# From Rapid Prototyping to Rapid Manufacturing

***Manfred Hofmann, 3D Systems SA, Marly, Switzerland***

## Abstract

*Rapid Prototyping is now a well introduced technique to convert CAD and other unique geometry data into physical models by an automatic process. This paper describes the basic principles and the most widely used commercial processes, which build parts by adding material layer by layer with an imaging method. Some features which distinguish these techniques are discussed, as well as the materials which can be used. The last section describes the emerging use of RP machines and materials for digital fabrication (or Rapid Manufacturing) with some practical examples.*

## Introduction

Rapid Prototyping (RP) is used in the mechanical design community for techniques which use computer controlled machinery to build up arbitrary 3-Dimensional (3-D) objects based on a geometric description, generally in the form of a file with 3-D coordinates. The resulting models need not necessarily be real functional prototypes, but essentially a materialized representation of the geometry. Mechanical CAD, which is generally used by designers and engineers, is the primary source of data, but reverse engineering using scanning and tomography can help to replicate and modify existing objects. The rapid availability of real representations of original designs, in a realistic and cost efficient way, has revolutionized the way the industry can design, develop and manufacture new products; design ideas can be verified, conveyed and approved much faster, and with improved accuracy. Among dozens of inventions of specific techniques to put automated building of models to reality, just a few have reached a sustainable and reliable commercial status, among them Stereolithography (SLA®), Selective Laser Sintering (SLS®), Fused Deposition Modeling, Layered Object Modeling and 3-D Printing. The practical value or 'usability' of these prototypes depends largely on the accuracy and realism of their appearance, but for functional prototypes and handling aspects also on their material properties, which are generally different from known production materials. As the established RP techniques are finding a growing migration into specialized manufacturing applications, thermo mechanical and optical properties of the material for these end use parts are becoming a decisive factor. On the other hand, RP machines are also being developed towards production ready reliability, throughput, integration and cost efficiency. While these technological developments and increasing manufacturing applications are mutually stimulating progress, experts predict a transition from standardized mass production towards smaller lot sizes and eventually mass customization of consumer products.

## Overview of Popular RP Techniques

The original idea to 'print' 3 dimensional objects directly from computer models has tempted inventors since the 1970's, but the creation of commercially viable devices had to wait for the availability of affordable control computers, such as the microprocessor based PC. CNC machining of 3-D parts and molds had already been used before the current RP era, but had severe limitations for complex, concave shapes and required a lot of skilled human input for tool selection and programming. All the successful RP methods, which are also summarized as 'additive' techniques, are based on a layer-by-layer buildup of a model, based on data sets which are previously 'sliced' from the 3-D model data. Physically the material which constitutes the model is mostly applied in some fluid form, and is then solidified by a phase change, which also results in a solid stacking of the layers.

An important distinction between different techniques is the step where the 'image' information is transferred to the new layer: if a full layer is coated onto the previous layer, an imaging step is needed to define and solidify the current cross section; some methods also cut the contour of an already solid film, which is adhesively bonded to the stack. Another method is to selectively deposit material for each cross section, which is then solidified by physical or chemical means.

A common problem which had to be solved for these techniques, also known in 2-D printing on many substrates, is shrinkage of the applied layer as it goes through the phase change, which can lead to internal stresses and deformation of the parts. The global shrinkage is rather easily compensated on the data set, in X, Y and Z direction.

Just as a workpiece has to be fastened on a milling machine for processing, RP machines have to attach the prototype which is being built on a mechanical base, in general with a conformal support which is built up simultaneously with the part on the flat build platform. Once the part is built, this support is removed in a finishing process and discarded. The RP methods which start out with a solid material – powder or sheet stock – can use this substrate as a support, as it surrounds the growing part. But in any case some work and time is required to 'free' the parts of their supports. This is normally done in a properly configured workspace, including dust ventilation, cleaning baths and some specific tools, depending on the RP parts.

A selection of the most widely used RP methods along with their commercial designations and abbreviations are given in Table 1.

Among the pioneering technologies, Stereolithography has established itself as the leader in accuracy and surface quality, while Selective Laser Sintering has an advantage in materials properties, as the starting material is an engineering thermoplastic (polyamide in most cases). Even though the ultimate properties of a comparable material processed by injection molding are not obtained, and the parts are still porous, they can be used for rigorous testing and some manufacturing applications.

Stereolithography offers a vast choice of materials, which are mostly based on epoxy resins, but formulated for specific materials properties and appearance. Many of them are designed to mimic the essential properties of mass production plastics, such as ABS, polypropylene or polyethylene, although the current materials are crosslinked polymers and can only achieve a subset of the properties. They mostly fall short in impact resistance and stability at elevated temperatures (heat deflection temperature as an engineering specification). Both techniques transform each layer with a scanned laser beam, which sweeps the current cross section of the part on the platform. The scan speed is largely determined by the material's sensitivity and the laser power.

Fused Deposition Modeling is a precision extrusion of thermoplastic filament, including some higher performance materials like polycarbonate and polyether sulfone, which is spread on a platform in layers, and therefore is also close to those materials properties. The layer adhesion depends on the processing conditions and is generally not as strong as the bulk material strength, but mostly sufficient for demanding applications. Due to the linear, mechanical movement of the deposition, the process is slower than the laser based SLA or SLS systems and therefore marginal for manufacturing use.

Layered Object Modeling uses thermally adhesive sheet material (paper) which is stacked up, glued together with a heated roller, and cut into the part's cross sections with an IR laser. As only the contour of each layer has to be cut, it is a fast process, even when thin sheets are used for good height resolution. The original laser based machines are not manufactured anymore, but a similar technology which uses engineered thermoplastic sheet stock with an elaborate combination of liquid adhesive and release agent, and cuts the contours with a stencil, is now introduced as a very affordable RP entry level system.

3-D Printing technology was initially developed at MIT, and then licensed to several equipment manufacturers, who offer different material combinations. The essential steps are spreading of a thin powder layer, and then imagewise jetting of a binder solution, which penetrates the powder of each cross section; upon drying of the solvent, the binder and powder stick together and form a solid object. As the jetting head has a large number of nozzles, the process is fast and economical, as it works without a laser or other special light source. Materials selection is rather limited, with a starch based powder and a ceramic similar to gypsum as the most popular variants. The medium-dense parts can be infiltrated with a wax or resin to give them a compact structure and higher strength. An interesting feature is the selective coloration of the parts which can be obtained by a selection of colored binder cartridges. Individual sections of the parts get a defined color in their entire volume. These parts are being built up in their powder bed, and this serves also as the support for any geometry.

Another set of jet based techniques uses multiple-nozzle, heated jets to print accurately each layer of liquefied build material. As the droplets cool down after impact on the growing part, they attach to the support and previous layers and solidify. A first generation of these machines uses a wax material, which is sufficient for concept models, but also produces parts which can be used for metal castings as in the traditional lost wax method.

The latest generation of machines uses wax as a support material, but a photocuring mixture for the parts. As they are hardened inside the machine with a powerful UV lamp, they are more robust and do not melt at elevated temperatures.

**Table 1: Popular RP Techniques**

| Name (abbreviation) | Method | Materials | Main characteristics | Manufacturing use |
|---|---|---|---|---|
| Stereolithography Apparatus (SLA®) | UV laser scanning | Liquid photopolymer (neat or filled) | Accuracy, smooth surfaces, choice of materials | In-the-ear hearing aids, dental, casting patterns |
| Selective Laser Sintering (SLS®) | IR laser scanning of powder | Plastic, metal, ceramic (powder) | Robust materials, engineering applications; choice of plastic and metal | Ducting, metal parts and injection mold tools for various end-use capabilities |
| 3D Printing (ZCorp) | Jetting binder on a powder bed | Starch Ceramic | Fast, cost efficient, color capable | |
| 3-D Printing (InVision 3-D Printer) | Jet based printer technology | Engineered Plastic, photopolymer | Cost efficient, usable for investment casting | Casting patterns for dental copings, jewelry |
| Fused Deposition Modeling | Extruding filament of molten material | Thermoplastics, wax | Good material properties; selection of materials w. easy changeover | |
| Layered Object Modeling (LOM) | Stacking and cutting layers of sheet material | Paper, plastic with glue layer | Fast, cost efficient (large parts) | Pattern for sand casting |

All of these RP methods convert geometric data into real 3-D objects, in an essentially automatic and unattended process, and can therefore be used to manufacture unique or low volume products. This has been recognized at an early stage (1, 2) when the available machines and materials were far behind current production standards. The machines and process control were not consistent and reliable enough for a production process, and above all accuracy and materials properties did only match some very rare cases for real parts.

## The Step to Rapid Manufacturing

Using RP models as master patterns for plastic and metal castings has soon gained wider acceptance, in particular after the transition from acrylate to epoxy resins for Stereolithography dramatically improved the accuracy of these patterns. They were mostly used to cast silicone RTV molds, which could then produce some tens of copies in a urethane or epoxy resin with the desired material properties. This multiplication step also saves build time on the more expensive RP machine, which can then be used to produce more of the unique patterns.

The desire to use RP parts directly for the final application has always existed, but cost considerations, materials choice and accuracy have often limited this approach to a few special applications, or time constraints. It is most profitable for complex, small parts which are built in a short time, when multiple copies or designs are manufactured in one run. Typical examples of these parts are electronics connectors and test adapters with large numbers of miniature connector pins, which can be built efficiently with Stereolithography.

Another field of growing importance are personalized items in the healthcare field, in particular the shells of hearing aids which are worn in the ear. Each patient's ear is scanned individually, and then the data are matched with the standardized engineering drawing to create the functional model. A large number of these shells are then built in each run, with specially formulated, biocompatible SL materials. Recent developments in machine design, software and handling equipment have transformed these RP machines into productive manufacturing lines.

For mechanically demanding applications, Selective Laser Sintering is offering properties close to molded engineering plastics, but without the geometric limits of the molding process. A typical example is complex air ducts in helicopters and airplanes, which have to fit into tight spaces and distribute the airflow to several locations. Low production numbers, mainly in military aircraft, has made laser sintering of polymers more efficient than molding.

This increased use of original RP equipment for real manufacturing has also created new demand and this feedback has induced progress in machine design, reliability, process and software. A Selective Laser Sintering machine specifically devoted to a production environment has been introduced earlier this year.

From an applications point of view, new possibilities are hinged on the development of materials. For each project, accuracy, speed and the material's end use properties in the required temperature range determine the selection of the best technology.

## References


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## Author Biography

*Manfred Hofmann graduated at the University of Bern with a PhD degree in Chemistry, which was based on laser spectroscopy of metal clusters.*

*In a postdoctoral term at the University of Colorado and Pennsylvania State University, the work was extended with investigations of ion – molecule aggregates.*

*The first industrial activity with Ciba-Geigy was in Central Research, Analytical Department, which was followed by a transfer to the Polymer Division.*

*Heading the Laser Laboratory within Ciba´s Materials Science department, he performed several projects on laser interactions with polymers, including basic investigations on photopolymers for Stereolithography in a joint project with 3D Systems.*

*In 1997 he co-founded RPC, which is now a part of 3D Systems, to start up independent development and commercialization of special materials for Stereolithography.*