❖ Accurately measure in 2D and 3D
- ❖ Export 3D models in STL format for additive manufacturing
- ❖ Export 3D models to 3-matic to optimize the mesh for FEA or CFD

Magics:

Magics is rapid prototyping software and is a key element of the Magics e-Solution Suite, a full range of market-leading software products that will streamline, automate and boost almost every step in your rapid prototyping and manufacturing (RP&M) process.

Magics rapid prototyping software enables you to import a wide variety of CAD formats and to export STL files ready for rapid prototyping, tooling and manufacturing. Its applications include repairing and optimizing 3D models; analyzing parts; making process-related design changes on your STL files; designing fixtures; documenting your projects; production planning and much more.

Magics, a user-friendly data preparation software package and STL editor, can guide you through every step of your Additive Manufacturing or 3D Printing workflow.

1. Import Files

With Magics, you can import nearly all file formats and native color information, and stay in control of your original data

Fig 4.15: Import File with color information

2. Fix and Prepare STL Files

The STL editor in Magics allows you to correct problems, as well as create watertight data and shortcuts to suit your workflow, all in a user-friendly interface. STL File fixing includes repair of flipped triangles, bad edges, holes and other defects.

Fig 4.16: STL File Fixing

3. Enhance and Edit Data

With Magics, you can also take your designs to the next level: add logos, serial numbers, and hollow parts; apply textures; and perform Boolean operations and advanced cuts.

Fig 4.17: Make edits in design

4. Prepare the Platform

Magics has the tools you need to duplicate parts, orient them in an ideal way, and create no-build zones.

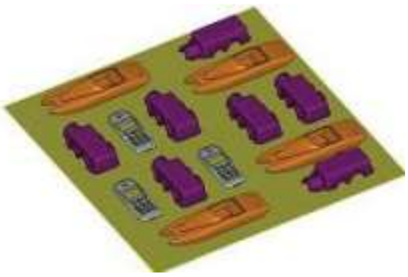


Fig 4.18: Prepare the Platform

SolidView/Pro RP is the most robust of the SolidView family of products and is designed for companies doing their own rapid prototyping work. SolidView/Pro RP offers all SolidView/Pro features as well as advanced rapid prototyping tools; compound cutting, file repair, z-correction, shelling, offset, and automatic or manual object layout. Optional CAD formats and network licenses are also available for SolidView/Pro RP.

The following features are included with SolidView/Pro RP:

- View and Print STL, SVD, and SolidWorks formats
- Print STL, SVD, and SolidWorks formats
- Measure SVD, STL, and SolidWorks formats
- Create PLY files
- Create SVD files View 2D drawings
- Translate

- ❖ Scale
- ❖ Rotate
- ❖ Mirror
- ❖ Copy
- ❖ Combine
- ❖ CAD Formats Available
- ❖ Network Licenses Available
- ❖ Cut (cross-section)
- ❖ Shell
- ❖ Repair
- ❖ Manual RP Layout
- ❖ Auto RP Layout

Key Features

- Software "wizards" guide users with nominal training through the entire process. Includes an extensive help function and templates.
- Automates all steps needed to import MRI and CT scan files, select structures, conduct editing and masking, and export data.
- Processes industry standard DICOM data and outputs ZPR files optimized for printing on 3D Systems ZPrinters.
- Tight integration with ZEdit software, enabling users to add colour to highlight areas of interest (such as a bone tumour), and annotation features that make it possible to label models with critical patient data and doctor comments.

Bridge the gap between 2D image data & 3D engineering applications

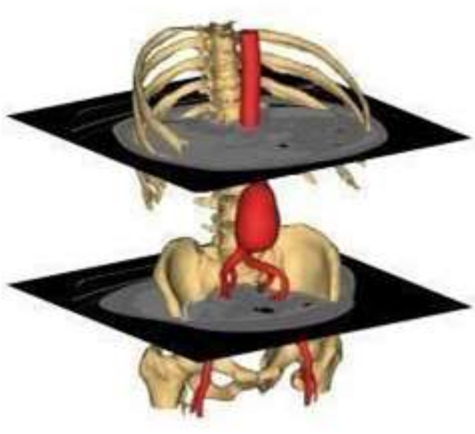


Fig 4.19: Give different colors and highlight the areas of interest

Mimics software allows you to process and edit your 2D image data (CT, µCT, MRI, etc.) to construct 3D models with the utmost accuracy, flexibility and user-friendliness. The powerful segmentation tools allow you to segment your medical CT/MRI images, take measurements and engineer directly on your 3D model. From there you can export your 3D data to a wide range of output formats and engineering applications; such as FEA, design, surgical simulation, additive manufacturing and more. Mimics is part of Materialise' total solution for advancing biomedical R&D

Mimics has been adopted by biomedical engineers and device manufacturers for R&D purposes in various medical industries:

- Cardiovascular
- Craniomaxillofacial
- Orthopedic
- Pulmonology

These industries use patient-specific 3D data to improve their implants and devices or to get a better understanding of biomechanical processes. Also non-medical industries like materials science use Mimics in image-based R&D. Materialise Mimics is a platform to bridge stacked image data to a variety of different medical engineering applications:

- 3D measurements and analyses
- Computer Aided Design: 3-matic, SolidWorks, Pro/E...etc.
- Computational Fluid Dynamics: FLUENT, CFX,...etc.
- Customized implant design
- Finite Element Analysis: ABAQUS, ANSYS,...etc.
- Rapid Prototyping: EOS, Stratasys, 3D Systems, ZCorp, Dimension, Objet, ... etc.
- Surgical simulation

Magics communicator:

Magics rapid prototyping software enables you to import a wide variety of CAD formats and to export STL files ready for rapid prototyping, tooling and manufacturing. Its applications include repairing and optimizing 3D models; analyzing parts; making process-related design changes on your STL files; designing fixtures; documenting your projects; production planning; Visualize

View STL, IGES*, VDA* and DXF 3d faces*, with fast rotation, zooming and cross sectioning.

Annotate

Add 2D and 3D annotations, shapes, text and bitmaps.

Measure

Easily create 2D drawings from 3D files. Extensive feature recognition allows measuring of distances, radii and angles in 3D. Add tolerances and additional info.

Present

Make a 3D slide show with adjustable colours, shading and transparency.

TEXT / REFERENCE BOOKS

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3. Paul F Jacobs, "Stereo lithography and other RP&M Technologies", SME, 1996.
4. FDM Maxum User Guide.
5. FDM 1650 User Guide.
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7. MK-Technology Gmbh. System User Guide.

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SCHOOL OF MECHANICAL ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

UNIT – V – RAPID MANUFACTURING PROCESS OPTIMIZATION – SPR1616

PROCESS OPTIMIZATION

The parameters of rapid prototyping can be classified as nuisance parameters, constant and control parameters. Nuisance parameters include age of the laser, beam position accuracy, humidity and temperature, which are not controlled in the experimental analysis but may have some effect on a part. Constant parameters include beam diameter, laser focus and material properties, etc. the constant parameters will affect the output of the process and are controllable in a run. These include layer thickness, hatch space, scan pattern, part orientation, shrinkage of the material and beamwidth compensation, etc. Layer thickness, hatch space, part orientation and depth of cure are the most vital among the control parameters.

Identification of requirements and key manufacturing parameters

The functional requirements of a manufacturing process include accuracy, strength, buildtime and efficiency of the process. All the manufacturing requirements are also applicable to RP. Surface accuracy is gaining a greater significance as more parts are used as master patterns for secondary manufacturing process. Build time is important in the general context of manufacturing for scheduling and cost estimation. Layer thickness, hatch space and orientation are the key control parameters for SLS and SLA. These are required indeed process-independent parameters, and can be applied to other processes, such as LOM, FDM, etc. Support structures are essential for SLA and FDM, but they are not needed for LOM and SLS processes.

FACTORS INFLUENCING ACCURACY

Accuracy of a model

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

Errors due to tessellation:

In tessellation surfaces of a CAD model are approximated piecewise by using triangles. It is true that by reducing the size of the triangles, the deviation between the actual surfaces and approximated triangles can be reduced. In practice, resolution of the STL file is controlled by a parameter namely chordal error or facet deviation as shown in figure 5.1.

It has also been suggested that a curve with small radius (r) should be tessellated if its radius is below a threshold radius (ro) which can be considered as one tenth of the part size, to achieve a maximum chordal error of (r/ro). Value of can be set equal to 0 for no improvement and 1 for maximum improvement. Here part size is defined as the diagonal of an imaginary box drawn around the part and is angle control value (Williams et al., 1996).

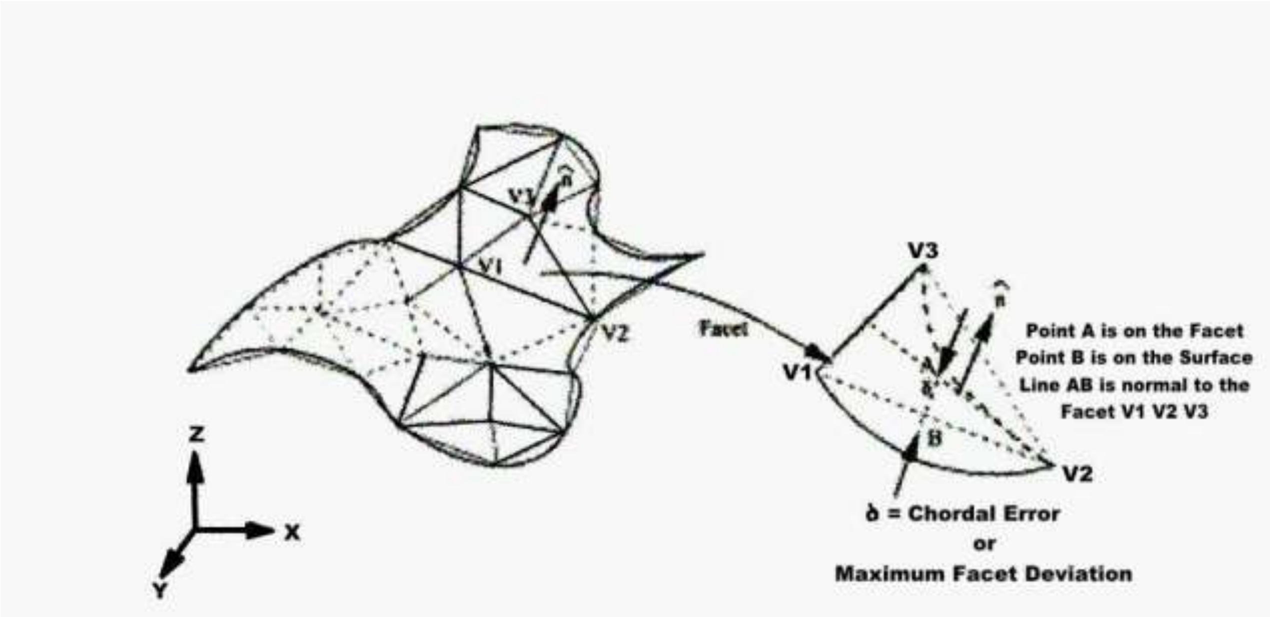
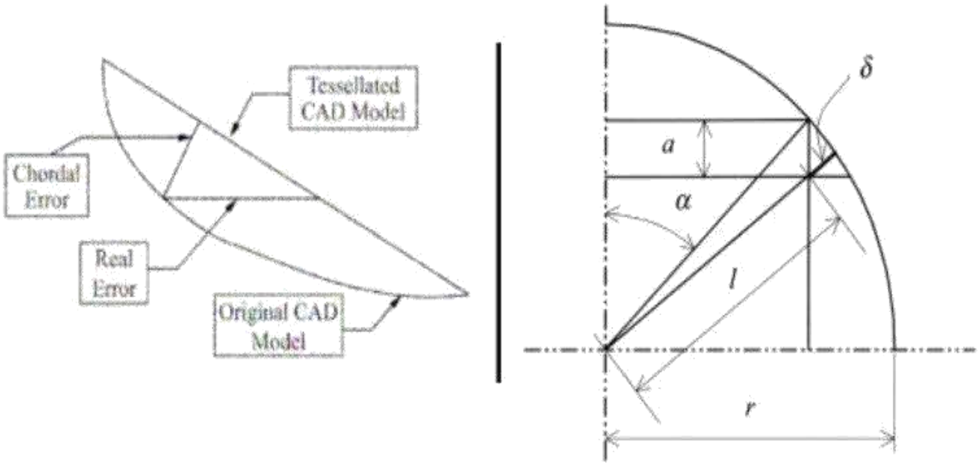


Fig 5.1: Tessellation of a typical surface of CAD model

Errors due to slicing:

Real error on slice plane is much more than that is felt, as shown in figure 5.2 (a). For a spherical model Pham and Demov (2001) proposed that error due to the replacement of a circular arc with stair-steps can be defined as radius of the arc minus length up to the corresponding corner of the staircase, i.e., cusp height (figure 5.2 (b)). Thus, maximum error (cusp height) results along z direction and is equal to slice thickness. Therefore, cusp height approaches to maximum for surfaces, which are almost parallel with the x-y plane. Maximum value of cusp height is equal to slice thickness and can be reduced by reducing it; however, this results in drastic improvement in part building time. Therefore, by using slices of variable thicknesses (popularly known as adaptive slicing, as shown in figure 5.3), cusp height can be controlled below a certain value. Except this, mismatching f height and missing features are two other problems resulting from the slicing. Although most of the RP systems have facility of slicing with uniform thickness only, adaptive slicing scheme, which can slice a model with better accuracy and surface finish without losing important features must be selected.



(a) Real error slice plane (after Pandey et al., 2003a)

(b) Error due to replacement of arcs with stair-steps, cusp height δ (after Pham and Demov, 2001)

Figure 5.2: slicing error

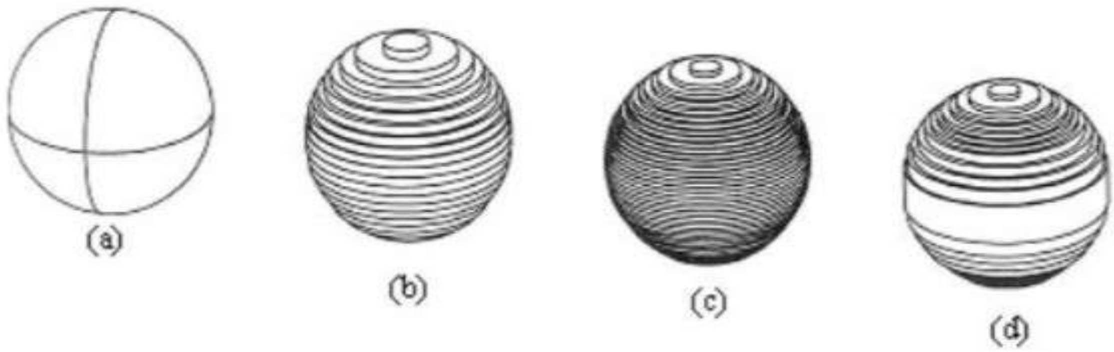


Figure 5.3: Slicing of a ball, (a) No slicing (b) Thick slicing (c) This slicing (d) Adaptive slicing

DATA PREPARATION ERRORS

COMMON ERRORS IN CAD TO STL CONVERSION

Inverted normal:

The meaning of an inverted normal is that one surface does not have a consistent direction. Occasionally, the interpretation of the surface between CAD and STL results in inverted normal like in the example below:

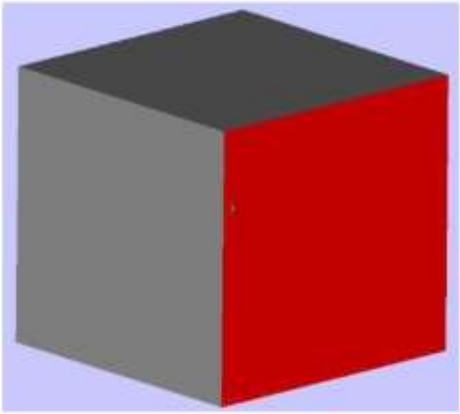


Fig 5.4: CAD Model

The box above has one face with an inverted normal. This means we will need to fix the file in order to print it using an Object 3D printer. We will discuss later on this document on how this can be achieved.

Zero thickness:

Since files printed on Object printers have to be fabricated in real world. The files have to have a volume which is larger than zero. Sometimes, a model is represented on the CAD software using just a 2D model, which has no volume:

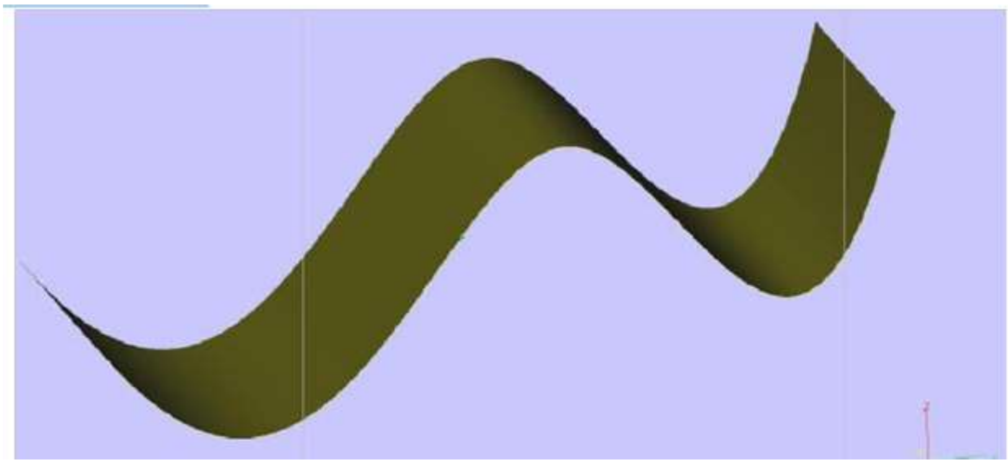


Fig 5.5: 2D Model

The part shown above is a sheet of material which has no volume, though it is three dimensional

In order for the file to be printable, we must give it some volume:

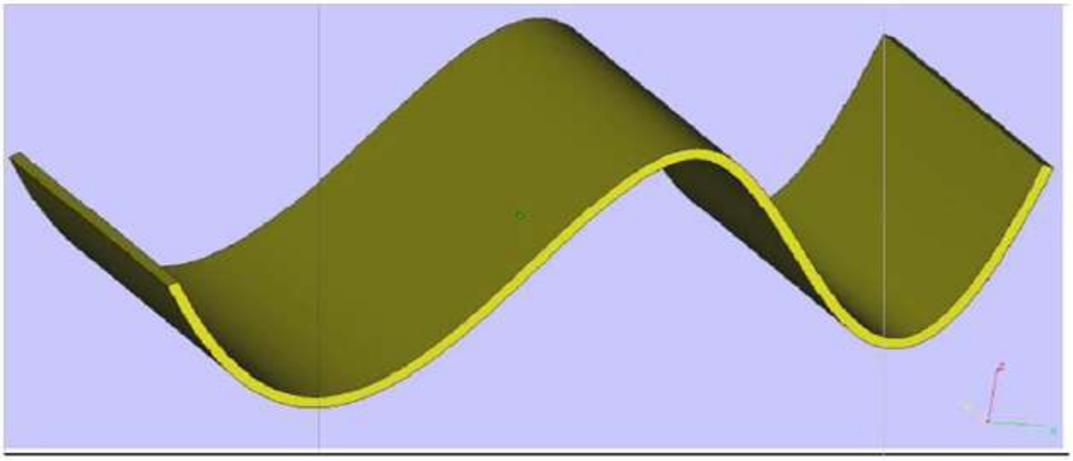


Fig 5.6: 2D Model

The second part is printable, since it has a positive volume

Bad edges:

If we look into the definition of ―watertight‖, we discover that all triangles must be connected: we cannot allow gaps between triangles. Gaps like this are commonly referred to as ―bad edges‖. Let‘s look at an example: The two hemispheres of the shape above are no connected, and are marked with a thick yellow line to indicate this (note that each software suite has a different marking) in order to close those gaps we would need to fill those gaps-an action referred to as stitching.

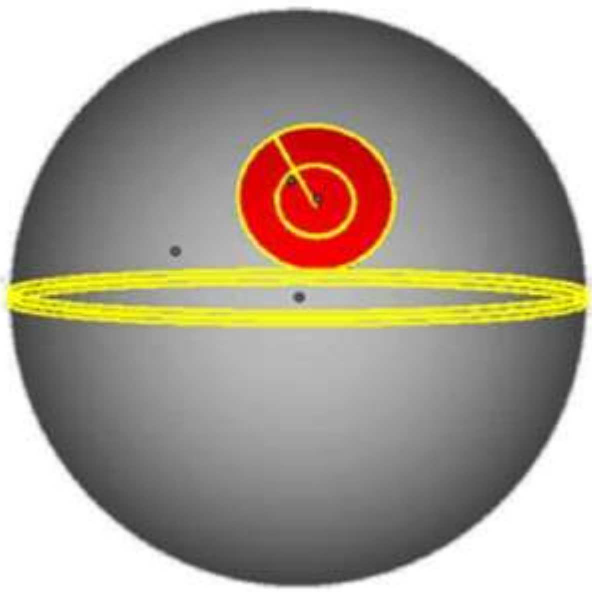


Fig 5.7: Bad edges

We distinct between two cases of bad edges:

Near bad edges:

Near bad edges are defined as edges which have a neighbour triangle which is closer than a set threshold. Those are usually closed automatically using your software of choice.

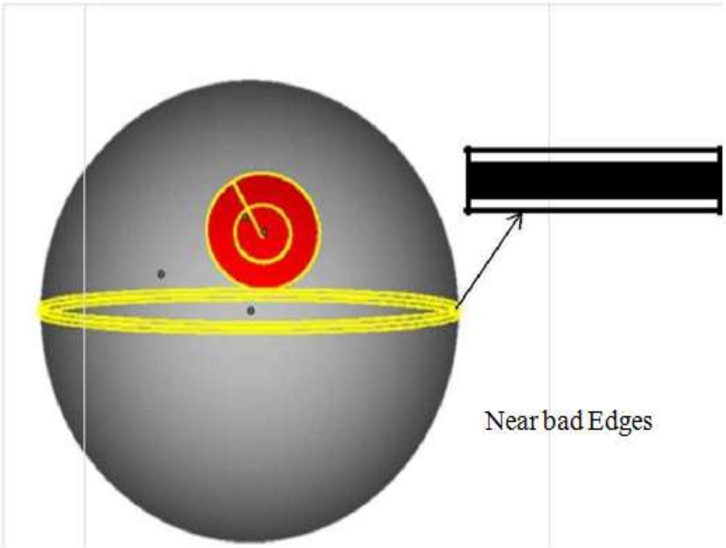


Fig 5.8: Bad edges

Real bad edges/Planar holes

Real bad edges typically enclose a hole in the shape. This is slightly more complex, as it might cause a case of zero thickness.

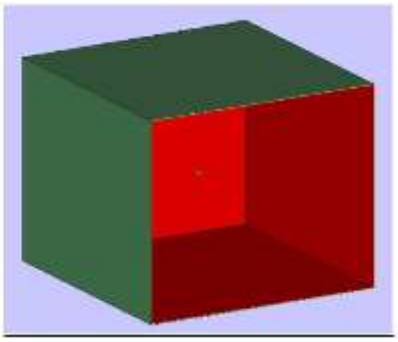


Fig 5.9: Real bad edges

The part above has a real bad edge in one of his faces. As a result, the boundaries of the box have zero thickness. Since Objet printers require a positive thickness in order for a file to be printable, this will require one of two solutions:

a. Close the hole

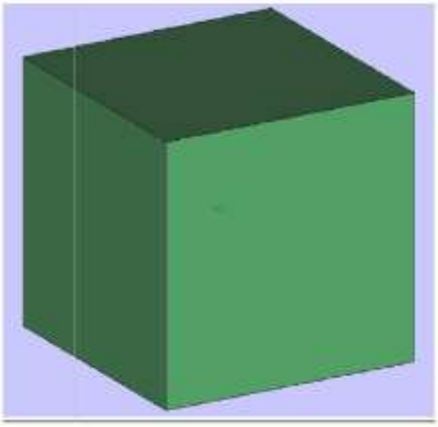


Fig 5.10: Close the hole

Once the user closes (adds triangles) to the hole, the model is once again watertight and has a positive volume. Once again, it is printable.

b. Create thickness

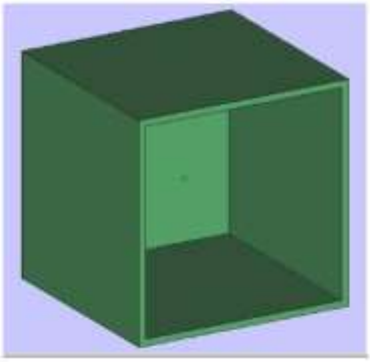


Fig 5.11: Create thickness

If the design intent was to create a box with one missing face, the user would need to create thickness, making the part printable. This is typically achieved using the ―offset‖ command.

STL File Resolution

Regardless of the CAD program used to design a part or product assembly, the ultimate input file for stereolithography and most other RP processes is called the STL file. Fortunately, most major CAD programs offer the capability to output an STL file suitable for the process. The catch is that the output process involves a configuration step, and the quality of the final RP part is dependent upon a proper configuration. To understand what is involved with proper STL output file configuration requires a look at the STL file itself.

The STL file is intended to simplify the complex mathematical descriptions of surface and solid geometry into a form that can be readily used to drive the imaging systems of RP machines. To do this, the architects of the STL

file type chose to use the most basic form of surface that can be described from point data only — the triangle. If any three points are chosen from a 3-dimensional surface then a triangle can be described by those points to approximate a portion of that surface. Of course, a triangle is by definition flat — lacking any curvature whatsoever — so if the surface in question contains any curvature then there is some error, or deviation, in the approximation. However, if the triangle size is reduced to the point where it is much smaller than any curvature in the surface, then the deviation can be brought down to a level where it is negligible. What is the limit to such a reduction? There is a practical limit — as the triangles decrease to an infinitesimally small size, the number of them required to complete the surface becomes infinitely large, as does the size of the final STL file. Most configuration settings for outputting STL files are aimed at this very issue how small to make the triangles to best approximate the surface geometry while not making enormous file sizes. This knowledge base article will attempt to give you the tools you need to understand this configuration process, and visualize the outcome of the final part.

Take a look at a ―perfect‖ CAD shape and a rather coarse STL file approximation of it.

We would not suggest using a file as coarse as this — we merely include it for the sake of illustration:

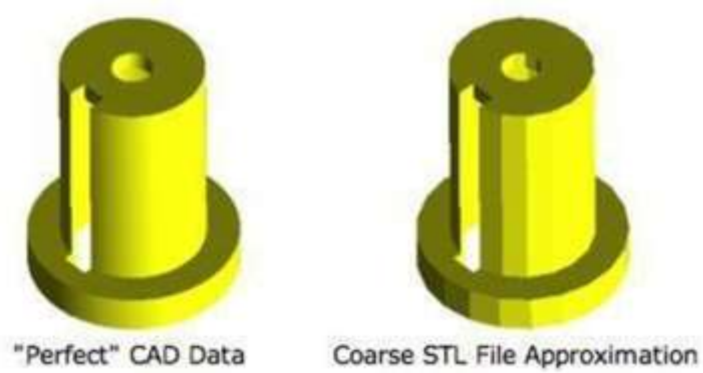


Fig 5.12: STL File Resolution

Notice how the areas of curvature are approximated in the STL file with large flats — deviating from the proper geometry. This effect is called ―faceting‖ and it would be evident in the final RP part if built with this coarse file.Let's take a closer look at the small hole in the centre, and highlight the edges of the triangles used to create it:

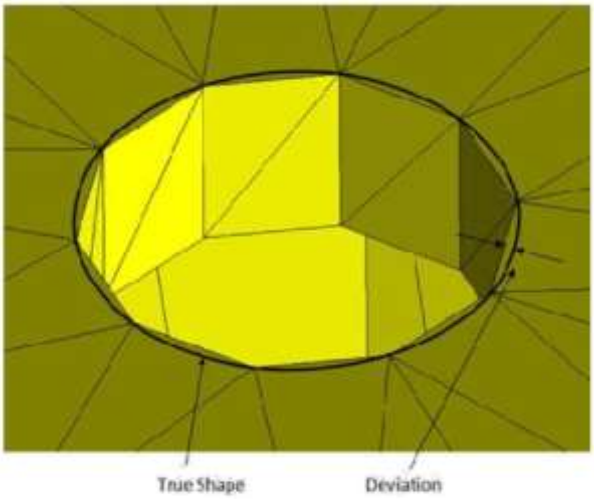


Fig 5.13: STL File Resolution

Note that the true shape of the hole is drawn here, and an indication as to the deviation from true, due to the use of large triangles. Now let's reduce the size of the triangles to get a better approximation and compare:

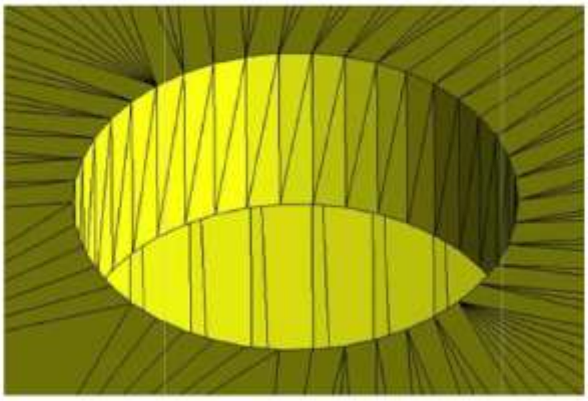


Fig 5.14: STL File Resolution

Clearly, this does a much better job of approximating the curvature, and the triangles are not so numerous as to make a huge file size. The coarse STL file size was 77KB while the fine STL file is 308KB.

Armed with this information, you can use the help function for the CAD software that you use, and develop an approximation that works for your needs. The major CAD software programs such as ProEngineer and SolidWorks actually show you an image of the faceted STL file so that you can see for yourself how closely the triangles approximate your geometry. The proof is in the pudding, so to speak, so we recommend installing a file viewer for STL files just to be sure. Doing so, you can rotate, zoom, pan and cross-section the file to be sure that it is true to form. Here are links to some good STL viewers that are free to install and use.

Part Building Errors in RP Technologies

SEVEN Part Building Errors in RP Technologies are as follows

1. **The part design has thin features or walls that are less than .030” for standard resolution or .015” – .020” for high resolution machines**.

Due to the ―layer by layer‖ approach of the additive manufacturing process, anything smaller or thinner that this will often times not build and will not be present in the final model. Pay very close attention to raised or recessed logos and areas of small text, ―knife edge‖ features which taper down to zero thickness, and curvy sections of any design where thickness can fluctuate.

2. The native CAD model is converted to .STL format with a very low resolution, resulting in heavy faceting in the model.

If the resolution of the .STL file is too low, the model will be faceted instead of having smooth surfaces and curves. This can be quite common and produces unattractive parts. Typically, to achieve a smooth finish on a model there should be an edge-to-edge distance of less than .020‖ between facets on the .STL file. Check the parameters on the native CAD program being used to determine the best method of exporting acceptable .STL files.

3. The original CAD data has numerous unstitched surfaces (rather than solids), resulting in errors when converting to .STL format

Make sure that the surfaces in the original CAD model are ―water tight‖, in that only solids are modeled. The .STL file can also be inspected to ensure that all dimensions, part volume, and surface area all appear to be correct.

4. The part design has an enclosed hollow space from which support and build materials cannot be removed.

Any enclosed hollow void in the design will contain support materials which cannot be removed through the finishing process. This area may also be filled with unused resin or powder depending on the selected prototyping process. Consider filling in voids to be solid, building the design in halves to allow access to the enclosed space, or adding a hole of some kind in the model to allow for the removal of the support materials

5. Assemblies, threads, and mating features are designed with improper clearance

The standard tolerances for most additive manufacturing processes start at +/- .005‖ and compound from there as the design increases in size. It is not uncommon for first time customers to receive parts that, while within the published tolerances of the manufacturing process, do not ―fit together‖ or mate up as intended. Typically, there should be a .015‖ – .020‖ clearance between mating parts, which is different from what is required for traditional injection molding. This is an important point to remember when the success of the project depends on how well different designs mate up or assemble with one another.

6. The design includes a living hinge which needs to function.

Living hinge designs on most parts produced via additive manufacturing don't typically function as intended. The build material involved is often too rigid, especially in such a thin section, and will break. While there have been a few materials developed that look to address this need (the Duraform EX material using the SLS process can often work well), expect limited usage from a living hinge design produced via additive methods.

7. The units of measurement for the .STL file differ from what was intended.

Double check the .STL files properties to ensure that the correct unit of measurement is selected. This is especially true when there is more than one design with varying units of measurement being built together. Some CAD packages also have default settings where .STL files may be exported in a different unit of measurement from what was used during the design process. When there is a tight time line and the project is on the line, it can be difficult to see the comedy in dramatically oversized or undersized parts as they come out of the box.

Keep these seven common mistakes in mind when considering any additive manufacturing project. Be careful to confirm the integrity of the original CAD data, and be mindful of living hinge designs, enclosed or trapped hollow spaces, and clearance between mating features, and any features or walls that are smaller or thinner than .030‖. After exporting the .STL file from the native CAD file, take time to confirm that the overall resolution of the file is sufficient and that the selected units of measurement are correct.

Part building Orientation:

During part deposition generally two types of errors are observed and are namely curing errors and control errors. Curing errors are due to over or under curing with respect to curing line and control errors are caused due to variation in layer thickness or scan position control. Figures illustrate effect of over curing on part geometry and accuracy. Adjustment of chamber temperature and laser power is needed for proper curing. Calibration of the system becomes mandatory to minimize control errors. Shrinkage also causes dimensional inaccuracy and is taken care by choosing proper scaling in x, y and z directions. Polymers are also designed to have almost negligible shrinkage factors. In SL and SLS processes problem arises with downward facing layers as these layers do not have a layer underneath and are slightly thicker, which generate dimensional error. If proper care is not taken in setting temperatures, curling is frequently observed.

PART ORIENTATION AND SUPPORT

Layered manufacturing is a method of rapid prototyping where objects are constructed layer by layer; see. for an overview of various methods and application areas. Many different processes are available for layered manufacturing, but we are concerned only with those processes that might require the use of external support structures during the formation of the object. Two common examples of machines that use this type of process are stereolithography as found in 3D Systems machines and material deposition methods as found in machines built by Stratasys. (To the best of our knowledge, in the layered manufacturing machines of Cubital, Helisys, DTM, and MD* the object is enclosed in material that acts as support, so no external support structure is needed.)

By external support structures, we refer to the scaffolds that have to be built simultaneously with an object in order to prevent it from toppling and to support material that would otherwise droop or fall. Therefore, for some layered manufacturing methods the inclusion of support structures increases the domain of parts that are constructible. In this paper, we describe a method for determining the best orientation for constructing an object by layered manufacturing. The criteria for choosing the orientation include stability of the object and minimum area of contact with support structures.

NEED FOR SUPPORT STRUCTURES

To motivate the need for support structures, we briefly describe the stereolithography process, a popular layered manufacturing technique. The object is constructed in a vat of photocurable liquid on a platform whose height can be controlled. At first the platform is just below the surface of the liquid at a distance of one layer thickness. A laser 'draws' the first layer of the object on the liquid, causing the liquid to harden. The platform is lowered to expose another layer of liquid on the surface and the laser draws the next layer of the object. This process continues until the object is formed. In material deposition methods, the concept is similar, except here at material laying nozzle plays the role of the laser and liquid. Note, in the current methods, layers of constant thickness are used; a method for determining best orientation for minimizing the number of slices of variable thickness and the total stair-case area. Consider an object to be built in a given orientation. Support structure will be needed in three different situations. The most common need for support structure occurs when material on one layer overhangs the previous layer by more than a specified amount. In Figure 5.15 based on the allowable overhang, face B might require a support but not face A. Note, in this case, supports are not required to prevent the object from toppling.

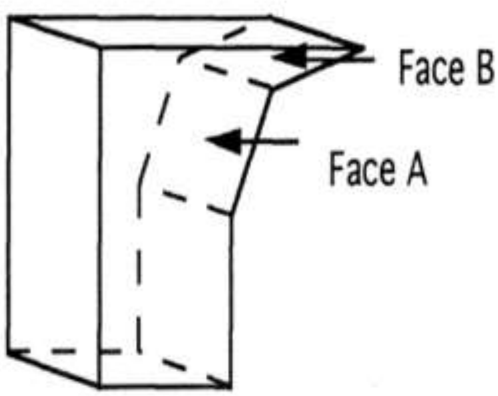


Fig 5.15: Need for Support Structures

Including support structure to take care of this case is often sufficient to handle the remaining two cases (and currently in practice the automatic computation of support structure stops here). The second situation where support structures are needed is when a 'floating' component is introduced during the construction. These are parts of the object introduced at a height greater than zero but not joined to the rest of the object until later in the construction; see, for example, Figure 5.16.

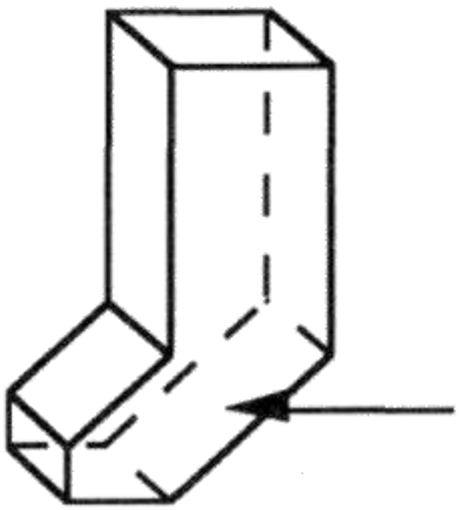


Fig 5.16: During the construction of the object, support structure is required to carry the floating component.

The third case where external supports might be required is when the object becomes unstable during the construction. In Figure, the object will topple if the face indicated by the arrow is not supported. Note, this situation is different from the one illustrated in Figure where the object is in a stable orientation.

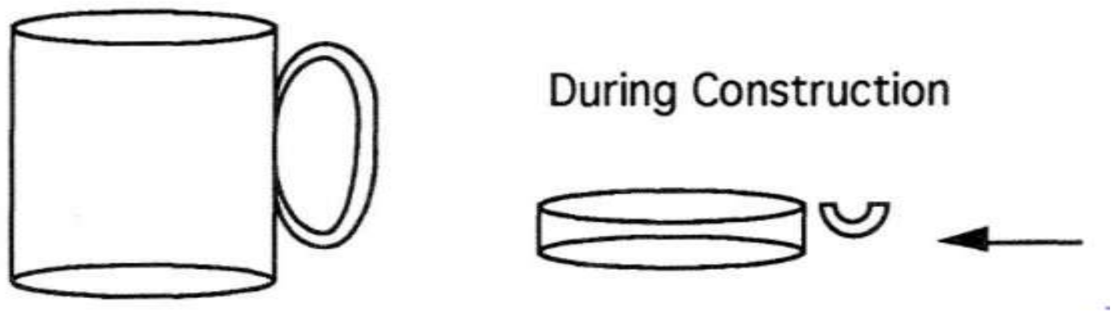


Fig 5.17: T~ prevent the object from falling, support structure is needed on the indicated face.

We note, the need for support structures in the third case is somewhat weak if considered in light of the physical process. Factors include the fact that the object's base usually weakly adheres to the platform on which the object is grown, and in the case of stereolithography the liquid in which the object sits adds further stability. However, situations where stability is an issue are conceivable.

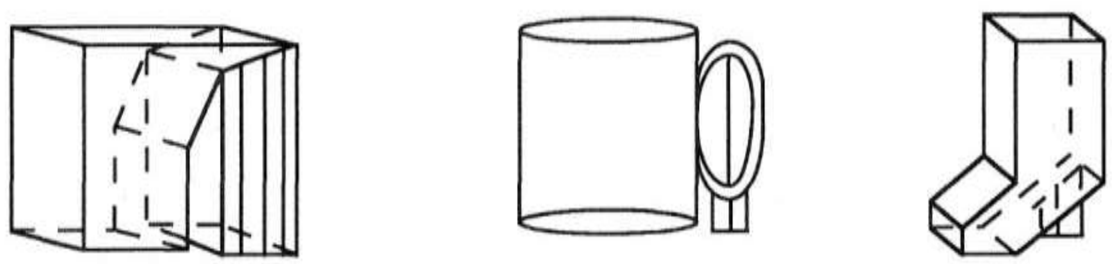


Fig 5.18: Examples of support structure for the objects shown in the Figures 5,6, and 7. Notice that the second object needed support structure at the top of the handle because of overhang between layers, and support at the bottom of the handle because of a floating component.

Our approach imposes no restrictions on the geometric domain of objects. In addition to solid objects with or without voids, we also consider the layer manufacture of (thin) surfaces, e.g., a hollow cylinder, sheet metal parts, etc. However, we make the assumption that a curved surface cannot act as a base for the construction. This assumption stems from the observation that whenever a physical object, at rest on some plane P, is in a stable orientation, it has at least a 3- point contact with P. This contact requirement can be met whenever the object has either of the following in contact with P: (i) three distinct non collinear points, (ii) a line and a point, (iii) a plane, (iv) a non-degenerate planar curve. For example, a sphere resting on a plane will not meet any of the aforementioned requirements, and hence is unstable. For any object G, every planar face on the convex hull of G will either be an (original) face of G, or will be a (new) face that satisfies the contact criteria. Therefore, our approach to determine stable orientation involves reasoning based on the convex hull of the object. To compute the convex hull of an object we require sample points on its surface. We adopt this point based approach due to the difficulties in computing the convex hull of free form objects. In this paper, we first facet (triangulate) the object and then use the vertex set of the faceted object as sample points. We assume every object to be constructible and every orientation (for construction) to be valid with the addition of sufficient support structures. The interested reader can compare this use of support structures to the approach taken in. Polyhedral objects are tested for orientations in which the object has no overhanging material between layers. Any object without such an orientation, according to, is not constructible.

The support structures are built, layer by layer, simultaneously with the object. After the object is constructed, the support structure must be removed, often manually. For a complicated object this removal may be difficult, requiring the supports to be dug out of tight spaces, while also reducing the quality of the surface finish. To reduce the time required to manufacture the object and to improve the quality of the surface finish, we wish to minimize the surface area of the support structure that is in contact with the object. Finally, given two orientations of an object with the same amount of support structure, our algorithm will pick the orientation in which the object is more stable, Le., has lower center of mass. In addition to, the problem of determining optimal orientation in layered manufacturing has been considered in where simulated annealing (SA) is used for selecting the orientation. Orientations are evaluated with respect to the object's height, the total area of the surfaces of the object subject to staircase effect, and the volume of the trapped liquid (specific to SLA process without regard to support structure).

DEFINITIONS

We define the following with respect to an object G that is being considered for layered manufacture with a direction of formation along the z-axis.

Up_vector: The up_vector is a unit vector that specifies an orientation of G.

Base: The base of G is the convex hull of the set of points on G whose dot product with the up_vector is minimal.

The orientation of G during formation is obtained by rotating G so that the up_vector is parallel to the positive z-axis and then translating G so that its base rests on the x-y plane. See Figure 5.20

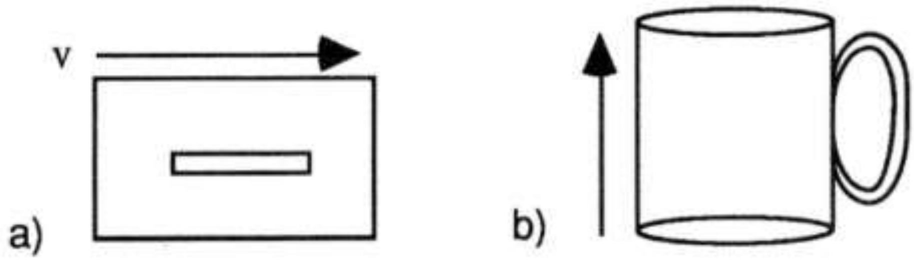


Fig 5.19: a) An object given in its initial orientation with an up_vector v, and b) the orientation determined by v.

Supported Point: A point p on the surface of G is a supported point if the following hold:

1) the outward pointing normal at p has a negative z coordinate

2) p lies on the surface of a support structure for G

All other points on G are unsupported points. Each sample point chosen on G is classified as supported or unsupported. This information is used later to construct an approximation to the necessary support structure.

Extended Base:

An extended base of G is the convex hull of point sets PI and P2 where PI contains all sample points ofG that lie in the x-y plane and P2 contains the projection into the x-y plane of all supported_points of G; see also Figure 5.21.

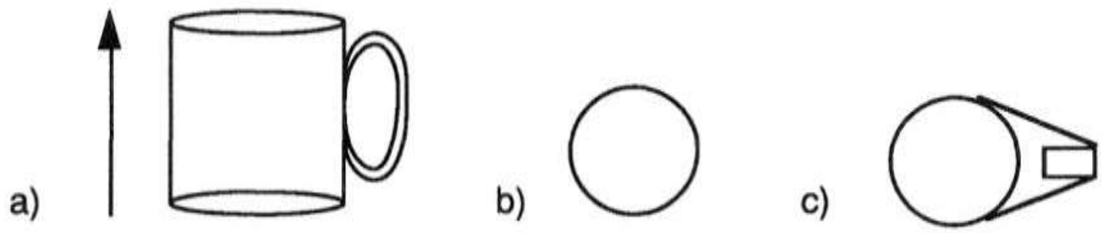


Fig 5.20: a) An object and its direction of formation. Note that some of the sample points on the handle must be supported, since during the construction a floating component is introduced. b) The base of the object. c) The extended base of the object.

The Algorithm

Our method for the determination of the best orientation for the layered manufacture of an object consists of three steps. First, a candidate list of orientations for the object is made. Second, for each orientation in this list, an approximation to a sufficient support structure for the construction of the object is computed. Also, the center of mass of the object in this orientation is found. Finally, the best orientation is selected from the candidate list. The selection criteria includes (i) the surface area of contact between the support structure and the object, which wee seek to minimize, and (ii) the stability of the object.

Determination of Candidate List of Orientations

Consider an object G. The sample points of G are elements of the vertex set of the faceted representation (triangulation) of G. Let CH(G) denote the convex hull of the set of sample points. Note, if G did not contain any planar faces, then CH(G) could possibly contain a large number of faces depending on the coarseness of the triangulation. The inward pointing normal to each face! of CH(G) corresponds to the up vector for the orientation of G with! as the base. In order to limit the number of candidate orientations, we use only those up vectors that correspond to faces of CH(G) with a relatively large area. First, we set a threshold value A for the surface area of a face. In general, Ais chosen higher than the value for the area of a facet that corresponds to a curved surface region of the original object G. Next, all faces that have surface area less than Aare eliminated. The up vectors corresponding to the remaining faces of CH(G), with surface area greater than A, form the list of candidate orientations. In these orientations, sits on a large base which acts to increase stability and decrease the size of the support structure needed.

Computation of the Support Structure

Consider an object G and an up_vector v. The computation of the approximate support structure for G in the orientation corresponding to v can be broken down into the following steps. First, G is moved into the orientation corresponding to v. Second, the sample points on G are classified as either supported or unsupported. Third, using the classification of the sample points and normals on G's surface, an approximate support structure is made. We elaborate on the second and the third steps next.

Classification of Sample Points

Initially all sample points in G are classified as unsupported. A sample point p will be classified as supported if, after adding support at p, either of the following hold:

❖ a floating component introduced during the construction ofG is supported

❖ a component, that would otherwise topple as the object is grown, is stabilized; see Figure

To determine which sample points need to be supported, the growth of G is simulated. This simulation is necessary due to the difficulties in tracking the center of mass of a curved object as the object is formed. We note that if the object domain were restricted to polyhedral objects, such an approach would not be necessary.

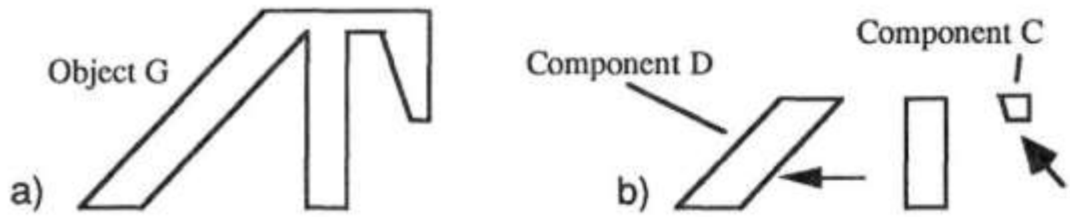


Fig 5.21: a) The profile of an object and b) the connected components of G during formation. The component is unstable. C is floating. Adding support at the indicated sample points would stabilize these components.

If a new component C is introduced during G's growth, then C is floating since its extended base does not lie on the x-y plane. See Figure. To indicate the need for support on C, all sample points in the new component are classified as supported. When the next layer is added, the component is no longer new. Global methods exist for the detection of floating components that do not involve the growth of G. However, since must be grown to test for unstable components, we make use of this simulation here. As layers are added, the center mass of each connected component of the partially formed object is computed. The center of mass of some connected component is not directly above its extended base then component is unstable. D can be stabilized by adding support to G at sample points that lie in D, so that D's center of mass lies above the new extended base.

Computing Approximate Support Structure (Rays Structure)

Assume the object G is in some (candidate) orientation. The approximate support structure for the object in a particular orientation is stored in a (n¥n) array which we refer to as the rays structure. The cells rays structure correspond to a grid of rectangles the x-y plane. The projection ofG onto the x-y plane is contained in the union of these rectangles. Let Pij denote the center of rectangle (i,j) in the x-y plane and let Lij be the half line originating at Pij and parallel to the z-axis. The points of intersection between the object G and Lij is stored in the cell (i,j) of rays structure. Note, there can be several points of intersections between Lij and G. These points are stored in the same order as Lij intersects G, i.e., the points have Increasing z values. Next, these points of intersection are classified. The primary classification is based on the direction of the face normal. If the face normal points upwards the corresponding point on G does not require support; all other points may require support. Next, for points that may require support, a classification of supported or unsupported is done. Initially, support will be added to those points where the angle a, between the face normal and the negative z axis, is smaller than a user Specified angle~. Decreasing values of a (down to 0 degrees) correspond to increasing material overhang from the previous layer during the construction. So, if a is less than the user specified the point of intersection is classified as supported; all others are classified as unsupported.

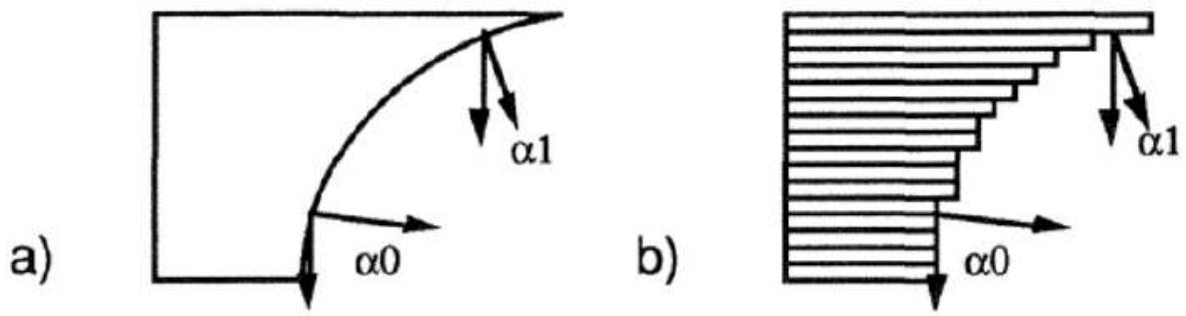


Fig 5.22: a) An object G and the angles ao and al between the normals to G's surface and the negative z-axis. b) The layers added in the formation of G. Note the overhang between layers is greater for the smaller angle $\alpha 1$.

After the initial rays_structure classification, the support information that was attached to the sample points is used to complete the approximate support structure. A sample point p of an object G is classified as supported only when the support structure added at p helps stabilize G or carries a floating component of G. So to ensure that adding support at p doesn't create a new unstable component, the support structure here is grown from the x-y plane. With this in mind, let p be any supported sample point. Suppose p lies above the rectangle in the x-y plane that has center Pij- Then each point of intersection of G and Lij with support type not supported that has z value near or below the z value of p is changed to type supported. Once each sample point's contribution is included, the approximate support structure stored in rays structure is a sufficient support for the object during its manufacture.

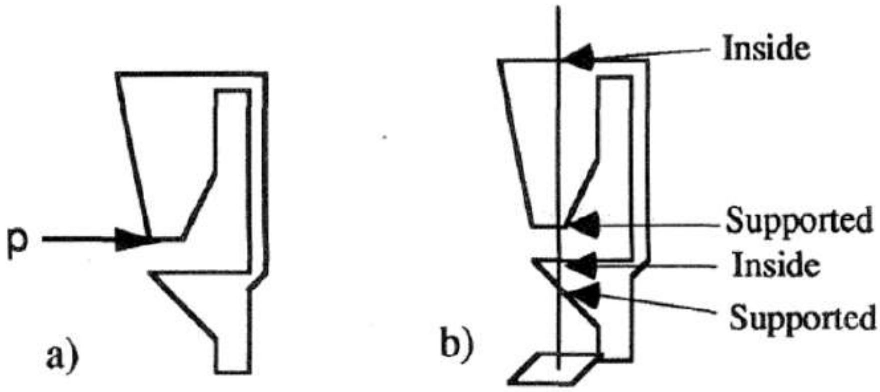


Fig 5.23: a) Supported sample point p on G, and b) the classification of the points of intersection of Lij and G.

By the above process, all points of intersection corresponding to each half-line are classified (as inside, supported, or unsupported). These points break the half-line into several line segments; those segments between consecutive points of intersection along the ray. Since, the points are stored in rays structure in order of increasing z-values, the points alternate between inside and supported/unsupported; see Figure. Finally, we add the approximate support structures by considering the directed line segments corresponding to each half-line. First, a support structure is added to each line segment 1= (u,v) where the endpoints u = point on the x-y base, and v = supported point on G. This corresponds to adding support structures A in. Next, support structures are added to line segments I = (u,v) where the end points u = inside and v = supported. This step corresponds to adding the support structure B in figure 10 (b). This is required to add support at intermediate levels. Finally, the total surface area of contact between a support structure and the object G is computed as the product of the area of the base of the cell times the number of places where the support touches the object.

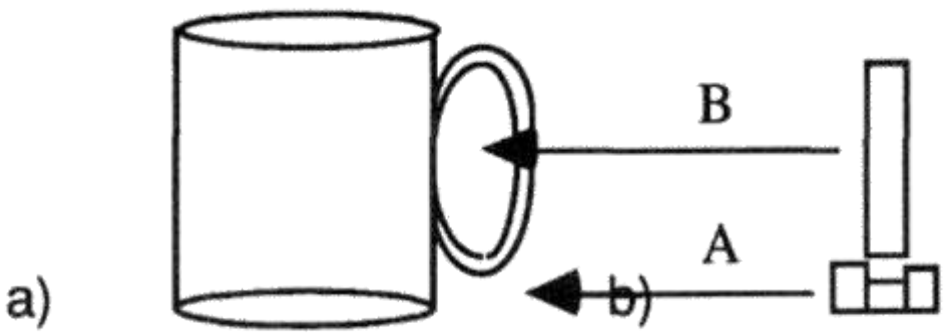


Fig 5.24: a) An object G, and b) a graphical representation of the support structure approximated by the rays structure for G. Note that support A is added to carry a floating component and support B is added to support overhangs.

Therefore, by using each half line Lij to approximate the support structure needed over the corresponding box in the x-y plane, the information stored in the rays structure is used to quickly calculate the surface area of the support structure in contact with the object. The best orientation is chosen from the list of candidate orientations. This orientation the support structure for G has minimal surface area of contact with G. If two orientations require support structures with equal surface areas of contact, the orientation in which G has a lower center of mass is chosen as best.

Post Processing or Finishing Process

1. Cleaning

All prototypes are cleaned immediately following machine production and can require everything from a simple wipe-down to multipart chemical rinse to move onto the next step. Stereolithography (SLA) parts are created in a vat of resin which must be drained, wiped away, and fully washed with a three-part rinse to make them safe to handle. SLS parts simply need to have excess powdered materials brushed away.

2. Support Material Removal

To hold complex geometries in place during the build, all additive manufactured parts have some type of support method. SLA parts are attached to the build tray using latticework-like scaffolding, all of which needs to be removed with hand tools, grinders or wheels. FDM parts have to have their supports chemically melted off. Poly Jet's gelatinous polymer supports are removed by scraping and using high-pressure water jets, followed by a chemical bath and another round of water jets. All of these processes are both labor intensive and delicate. It doesn't take much to lose the exceptional detail and dimensional tolerance required, or to destroy a part altogether.

3. Finishing

Finally, additive manufactured parts get finished. Again, final finish processes can range from the bone simple to the super complex and will vary depending on which method and material is being used. Parts can be hand-sanded, bead blasted, or multi-process sanded. They can be primed, urethane, coated, or painted; and only service bureaus like Proto CAM can offer specialty finishes such as medical-grade coating processes and crystal-clear bottle finishes that result in a completely transparent piece no matter how challenging the shape. Click here to read more about the finishing options Proto CAM offers. All rapid prototypes whether generated on industrial-scale machines that produce top-of-the-line prototypes or "office-scale" 3D printers that spit out serviceable rough samples require considerable work once the machine has done its work. Post-processing is where parts start to look like parts and where experienced engineers make a huge difference in the quality of your final product. Get in touch with Proto CAM today to see how we can help make your prototype happen from “printing” all the way through finishing.

Finishing Processes

As there are various influencing factors such as shrinkage, distortion, curling and accessible surface smoothness, it is necessary to apply some post-RP finishing processes to the parts just after they have been produced. These processes can be carried out before the RP parts are used in their desired applications. Furthermore, additional processes may be necessary in specific cases, e.g., when creating screw threads.

1) Cutting Processes

In most cases, the resins or other materials used in the RP systems can be subjected to traditional cutting processes, such as milling, boring, turning, and grinding.These processes are particularly useful for the following: Deviations in geometrical measurements or tolerances due to unpredictable shrinkage during the curing or bonding stages of the RP process.

- Incomplete generation of selected form features. This could be due to fine or complex-shaped features.

- Clean removal of necessary support structures or other remainder materials attaching to the RP parts.

In all these cases, it is possible to achieve economic surface finishing of the objects generated with a combination of NC machining and computer-aided NC programming.

2) Sand-Blasting and Polishing

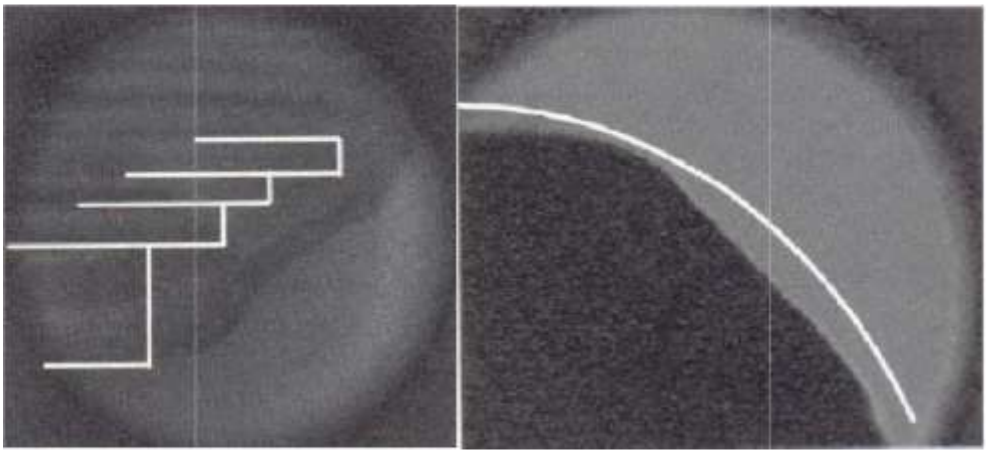
Sand blasting or abrasive jet de-burring can be used as an additional cleaning operation or process to achieve better surface quality. However, there is a trade-off in terms of accuracy. Should better finishing be required, additional polishing by mechanical means with super-fine abrasives can also be used after sandblasting.

3) Coating

Coating with appropriate surface coatings can be used to further improve the physical properties of the surface of plastic RP parts. One example is galvano-coating, a coating which provides very thin metallic layers to plastic RP parts.

4) Painting

Painting is applied fairly easily on RP parts made of plastics or paper. It is carried out mainly to improve the aesthetic appeal or for presentation purposes, e.g., for marketing or advertising presentations.



a) Thicker bottom layer **(b) Deformed whole boundary**

Fig 5.25: Over-curing effects on accuracy in Stereolithography

Part finishing:

Poor surface quality of RP parts is a major limitation and is primarily due to staircase effect. Surface roughness can be controlled below a predefined threshold value by using an adaptive slicing. Further, the situation can be improved by finding out a part deposition orientation that gives minimum overall average part surface roughness. However, some RP applications like exhibition models, tooling or master pattern for indirect tool production etc. require additional finishing to improve the surface appearance of the part. This is generally carried by sanding and polishing RP models which leads to change in the mathematical definitions of the various features of the model. The model accuracy is mainly influenced by two factors namely the varying amount of material removed by the finishing process and the finishing technique adopted. A skilled operator is required as the amount of material to be removed from different surfaces may be different and inaccuracies caused due to deposition can be brought down. A finishing technique selection is important because different processes have different degrees of dimensional control. For example models finished by employing milling will have less influence on accuracy than those using manual wet sanding or sand blasting.

Selection of part deposition orientation:

This is one of the crucial decisions taken before slicing the part and initiating the process of deposition for a particular RP process. This decision is important because it has potential to reduce part building time, amount of supports required, part quality in terms of surface finish or accuracy and cost as well. Selection of part deposition orientation is process specific where in designer and RP machine operators should consider number of different process specific constraints. This may be a difficult and time-consuming task as designer has to trade-off among various conflicting objectives or process outcomes. For example, better part surface quality can be obtained but it will lead to increase in the building time.

Vacuum Casting

Vacuum mold casting, also known in manufacturing industry as the V process, employs a sand mold that contains no moisture or binders. The internal cavity of the mold holds the shape of the casting due to forces exerted by the pressure of a vacuum. Vacuum molding is a casting process that was developed in Japan around 1970.

The Process

A special pattern is used for the vacuum mold casting process. It is either a match-plate or a cope and drag pattern with tiny holes to enable a vacuum suction. A thin plastic sheet is placed over the casting pattern and the vacuum pressure is turned on, causing the sheet to adhere to the surface of the pattern.

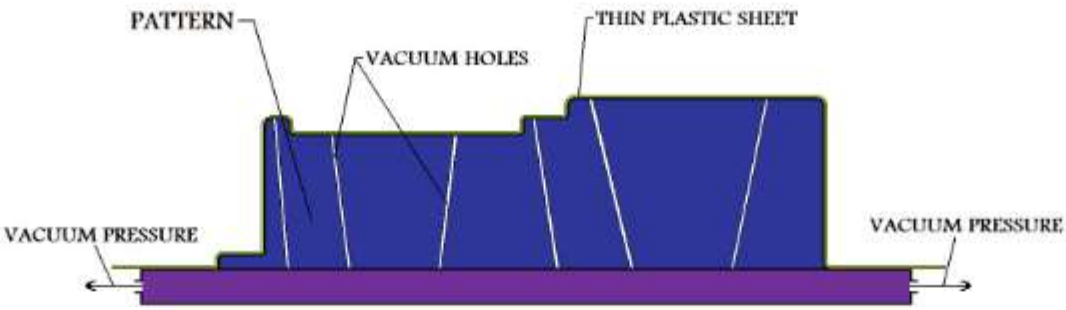


Fig 5.26: A thin plastic sheet is placed over the casting pattern

A special flask is used for this manufacturing process. The flask has holes to utilize vacuum pressure. This flask is placed over the casting pattern and filled with sand.

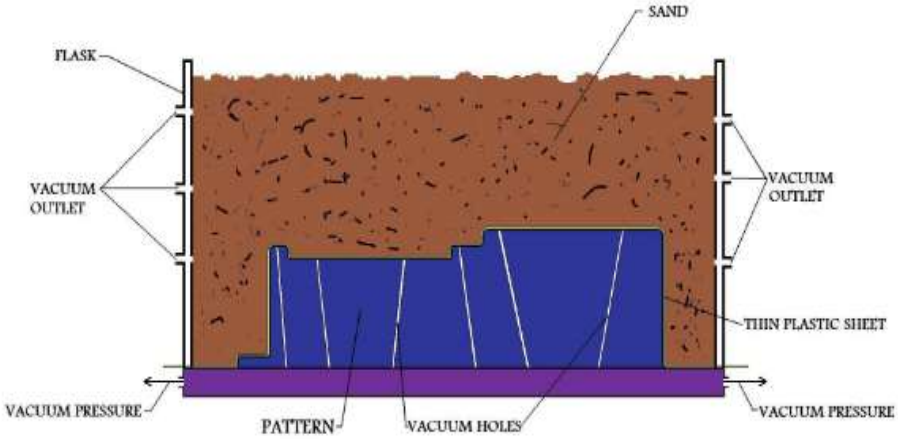


Fig 5.27: Casting pattern and filled with sand

A pouring cup and sprue are cut into the mold for the pouring of the metal casting.

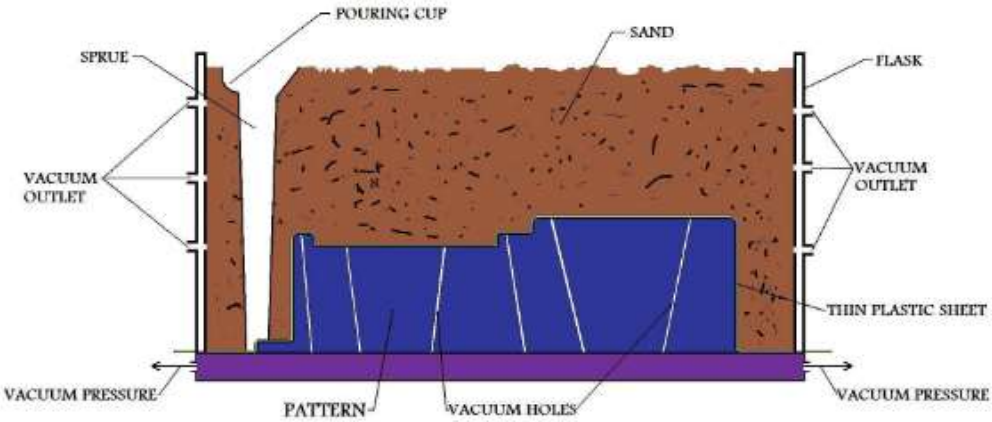


Fig 5.28: Casting pouring cup and sprue are cut into the mold

Next, another thin plastic sheet is placed over the top of the mold. The vacuum pressure acting through the flask is turned on, and the plastic film adheres to the top of the mold.

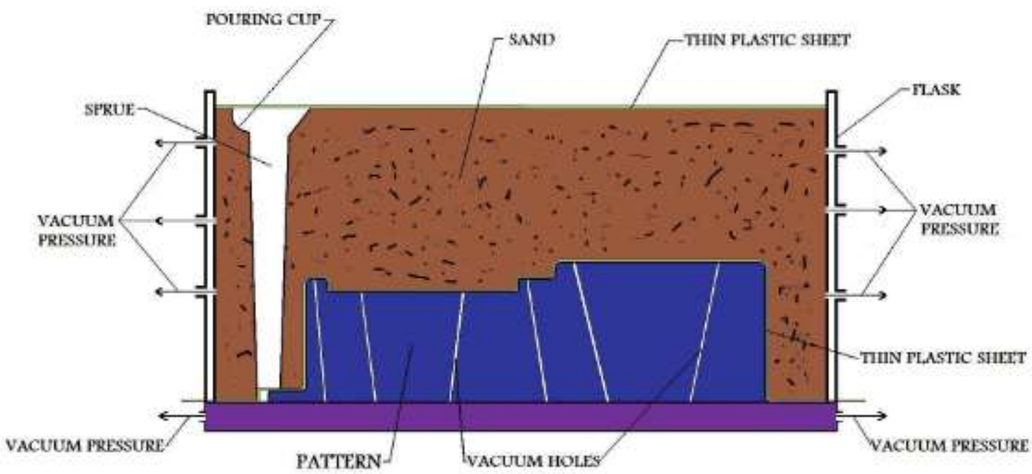


Fig 5.29: Vacuum pressure acting

In the next stage of vacuum mold casting manufacture, the vacuum on the special casting pattern is turned off and the pattern is removed. The vacuum pressure from the flask is still on. This causes the plastic film on the top to adhere to the top and the plastic film formerly on the pattern to adhere to the bottom. The film on the bottom is now holding the impression of the casting in the sand with the force of the vacuum suction.

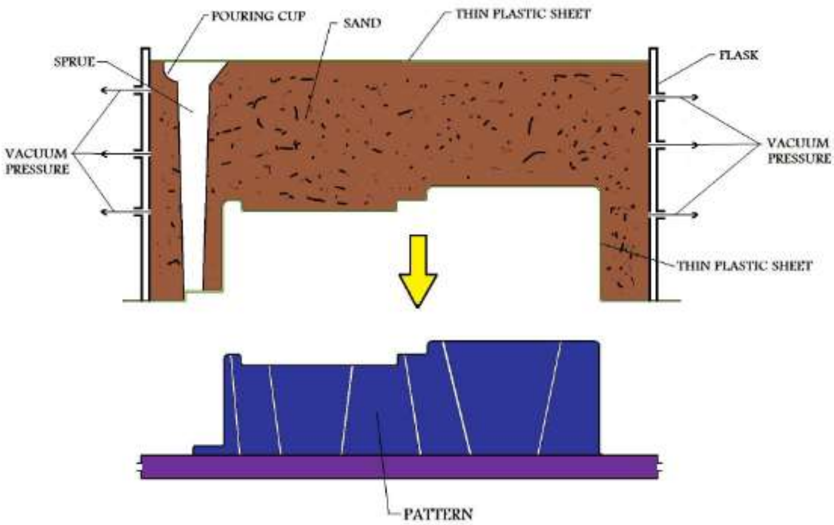


Fig 5.30: Pattern removal process

The drag portion of the mold is manufactured in the same fashion. The two halves are then assembled for the pouring of the casting. Note that there are now 4 plastic films in use. One on each half of the internal casting cavity and one on each of the outer surfaces of the cope and drag.

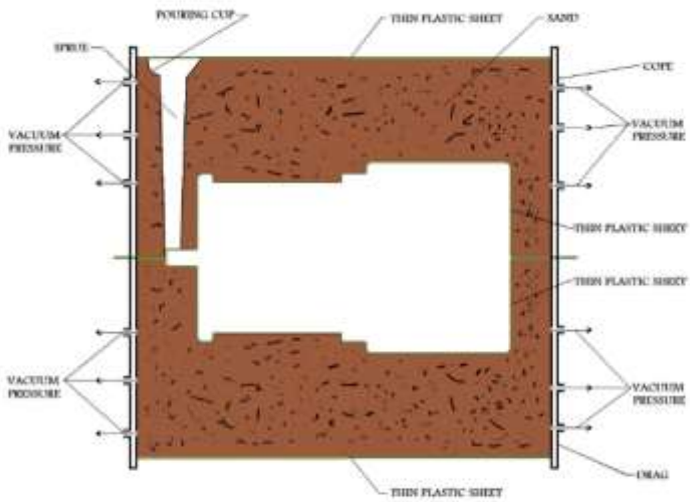


Fig 5.31: Full cavity making process

During the pouring of the casting, the molten metal easily burns away the plastic.

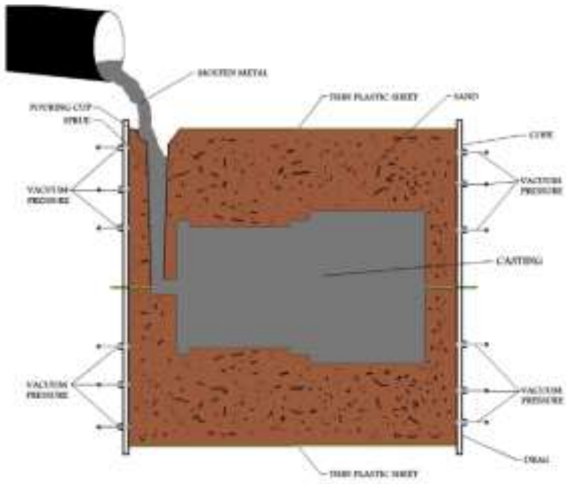


Fig 5.32: Casting process

Properties and Considerations of Manufacturing By Vacuum Mold Casting

- In vacuum mold casting manufacture there is no need for special molding sands or binders.
- Sand recovery and reconditioning, a common problem in metal casting industry, is very easy due to the lack of binders and other agents in the sand.
- When manufacturing parts by vacuum mold casting the sand mold contains no water, so moisture related metal casting defects are eliminated.
- The size of risers can be significantly reduced for this metal casting process, making it more efficient in the use of material.
- Casting manufacture by vacuum molding is a relatively slow process.
- Vacuum mold casting is not well suited to automation.

Surface digitizing

The Industrial Technology Research Institute (ITRI) of Taiwan has been devoting to the research and development of 3D surface digitizing and modeling for almost a decade. As a major technology and consulting service provider of the area, ITRI has developed 3D laser scanning digitizers ranging from low-cost compacts, industrial CAD/CAM digitizing, to large human body scanner, with in-house 3D surface modeling software to provide total solution in reverse engineering. The core abilities to acquire 3D information from sophisticated-shaped objects and to process and manipulate its large number of 3D coordinate data have enabled the applications in reverse engineering, body scanning, and 3D animation.

3D laser stripe digitizer

The concept of ITRI's non-contact 3D digitizer is illustrated in Figure 1. A stripe of laser is projected onto the surface of an object, and the reflected light is captured by either of the CCD cameras to avoid occlusion. Based on optical triangulation and camera calibration parameters, the 3D coordinates of the illuminated data points on the object surface can be calculated as shown in Figure 2. The digitizer head has a depth of field of 170 mm, and the system scans at speeds up to 3,000 points per second and precision up to 50 pm. The digitization generates a large number of 3D coordinates from different viewing angles. Figure 4 illustrates the surface modeling process to make these unorganized 3D data useful.

A low-cost compact version with only one CCD camera for triangulation in PC-based applications is shown in Figures 3 and 5. It is designed so that one CCD retains the information of two fields of view of the original two-CCD design to account for occlusion issues without compromising precision and accuracy [2]. We further design the scanner to equip with a color CCD camera for building a complete color 3D model.

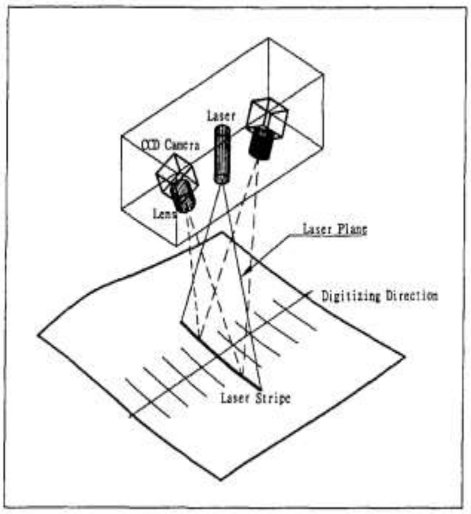


Figure 1. 3D laser stripe digitizer schema.

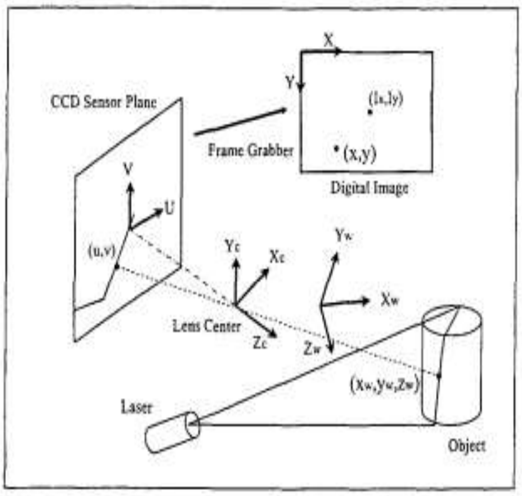


Figure 2. 3D image formation.

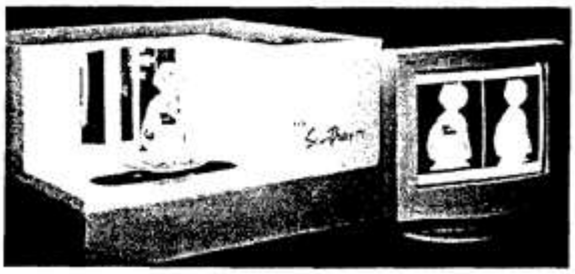


Figure 3. ITRI low-cost 3D scanner.

Fig 5.33: 3D laser stripe digitizer

3D surface modeling (3D digitizing)

As illustrated in Figure 4, after acquiring large number of 3D coordinates from many viewing angles, registration and merging are two fundamental steps to create a useful 3D surface model. A polygon-based method for describing a complete object is proposed. Multiple range images are integrated into a single polygonal, usually triangular, mesh. Registration is to align the multiple range images into the same coordinate system. Merging then removes redundant data and stitches these images to a single mesh. Our program needs no additional information from the digitizer. Surface modeling from 3D laser digitizer enables the capture of detailed description of the object surface, but the large number of 3D coordinates or polygonal information hinders efficient usage and effective applications of the surface models. Here proposed a sequential decimation process to reduce the number of polygons in a triangular mesh after the registration and merging of multiple range images are performed . An iterative vertex decimation method is used to remove vertices with minimum re-triangulation error. To reduce the distortion resulting from polygon reduction, vertices are characterized by local geometry and topology before the re-triangulation error is evaluated. This algorithm can be applied to not only triangular meshes generated from 3D digitizer, but also general volume meshes and terrain meshes.

Common issue in 3D digitizing is finding the next best view to efficiently digitize the object by calculating the next best position or a working path of the sensor, which has been well addressed by peers. In developing our low-cost scanning system that has significant less degrees of freedom in movement, however, we tackle a similarly important issue of deciding the best positions of the object for efficient scanning in building an effective 3D surface model. A low-occlusion approach is proposed to find the best viewing position for scanning by considering the position of the object instead of the sensor. The efficiency improves significantly by combining carefully planned working path of the sensor and optimum positions of the object.

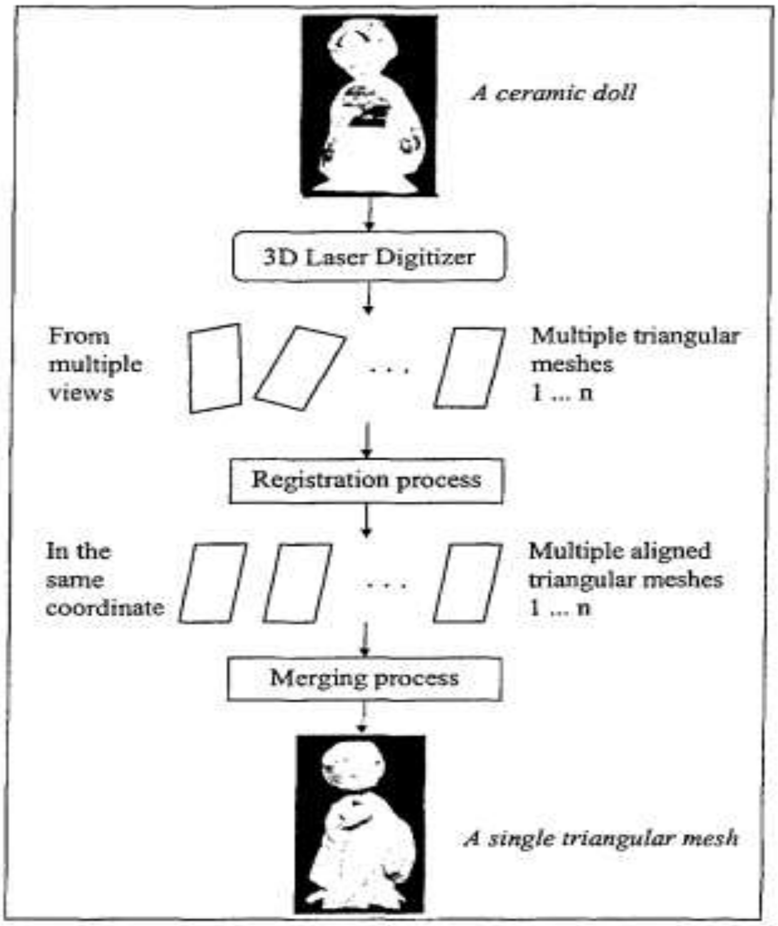


Figure 4. Procedure of surface model integration.

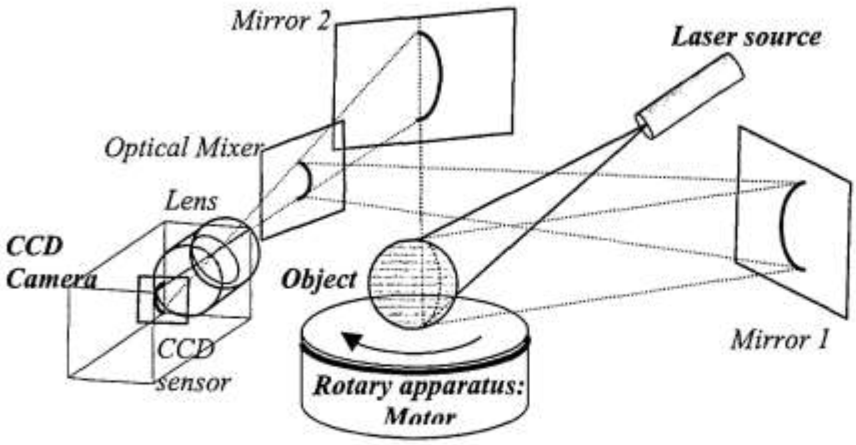


Fig 5.34: Low-cost scanner schema

SURFACE GENERATION FROM POINT CLOUD

A **point cloud** is a set of data points in space. Point clouds are generally produced by 3D scanners, which measure a large number of points on the external surfaces of objects around them. As the output of 3D scanning processes, point clouds are used for many purposes, including to create 3D CAD models for manufactured parts, for metrology and quality inspection, and for a multitude of visualization, animation, rendering and mass customization applications.

Point clouds are often aligned with 3D models or with other point clouds, a process known as registration. For industrial metrology or inspection using industrial computed tomography, the point cloud of a manufactured part can be aligned to an existing model and compared to check for differences. Geometric dimensions and tolerances can also be extracted directly from the point cloud.

While point clouds can be directly rendered and inspected. point clouds are often converted to polygon mesh or triangle mesh models, NURBS surface models, or CAD models through a process commonly referred to as surface reconstruction. There are many techniques for converting a point cloud to a 3D surface. Some approaches, like Delaunay triangulation, alpha shapes, and ball pivoting, build a network of triangles over the existing vertices of the point cloud, while other approaches convert the point cloud into a volumetric distance field and reconstruct the implicit surface so defined through a marching cubes algorithm. In geographic information systems, point clouds are one of the sources used to make digital elevation model of the terrain. They are also used to generate 3D models of urban environments.

Point clouds can also be used to represent volumetric data, as is sometimes done in medical imaging. Using point clouds, multi-sampling and data compression can be achieved.

ORGANIZING POINT CLOUDS WITHIN A TRIANGULAR MESH

Over the years, several techniques have been proposed to solve the problem of surface reconstruction from point clouds, using concepts from computational geometry to models based on partial differential equations. Most of the methods can be classified as implicit or parametric

Classified the methods into four groups:

1) **Methods based on local projections:**

approximation is performed treating the surface as a function defined in a local reference domain;

2) **Sculpting Methods**:

The methods are based on the removal of triangles from a spatial arrangement, as the Delaunay triangulation;

3) **Implicit Methods:**

The methods are based on an implicit definition of a function of distance with signal f and in the realization of a triangulation approximation of the isosurface f (x) = c. This process of approximation of the function f is performed using techniques of extraction of isosurfaces;

4) **Methods based on deformable models:**

From an initial shell (membrane) deformation are applied to minimize a function of energy and get closer to surface.

All kinds of methods listed above are based on the functional characteristics of the algorithm. However, other types of classification are possible, such as divisions based on computational complexity or quality demanded by the sampling algorithms. Among the previous methods, a method based on deformable models was chosen because it offers more speed in the process of organizing the point clouds within a mesh. Also, it minimizes the computational cost as the 3D surface is modeled. The algorithm is divided into three steps, and each step is divided into several sub-steps (Chui, 2008): (a) Projection of the cloud of points on the mesh grid, (b) Nodal point repositioning, (c) Reconstruction of the 3D triangular mesh from the 2D triangular mesh.

Projection of the cloud of points on the mesh grid

1. A cloud of points is projected from R3 to R2 on the plane in the following figure (Fig.a and Fig. b).
2. Adjust the cloud of points inside a parallelogram (angle of 60 ° (Fig. c). This polygon involves all points of the sample that are to be analyzed in all subsequent steps of the algorithm.
3. Divide the polygon into horizontal and vertical lines separated of a distance t. This separation influences the resolution of the 3D surface (Figure (d) and Figure (e)).
4. Diagonal lines are projected from the left to the right of the polygon, forming equilateral triangles (Fig. f).

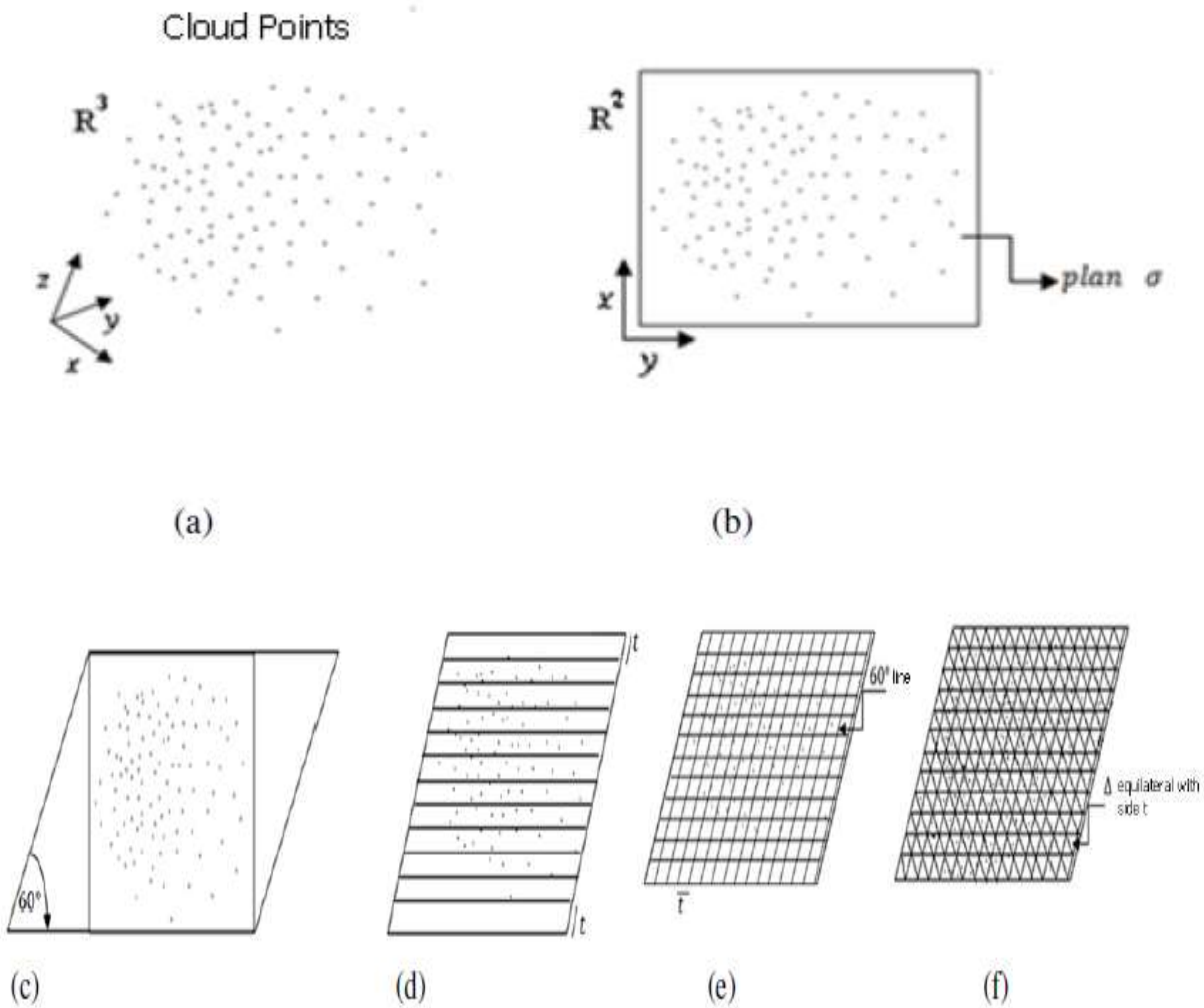


Fig 5.35: Projection of the cloud of points on the mesh grid

Nodal Point Repositioning

Nodal point repositioning is a essential step to adjust a mesh nodal point to the a cloud point. In each mesh nodal point a circle is drawn connecting the adjacent nodal points, in order to select only one point among many that are within the area enclosed by the circle. The point selected is the one that is closer to the node of the mesh inscribed in the corresponding circle (Fig. a). The procedure is repeated for the other node points, and those points that have not been selected will be deleted.

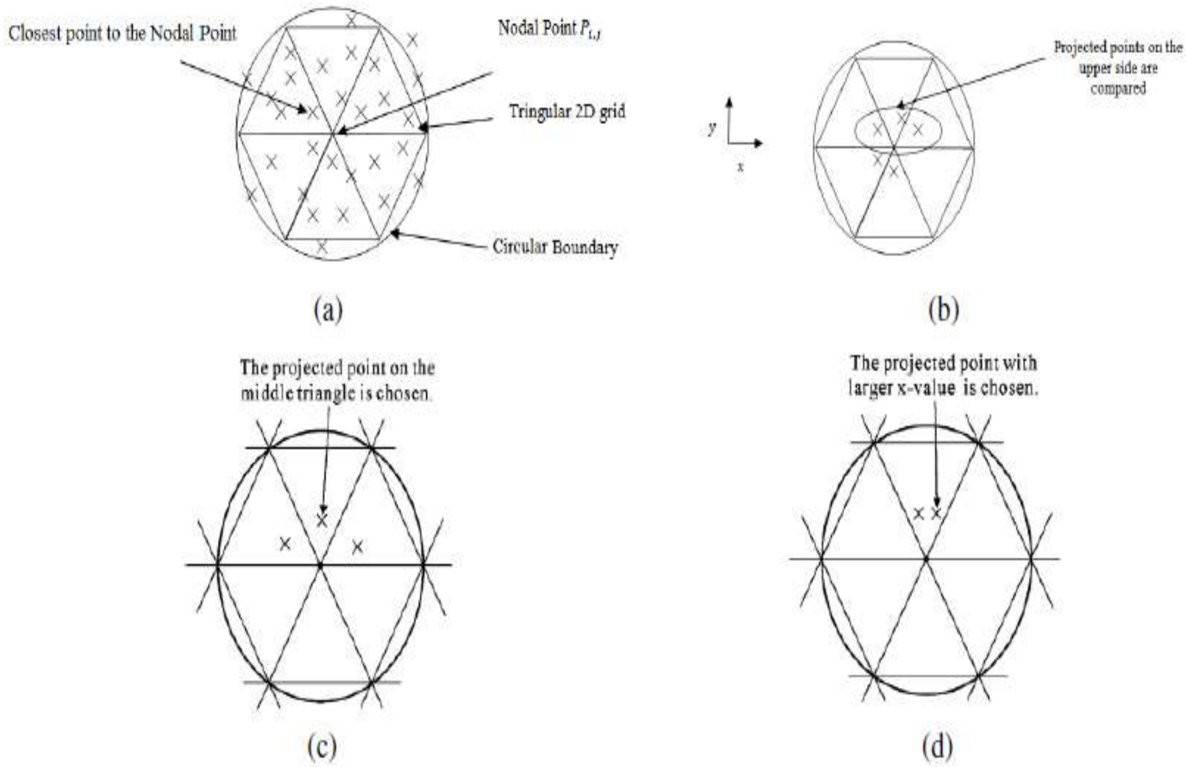


Fig 5.36: Repositioning of nodal points. (a) Point selection approach, (b) An example case for choosing projected points using Critirion A, (c) A projected point is selected as the new nodal point position using Critirion B, (d) Projected point being chosen using Critirion C.

For example, in above Fig. a, the nearest projected point will be considered as the new position of the nodal point Pi, j. However, if there are two or more points satisfying closer distances, the following criteria should be established:

Criterion A. If two or more projected points are equal in distance to P(i, j) but are located in different triangles, the projected point at the top (i.e., higher y) will be chosen. For example, in Fig. b, five points are projected in equal distances from the nodal point P(i, j). Items found in the upper nodal point will be selected. The choice of the new position of the nodal point will be explained using Criterion B.

Criterion B. If two or more projected points are equal in distance in the same horizontal line (Fig. c), but in several different triangles, the projected point in the triangle is chosen as the new position of the nodal point Pi, j.

Criterion C. If two or more projected points are equal in distance in the same horizontal line and same triangle, the projected point with higher value x is chosen (Fig.d).

Reconstruction of the 3D triangular mesh from the 2D triangular mesh.

The 3D triangular mesh can be reconstructed next to the process of displacing the nodes of the 2D mesh (Fig. a) by using the depth values of each displaced nodal point (criterion A, criterion B or criterion C) (Fig. b).

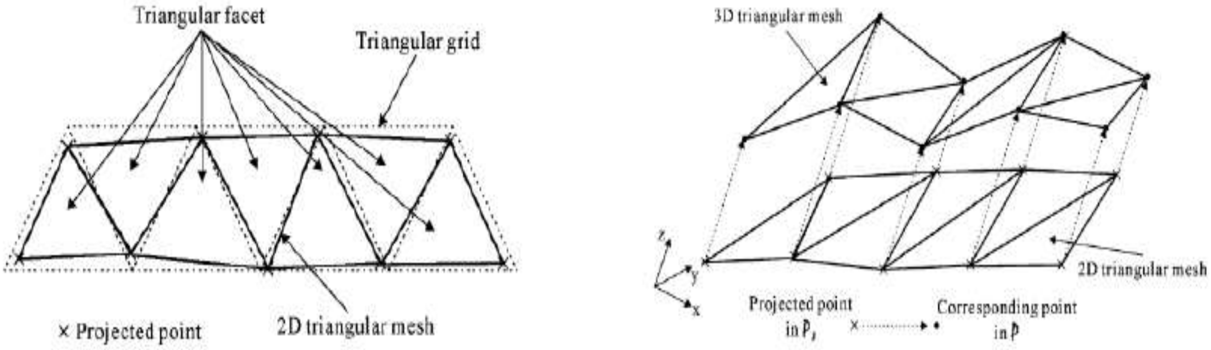


Fig 5.37: (a) 2D triangular mesh constructed from the projected points next to nodal points repositioning. (b) 3D triangular mesh is constructed based on its corresponding 2D triangular mesh.

NURBS SURFACE REPRESENTATION

The construction of a 3D model using parametric surfaces is a process that requires an adjustment of approximation between the geometrical structures of a structured mesh in the space R^3 NURBS (Non Uniform Rational Basis Spline) is an industrial standard tool for modeling and design of simple and complex geometries. The reasons for such widespread use are: a) based on common mathematical methods to represent free form objects; b) provides a high flexibility in the design of shapes; c) the processing time is reasonably small; d) are generalizations of curves and surfaces of B-spline and Bezier. The NURBS surfaces are curve sets of the same type that can be defined as.:

$$S(u,v) = \frac{\sum_{i=0}^{n}\sum_{j=0}^{m} T_{i,p}(u)T_{j,q}(v)W_{i,j}D_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m} T_{i,p}(u)T_{j,q}(v)W_{i,j}}$$

where Di, j are the control points; Wi, j are the weights defining how significant will be the control point on the curve; Ti,p and Tj,q are the B-spline functions defined in two parametric directions. The number of control points is defined by the surface degree in each parametric direction ("u" and "v").

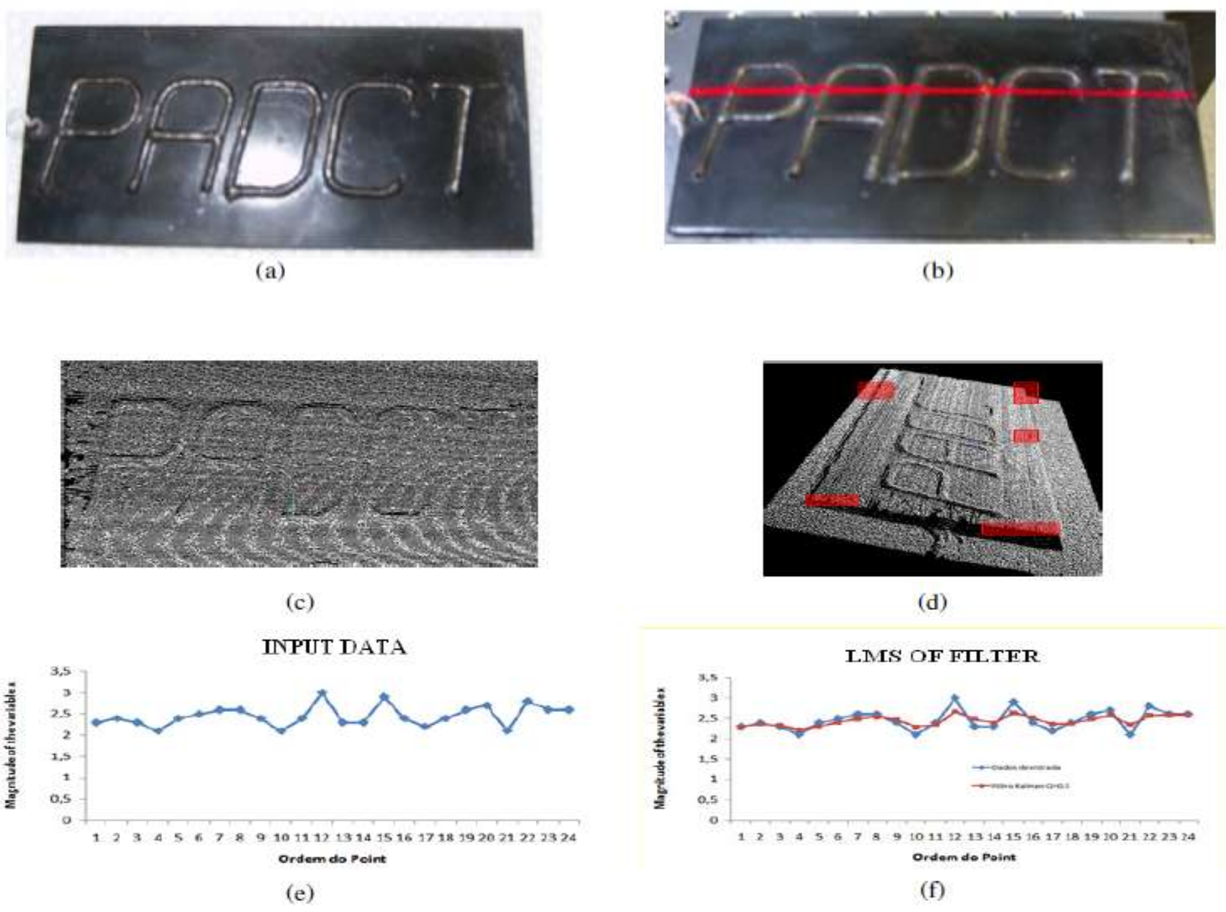
Therefore, in each direction there is a number of control points. The B-spline functions are functions of the nodes (ti) that are increasing sequences. So, one can define a B-spline function as:

$$T_{i,p}(u) = \begin{cases} 1 & t_i \leq u \leq t_{i+1} \\ 0 & else \end{cases}$$

with

$$T_{i,p}(u) = \frac{u-t_i}{t_{i+k-1}-t_i} \cdot T_{i,k-1}(u) + \frac{t_{i+k}-u}{t_{i+k}-t_{i+1}} \cdot T_{i+1,k-1}(u)$$

The nodes are represented by a list of numbers that is commonly called the node vector. The node vector needs to be a sequence of numbers equal or increasing (uniformly or not).



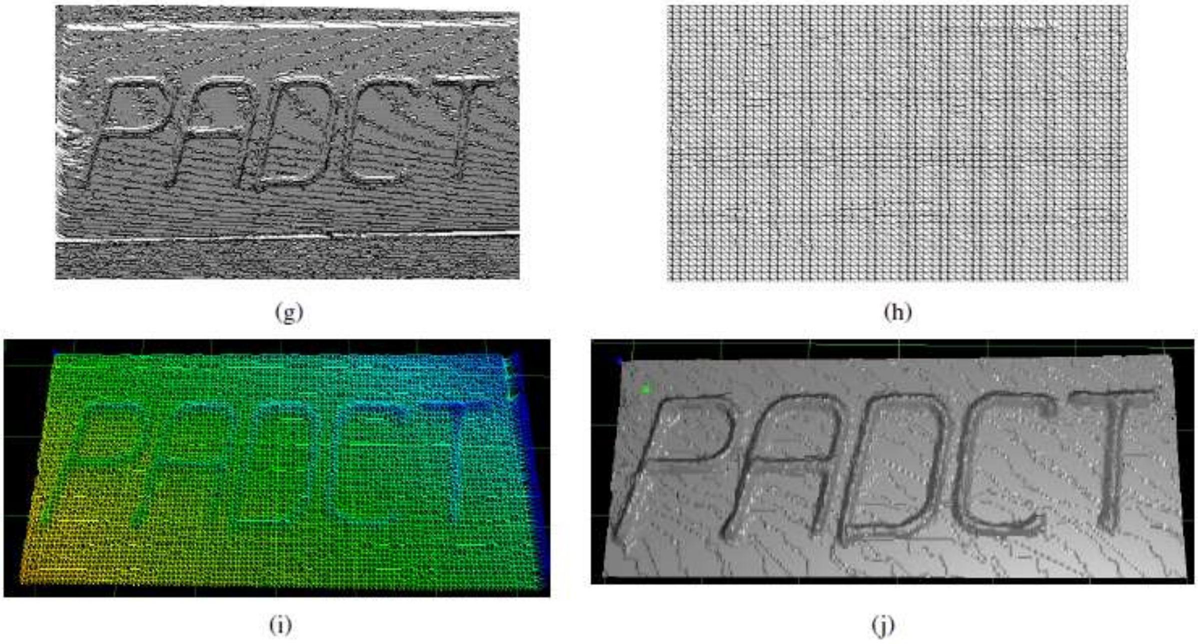


Fig 5.38: Several steps for surface fitting in point clouds: (a) Weld bead; (b) Laser scanning on the weld bead; (c) Point cloud acquired from the weld bead image; (d) Noise detected visually in the point cloud; (e) Plot of a section of the weld bead in Z coordinates; (f) Plot of the section filtered with the adaptive LMS algorithm; (g) Point cloud projected on the 2D plane; (h) 2D triangular mesh; (i) 3D triangular mesh; (j) Parametric surface fitted in the 3D triangular mesh

SURFACE MODIFICATION

Surface modification is the act of modifying the surface of a material by bringing physical, chemical or biological characteristics different from the ones originally found on the surface of a material. This modification is usually made to solid materials, but it is possible to find examples of the modification to the surface of specific liquids.

SURFACE MODIFICATION METHODS/ TECHNIQUES

Numerous processes are used for surface treatments, based on mechanical, chemical, thermal and physical.

- Physical Vapour Deposition **(**PVD) process
- Chemical Vapour Deposition CVD process
- Thermal spraying
- Surface welding
- Ion Implantation, etc

Physical Vapour Deposition (PVD) In this process, the work piece or substrate is subjected to high temperature vacuum evaporation or plasma sputter bombardment to deposit thin films by the condensation of a vaporized form of the material onto substrate surfaces. This process contains the three major techniques; evaporation, sputtering and ion plating. It produces a dense, hard coating. The primary PVD methods are.ion plating, ion implantation, sputtering and laser surface alloying.

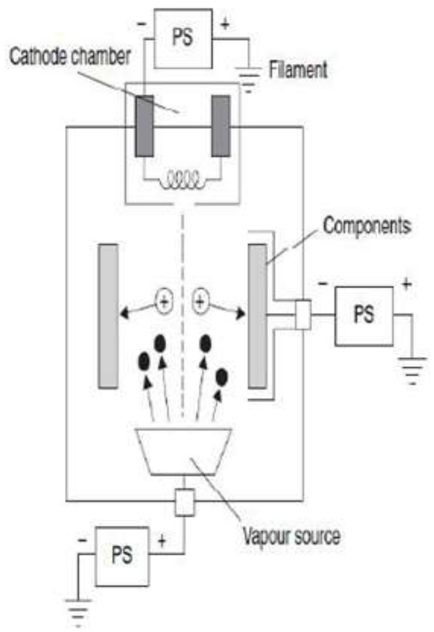


Fig 5.39: PVD using Plasma Evaporation

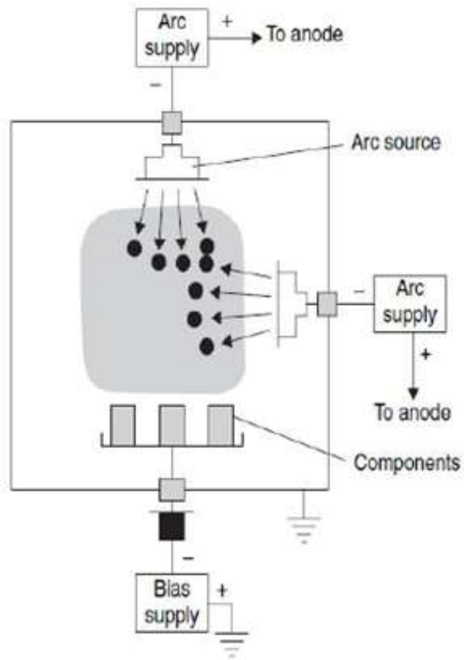


Fig 5.40: PVD using Arc sputtering

PVD is used in the manufacture of semiconductor wafers, aluminized PET film for snack bags and balloons, cutting tools for metalworking and generally used for extreme thin films like atomic layers and mostly for small substrates.

Chemical Vapour Deposition (CVD)

In these processes, thermal energy heats the gases in the coating chamber and drives the deposition reaction and then this reactant gas mixture (mixture of gas precursors and coating material also known as a reactive vapour) impinges on the substrate. CVD processes can be used to deposit coating materials, form foils, powders, composite materials in the shape of spherical

particles, filaments, and whiskers and also in structural applications, optical, chemical, photovoltaic and electronics.. Start-up costs are typically very expensive. CVD includes sputtering, ion plating, plasma-enhanced CVD, low pressure CVD, laser-enhanced CVD, active-reactive evaporation, ion beam, laser beam evaporation, and many other variations. These variants are distinguished by the manner in which precursor gases are converted into the reactive gas mixtures. It is usually in the form of a metal halide, metal carbonyl, a hydride, or an organ metallic compound. The precursor may be in gas, liquid, or solid form. Gases are delivered to the chamber under normal temperatures and pressures, whereas solids and liquids require high temperatures and/or low pressures in conjunction with a carrier gas. Once in the chamber, energy is applied to the substrate to facilitate the reaction of the precursor material upon impact. The ligand species is liberated from the metal species to be deposited upon the substrate to form the coating. Because most CVD reactions are endothermic, the reaction may be controlled by regulating the amount of energy input.

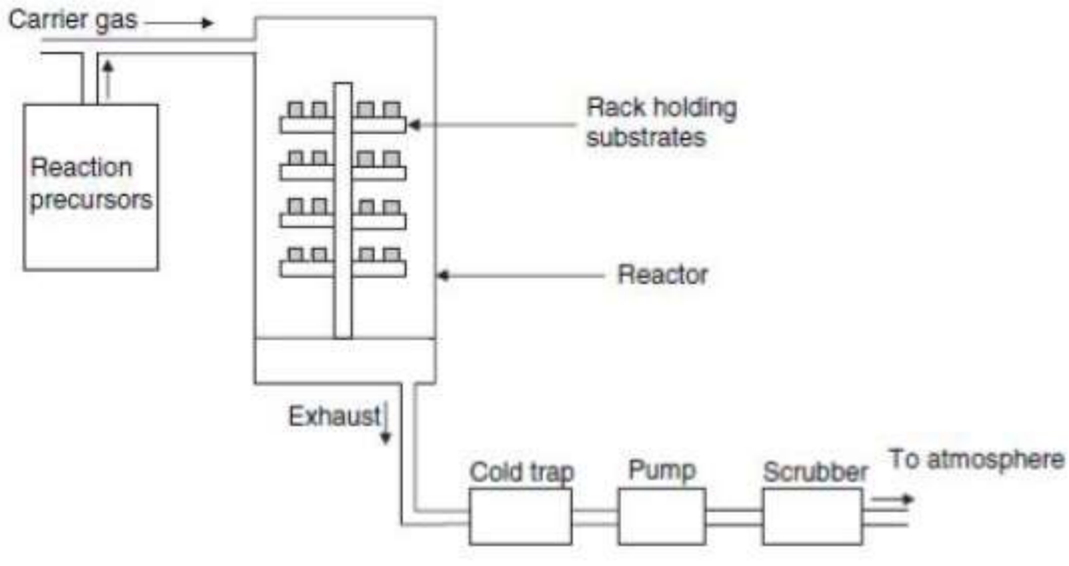


Fig 5.41: Schematic diagram of CVD process

Disadvantages of CVD, the precursor chemicals should not be toxic, and exhaust system should be designed to handle any reacted and unreacted vapors that remain after the coating process is complete. Other waste effluents from the process must be managed appropriately. Retrieval, recycle, and disposal methods are dictated by the nature of the chemical. For example, auxiliary chemical reactions must be performed to render toxic or corrosive materials harmless, condensates must be collected.

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