Another group of terms emphasizes on the unique characteristic of RP — layer by layer addition as opposed to traditional manufacturing methods such as machining which is material removal from a block. This group includes *Layer Manufacturing*, *Material Deposit Manufacturing*, *Material Addition Manufacturing* and *Material Incress Manufacturing*.

There is yet another group which chooses to focus on the words "solid" and "freeform" — *Solid Freeform Manufacturing* and *Solid Freeform Fabrication*. *Solid* is used because while the initial state may be liquid, powder, individual pellets or laminates, the end result is a solid, 3D object, while *freeform* stresses on the ability of RP to build complex shapes with little constraint on its form.

1.6 CLASSIFICATION OF RAPID PROTOTYPING SYSTEMS

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

1.6.1 Liquid-Based

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

(1) 3D Systems' Stereolithography Apparatus (SLA)
(2) Cubital's Solid Ground Curing (SGC)
(3) Sony's Solid Creation System (SCS)
(4) CMET's Solid Object Ultraviolet-Laser Printer (SOUP)
(5) Autostrade's E-Darts
(6) Teijin Seiki's Soliform System

(7) Meiko's Rapid Prototyping System for the Jewelry Industry
(8) Denken's SLP
(9) Mitsui's COLAMM
(10) Fockele & Schwarze's LMS
(11) Light Sculpting
(12) Aaroflex
(13) Rapid Freeze
(14) Two Laser Beams
(15) Microfabrication

As is illustrated in the RP Wheel in Figure 1.3, three methods are possible under the "*Photo-curing*" method. The *single laser beam* method is most widely used and include all the above RP systems with the exception of (2), (11), (13) and (14). Cubital (2) and Light Sculpting (11) use the *masked lamp* method, while the *two laser beam* method is still not commercialized. Rapid Freeze (13) involves the freezing of water droplets and deposit in a manner much like FDM to create the prototype. Each of these RP systems will be described in more detail in Chapter 3.

1.6.2 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:

(1) Cubic Technologies' Laminated Object Manufacturing (LOM)
(2) Stratasys' Fused Deposition Modeling (FDM)
(3) Kira Corporation's Paper Lamination Technology (PLT)
(4) 3D Systems' Multi-Jet Modeling System (MJM)
(5) Solidscape's ModelMaker and PatternMaster
(6) Beijing Yinhua's Slicing Solid Manufacturing (SSM), Melted Extrusion Modeling (MEM) and Multi-Functional RPM Systems (M-RPM)

(7) CAM-LEM's CL 100
(8) Ennex Corporation's Offset Fabbers

Referring to the RP Wheel in Figure 1.3, two methods are possible for solid-based RP systems. RP systems (1), (3), (4) and (9) belong to the *Cutting and Glueing/Joining* method, while the *Melting and Solidifying/Fusing* method used RP systems (2), (5), (6), (7) and (8). The various RP systems will be described in more detail in Chapter 4.

1.6.3 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 this definition:

(1) 3D Systems's Selective Laser Sintering (SLS)
(2) EOS's EOSINT Systems
(3) Z Corporation's Three-Dimensional Printing (3DP)
(4) Optomec's Laser Engineered Net Shaping (LENS)
(5) Soligen's Direct Shell Production Casting (DSPC)
(6) Fraunhofer's Multiphase Jet Solidification (MJS)
(7) Acram's Electron Beam Melting (EBM)
(8) Aeromet Corporation's Lasform Technology
(9) Precision Optical Manufacturing's Direct Metal Deposition (DMD™)
(10) Generis' RP Systems (GS)
(11) Therics Inc.'s Theriform Technology
(12) Extrude Hone's Prometal™ 3D Printing Process

All the above RP systems 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. Similarly, the above RP systems will be described in more detail in Chapter 5.

Chapter 2
RAPID PROTOTYPING PROCESS CHAIN

2.1 FUNDAMENTAL AUTOMATED PROCESSES

There are three fundamental fabrication processes [1, 2] as shown in Figure 2.1. They are *Subtractive*, *Additive* and *Formative* processes.

In the subtractive process, one starts with a single block of solid material larger than the final size of the desired object and material is removed until the desired shape is reached.

In contrast, an additive process is the exact reverse in that the end product is much larger than the material when it started. A material is manipulated so that successive portions of it combine to form the desired object.

Lastly, the formative process is one where mechanical forces or restricting forms are applied on a material so as to form it into the desired shape.

There are many examples for each of these fundamental fabrication processes. Subtractive fabrication processes include most forms of machining processes — CNC or otherwise. These include milling, turning, drilling, planning, sawing, grinding, EDM, laser cutting, water-

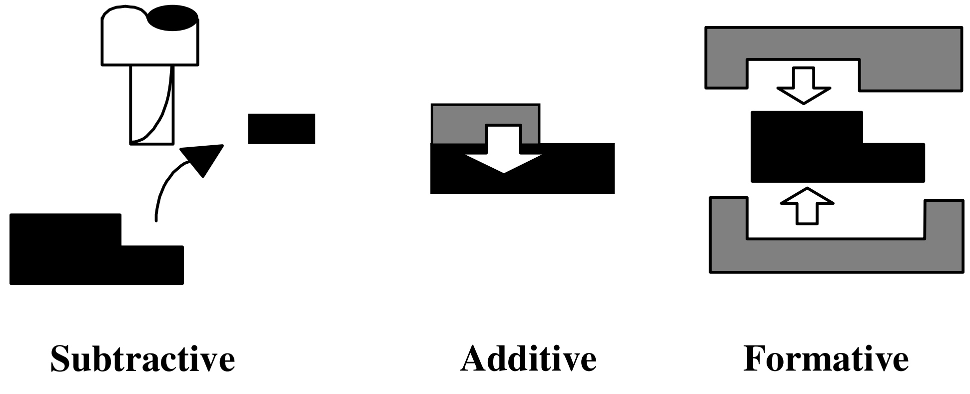

Figure 2.1: Three types of fundamental fabrication processes

jet cutting and the likes. Most forms of rapid prototyping processes such as Stereolithography and Selective Laser Sintering fall into the additive fabrication processes category. Examples of formative fabrication processes are: Bending, forging, electromagnetic forming and plastic injection molding. These include both bending of sheet materials and molding of molten or curable liquids. The examples given are not exhaustive but indicative of the range of processes.

Hybrid machines combining two or more fabrication processes are also possible. For example, in progressive pressworking, it is common to see a hybrid of subtractive (as in blanking or punching) and formative (as in bending and forming) processes.

2.2 PROCESS CHAIN

As described in Section 1.3, all RP techniques adopt the same basic approach. As such all RP systems generally have a similar sort of process chain. Such a generalized process chain is shown in Figure 2.2 [3]. There are a total of five steps in the chain and these are 3D

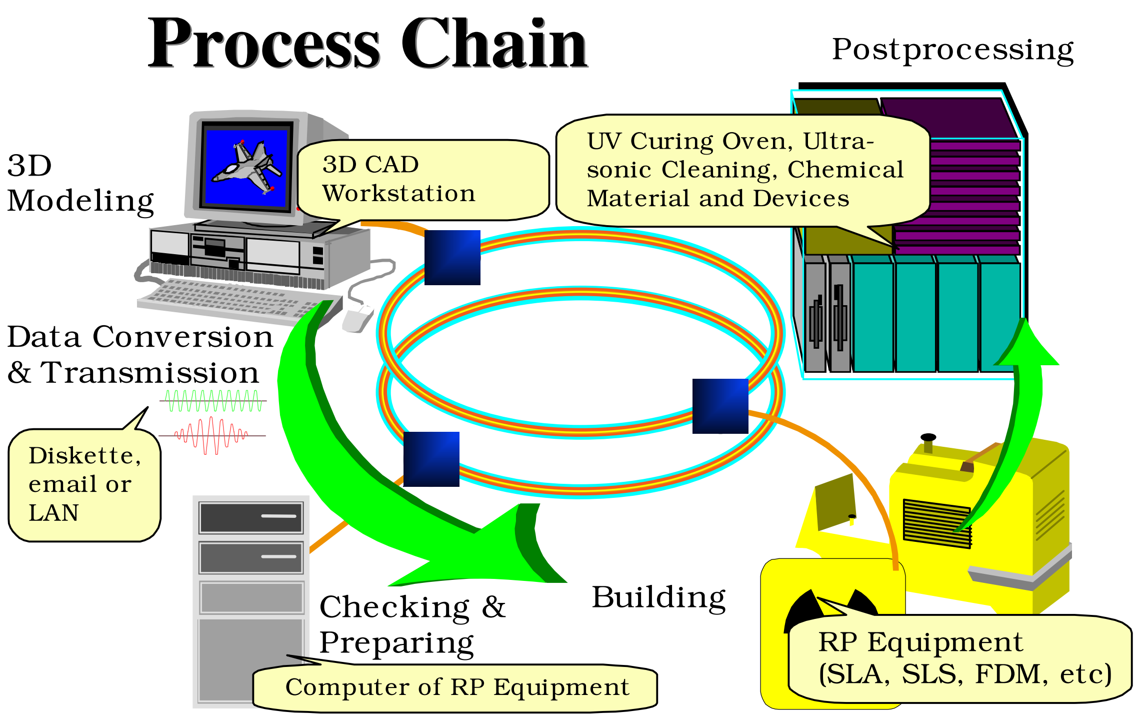

Figure 2.2: Process chain of Rapid Prototyping process

modeling, data conversion and transmission, checking and preparing, building and postprocessing. Depending on the quality of the model and part in Steps 3 and 5 respectively, the process may be iterated until a satisfactory model or part is achieved.

However, like other fabrication processes, process planning is important before the RP commences. In process planning, the steps of the RP process chain are listed. The first step is 3D geometric modeling. In this instance, the requirement would be a workstation and a CAD modeling system. The various factors and parameters which influence the performance of each operation are examined and decided upon. For example, if a SLA is used to build the part, the orientation of the part is an important factor which would, amongst other things, influence the quality of the part and the speed of the process. Needless to say, an operation sheet used in this manner requires proper documentation and guidelines. Good documentation, such as a process logbook, allows future examination and evaluation, and subsequent improvements can be implemented to process planning. The five steps are discussed in the following sections.

2.3 3D MODELING

Advanced 3D CAD modeling is a general prerequisite in RP processes and, usually is the most time-consuming part of the entire process chain. It is most important that such 3D geometric models can be shared by the entire design team for many different purposes, such as interference studies, stress analyses, FEM analysis, detail design and drafting, planning for manufacturing, including NC programming, etc. Many CAD/CAM systems now have a 3D geometrical modeler facility with these special purpose modules.

There are two common misconceptions amongst new users of RP. First, unlike NC programming, RP requires a closed volume of the model, whether the basic elements are surfaces or solids. This confusion arises because new users are usually acquainted with the use of NC programming where a single surface or even a line element can be an NC element. Second, new users also usually assume *what you see is what you get*. These two misconceptions often lead to underspecifying parameters to the RP systems, resulting in poor performance and nonoptimal utilization of the system. Examples of considerations that have to be taken into account include orientation of part, need for supports, difficult-to-build part structure such as thin walls, small slots or holes and overhanging elements. Therefore, RP users have to learn and gain experience from working on the system. The problem is usually more complex than one can imagine because there are many different RP machines which have different requirements and capabilities. For example, while a SLA requires supports, SGC does not, and SGC works most economically if many parts are nested together and processed simultaneously (see Chapter 3, Sections 3.1 and 3.2).

2.4 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. The STL file format will be discussed in detail in Chapter 6.

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.

2.5 CHECKING AND PREPARING

The computer term, *garbage in garbage out*, is also applicable to RP. Many first time users are frustrated at this step to discover that their STL files are faulty. However, more often than not, it is due to both the errors of CAD models and the nonrobustness of the CAD-STL interface. Unfortunately, today's CAD models — whose quality are dependent on the CAD systems, human operators and postprocesses — are still afflicted with a wide spectrum of problems, including the generation of unwanted shell-punctures (i.e. holes, gaps, cracks, etc.). These problems, if not rectified, will result in the frequent failure of applications downstream. These problems are discussed in detail in the first few sections of Chapter 6.

At present, the CAD model errors are corrected by human operators assisted by specialized software such as MAGICS, a software developed by Materialise, N.V., Belgium [4]. This process of manual repair is very tedious and time consuming especially if one considers the great number of geometric entities (e.g. triangular facets) that are encountered in a CAD model. The types of errors and its possible solutions are discussed in Chapter 6.

Once the STL files are verified to be error-free, the RP system's computer analyzes the STL files that define the model to be fabricated and slices the model into cross-sections. The cross-sections are systematically recreated through the solidification of liquids or binding of powders, or fusing of solids, to form a 3D model.

In a SLA, for example, each output file is sliced into cross-sections, between 0.12 mm (minimum) to 0.50 mm (maximum) in thickness. Generally, the model is sliced into the thinnest layer (approximately 0.12 mm) as they have to be very accurate. The supports can be created using coarser settings. An internal cross hatch structure is generated between the inner and the outer surface boundaries of the part. This serves to hold up the walls and entrap liquid that is later solidified with the presence of UV light.

Preparing building parameters for positioning and stepwise manufacturing in the light of many available possibilities can be difficult if not accompanied by proper documentation. These possibilities include determination of the geometrical objects, the building orientation, spatial assortments, arrangement with other parts, necessary support structures and slice parameters. They also include the determination of technological parameters such as cure depth, laser power and other physical parameters as in the case of SLA. It means that user-friendly software for ease of use and handling, user support in terms of user manuals, dialogue mode and online graphical aids will be very helpful to users of the RP system.

Many vendors are continually working to improve their systems in this aspect. For example, a software, *Partman Program*, was introduced by 3D Systems [5] to reduce the time spent on setting parameters for

Table 2.1: Parameters used in the SLA process

1.	X–Y shrink
2.	Z shrink
3.	Number of copies
4.	Multi-part spacing
5.	Range manager (add delete, etc.)
6.	Recoating
7.	Slice output scale
8.	Resolution
9.	Layer thickness
10.	X–Y hatch-spacing or 60/120 hatch spacing
11.	Skin fill spacing (X, Y)
12.	Minimum hatch intersecting angle

the SLA process. Before this software is introduced, parameters (such as the location in the 250 mm × 250 mm box and the various cure depths) had to be set manually. This was very tedious for there may be up to 12 parameters to be keyed in. These parameters are shown in Table 2.1.

However, the job is now made simpler with the introduction of default values that can be altered to other specific values. These values can be easily retrieved for use in other models. This software also allows the user to orientate and move the model such that the whole model is in the positive axis' region (the SLA uses only positive numbers for calculations). Thus the original CAD design model can also be in "negative" regions when converting to STL format.

2.6 BUILDING

For most RP systems, this step is fully automated. Thus, it is usual for operators to leave the machine on to build a part overnight. The building process may take up to several hours to build depending on the size and number of parts required. The number of identical parts that can be built is subject to the overall build size constrained by the build volume of the RP system.

2.7 POSTPROCESSING

The final task in the process chain is the postprocessing task. At this stage, generally some manual operations are necessary. As a result, the danger of damaging a part is particularly high. Therefore, the operator for this last process step has a high responsibility for the successful process realization. The necessary postprocessing tasks for some major RP systems are shown in Table 2.2.

The cleaning task refers to the removal of excess parts which may have remained on the part. Thus, for SLA parts, this refers to excess resin residing in entrapped portion such as a blind hole of a part, as well as the removal of supports. Similarly, for SLS parts, the excess powder has to be removed. Likewise for LOM, pieces of excess wood-like blocks of paper which acted as supports have to be removed.

Table 2.2: Essential postprocessing tasks for different RP processes
(✓ = is required; ✘ = not required)

Rapid Prototyping Technologies				
Postprocessing Tasks	**SLS**[1]	**SLA**[2]	**FDM**[3]	**LOM**[4]
1. Cleaning	✓	✓	✘	✓
2. Postcuring	✘	✓	✘	✘
3. Finishing	✓	✓	✓	✓

[1]SLS — Selective Laser Sintering
[2]SLA — Stereolithography Apparatus
[3]FDM — Fused Deposition Modeling
[4]LOM — Layered Object Manufacturing

As shown in Table 2.2, the SLA procedures require the highest number of postprocessing tasks. More importantly, for safety reason, specific recommendations for postprocessing tasks have to be prepared, especially for cleaning of SLA parts. It was reported that accuracy is related to the post-treatment process [6]. Specifically, Ref. 6 refers to the swelling of SLA-built parts with the use of cleaning solvents. Parts are typically cleaned with solvent to remove unreacted photosensitive resin. Depending upon the “build style” and the extent of crosslinking in the resin, the part can be distorted during the cleaning process. This effect was particularly pronounced with the more open “build styles” and aggressive solvents. With the “build styles” approaching a solid fill and more solvent-resistant materials, damage with the cleaning solvent can be minimized. With newer cleaning solvents, like TPM (tripropylene glycol monomethyl ether) introduced by 3D Systems, part damage due to the cleaning solvent can be reduced or even eliminated [6].

For reasons which will be discussed in Chapter 3, SLA parts are built with pockets of liquid embedded within the part. Therefore, postcuring is required. All other nonliquid RP methods do not undergo this task.

Finishing refers to secondary processes such as sanding and painting used primarily to improve the surface finish or aesthetic appearance of the part. It also includes additional machining processes such as drilling, tapping and milling to add necessary features to the parts.

REFERENCES

[1] Burns, M., Research Notes. *Rapid Prototyping Report* **4**(3) (1994): 3–6.

[2] Burns, M., *Automated Fabrication*, PTR Prentice Hall, New Jersey, 1993.

[3] Kochan, D. and Chua, C.K., "Solid freeform manufacturing — Assessments and improvements at the entire process chain," *Proceedings of the International Dedicated Conference on Rapid Prototyping for the Automotive Industries*, ISATA94, Aachen, Germany, 31 Oct to 4 Nov 94.

[4] Materialise, N.V., Magics 3.01 Materialise User Manual. Materalise Software Department, Kapeldreef 60, B-3001 Heverlee, Belgium, 1994.

[5] 3D Systems, *SLA User Reference Manual.*

[6] Peiffer, R.W., "The laser stereolithography process — Photosensitive materials and accuracy," *Proceedings of the First International User Congress on Solid Freeform Manufacturing*, Germany, 28–30 Oct 1993.

PROBLEMS

1. What are the three types of automated fabricators? Describe them and give two examples each.
2. Each one of the following manufacturing processes/methods in Table 2.3 belongs to one of the three basic types of fabricators. Tick [✓] under the column if you think it belongs to that category. If you think that it is a hybrid machine, you may tick [✓] in more than one category.