CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Global competition, customer driven product customization, accelerated product obsolescence and continued demands for cost reduction are forcing companies to look for new technologies to improve their business processes and reduce the product development cycle time. This is the era of information technology and it has influenced every realm of society and dramatically impacted on the traditional industry. Current industries are facing the new challenges, quick response to business opportunity has been considered as one of the most important factors to ensure company competitiveness.

Manufacturing industry is evolving towards digitization, networking and globalization. In order to respond to the change effectively, manufacturing strategy has to be modified from time to time in accordance with the market situation and customer demand. Any change of strategy should enable manufacturers to be better equipped with capabilities to cope with demands such as faster response to market changes, a shortened lead time of production, improved quality and speed, the ability to deliver quality products to global customers and improved communications and transportation system. It is an established fact that the use of computers in design and manufacturing constitutes the most significant opportunity for substantial productivity gain in industry. It has now been widely accepted that the future of manufacturing
organizations will be information-oriented, knowledge-driven and much of their daily operations will be automated around the global information network that connects everyone together. In order to meet the demand of rapid product development, various new technologies such as Rapid Prototyping (RP), Reverse Engineering (RE) and Rapid Tooling (RT) have emerged and are regarded as enabling tools with abilities to shorten the product development and manufacturing time.

1.2 RAPID PROTOTYPING

Rapid prototyping is a new approach in the prototyping and manufacturing arena, which gained a significant interest in recent years because of its inherent flexibility for manufacturing simple and complex shaped parts from a Computer Aided Design (CAD) file without the use of any specific tooling. This technology has been referred to as ‘Layered Manufacturing’ (LM), ‘Solid Freeform Fabrication’ (SFF), ‘material addition manufacturing’ and ‘Three-Dimensional Printing (3DP)’. By enabling engineering changes quickly, rapid prototyping processes offer tremendous advantages in terms of cost and time, getting new products to market faster, providing necessary edge in today’s competitive market, (Bandhopadhyay et al 1998). Over the last decade, several RP techniques have been developed and commercialized to produce parts, tools or moulds for form and fit applications.

The demand for reduced lead-time and costs has driven the technology forward at a remarkable pace. A logical progression from the rapid prototyping field has been to manufacture actual tooling using similar layering techniques to those already in place in the RP field (Bryden et al 2001). Rapid prototyping is the fabrication of a physical, three dimensional part of arbitrary
shape directly from a numerical description - typically a computer aided design model, by a quick, highly automated and totally flexible manufacturing process.

1.3 CLASSIFICATION OF RP PROCESSES

RP processes may be divided broadly into those involving the addition of material and those involving its removal. According to Kruth (1991), material addition processes may be divided by the state of the prototype material before part formation, namely, liquid, powder or solid sheets. Liquid based processes may entail the solidification of a resin on contact with a laser, the solidification of an electrosetting fluid or the melting and subsequent solidification of the prototype material. Processes using powders aggregate them either with a laser or by the selective application of binding agents. Those processes, which use solid sheets, may be classified according to whether the sheets are bonded with a laser or with an adhesive. Figure 1.1 shows Kruth’s classification of rapid prototyping methods, which has been adapted to include new processes.

1.4 RP INFORMATION WORKFLOW

All RP systems have a common information flow as shown in Figure 1.2. The main stages in preparing and pre-processing data for automated fabrication of 3D objects are as follows:

1.4.1 Data creation

A 3D CAD package or 2-Dimensional (2D) scanning device can be employed to create geometric data.
RAPID PROTOTYPING

**Material addition**

**Material removal**
DM- Desktop

**Combined (addition and removal)**

**Liquid**
Solidification of a liquid polymer
Point by Point (SL - Stereolithography, LTP - Liquid Thermal Polymerization, BIS - Beam Interference Solidification)
Layer by Layer (Object, SGC - Solid Ground Curing)
Holographic Surface (HIS - Holographic Interference Solidification)

**Discrete**
Solidification of an Electroset Fluid (ES-Electro Setting)
Point by Point (BPM - Ballistic Particle Manufacture, MJM - Multi Jet Modelling, FDM - Fused Deposition Modeling, 3DW - Three Dimensional Welding)

**Solid sheets**
Solidification of a Molten Material
Layer by Layer (SDM - Shape Deposition Manufacturing)
Fusing of particles by Laser (SLS - Selective Laser Sintering, LENS - Laser Engineering Net Shaping, GPD - Gas Phase Deposition)
Joining of Particles With a binder (3DP - Three Dimensional Printing, SF - Spatial Forming)
Bonding of sheets with adhesive (LOM - Laminated Object Manufacturing, PLT - Paper Lamination Technology)
Bonding of sheets with Light (SFP - Solid Foil Polymerization)

Figure 1.1 Classifications of rapid prototyping methods

1.4.2 Data export

The valid 3D model is exported from the CAD package in a neutral format, which in most cases are ‘.STL’ (STereoLithography file format).

1.4.3 Data validation and repair

The exported data is an approximation of the precise internal 3D model. During this approximation process the model surfaces are represented
with simple geometrical entities in the form of triangles. Unfortunately, STL models created in this way can contain undesirable geometrical errors such as holes and overlapping areas along surface boundaries. Therefore, the generated files have to be validated before being further processed. Some RP packages offer facilities for automatic and/or manual model repair. These packages include software tools that evaluate the STL models and determine whether any triangles are missing. In case of errors, the gaps in the models are filled with new triangles.

1.4.4 Part orientation and scaling

RP systems build parts along Z axis of their STL models. Through reorientation of the parts relative to the model coordinate systems, their accuracy, surface finish and build time can be optimized. Some RP systems allow several parts to be nested in the chamber in order to be built simultaneously. In addition, the parts can be scaled to compensate for anticipated anomalies that might be introduced by downstream processes such as deformation, shrinkage, warpage and curling.

1.4.5 Support structures generation

Liquid based RP processes require support structures to build overhanging areas of the parts. These structures are usually generated automatically employing specialized software tools. The areas requiring support structures can be minimized by appropriately selecting the part build direction.
1.4.6 Setting-up of process parameters

Process-related parameters are entered to specify the build style and desired system attributes. These parameters can be adjusted based on part requirements and the RP material being used.

1.4.7 2D slice data generation

Successive cross-sectional layers are obtained by slicing the STL file. In each cross section, polylines are used to approximate the exterior and interior boundaries of the RP models. These polyline boundaries can be offset by a particular value to compensate for process errors. The slice data can be generated off-line for the entire model or on-line, one cross-section at a time during part building.

The process data generated following the stages outlined above is stored in a build file. This file contains all the information needed to guide material additive processes to build 3D objects. Other basic principles of RP are the need for specific materials such as fluids, powders, wire or laminates as well as the need for sophisticated equipment employing different physical principles such as laser, sintering, etc. Though there are no restrictions concerning complexity and geometrical features, the physical objects are limited in their size. An advantage is the fact that the same data used for the prototype creation can be used to go directly from prototype to production, eliminating further sources of human errors.
Figure 1.2  RP information workflow (Pham and Dimov 2001)
1.5 POPULAR RAPID PROTOTYPING PROCESSES
1.5.1 Stereolithography

Stereolithography uses the principle of photo-polymerization, whereby a liquid plastic monomer (resin) is converted into a solid polymer by exposure to Ultra-Violet (UV) light. The UV light is provided by a laser, which, by varying its power output can control the thickness of each layer. The schematic diagram of stereolithography is shown in Figure 1.3.

![Figure 1.3 Schematic diagram of stereolithography](image)

The solid object is made by scanning an ultraviolet laser beam over the surface of a bath of epoxy resin. The resin hardens on exposure to the UV light. Once a layer is complete, the base plate moves down a little in the bath and a new layer of liquid flows in over the top. Then the laser beam draws the next layer. Any loose or overhanging elements of the object are secured by supporting structure to prevent them drifting away. The supports are made by
the same process and at the same time as the main object; the necessary computer code is generated automatically when the slice files are produced.

At the end of the build, the base plate is raised in the bath to lift the object clear and it is drained, washed and the support structures broken away. The hardened resin is translucent and hence the interior structure is easy to see in stereolithography models.

Merits

- Accuracy of ± 0.1 mm. and surface finish are best amongst all the processes.
- Model building can take place unattended.
- Capable of high detail and thin walls.
- Good surface finish.

Demerits

- Experience and expertise are required in deciding support structures.
- Material is toxic and hazardous.
- Part strength is less and may undergo warpage in presence of excess moisture.
- Post-curing of the part is required and may result in slight distortion.
- The material has a finite shelf life and needs to be replaced (even if unused) after a period of about two years.
1.5.2 Fused Deposition Modeling (FDM)

Here the object is made by squeezing a continuous thread of the material through a narrow, heated nozzle, which is moved over the base plate. As the thread passes through the nozzle it melts, only to harden again immediately as it touches the layer below. For certain shapes, a support structure is needed and this is provided by a second nozzle squeezing out a similar thread, usually of a different colour to separate the two easily. At the end of the build process, the support structure is broken away and discarded, freeing the object. FDM method produces models, which are physically robust. Wax can be used as the material, but generally models are made of Acrylonitrile Butadiene Styrene (ABS) plastic. Just out of the machine, models may have a fairly rough surface finish, but they can easily be cleaned up. Because of the use of a single well-defined thread to build the model, this is the only one of the processes where it is relatively easy to change colours; the ABS fiber is available in a range of bright primary colours. Alternatively, models can be painted. The manufacturers of FDM machines are Stratasys Inc. USA. Figure 1.4 shows the working principle of FDM.

![Diagram of FDM process](image)

Figure 1.4 Working principle of fused deposition modeling
Merits

- The machine is less expensive.
- Variety of materials can be used and the material change over.
- No post-curing is required.
- There is little wastage of material.
- The part building remains unaffected if not removed from the packing provided.

Demerits

- Surface finish and delicate features are inferior to other processes.
- The process is slow on bulky parts.
- The strength is low in vertical direction.
- Accuracy and surface finish is less as compared to other RP processes.

1.5.3 Solid Ground Curing (SGC)

In SGC, each cross section is imaged on to an erasable mask plate produced by charging the plate via an ionographic process and then developing the image with an electrostatic toner as shown in Figure 1.5. An erasable mask plate carrying an electrostatic image of a model slice is positioned over a uniform layer of liquid polymer and an intense pulse of UV light is passed through it to selectively cure the material. Uncured resin is removed and replaced with low melting point wax, which serves as a sacrificial support.
Wiping off toner erases the pattern and next image is created on the mask and the entire process is repeated. Wax is removed by melting after the part completion.

Figure 1.5  Schematic diagram of solid ground curing process

Merits

- Build-time is independent of the number of parts being made at a time. Therefore, it can act as a production machine.
- No external support structures are required.
- No warping or curling of the part takes place, as there is no post-curing operation.
- Large variety of photopolymers can be used for building the parts.
- Accuracy of parts is good.
Demerits

- There is lot of wastage of material and wax. The resin picked up by the aerodynamic wiper and vacuum during the milling process cannot be used again. Additionally, the material which does not form the part of the model, but gets exposed to the UV light needs to be replaced. Only fifty percent of this affected material can be converted into usable form.
- The cost of the machine is the highest among all RP machines.
- The process operation is complex and maintenance cost is high.
- Monitoring of the building process is required.
- Material has a finite shelf life and needs to be replaced after a certain period, even if not used.
- Wax is sticky and difficult to remove.

1.5.4 Selective Laser Sintering (SLS)

It is a layered manufacturing method that creates solid, three-dimensional objects by fusing powdered materials with a CO₂ laser. Figure 1.6 shows the working principle of selective laser sintering process.

This process uses a flat sheet of powder, heated to close to its melting point. The carbon dioxide laser beam scans over the powder and heats the grains so that they melt on the outside and stick together (sinter). Then the base plate moves down slightly and the next layer of powder is spread across the surface by a rotating roller. The object is supported by the tightly packed unsintered powder and hence there is no need for extra supporting structures. At
the end of the build process, the entire cake of powder, sintered and unsintered, is allowed to cool down and lifted out of the machine. Then the loose powder is shaken off (it can be used again) and the sintered object is freed.

Objects made by SLS using nylon powder have a powdery white appearance. The surface is absorbent and marks easily, but otherwise the objects are fairly robust and moving parts such as hinges can be made. Models can be sanded down and painted if required, to give a smooth finish. SLS models can be made in wax, sand or steel powder as well as nylon.

Merits

- Any material that can be converted into powder bonded together by fusing them at a reasonably low temperature (about 350-500°C), can be used for making the parts in this process.
Materials commonly used for making parts in this process are nylon, ABS and investment casting wax.

- Parts obtained are tough.
- No support structures are required.
- No post curing is required.
- Functional metal and ceramic parts can be obtained.
- There is no wastage of material.

Demerits

- Surface finish of parts is grainy.
- Parts are porous in nature.
- The building operation needs to be monitored.
- Long times are required to heat up the material chamber before building the parts and to cool it down after the building is over.
- The parts are brittle.

1.5.5 Laminated Object Manufacturing (LOM)

The layers are built up by pulling a long, thin sheet of pre-glued paper or plastic across the base plate and fixing it in place with a heated roller that activates the glue. Then a laser beam is scanned over the surface and cuts out the outline of that layer of the object. The laser intensity is set at just the level needed to cut through a single layer of material. Then the rest of the paper is crosshatched to make it easier to break away later. The base plate moves down and the whole process starts again. The sheet of material is made significantly wider than the base plate, so when the base plate moves down, it leaves a neat
rectangular hole behind. This scrap material is wound onto a second roller, pulling a new section across the base plate as it goes. At the end of the build process, the little cross-hatched columns are broken away to free the object. The working principle of LOM process is shown in Figure 1.7. The material used is usually paper, though acrylic plastic sheet can be used and some experimental work has been done with a ceramic "felt". The paper models look like balsa wood, with visible "contouring" lines where the laser beam has scorched the edge of the paper layers in the cutting process. Once the models have been varnished to prevent water seeping in, they are quite robust. Because the raw material (paper) is cheap, LOM is particularly suitable for large models.

![Figure 1.7 Working principle of LOM](image)

**Merits**

- Only the outline is cut. Therefore, no time is spent in building body of the layer.
• The materials used for building the parts (viz. wood and paper) are the least expensive amongst all RP processes.
• Cost of the machine is one of the lowest.
• No support structures or post-curing is required.
• It is suitable and economical for making large parts to be used as patterns for sand castings.
• The process can be carried out unattended.

Demerits

• Parts are weak in the Z-direction.
• Parts have poor surface finish and absorb moisture.
• The process is not suitable for making small intricate parts. As the parts need to be chipped out from a wooden box after they are built, a lot of skill is required if parts with intricate details need to be chipped out.
• There is a lot of material wastage.
• The laser spends more time in cutting the grids than the useful part contours.

1.6 APPLICATION FIELDS

Rapid Prototyping is a continuously evolving technology. RP models are becoming widely used in many industrial sectors. Initially conceived for design approval and part verification, RP now meets the need for a wide range of applications from building test prototypes with material properties close to those of production parts to fabricating models for art and medical applications.
In order to satisfy the specific requirements of a growing number of new applications, special software tools, build techniques and materials have been developed. Although the possible applications are virtually limitless, nearly all fall into one of the following categories: prototyping, rapid tooling or rapid manufacturing.

1.6.1 Functional models

There are number of RP technologies that now meet the need for building functional prototypes with material properties close to those of production parts. One of the RP processes that are widely used for producing models for functional tests is SLS.

1.6.2 Patterns for investment and vacuum casting

RP technologies are widely used for building patterns for investment and vacuum casting. For example, models built employing SLA, SLS and FDM can be used as patterns for both casting processes.

1.6.3 Medical models

RP technologies are applied in medical domain for building models that provide visual and tactile information. In particular, RP models can be employed in the following applications (D’Urso et al 1998, 1999 a and b).

- Operation planning: Using real size RP models of patient’s pathologic regions, surgeons can much more easily understand
physical problems and gain a better insight into the operations to be performed. RP models can also assist surgeons in communicating the proposed surgical procedures to the patients.

- **Surgery rehearsal**: RP models offer unique opportunities for surgeons and surgical teams to rehearse complex operations using the same techniques and tools as during actual surgery. Potentially, such rehearsals can lead to changes in surgical procedures and significantly reduce risk.

- **Training**: RP models of specimens of unusual medical deformities can be built to facilitate the training of student surgeons and radiologists. Such models can be employed for student examinations.

- **Prosthesis design**: RP models can be used to fabricate master patterns which are then replicated using a bio-compatible plastic material. Implants produced in this way are accurate and cost effective than those produced employing conventional techniques.

The building of RP models of anatomical structures involves the following steps:

i. **Data acquisition with medical equipment**: Conventional 3D medical scanners (Computer Tomography (CT) scans, Magnetic Resonance Imaging (MRI) Scans, 3D Ultrasound) are employed to capture a sequence of images of a particular anatomic structure.
ii. Generation of STL files from the scan data: Interactive software tools exist for segmentation of scanned images and generation of STL files. This technique can be employed for segmentation of soft tissue in CT images or for segmentation of several structures in MR images.

iii. Building RP models from the generated STL files: Any RP technology can be employed for building medical models. In addition to the general-purpose materials for each RP technology, special materials have been developed for medical applications.

1.6.4 Engineering analysis models

Computer Aided Engineering (CAE) analysis is an integral part of time-compression technologies. Various software tools exist, mainly based on Finite Element Analysis (FEA), to speed up the development of new products by initiating design optimization before physical prototypes are available. However, the creation of accurate FEA models for complex engineering objects sometimes requires significant amounts of time and effort. By employing RP techniques it is possible to begin test programmes on physical models much earlier and complement the CAE data. Some applications for engineering analysis are visualization of flow patterns, thermo elastic tension analysis, photoelastic stress analysis and fabrication of models for wind tunnel tests.

1.6.5 Art and design

Another growing application area for RP technologies is in art and design. Through building RP models, artists can experiment with complex
artworks which support and enhance their creativity. Initially, the high cost of RP models meant strict limits on the size of the models. However, recently, with the introduction of concept modelers, it has become cost effective to employ RP techniques in many artistic applications. Taking into account the accuracy of art models and the RP materials available, the technological capabilities of concept modelers are more than adequate for the majority of art applications.

1.6.6 Rapid manufacturing

A natural extension of RP is Rapid Manufacturing (RM), the automated production of saleable products directly from CAD data. Currently only a few final products are produced by RP machines, but the number will increase as metals and other materials become more readily usable. For short production runs RM is much cheaper, since it does not require tooling. RM is also ideal for producing custom parts tailored to the user's exact specifications. A University of Delaware research project uses a digitized 3-D model of a person's head to construct a custom-fitted helmet. NASA is experimenting with using RP machines to produce spacesuit gloves fitted to each astronaut's hands. From tailored golf club grips to custom dinnerware, the possibilities are endless. The other major use of RM is for the products that cannot be made easily by subtractive (machining, grinding) or compressive (forging, rolling etc.) processes. This includes objects with complex features, internal voids and layered structures.