Section VI

Rapid Prototyping

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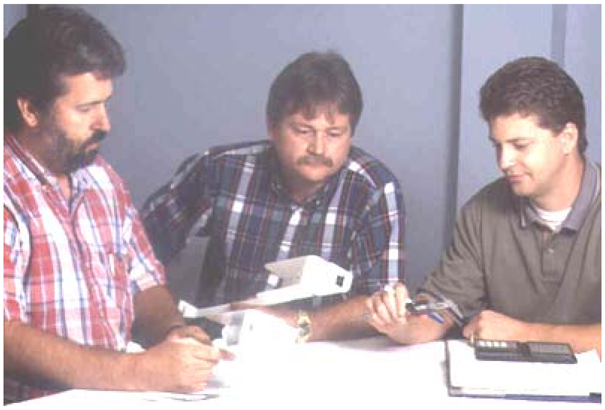
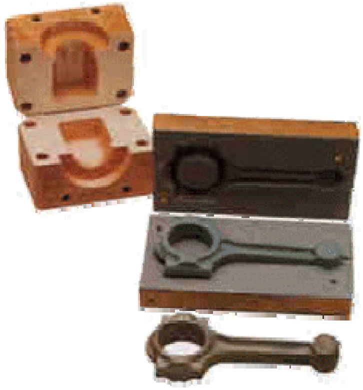
1.0 What is Rapid Prototyping?

The term *rapid prototyping* (RP) refers to a class of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data. These "three dimensional printers" allow designers to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures. Such models have numerous uses. They make excellent visual aids for communicating ideas with co-workers or customers. In addition, prototypes can be used for design testing. For example, an aerospace engineer might mount a model airfoil in a wind tunnel to measure lift and drag forces. Designers have always utilized prototypes; RP allows them to be made faster and less expensively.



Rapid Prototyping can be used to help engineers design products faster. RP models can also be used to identify problems early in the design process, which saves time and money.

In addition to prototypes, RP techniques can also be used to make tooling (referred to as *rapid tooling*) and even production-quality parts (*rapid manufacturing*). For small production runs and complicated objects, rapid prototyping is often the best manufacturing process available. Of course, "rapid" is a relative term. Most prototypes require from three to seventy-two hours to build, depending on the size and complexity of the object. This may seem slow, but it is much faster than the weeks or months required to make a prototype by traditional means such as machining. These dramatic time savings allow manufacturers to bring products to market faster and at a lower price. In 1994, Pratt & Whitney achieved "an order of magnitude [cost] reduction [and] . . . time savings of 70 to 90 percent" by incorporating rapid prototyping into their investment casting process.



Many RP techniques can even be used to make small final production runs. This LOM (Laminated Object Manufacturing) model was used to cast a finished metal connecting rod for an engine.

At least six different rapid prototyping techniques are commercially available, each with unique strengths. Because RP technologies are being increasingly used in non-prototyping applications, the techniques are often collectively referred to as *solid free-form fabrication*, *computer automated manufacturing*, or *layered manufacturing*. The latter term is particularly descriptive of the manufacturing process used by all commercial techniques. A software package "slices" the CAD model into a number of thin (~0.1 mm) layers, which are then built up one atop another. Rapid prototyping is an "additive" process, combining layers of paper, wax, or plastic to create a solid object. In contrast, most machining processes (milling, drilling, grinding, etc.) are "subtractive" processes that remove material from a solid block. RP's additive nature allows it to create objects with complicated internal features that cannot be manufactured by other means.

Hollow parts such as these shampoo bottles can be made with Rapid Prototype machines. These parts would be nearly impossible to make with conventional machining.

Of course, rapid prototyping is not perfect. Part volume is generally limited to 0.125 cubic meters or less, depending on the RP machine. Metal prototypes are difficult to make; though this should change in the near future. For metal parts, large production runs, or simple objects, conventional manufacturing techniques are usually more economical. These limitations aside, rapid prototyping is a remarkable technology that is revolutionizing the manufacturing process.

2.0 The 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

First, the object to be built is modeled 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 modelers 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.

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." 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.

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 in building the model. Placing the shortest dimension in the z direction reduces the number of layers, thereby shortening build time.

The preprocessing 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.

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 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.

3.0 Rapid Prototyping Techniques

Most commercially available rapid prototyping machines use one of six techniques. Here we will discuss three of the most widely used processes.

3.1 Stereolithography

Patented in 1986, stereolithography started the rapid prototyping revolution. The technique builds three-dimensional models from liquid photosensitive polymers that solidify when exposed to ultraviolet light. As shown in the figure below, the model is built upon a platform situated just below the surface in a vat of liquid epoxy or acrylate resin. A low-power highly focused UV laser traces out the first layer, solidifying the model's cross section while leaving excess areas liquid.

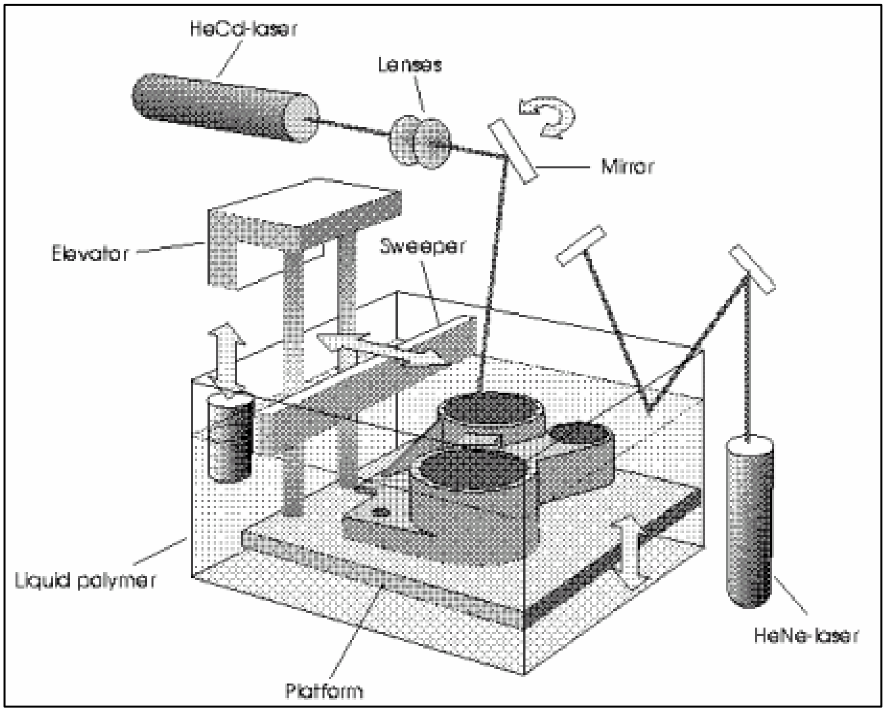


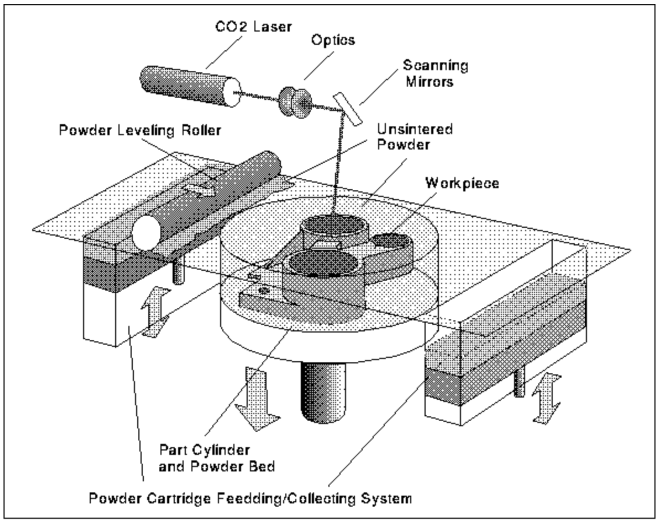
Figure 6.1 Diagram of the Stereolithography

Next, an elevator incrementally lowers the platform into the liquid polymer. A sweeper re-coats the solidified layer with liquid, and the laser traces the second layer atop 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 liquid. Supports are broken off and the model is then placed in an ultraviolet oven to complete the curing.

Stereolithography Apparatus (SLA) machines have been made since 1988 by 3D Systems of Valencia, CA. To this day, 3D Systems is the industry leader, selling more RP machines than any other company. Because it was the first technique, stereolithography is regarded as a benchmark by which other technologies are judged. Early stereolithography prototypes were fairly brittle and prone to curing-induced warpage and distortion, but recent modifications have largely corrected these problems.

3.2 Selective Laser Sintering

Developed by Carl Deckard for his master's thesis at the University of Texas, selective laser sintering was patented in 1989. The technique, shown in Figure 3, uses a laser beam to selectively fuse powdered materials, such as nylon, elastomer, and metal, into a solid object. Parts are built upon a platform, which sits just below the surface in a bin of the heat-fusable powder. A laser traces the pattern of the first layer, sintering it together. The platform is lowered by the height of the next layer and powder is reapplied. This process continues until the part is complete. Excess powder in each layer helps to support the part during the build. SLS machines are produced by DTM of Austin, TX.



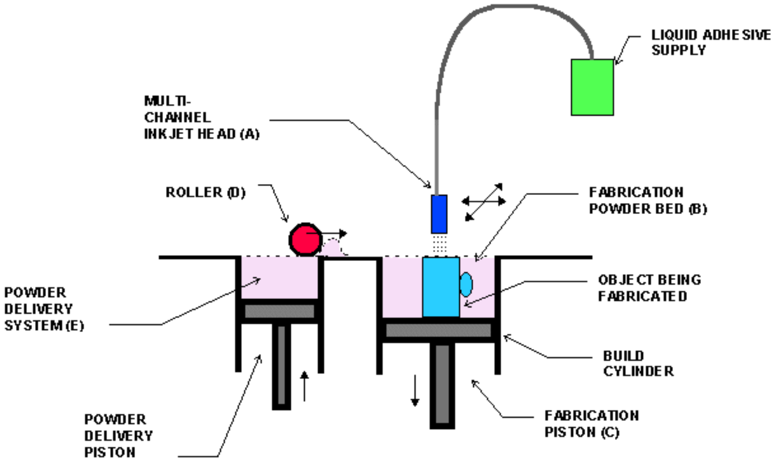
A schematic drawing of an SLS process.

3.3 Three Dimensional Ink-Jet Printing

Unlike the above techniques, Ink-Jet Printing refers to an entire class of machines that employ ink-jet technology. The first was 3D Printing (3DP), developed at MIT and licensed to Soligen Corporation, Extrude Hone, and others. As shown in the picture below, parts are built upon a platform situated in a bin full of powder material. An ink-jet printing head selectively "prints" binder to fuse the powder together in the desired areas. Unbound powder remains to support the part. The platform is lowered, more powder added and leveled, and the process repeated. When finished, the green part (not fully cured) is sintered and then removed from the unbound powder. Soligen uses 3DP to produce ceramic molds and cores for investment casting, while Extrude Hone hopes to make powder metal tools and products.

Sanders Prototype of Wilton, NH uses a different ink-jet technique in its Model Maker line of concept modelers. The machines use two ink-jets (see picture c below). One dispenses low-melt thermoplastic to make the model, while the other prints wax to form supports. After each layer, a cutting tool mills the top surface to uniform height. This yields extremely good accuracy, allowing the machines to be used in the jewelry industry. 3D Systems has also developed an ink-jet based system. The Multi-Jet Modeling technique (picture d) uses an array of 96 separate print heads to rapidly produce thermoplastic models. If the part is narrow enough, the print head can deposit an entire layer in one pass. Otherwise, the head makes several passes.

A similar process, Ballistic particle manufacturing, was developed by BPM Inc., which has since gone out of business.



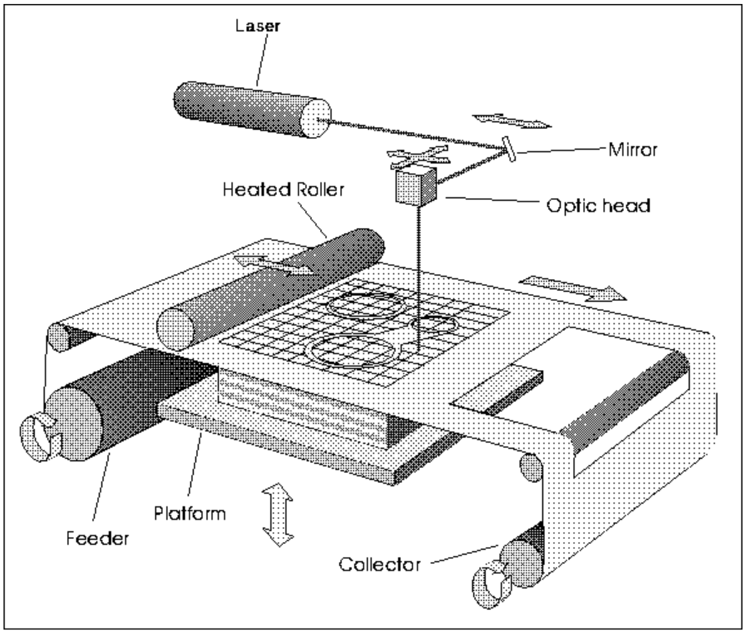
Three dimensional printing.

The rapid prototyping machine used in the AML is a Z-Corp Z402 system. Z-Corp is a relatively new contender in the 3DP business. Founded in 1994 it is the first office-compatible 3D printer because it's powder is composed primarily of cornstarch and sugar or plaster. Another key advantage is that it's remarkably quicker than other RP machines (1~2 vertical inches/hour). Also it features a generous (8x10x8 in.) build volume.

3.4 Laminated Object Manufacturing (LOM)

Laminated Object Manufacturing was developed in 1985 by Hydronetics in Chicago, IL. Helisys, Inc. is now the primary manufacturer LOM machines. This method can make use of a large selection of materials to create the model. However, paper is the most common, forming essentially a wooden finished product.

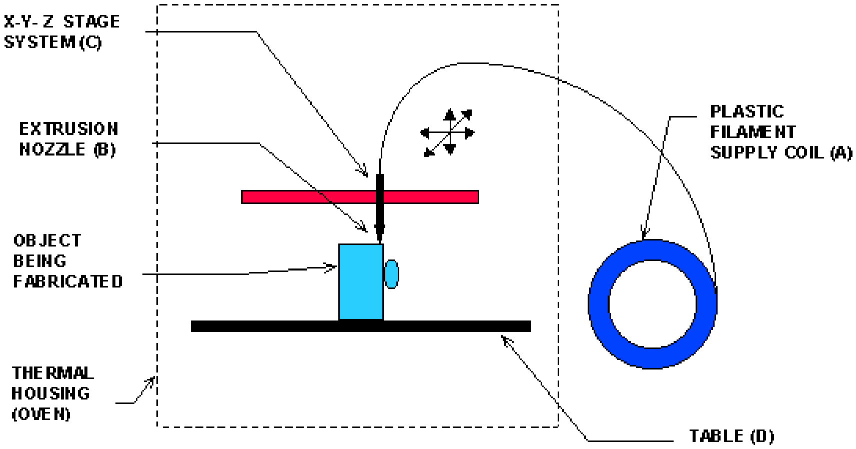
The process starts by coating a support platform with adhesive. Rollers feed a sheet of paper across the platform and then press and adhere the paper to the platform. A laser then performs a "cookie cutter" operation. It cuts out the model and any features on that plane. The laser also cross-hatches the material that is not in the model, allowing for easier removal after the process is done. The paper is left in place but has in effect been scored. The platform then drops down by one layer, the “stamped out” scrap paper is rolled onto the take-up spool and a new length of paper is rolled into position. The sheet is then coated with adhesive and the next sheet is applied and cut. Eventually, the model is detached from the platform and the model is broken out of the solid structure.



A schematic drawing of a LOM process.

Material from paper to composite sheets can be used in this process. Thickness ranges from 0.002 to 0.015 inches. Since there is no material phase change, there is no problem with shrinkage or warping due to internal stresses. The process gives essentially a laminated wood end product, which is very sturdy.

3.5 Fused Deposition Modeling (FDM)



Fused deposition modeling.

Fused Deposition Modeling was developed in 1988 by S. Scott Crump. This method of Rapid Prototyping has been described as applying decorative icing to a cake. The process again makes use of horizontal slices that come from the STL file which the CAD software generates. Each layer is created by a heated nozzle moving around the build area and depositing molten or semi-molten material onto the previous layers, building up the model. The heated nozzle accurately heats the material (usually a thermoplastic) to approximately 1-5 degrees F above the melting point. This allows for rapid cooling and solidification upon deposition. The material is fed into the nozzle in the form of wire or filament. The slices range between 0.01 and 0.125 inches thick. The filament or wire is usually about 0.05 inches in diameter. Many different materials can be used, as long as the nozzle can heat the material to melting. Stratasys, Inc., manufactures FDM machines.

4.0 Applications of Rapid Prototyping

Rapid prototyping is widely used in the automotive, aerospace, medical, and consumer products industries. Although the possible applications are virtually limitless, nearly all fall into one of the following categories: prototyping, rapid tooling, or rapid manufacturing.

4.1 Prototyping

As its name suggests, the primary use of rapid prototyping is to quickly make prototypes for communication and testing purposes. Prototypes dramatically improve communication because most people, including engineers, find three-dimensional objects easier to understand than two-dimensional drawings. Such improved understanding leads to substantial cost and time savings. As Pratt & Whitney executive Robert P. DeLisle noted: "We’ve seen an estimate on a complex product drop by $100,000 because people who had to figure out the nature of the object from 50 blueprints could now see it." Effective communication is especially important in this era of concurrent engineering. By exchanging prototypes early in the design stage, manufacturing can start tooling up for production while the art division starts planning the packaging, all before the design is finalized.

Prototypes are also useful for testing a design, to see if it performs as desired or needs improvement. Engineers have always tested prototypes, but RP expands their capabilities. First, it is now easy to perform iterative testing: build a prototype, test it, redesign, build and test, etc. Such an approach would be far too time-consuming using traditional prototyping techniques, but it is easy using RP.

In addition to being fast, RP models can do a few things metal prototypes cannot. For example, Porsche used a transparent stereolithography model of the 911 GTI transmission housing to visually study oil flow. Snecma, a French turbo-machinery producer, performed photoelastic stress analysis on a SLA model of a fan wheel to determine stresses in the blades.

4.2 Rapid Tooling

A much-anticipated application of rapid prototyping is rapid tooling, the automatic fabrication of production quality machine tools. Tooling is one of the slowest and most expensive steps in the manufacturing process, because of the extremely high quality required. Tools often have a complex geometry, yet must be dimensionally accurate to within a hundredth of a millimeter. In addition, tools must be hard, wear-resistant, and have very low surface roughness (about 0.5

micrometers root mean square). To meet these requirements, molds and dies are traditionally made by CNC-machining, electro-discharge machining, or by hand. All are expensive and time consuming, so manufacturers would like to incorporate rapid prototyping techniques to speed the process. Peter Hilton, president of Technology Strategy Consulting in Concord, MA, believes that "tooling costs and development times can be reduced by 75 percent or more" by using rapid tooling and related technologies. Rapid tooling can be divided into two categories, indirect and direct.

4.2.1 Indirect Tooling

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

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

  A more useful variant, known as the Keltool powder metal sintering process, uses the rubber molds to produce metal tools. Developed by 3M and now owned by 3D Systems, the Keltool process involves filling the rubber molds with powdered tool steel and epoxy binder. When the binder cures, the "green" metal tool is removed from the rubber mold and then sintered. At this stage the metal is only 70% dense, so it is infiltrated with copper to bring it close to its theoretical maximum density. The tools have fairly good accuracy, but are limited to less than 25 centimeters in size.

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

- Investment Casting: Some RP prototypes can be used as investment casting patterns. The pattern must not expand when heated, or it will crack the ceramic shell during autoclaving. Both Stratasys and Cubital make investment casting wax for their machines. Paper LOM prototypes may also be used, as they are dimensionally stable with temperature. The paper shells burn out, leaving some ash to be removed.

  To counter thermal expansion in stereolithography parts, 3D Systems introduced QuickCast, a build style featuring a solid outer skin and mostly hollow inner structure. The part collapses inward when heated. Likewise, DTM sells Trueform polymer, a porous substance that expands little with temperature rise, for use in its SLS machines.

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

4.2.2 Direct Tooling

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

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

  In 1996 Rubbermaid produced 30,000 plastic desk organizers from a SLS-built mold. This was the first widely sold consumer product to be produced from direct rapid tooling. Extrude Hone, in Irwin PA, will soon sell a machine, based on MIT's 3D Printing process, which produces bronze-infiltrated PM tools and products.

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

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

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

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

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

4.3 Rapid Manufacturing

A natural extension of RP is rapid manufacturing (RM), the automated production of salable products directly from CAD data. Currently only RP machines produce only a few final products, but the number will increase as metals and other materials become more widely available. RM will never completely replace other manufacturing techniques, especially in large production runs where mass-production is more economical.

For short production runs, however, 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 products that simply cannot be made by subtractive (machining, grinding) or compressive (forging, etc.) processes. This includes objects with complex features, internal voids, and layered structures. Specific Surface of Franklin, MA uses RP to manufacture complicated ceramic filters that have eight times the interior surface area of older types. The filters remove particles from the gas emissions of coal-fired power plants. Therics, Inc. of NYC is using RP’s layered build style to develop "pills that release measured drug doses at specified times during the day" and other medical products.

5.0 Summary of Techniques

Often the most decisive factor in choosing a RP technique is cost. Other factors that can sway this decision are how close the RP material mimics the characteristics of the intended material and its application. The following matrix summarizes many of the advantages and disadvantages as well as costs of various RP techniques.

6.0 Future Developments

Rapid prototyping is starting to change the way companies design and build products. On the horizon, though, are several developments that will help to revolutionize manufacturing as we know it.

One such improvement is increased speed. "Rapid" prototyping machines are still slow by some standards. By using faster computers, more complex control systems, and improved materials, RP manufacturers are dramatically reducing build time. For example, Stratasys recently (January 1998) introduced its FDM Quantum machine, which can produce ABS plastic models 2.5-5 times faster than previous FDM machines. Continued reductions in build time will make rapid manufacturing economical for a wider variety of products.

Another future development is improved accuracy and surface finish. Today’s commercially available machines are accurate to ~0.08 millimeters in the x-y plane, but less in the z (vertical) direction. Improvements in laser optics and motor control should increase accuracy in all three directions. In addition, RP companies are developing new polymers that will be less prone to curing and temperature-induced warpage.

The introduction of non-polymeric materials, including metals, ceramics, and composites, represents another much anticipated development. These materials would allow RP users to produce functional parts. Today’s plastic prototypes work well for visualization and fit tests, but they are often too weak for function testing. More rugged materials would yield prototypes that could be subjected to actual service conditions. In addition, metal and composite materials will greatly expand the range of products that can be made by rapid manufacturing.

Many RP companies and research labs are working to develop new materials. For example, the University of Dayton is working with Helisys to produce ceramic matrix composites by laminated object manufacturing. An Advanced Research Projects Agency / Office of Naval Research sponsored project is investigating ways to make ceramics using fused deposition modeling. As mentioned earlier, Sandia/Stanford’s LENS system can create solid metal parts. These three groups are just a few of the many working on new RP materials.

Another important development is increased size capacity. Currently most RP machines are limited to objects 0.125 cubic meters or less. Larger parts must be built in sections and joined by hand. To remedy this situation, several "large prototype" techniques are in the works. The most fully developed is Topographic Shell Fabrication from Formus in San Jose, CA. In this process, a temporary mold is built from layers of silica powder (high quality sand) bound together with paraffin wax. The mold is then used to produce fiberglass, epoxy, foam, or concrete models up to 3.3 m x 2 m x 1.2 m in size. At the University of Utah, Professor Charles Thomas is developing systems to cut intricate shapes into 1.2 m x 2.4 m sections of foam or paper. Researchers at Penn State’s Applied Research Lab (ARL) are aiming even higher: to directly build large *metal* parts such as tank turrets using robotically guided lasers. Group leader Henry Watson states that product size is limited only by the size of the robot holding the laser.

All the above improvements will help the rapid prototyping industry continue to grow, both worldwide and at home. The United States currently dominates the field, but Germany, Japan, and Israel are making inroads. In time RP will spread to less technologically developed countries as well. With more people and countries in the field, RP’s growth will accelerate further.

One future application is Distance Manufacturing on Demand, a combination of RP and the Internet that will allow designers to remotely submit designs for immediate manufacture. Researchers at UC-Berkeley, among others, are developing such a system. RP enthusiasts believe that RP will even spread to the home, lending new meaning to the term "cottage industry." Three-dimensional home printers may seem far-fetched, but the same could be said for color laser printing just fifteen years ago.

Finally, the rise of rapid prototyping has spurred progress in traditional subtractive methods as well. Advances in computerized path planning, numeric control, and machine dynamics are increasing the speed and accuracy of machining. Modern CNC machining centers can have spindle speeds of up to 100,000 RPM, with correspondingly fast feed rates. Such high material removal rates translate into short build times. For certain applications, particularly metals, machining will continue to be a useful manufacturing process. Rapid prototyping will not make machining obsolete, but rather complement it.

7.0 Rapid Prototyping and the AML

The AML uses rapid prototyping as an indispensable tool in the development of the products manufactured for your projects. Some of the ways in which the AML uses rapid prototyping are:

- <u>3D Printing:</u> One of the rapid prototyping machine used at the AML is a Z-Corp Z402 system. A plaster or starch-based powder is used to create the prototype. The 3D Print head sprays liquid binder (mostly water) on the powder, much like a common ink-jet printer does. The “bound” powder solidifies and the next layer is added. Parts produced from the 3D Printer are quite soft and delicate when they are removed from the machine, and must be infiltrated with wax, polyurethane, or cyanoacrylate (i.e., superglue) to gain strength. The 3D Printer’s main advantage over other machines is that it is remarkably fast. A typical 2 x 2 x 2 inch part can take as little as an hour to print and another hour to dry and then infiltrate with wax. In practice, part tolerances can be met to within 0.01” if the model is treated carefully. These models are typically used only for form & fit prototypes, as they are quite delicate and have a rough surface finish.
- <u>FDM:</u> The other rapid prototyping machine available in the AML is a Stratasys Dimension Fused Deposition Modeler. This machine uses ABS plastic filament to build parts in 0.010” layers. Tolerances of ±0.010” can be achieved and finished part strength can be up to 75% the strength of an injection molded ABS part (across layers). Parts can be used for form, fit, and some function. A brittle ABS material is used to build supports beneath overhanging or unsupported sections of the model. This material is broken away after production to reveal the finished part.
- <u>SLA form and fit modeling:</u> This is the most traditional use of a rapid prototype. Benet Labs in Watervliet supply the SLA prototypes. As the name suggests the SLA prototypes are used to see if the shape that was drafted on Pro-E is really the shape that is desired, or if it needs to be redesigned. It is also used to see if the ergonomics of the design are sound. Finally it is used in student presentations to communicate to the company sponsors the features of a particular design.
- <u>RTV molds:</u> This is a form of indirect tooling. The SLA prototype is used as a model to create duplicates of it, using a silicone rubber material to make a mold out of the prototype. The silicone comes as a two part liquid solution, that when combined, sets into a rubber like material. To create the mold the SLA part is put in a sealed container and the silicone is poured half way. Once the silicone sets the second half is filled and let to set. When both sides have solidified the SLA part is taken out and holes are drilled on one side. To create a reproduction of the prototype, an epoxy resin is injected through the holes and let to cure. Once it is cured the reproduction is removed. The main advantages of these reproductions

are that they can be easily created and modified with out damaging the more expensive SLA part. Another use for these prototypes are for designing the part feeders used in the assembly phase of AML II.

- <u>Injection molding:</u> This is a relatively new development in the AML. With injection molding the SLA part is used as direct tooling. An injection mold insert is created in Pro-E similar to that of the RPI key chain mold. Since the SLA resin is not a very good conductor of heat a slight modification has to be made to the mold. This mold is usually created as a hollow 1/8 in. shell that is backfilled with a low melt alloy to disperse the heat. A considerable draft angle has to be added to the part because of the stair step effect created by the SLA machine. Although this kind of mold has a short lifespan ~100 + parts, it is useful in creating small simple shapes.

8.0 Tips for Using Rapid Prototyping in the AML

Z-Corporation 3D Printer:

Part geometry:

<u>Avoid Thin Walls:</u>
Avoid having very large, thin-walled sections. For example: roughly 1/8” or less in cross section over 2-3” in length. These sections will be very flimsy when taken out of the machine and will be difficult to clean without distortion.

<u>Avoid Very Tiny Features:</u>
Small snap-fits, delicate embossed lettering, tiny protrusions should all be avoided if possible. These features typically break off during the cleaning process and are not within the machine’s dimensional accuracy anyway.

<u>Avoid Small, Internal Features:</u>
While the machine can produce parts with intricate internal features, try to avoid this if you can. The powder is somewhat difficult to clean off of internal surfaces because there’s no way to get into the part with the air gun.

<u>Overhanging Sections:</u>
The 3D Printer can certainly create parts with overhanging geometry without the need for support structures because the unused powder supports everything. Unfortunately, this supporting powder is vacuumed away when you remove the part from the machine. Any overhanging sections should be thick enough to resist sagging when you’re cleaning the part. Break-away supports can also be used in the CAD model to support the overhangs. You can break these off once the part has been waxed.

General Tips:

Part Removal:

Be VERY careful when removing the part from the machine. The parts are very soft and can be permanently deformed just by pressing lightly on the edges (if you were to pick up a part in this way). ALWAYS use a flat surface (spatula, or plate) to remove the parts.

Also, when vacuuming the excess powder from around the part in the build box, be careful not to touch the vacuum nozzle to the part. This can dent the part, or worse, suck sections into the vacuum.

Part Cleaning:

Again, be very careful when handling the parts in the vacuum cleaner. Use a flat spatula to hold the part if you can. Use low air pressure when cleaning thin features, so you do not blow them away. Try to get the corners as clean as possible. Remember, any excess powder will become solid when it gets waxed.

Waxing:

Always place the part with any deep-pocketed features facing down. Also, try to support the part on a mesh plate if you can. These actions help the wax to drain away from the part and prevent wax from pooling in the pockets.

Stratasys Dimension FDM Machine:

Part Geometry:

Cross sections as small as 0.040” can be built on the machine. However, removing support material will be VERY difficult. The raster strategy used to fill part interior also results in holes or gaps which will greatly affect the strength of thin regions. For these reasons, part thickness should be at least 0.060”, and those sections requiring support should be at least 0.10” thick.

Orientation:

Think carefully when orientating parts in the build volume. It is easier to remove support from the exterior of a curve than the interior. Blind holes should face up if possible top eliminate interior supports. Thin narrow sections will be stronger if this geometry is within the layer (horizontal within the build volume) rather than across many layers (vertical). Extremely thin and/or tall parts should be built with the SURROUND support strategy.