PDHonline Course M383 (4 PDH)

Rapid Prototyping & Manufacturing (RP&M)

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2020

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Rapid Prototyping and Manufacturing (RP&M)

Robert P. Jackson, PE

INTRODUCTION:

Rapid prototyping is definitely a technology that has, and is, changing the way companies and commercial entities do business. We can certainly say this "emerging technology" has gained tremendous momentum over the past decade. The applications and uses represent a "best practice" for manufacturers and producers in general.

Being able to obtain prototype parts quickly allows a company to test for component form, fit and function and can help launch a product much faster than its competition. This can allow for adjustments in design, materials, size, shape, assembly, color and manufacturability of individual components and subassemblies. Rapid prototyping is one methodology that allows this to happen. It also is an extremely valuable tool for sales and marketing evaluation at the earliest stages of any program. Generally, an engineering scope study is initially performed in which all elements of the development program are evaluated. Having the ability to obtain parts "up front" provides a valuable advantage and definitely complements the decision making process. Several rapid prototyping processes are available for today's product design teams while other prototyping processes utilize traditional manufacturing methods, such as 1.) CNC Machining, 2.) Laser Cutting, 3.) Water Jet Cutting, 4.) EDN Machining, etc. Rapid prototyping technologies emerged in the '80s and have improved considerably over a relatively short period of time. When I started my career as a young engineer, the only process available for obtaining and producing prototype components was as follows:

- Produce an orthogonal drawing of the component. This drawing was a two-dimensional rendition, including auxiliary views, and generally did NOT use geometrical dimensioning and tolerancing methodologies, which opened the way for various interpretations relative to the part itself. Solid modeling did not exist at that time.
- Take that drawing or drawings to the model shop so initial prototypes could be made. Generally, one prototype would be made for immediate examination. Any remaining parts would be scheduled depending upon approval of the design engineer or engineering manager. We were after "basic intent"—that came first. When the first prototype was approved, the model shop made the others required.
- Wait one, two, three, four, etc weeks for your parts so the initial evaluation process could occur. From these initial prototypes we would examine form, fit and function.
- Apply the component to the assembly or subassembly for initial trials.
- Alter the drawing(s) to reflect needed changes.

- Resubmit the revised drawing(s) to the model shop for the first iteration of the design. (NOTE: This creates a REV 1 drawing which continues the "paper trail" and hopefully insures proper documentation.)
- Again, apply the component for evaluation.
- Repeat the process until engineering, engineering management, quality control and manufacturing management, etc signs off on the components.

The entire process could take weeks or sometimes months to complete. Things have changed considerably. The advent of three dimensional modeling; i.e. solid modeling, has given the engineer a tremendous tool for evaluating designs and providing iterations before the very first "hard" prototype has been produced. As we shall see later on, solid modeling of the component, using CAE and CAD techniques, is the first prerequisite for rapid prototyping. There are several options available when deciding upon the best approach and means by which RP&M technology is used. As prototyping processes continue to evolve, product designers will need to determine what technology is best for a specific application.

INDUSTRIES USING RP&M PROCESSES:

As you might expect, there are many disciplines and industries willing to take advantage of new, cost-saving, fast methods of producing component parts. RP&M has become the "best practice" and the acceptable approach to "one-off" parts. Progressive companies must look past the prototyping stereotypes and develop manufacturing strategies utilizing additive manufacturing equipment, processes and materials for high volume production. The pie-chart below will indicate several of those industries now taking advantage of the technology and the approximate percentage of use.

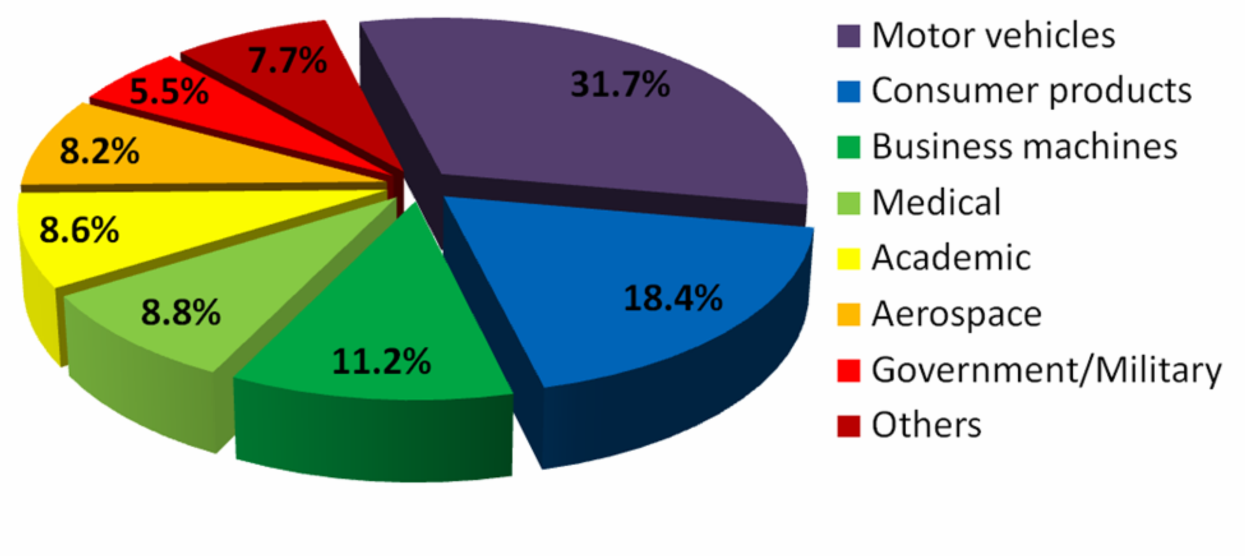
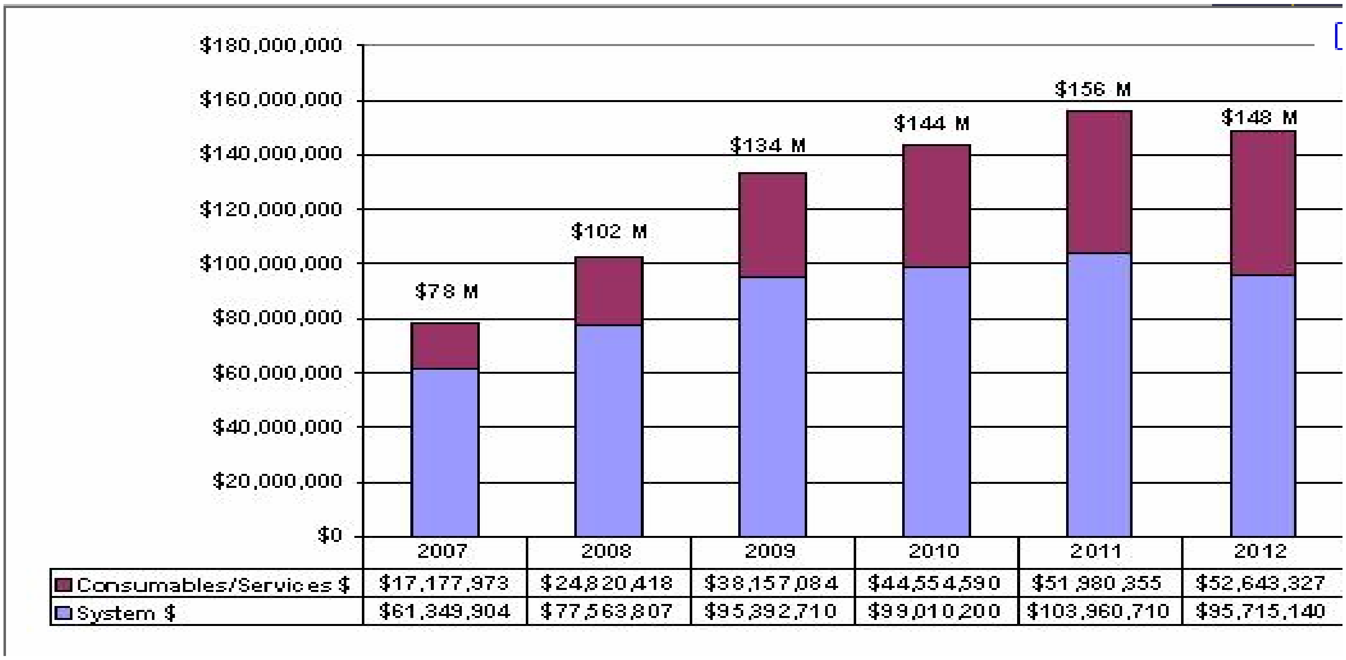


FIGURE 1: Institutions Using RP&M Technology

One of the statistics surprising to me is the percentage of use by the medical profession. I'm not too surprised by the seventeen percent from automotive because the development of stereolithography was actually co-sponsored by Chrysler Automotive. Consumer electronics is another field at eighteen percent (18.4%) that has adopted the process and another industry benefiting from fast prototyping methodologies. When getting there first is the name of the game, being able to obtain components parts in two to three days is a remarkable advantage. Many times these products have a "lifetime" of about eighteen month, at best, so time is of the essence.

The bar chart below will give a comparison between sales for RP&M services provided by vendors and companies providing RP&M machines to companies and independent providers. As you can see, the trends are definitely upward. Rapid prototyping has found a very real place with progressive companies and progressive institutions in this country and the world over.



	2007	2008	2009	2010	2011	2012
▨ Consumables/Services $	$17,177,973	$24,820,418	$38,157,084	$44,554,590	$51,980,355	$52,643,327
☐ System $	$61,349,904	$77,563,807	$95,392,710	$99,010,200	$103,960,710	$95,715,140

FIGURE 2: Annual Usage in Dollars

RAPID PROTOTYPING & MANUFACTURING (RP&M) TECHNOLOGIES:

There are several viable options available today that take advantage of rapid prototyping technologies. All of the methods shown below are considered to be rapid prototyping and manufacturing technologies.

- (SLA) Stereolithography
- (SLS) Selective Laser Sintering
- (FDM) Fused Deposition Modeling
- (3DP) Three Dimensional Printing

- (Pjet) Poly-Jet
- Laminated Object Manufacturing

Stereolithography was the first approach to rapid prototyping and all of the other methods represent "offshoots" or variations of this one basic technology. The processes given above are termed **"additative manufacturing"** processes because material is "added to" the part, ultimately producing the final form detailed by the 3-D model and companion specifications. This course will address the existing technology for all of these processes and give comparisons between them so intelligent decisions may be made as to which process is the most viable for any one given part to be prototyped.

As a result of the prototyping options given above, there are many materials available to facilitate assembly and trial after completion of the model. We are going to discuss processes vs. materials vs. post-forming and secondary operations later in this course. The variety of materials available today is remarkable and to a great extent, the material selection is dependent upon the process selected. We will certainly discuss this facet of the technology.

BASIC PROCESSES:

As you might expect, there is a definite methodology for creating actual parts, and the processes do not vary greatly from method to method. We are going to detail the sequential steps in the process. This detail will form the "backbone" for later discussions involving the mechanical and electronic operation of the equipment itself. **These steps apply to all of the RP&M processes.**

- Create a 3-D model of the component using a computer aided design (CAD) program. There are various CAD modeling programs available today, but the "additative manufacturing" process MUST begin by developing a three-dimensional representation of the part to be produced. **It is important to note that an experienced CAD engineer/designer is an indispensable component for success.** As you can see, RP&M processes were required to wait on three-dimensional modeling before the technology came to fruition.

- Generally, the CAD file must go through a CAD to RP&M **translator**. This step assures the CAD data is input to the modeling machine in the "tessellated" **STL format**. This format has become the standard for RP&M processes. With this operation, the boundary surfaces of the object are represented as numerous tiny triangles. (VERY INDENSABLE TO THE PROCESS!)

- The next step involves generating supports in a separate CAD file. CAD designers/engineers may accomplish this task directly, or with special software. One such software is "Bridgeworks". Supports are needed and used for the following three reasons:

    1. To ensure that the recoater blade will not strike the platform upon which the part is being built.

    2. To ensure that any small distortions of the platform will not lead to problems during part building.

3. To provide a simple means of removing the part from the platform upon completion.

- Next step— the appropriate software will “chop” the CAD model into thin layers—typically 5 to 10 layers per millimeter (MM). Software has improved greatly over the past years, and these improvements allow for much better surface finishes and much better detail in part description. The part **and** supports must be sliced or **mathematically sectioned** by the computer into a series of parallel and horizontal planes like the floors of a very tall building. Also during this process, the layer thickness, as discussed above, the intended building style, the cure depth, the desired hatch spacing, the line width compensation values and the shrinkage compensation factor(s) are selected and assigned.

- Merging is the next step where the supports, the part and any additional supports and parts have their computer representations combined. This is crucial and allows for the production of multiple parts connected by a “web” which can be broken after the parts are molded.

- Next, certain operational parameters are selected, such as the number or recoater blade sweeps per layer, the sweep period, and the desired “Z”-wait. All of these parameters must be selected by the programmer. “Z”-wait is the time, in seconds, the system is instructed to pause after recoating. The purpose of this intentional pause is to allow any resin surface nonuniformities to undergo fluid dynamic relaxation. The output of this step is the selection of the relevant parameters.

- Now, we “build the model”. The 3-D printer “paints” one layer exposing the material in the tank and hardening it. The resin polymerization process begins at this time, and the physical three-dimensional object is created. The process consists of the following steps:

    1. **Leveling**—Typical resins undergo about five percent (5%) to seven percent (7%) total volumetric shrinkage. Of this amount, roughly fifty percent (50%) to seventy percent (70%) occurs in the vat as a result of laser-induced polymerization. With this being the case, a level compensation module is built into the RP&M software program. Upon completion of laser drawing, on each layer, a sensor checks the resin level. In the event the sensor detects a resin level that is not within the tolerance band, a plunger is activated by means of a computer-controlled precision stepper motor and the resin level is corrected to within the needed tolerance.

    2. **Deep Dip**—Under computer control, the “Z”-stage motor moves the platform down a prescribed amount to insure those parts with large flat areas can be properly recoated. When the platform is lowered, a substantial depression is generated on the resin surface. The time required to close the surface depression has been determined from both viscous fluid dynamic analysis and experimental test results.

3. **Elevate**—Under the influence of gravity, the resin fills the depression created during the previous step. The "Z" stage, again under computer control, now elevates the uppermost part layer above the free resin surface. This is done so that during the next step, only the excess resin beyond the desired layer thickness need be moved. If this were not the case, additional resin would be disturbed.
4. **Sweep**—The recoater blade traverses the vat from front to back and sweeps the excess resin from the part. As soon as the recoater blade has completed its motion, the system is ready for the next step.
5. **Platform Drops**--The platform then drops down a fraction of a MM. The process is then repeated. This is done layer by layer until the entire model is produced. As you can see, the thinner the layer, the finer and more detailed the resulting part.
6. **Draining**--Part completion and draining.
7. **Removal**--The part is then removed from the supporting platform and readied for any post-processing operations. .

- Next, heat treating and firing may occur for further hardening. This phase is termed the post-cure operation.
- After heat treating and firing, the part may be machined, sanded, painted, etc until the final product meets initial specifications. As mentioned earlier, there have been considerable developments in the materials used for the process, and it is entirely possible that the part may be applied to an assembly or subassembly so that the designed function may be observed. No longer is the component necessarily for "show and tell" only.

The entire procedure may take as long as 72 hours, depending upon size and complexity of the part, but the results are remarkably usable and applications are abundant.

APPICATIONS:

The applications for RP&M technology are as numerous as your imagination. With the present state of the art, extremely accurate, detailed and refined prototypes may be produced. Components and structures that were impossible or extremely difficult to model are made possible today with existing methods and equipment. We will now take a look at figures representing very "real" components fabricated with rapid modeling techniques. Some of the applications are as follows:

- Dental Prototypes
- Orthopedic Prototypes
- Sculpture prototypes
- Prototypes for manufactured components

- Items used to decorate sets for plays, operas, etc
- Forensic investigations
- Surgical procedure planning
- Molds for investment castings
- Architectural models
- Scaled models
- Complex trays for fiber optics
- Light pipes for electronic devices

In addition to speed, very fine and intricate surface finishes may be had depending upon the material and process used to create the part. We have taken a look at those industries using RP&M, Figure 1, so let us now consider the various uses for the technology itself. Looking at Figure 3 below, we find the following major uses for the technology:

• Visual aids for engineering	16.5 %
• Functional models	16.1%
• Fit and assembly	15.6%
• Patterns for prototype tooling	13.4%
• Patterns for cast metal	9.2%

Over seventy percent (70%) of the total uses are given by the five categories above. This in no way negates or lessens the importance of the other uses, but obviously, visual aids, functional models and models to prove form, fit and function top the list.

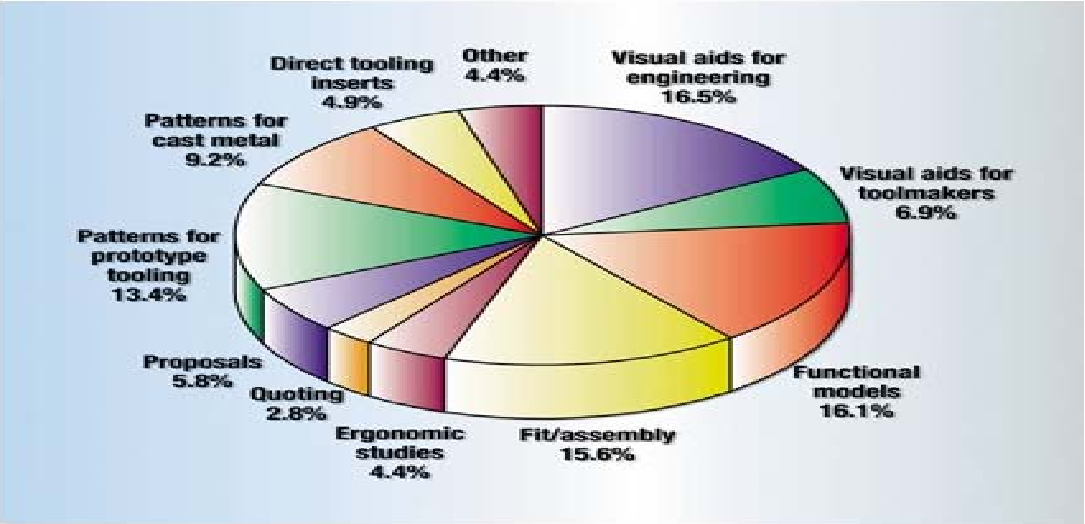


FIGURE 3: Uses for RP&M

DIGITAL PHOTOS DEPICTING USES FOR RP&M TECHNOLOGY:

Everyone says a "picture is worth a thousand words" so let's take a very quick pictorial look at some of the many applications noted by the text and the figures above. The following JPEGs should give you an idea as to what uses of RP&M technologies exist. These digital photographs are from actual models created for very specific purposes.

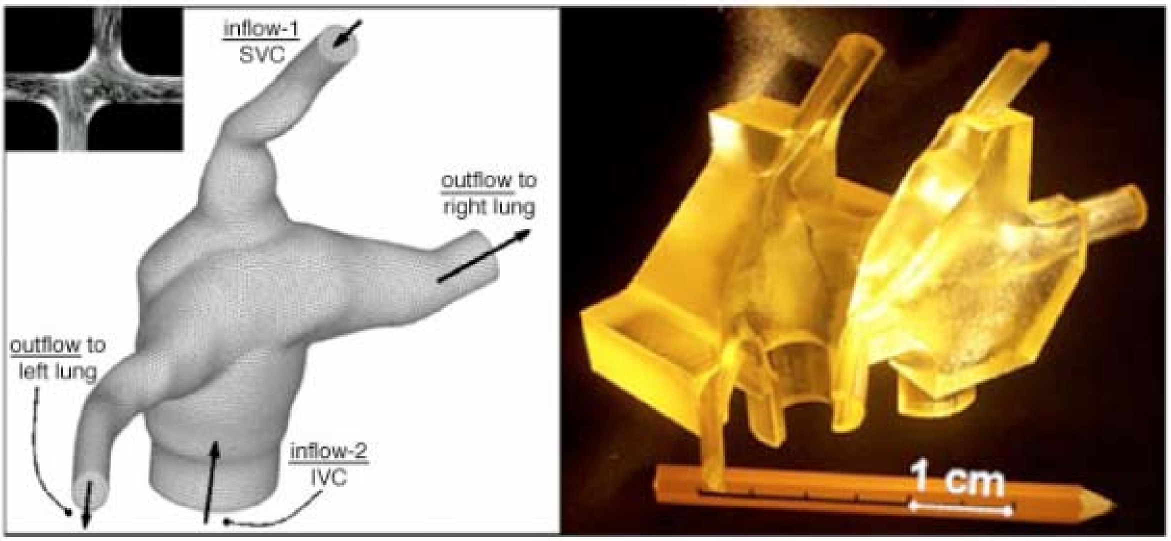


FIGURE 4: Left: Unstructured computational fluid dynamics grid of the anatomic solid model. Right: The corresponding stereolithographic duplicate for experiments confirming the solid model. The figure above is an excerpt from ***The Journal of Biomedical Engineering*** detailing work conducted by the Georgia Institute of Technology and Emory University Medical Units. As you might imagine, the resulting

stereolithographic model was required to be as exact as possible to verify the CAD solid model on the left. The rapid modeling process provided the tangible model needed to conduct desired experiments. Prototyping allowed for physical verification of the computerized solid model. The component took approximately 24 hours to complete.

FIGURE 5: Model of engine block produced by **Laser Sintering** methodology. This part was fabricated using the EOSINT P700 machine with a build volume of 700x380x580 mm. It is one example of a large part that can be produced. Please note the detail. The dimensional tolerances required were met by the process also.

I include the next JPEG to show how intricate patterns can be fabricated using RP&M technologies. It is very obvious that a tremendous amount of time would be needed to machine this part using conventional methods; i.e. lath, milling machine, laser, etc.—a tremendous amount of time. In actuality, this part required approximately thirty-two hours for completion using SLA technology. Please note that this does not include CAD time to develop the model, just the fabrication time. CAD time is a factor, possibly a huge factor when considering the total process; but, even using conventional fabrication methods, a computer model or drawing would have to be produced. Modern CAD using parametric modeling greatly reduces the time necessary to accurately depict a component of this complexity.

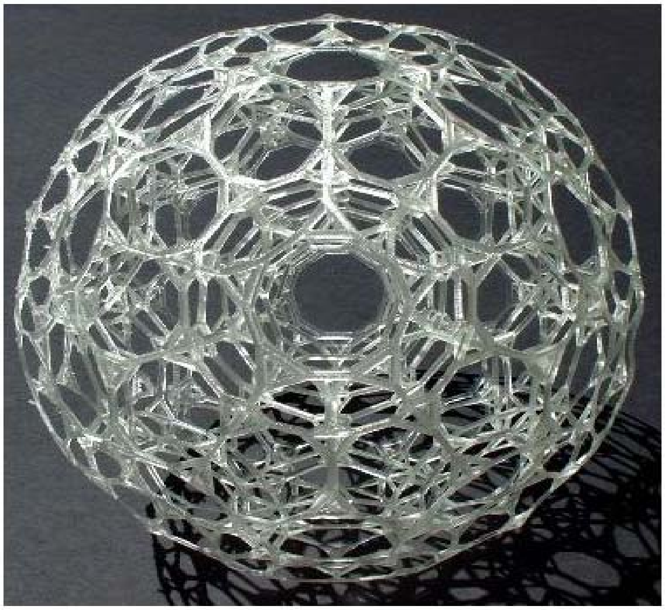


FIGURE 6: Example of very intricate pattern

FIGURE 7: Various manufactured parts produced by Rapid Prototyping.

Please note, the parts shown in Figure 7 above represent thin- and thick-walled components as well as very intricate forms required by their function. Each part was fabricated in hours—not days or even weeks by using **Stereolithography** RP&M technology.

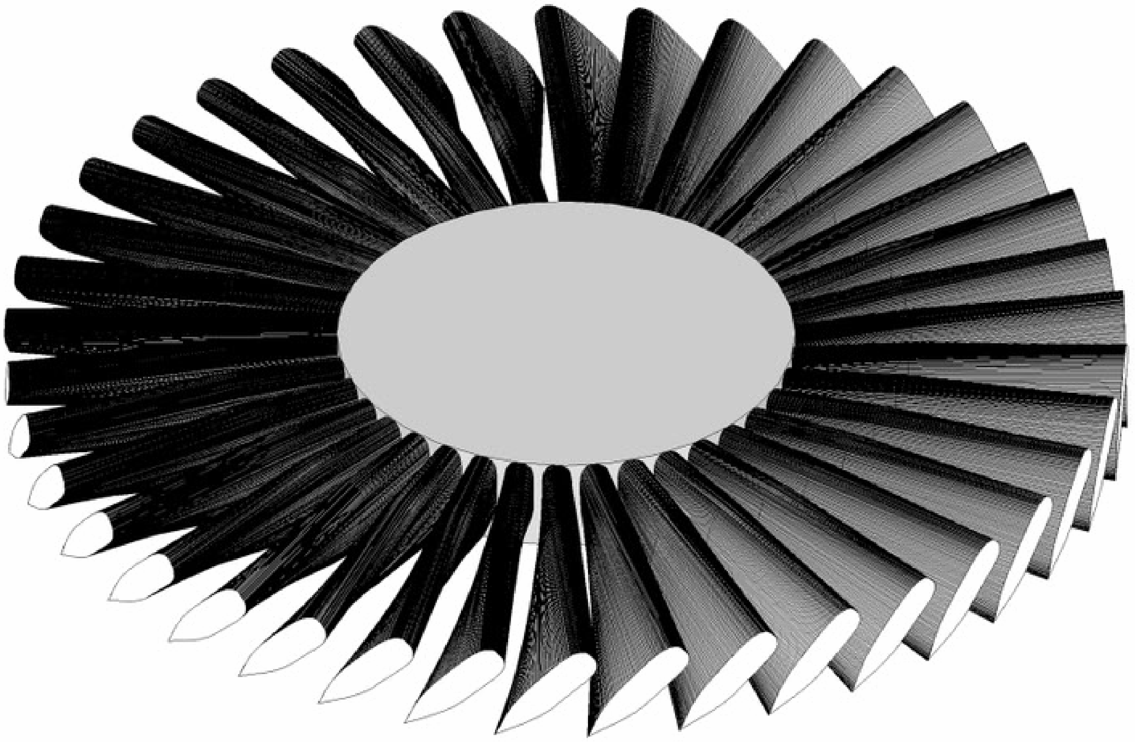


FIGURE 8: Turbine Rotor Blades

The turbine rotor above demonstrates the possibilities and underscores the fact that hours of engineering development time can possibly be saved by having initial models from which to study and apply. The iterative process of design-test-redesign, etc can be greatly reduced and options explored simply by having models available "up front".

This next one might seem a bit "far out" but the entertainment industry is much more frequently using RP&M technology to develop "character concepts" for video games. The next JPEG will show one such endeavor. This industry has been creating 3D virtual models for some time, but now there is a demand from people who want to build custom characters from their new generation video games. Many of the models are not of high resolution or fully closed volumes as required by additive fabrication, but that seems to be an insignificant issue. **Figure Prints, Inc.,** the brainchild of a former Microsoft vice president who ran its video game business, is about taking a character from World of Warcraft (one of the most popular video games in the world) and building a personalized character. The company uses color machines from Z Corp to "pull your character from the virtual world and bring it to life." As people play with their characters, they become personalized and actually enhance the video experience. Each figure is unique. Please note: after the character is modeled, a finishing process occurs that sands and smoothes the figure. Then hand-painting completes the process.

FIGURE 9: Figure from World of Warcraft

Figure 10 below is an LOM of an automobile exhaust header. As mentioned earlier, the automotive industry “hopped on board” very quickly when presented with the possibly of adopting RP&M technology. It gave them a physical part to hold while contemplating redesign or the approval of a modeled part. The Chrysler Corporation was a significant contributor to early efforts to develop stereolithography (SLA) technology.

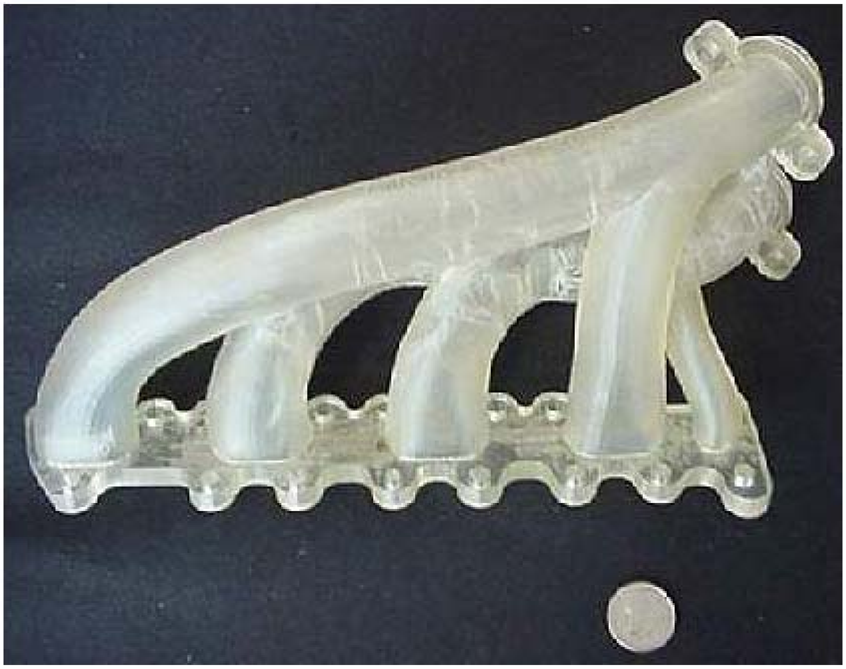


FIGURE 10: Header Assembly for Automotive Industry

FIGURE 11: The young lady in the figure below is holding an automobile bumper produced by stereolithography. We might mention that the part is to prove "form and fit" and not necessarily function. The material of choice would not withstand the forces necessary to pass the Federal regulations and guidelines but vital information is available with the model.

One last example that will demonstrate that the possibilities for prototyping are fairly limitless, depending only upon your imagination and willingness to do a minimal amount of exploration. The component in Figure 12 will show the diversity of possibilities.

FIGURE 12: Automotive Clamping Device

As you can see from the examples above, there is an ever –increasing number of applications for rapid prototyping. Let us now explore additional benefits of the methodology.

BENEFITS OF RP&M:

We have just looked at figures demonstrating the possibilities for RP&M, so let us now highlight the numerous benefits of the technology itself. These are as follows:

- To this author, the very first benefit results from the fact that the designers and engineers can actually hold examples of their concepts for early visualization, verification, iteration and optimization.
- The models can serve as an extremely valuable communication tool for simultaneous engineering. Manufacturing engineers, quality control specialists, jig and fixture designers, production specialists, marketing and sales managers, field repair technicians and last but not least, design engineers all can “take a look” prior to hard tools and dies being produced.
- Form, fit and function can be evaluated noting compliance with the original design intent.
- The prototype parts can serve as test samples for marketing studies to verify that the parts meet consumer demands and requirements.
- RP&M parts can help with production planning to determine the need for tools, jigs and fixtures.

- Material handling equipment such as conveyors, robotic devices, transfer devices, RFID systems, bar code systems, etc may be factored into early planning phases of the program by virtue of having parts to use when contemplating work cell layouts.
- RP&M complements bid packages for tooling quotations.
- Parts can be very useful in aiding efforts to design suitable packaging.
- Parts made with QuickCast, laminated object manufacturing (LOM), selective laser sintering (SLS), and fused deposition modeling (FDM) technologies can be used for functional testing.
- Depending upon the method of RP&M used, the parts can be used to fabricate core and cavity tooling pairs for functional parts. The resulting tooling can then be used to injection mold parts.
- There is a significant reduction in the time needed to produce a "first prototype". Using customary methods, the time from "board" to part could take as long as weeks, whereas most parts from RP&M methodologies is less than 72 hours of actual fabrication time. Now let's remember that this time for fabrication does not include the time necessary to model the design. The CAD process must occur first, but I think this would be the case for a part made by traditional methods.
- RP&M allows the engineer or designer time to make any necessary modifications to the part or even the part concept(s). This can be valuable time when conceptual issues may surface. Design optimization can result from having parts very early in the design cycle.
- To extend product life by adding necessary features and eliminating redundant features early in the design.
- Allowing for increased product complexity. As a result of having a prototype, redesign may occur allowing for combining two or more components, thereby reducing the overall number of components required for an assembly or subassembly.
- Reducing "time to market" thus, reducing the overall project costs and improving the launch date for a specific product.
- Significant reductions in program costs may occur as a result of being able to take the best design into production and eliminate needed redesigns.
- Beating the competition to market.
- RP&M can provide quick models with highly detailed and smooth surface finishes.
- RP&M can provide extremely small dimensional part tolerances when needed, thus meeting deign intent.
- Suppliers given a form, fit and function model can provide more accurate mold quotes and recommend any modifications for final tooling. From this information, a manufacturing plan and cost model can be developed far earlier in the design cycle.

NOW THE DOWNSIDE:

There are also very real obstacles to using RP&M but those, once understood, can be overcome with planning and organization. Most companies and institutions requiring prototypes go "outside" and contract those services, especially when considering rapid prototyping as an option. Very few will buy the equipment for installation into their facilities unless there is a significant return on that investment.

In any event, the considerations below represent very real concerns when using the equipment, whether you contract parts or fabricate parts yourself.

- RP&M is a very precise technology requiring adequate training for practitioners using the equipment. This training is very detailed and specific to a particular process and involves considerable "book knowledge" and time with the process itself. The right person must be selected for training, and that person should have an appreciation for detail, quality and accuracy.
- Materials in use at this time are continuously being adapted and developed to provide the mechanical, thermal and electrical properties required for the function of the model. Not every model produced will have ALL the proper characteristics needed for a fully-functioning part.
- Photopolymer shrinkage and SLA part accuracy can be a problem if not compensated for in the software and the model build. The processes are capable of generating parts with excellent dimensional accuracy; otherwise the parts would be useless, but known shrinkage values must be compensated for.
- Curl distortion is also a factor and must be considered with the modeling and merge programs.
- Green-creep distortion is known to occur during the post- cure process. Again, compensation is possible but must be recognized as a result of the process. The degree of green-creep distortion is dependent upon the material used during the build cycle.
- Green-creep distortion can produce parts that are less than flat or exceed part flatness specifications. Again, compensation can be made by virtue of program modification.
- Some epoxy photopolymers tend to be mildly hydroscopic, and if liquid resin is left in contact with water or a high-humidity atmosphere it will absorb a finite amount of water. This could bring about slight dimensional changes to the part.
- The first step in the process is to provide a 3-D model of the component to be modeled. Two-dimensional (orthogonal) drawings are <u>**not sufficient**</u> to fully define the part and can not be used to produce a part. If your company does not have CAD equipment and software to provide an adequate solid model, you will need to find an outside company that can.
- Right now, there is a limit to the physical size of a component that can be produced. As bigger and bigger machines are developed and the processes refined, these limits will be lessened.
- Even though the modeling process is time saving and considerably less expensive than traditional methods, it does cost money. The equipment and training necessary to provide a part that meets the intent of the solid model is not free. The following figures will indicate the complexity of the RP&M equipment "in play" at this time. As you can see from figures 10, 11 and 12, for a vendor, the cost of equipment is no small expenditure. That cost must provide a return on investment, which is derived from the customer base attracted through advertising.

PHYSICAL EQUIPMENT:

I will now like to give you some "feel" for the physical equipment, particularly the size of the equipment necessary for the processes we have been discussing. As we have mentioned, the very first step is to produce a solid model of the component to be fabricated. This is obviously accomplished through the use of a computer and CAD methods.

FIGURE 13: CRT showing a 3-D model required prior to prototyping.

This is the screen of a component that has been detailed by using software capable of producing a 3-dimensional parametric model. This step is the starting point for the RP&M process, regardless of which method of prototyping is used or what material is deemed proper for the part in question. **Two-dimensional drawings are not sufficient for this methodology.** We will discuss the software available to fulfill that need later on in our course. If CAE and CAD are not available at your facility, contract services are definitely available and a phone calls away.

Figures 13, 14 and 15 below show photographs of equipment and associated consoles needed to produce various components. The physical size can be significant with considerable floor space necessary. The 3-D printer, Figure 15, is a “desk-top” device but is limited to producing components of considerably smaller size. Obviously, as the size of the machine increases, so does the cost of purchase and the cost for installation. The auto bumper shown by Figure 11 required one of the largest “machines” available on the market today. Worth it—yes—but expensive.

FIGURE 14: Console necessary for rapid prototyping using stereolighography method.

FIGURE 15: A second version of equipment necessary for producing a component by stereolithography.

FIGURE 16: 3-D Printer—Bench Model

As with most "emerging" technologies, the path is evolutionary and not revolutionary. Rome was not built in a day, and the process of rapid prototyping did not occur overnight. A great deal of effort has been expended to bring the technology to the present state of the art. We will take a very brief look at how it all started.

HISTORY OF RAPID PROTOTYPING

In the late 1960s, Herbert Voelcker, a professor of engineering at the University of Rochester, now Cornell University, decided to take a sabbatical; the purpose being to contemplate how to go about doing interesting things with the automatic computer-controlled machine tools that were beginning to appear on factory floors. In particular, Voelcker wanted to find ways to take output from a computer design program and use that output to program automatic machine tools. This approach appeared to professor Voelcker as being a logical "marriage" of two emerging technologies.

With funding from the National Science Foundation (NSF), Voelcker approached the problem first by developing the basic mathematical model needed to unambiguously describe three-dimensional parts. The result was the early mathematical theory and algorithms of solid modeling. Today this model forms the basis for computer programs used to design almost everything mechanical, from toy cars to skyscrapers. During the 1970s, Voelcker's work transformed the way products were designed. One big problem remained, for the most part; they were still made the same old way. That is, either a machinist or a computer-controlled machine tool would cut away a "hunk" of metal until what remained was the required part, the same as Michelangelo removed chips of marble from a block of granite until all that remained was the statue of David. Then, a gentleman named Carl Deckard came up with a much better idea. Instead of making a part by cutting away material, why not build the part layer by layer? Deckard imagined "printing" three-dimensional models by using laser light to fuse metallic powder, or other materials, into solid prototypes, one layer at a time. Deckard took his idea to the NSF, which awarded him a $50,000 Small Grant for Exploratory Research (SGER) to pursue what he called selective laser sintering. Deckard's initial results were promising, and in the late 1980s his team was awarded one of the NSF's first Strategic Manufacturing Initiative grants. As a result of Voelcker and Deckard's work, an entirely new field of engineering and manufacturing was created.

In the late 1970s and early 1980s, A. Hebert of 3M in Minneapolis, H. Kodama of the Nagoya Prefecture Research Institute in Japan, and C. Hull of UVP (Ultra Violet Products, Inc.) in California worked independently on rapid prototyping concepts based on selectively curing a surface layer of photopolymer and building three-dimensional objects with successive layers. A revolutionary method of fabrication, but one who's time had come. It seemed to these three gentlemen a logical approach for prototyping and the production of individual parts and components.

Both Herbert and Kodama had difficulty maintaining ongoing support from their research organizations, and they each stopped work before entering the commercial or product phase. UVP continued to support Hull, and he worked through numerous problems of implementing photopolymer part building until he developed a complete system that could automatically build detailed parts. Hull coined the term StereoLithography, or three-dimensional printing. This system was patented in 1986, at which time Hull and R. Freed, jointly with stockholders from UVP, founded 3D Systems, Inc to develop commercial applications in three-dimensional printing.

America's venture capitalists were wary about this new idea of combining computers, lasers, chemicals, and the possibilities of better methods to design products, but the technology was too powerful to be denied. During a period of rushed innovation from the late 1986 through late 1987, many of today's rapid prototyping concepts were developed. The roles of hatching, up-facing and down-facing skins and near flat skins were defined. There were difficulties, but with any new promising technology, over time, those difficulties were satisfactorily resolved and considerable progress was made. One such issue was part distortion. Many modes of part distortion were identified and methods to control these distortions developed. Post processing was recognized as being often required and these requirements were identified, quantified and established. A reliable and workable precision imaging system was designed, including geometric calibration and drift correction. Computer graphic slicing software was written, and user interfaces to guide the processes were designed, completed and installed. All of these areas have been addressed over time, producing remarkable results relative to the parts themselves.

The SLA-1, the first commercial rapid prototyping product, was designed at 3D Systems throughout this period. It was publicly introduced at the AUTOFACT Show in Detroit in November, 1987. The SLA-1 Beta program included AMP, General Motors (CPC and Fisher Guide), Baxter Health Care, Eastman Kodak and Pratt & Whitney (commercial and military). The year 1988 produced swift expansion of the technology and significant growth for rapid prototyping. Many more large companies joined the ranks of early SL users contributing towards accumulating knowledge for rapid prototyping applications. A

Stereolithography Users Group was formed by the SL users themselves so that these companies could formally share information and provide a uniform voice to 3D Systems for future product direction.

In addition, several "service bureau" companies were founded and began providing engineering and rapid prototyping services to the general manufacturing community. 3D Systems went into partnership with Ciba-Geigy, Ltd of Switzerland and began a program of advanced photopolymer resin development. SL became available in Europe and Japan, reflecting the international nature of today's industrial environment.

The SLA-250, similar to the SLA-1 but with an upgraded resin recoating system, was announced in 1989. In 1992, the SLA-250 became, by far, the most widely used Rapid Prototyping and Manufacturing (RP&M) system in the world. The SLA-500, a larger and much faster machine, became available in 1990. The SLA-500 is about eight times greater than the SLA-250 and can provide much larger prototypes.

COMPARISON OF PROCESSES:

Before we actually get into the descriptive information for each process, I will provide several very basic definitions. Table 1 will give a brief comparison of mechanical properties with basic descriptive information. Please keep in mind that this technology is rapidly advancing, so the very best information is the timeliest information. That comes from vendors providing services to clients. Each process is mindful of the need to meet the mechanical specifications for the part. We will definitely provide specifics on the mechanics of each process, but first I will highlight and define the individual methodologies as follows:

STEREOLIGHOGRAPHY(SLA)--Stereolithography (SLA) was the first commercialized fabrication process, producing parts from **photo-sensitive polymer resins**. It operates by scanning the liquid surface of a bath of the resin with an **ultraviolet (UV)** laser beam that causes the resin to cure in the shape of a layer of the part. The lowest layer is carried on an elevator platform that is lowered by the slice thickness after each new layer is formed at the surface. The layers combine to form the desired 3D shape of the part. The SLA process can fabricate plastic molds for pattern making or blocks for metal sheet forming, as well as produce a wide range of polymer prototypes.

SELECTIVE LASER SINTERING(SLS)-- Selective Laser Sintering (SLS) is another process, with a wider range of material than SLA. SLS can produce highly complex parts from materials such as metal, plastic, ceramic, and sand. The material in **powdered form** is deposited on a platform, and a carbon dioxide (CO_2) laser is used to selectively melt or sinter powder into the desired shape for each layer. The layers are lowered on a platform, with loose powder around the growing structure acting as a support for the top powder layer. The strength and porosity of the material can be controlled by adjusting various process parameters, such as laser scanning speed and power. Products have ranged from turbine rotors to medical inserts.

SHAPE DEPOSITION MANUFACTURING(SDM)-- Shape Deposition Manufacturing (SDM) is another layer manufacturing process that combines the techniques of deposition and CNC machining. Each layer is machined after it is deposited, and support material is added and machined to receive subsequent layers. The incremental machining allows a smooth surface to be achieved, even with thick layers, and the use of support material allows layers with overhanging, undercut, and separated features to be supported during the fabrication. The support material is removed at the end by melting or dissolving, and final machining is not usually required. **SDM is a good choice for custom tooling, precision assemblies, structural ceramics, and wax molds for casting.** It allows a high quality surface finish, intricate undercut features, and multi-material structures with inserts.

LAMINATED OBJECT MANUFACTURING(LOM)-- The Laminated Object Manufacturing (LOM) process was developed by Helisys of Torrance, CA. It produces parts from a sheet material bonded together in layers to form a laminated structure. The original material used for the layers was paper, but several other sheet materials are now available, including plastic, water repellant paper, and ceramic and metal powder tapes. **The process has been used to make casting dies for automotive parts.**

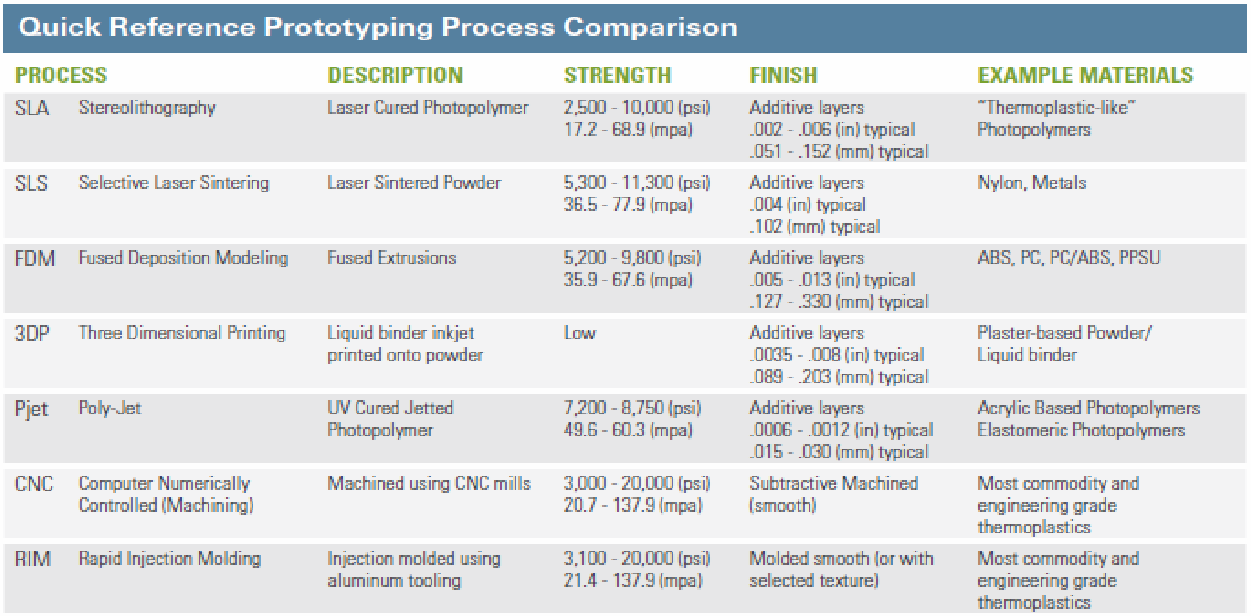
3-D PRINTING--The 3D Printing process is based on ink-jet printing technology. A group of print heads moves across a powdered material in a scanning pattern, distributing a liquid binder to bond the material in the shape of each layer. The part is lowered, additional powder is added, and the process is repeated. At the end, the part is removed from the powder bed and cleaned. The field of potential application ranges from functional metal parts to small-series parts and mold inserts. Such mold inserts are suitable for plastic injection, metal die casting, extrusion tooling, etc.

POLYJET PRINTING:

PolyJet Technology is a new Rapid Prototyping process that provides a quick turn around for smooth, fully cured parts. The process consists only of UV bulbs and photopolymer materials.

PolyJet machines fully cure each layer of super fine UV photopolymer and support materials as eight jetting heads precisely deposit the product. Support material is easily separated from the part by either a water jet or hand and brush. No special baths or extra finishing treatments are needed.

Finished PolyJet parts can readily absorb paint and can also be machined, drilled, chrome-plated or used as molds.



Quick Reference Prototyping Process Comparison

PROCESS		DESCRIPTION	STRENGTH	FINISH	EXAMPLE MATERIALS
SLA	Stereolithography	Laser Cured Photopolymer	2,500 - 10,000 (psi) 17.2 - 68.9 (mpa)	Additive layers .002 - .006 (in) typical .051 - .152 (mm) typical	"Thermoplastic-like" Photopolymers
SLS	Selective Laser Sintering	Laser Sintered Powder	5,300 - 11,300 (psi) 36.5 - 77.9 (mpa)	Additive layers .004 (in) typical .102 (mm) typical	Nylon, Metals
FDM	Fused Deposition Modeling	Fused Extrusions	5,200 - 9,800 (psi) 35.9 - 67.6 (mpa)	Additive layers .005 - .013 (in) typical .127 - .330 (mm) typical	ABS, PC, PC/ABS, PPSU
3DP	Three Dimensional Printing	Liquid binder inkjet printed onto powder	Low	Additive layers .0035 - .008 (in) typical .089 - .203 (mm) typical	Plaster-based Powder/ Liquid binder
Pjet	Poly-Jet	UV Cured Jetted Photopolymer	7,200 - 8,750 (psi) 49.6 - 60.3 (mpa)	Additive layers .0006 - .0012 (in) typical .015 - .030 (mm) typical	Acrylic Based Photopolymers Elastomeric Photopolymers
CNC	Computer Numerically Controlled (Machining)	Machined using CNC mills	3,000 - 20,000 (psi) 20.7 - 137.9 (mpa)	Subtractive Machined (smooth)	Most commodity and engineering grade thermoplastics
RIM	Rapid Injection Molding	Injection molded using aluminum tooling	3,100 - 20,000 (psi) 21.4 - 137.9 (mpa)	Molded smooth (or with selected texture)	Most commodity and engineering grade thermoplastics

TABLE 1: Comparison of RP&M processes

PROCESSES:

We will now explore the actual mechanical and electrical operation of each process. Stereolithography is by far the oldest and most-used process, so with that being the case, we will consider that method first and spend most of our time looking at the mechanics. All of the other processes are "off-shoots" of that basic "additative" process. As you might suspect, each methodology has its specific design. The mechanical components and associated assembly of those components is very unique—functional but unique. All depend upon solid modeling, laser operation and represent additive manufacturing.

STEREOLITHOGRAPHY:

Stereolithography was the first process developed; consequently, the oldest process. In the world today, over ninety percent of the machines sold represent this RP&M technology. Figure 16 below gives a very basic schematic look at the physical elements required to produce a model using this method.

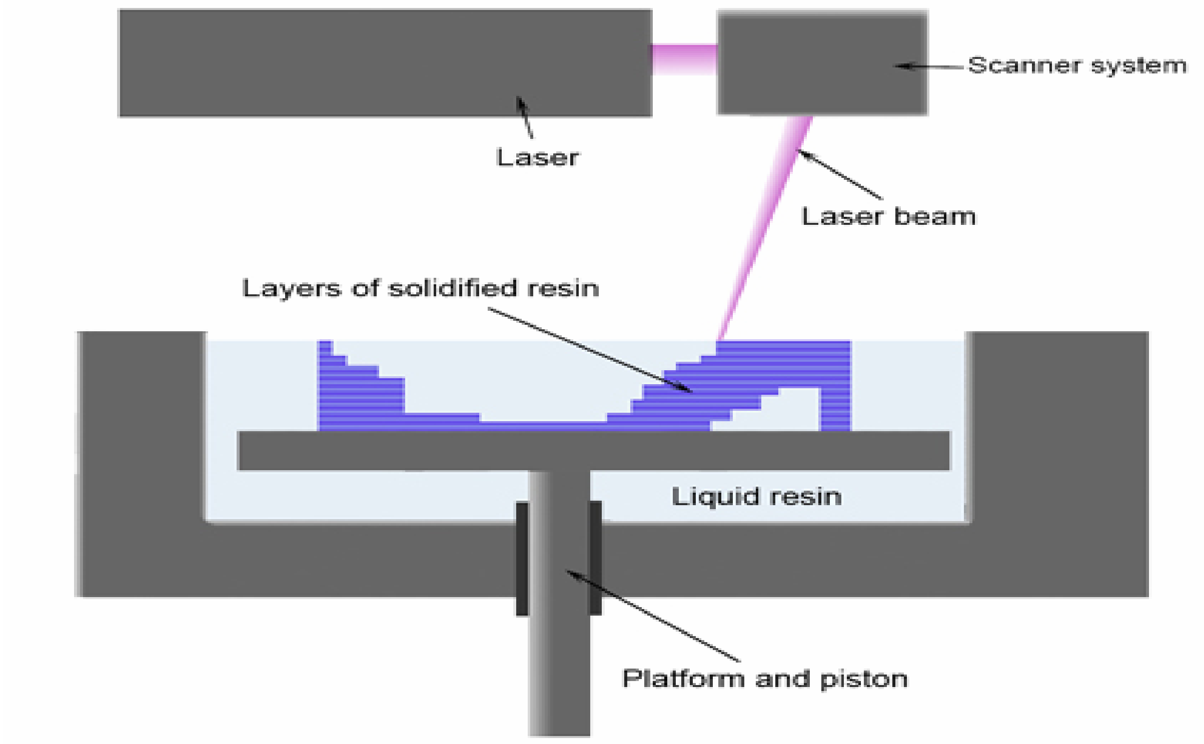
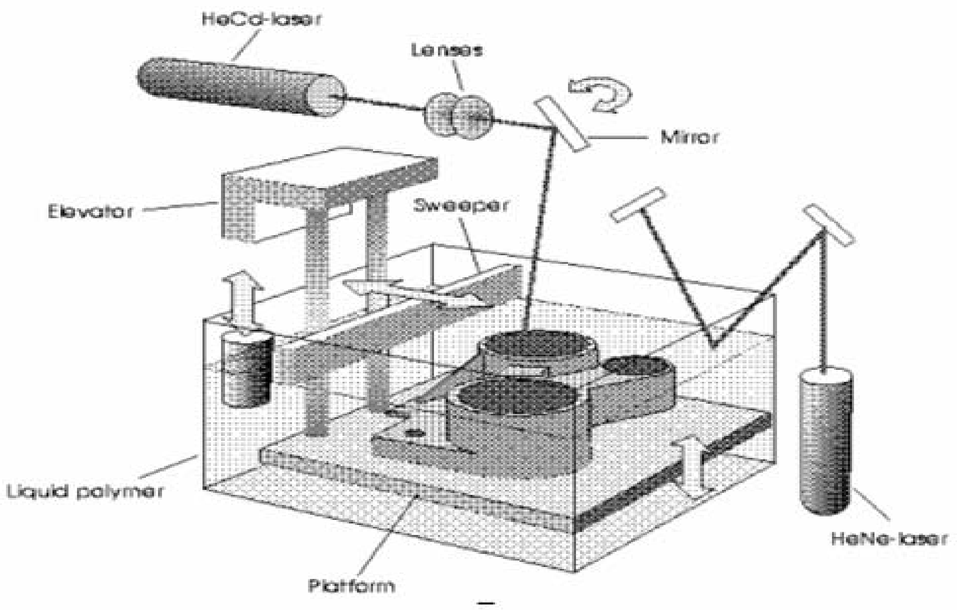


FIGURE 17: Stereolithography Mechanical Arrangement

Another more structured look may be seen below with Figure 18.



The technique builds three-dimensional models from liquid photosensitive polymers that solidify when exposed to ultraviolet light. As shown in the figures above, 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. Next, an elevator incrementally lowers the platform into the liquid polymer. A sweeper **re-coats** the solidified layer with liquid, and then 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 resin. Supports are broken off and the model is then placed in an ultraviolet oven for complete curing.

Figure 19 below will show a typical platform design used with SLA and other RP&M methodologies.

LAMINATED OBJECT MANUFACTURING:

In this technique, developed by Helisys of Torrance, CA, layers of adhesive-coated sheet material are bonded together to form a prototype. The original material consists of paper laminated with heat-activated glue and rolled up on spools. As shown in the figure below, a feeder/collector mechanism advances the sheet over the build platform, where a base has been constructed from paper and double-sided foam tape. Next, a heated roller applies pressure to bond the paper to the base. A focused laser cuts the outline of the first layer into the paper and then cross-hatches the excess area (the negative space in the prototype). Cross-hatching breaks up the extra material, making it easier to remove during post-processing. During the build, the excess material provides excellent support for overhangs and thin-walled sections. After the first layer is cut, the platform lowers out of the way and fresh material is advanced. The platform rises slightly below the previous height, the roller bonds the second layer to the first, and the laser cuts the second layer. This process is repeated as needed to build the part, which will have a wood-like texture. Because the models are made of paper, they must be sealed and finished with paint or varnish to prevent moisture damage.

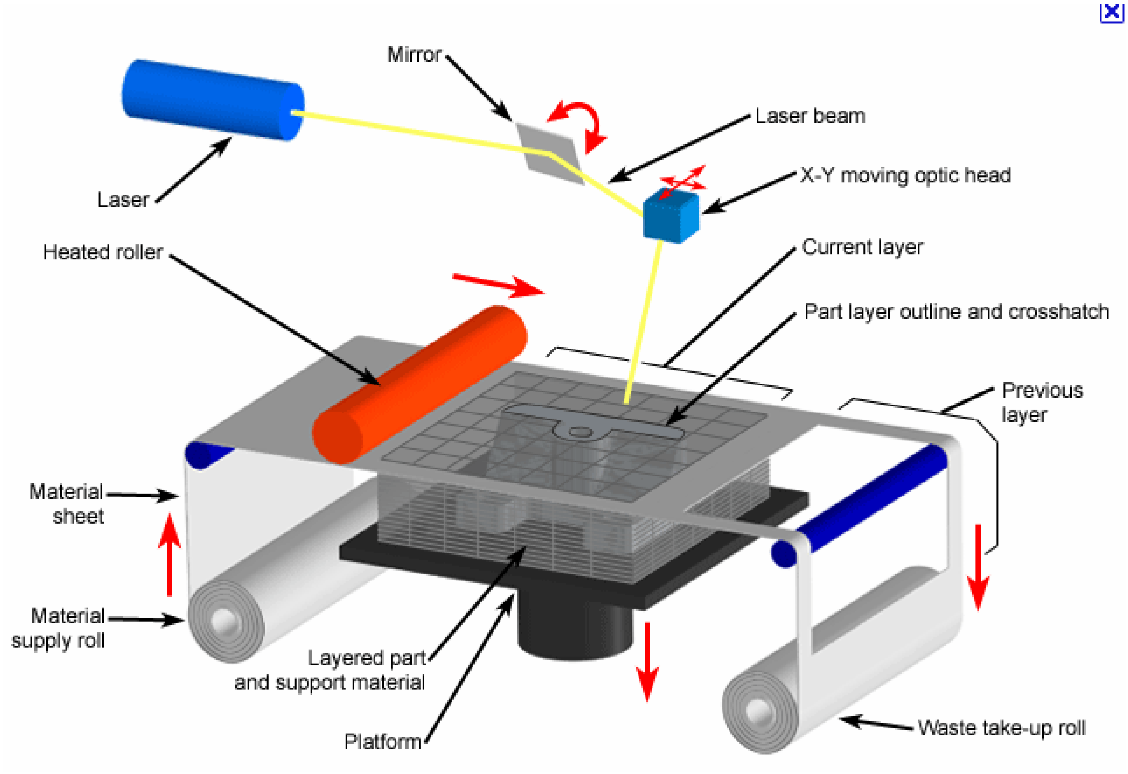


FIGURE 20: Laminated Object Manufacturing

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 uses a laser beam to selectively fuse powdered materials, such as nylon, elastomeric materials, and metal, into a solid object. Parts are built upon a platform which sits just below the surface in a bin of the heat-fusible 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.

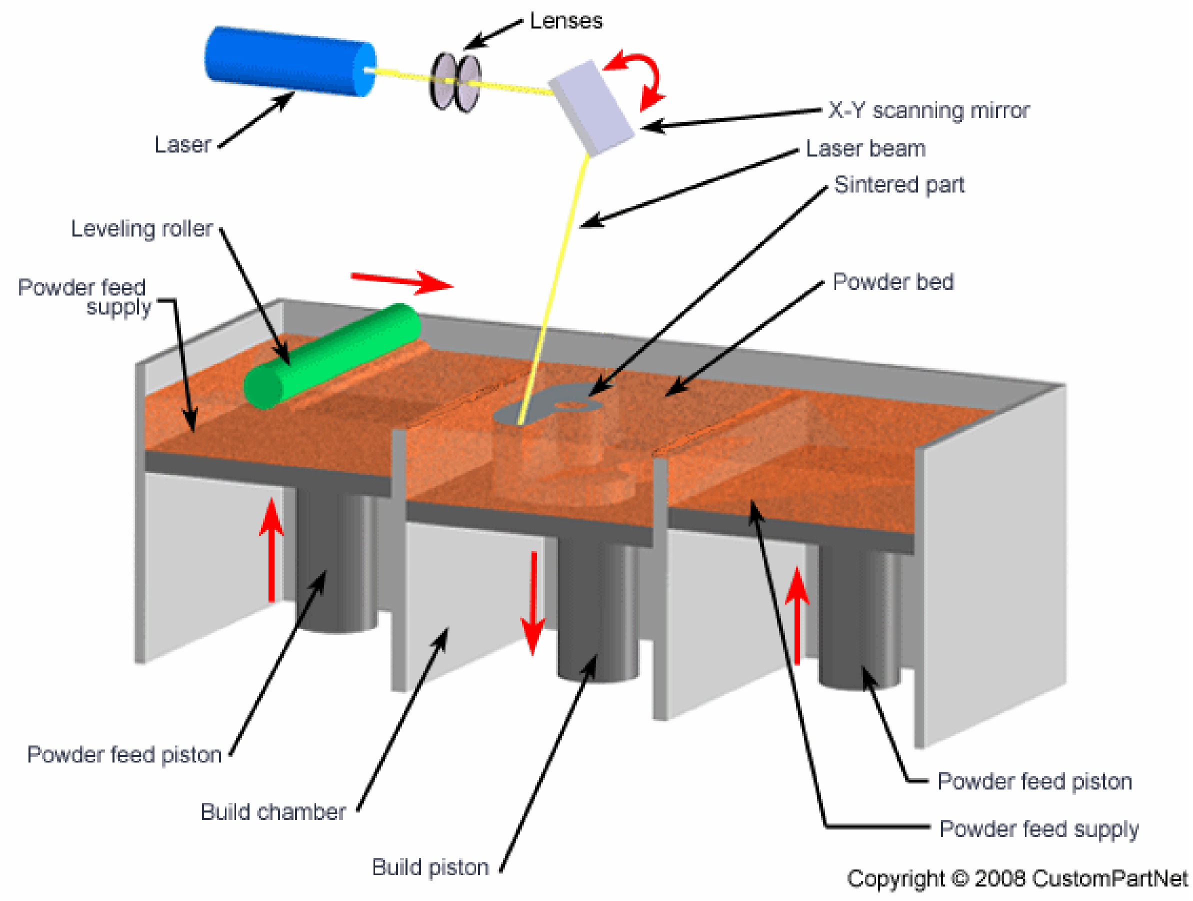


FIGURE 21: Selective Laser Sintering

FUSED DEPOSITION MODELING:

In this technique, filaments of heated thermoplastic are extruded from a tip that moves in the x-y plane. Like a baker decorating a cake, the controlled extrusion head deposits very thin beads of material onto the build platform to form the first layer. The platform is maintained at a lower temperature, so that the thermoplastic quickly hardens. After the platform lowers, the extrusion head deposits a second layer upon the first. Supports are built along the way, fastened to the part either with a second, weaker material or with a perforated junction.

Stratasys, of Eden Prairie, MN makes a variety of FDM machines ranging from fast concept modelers to slower, high-precision machines. Materials include ABS (standard and medical grade), elastomeric materials (96 durometer), polycarbonate, polyphenolsulfone, and investment casting wax.

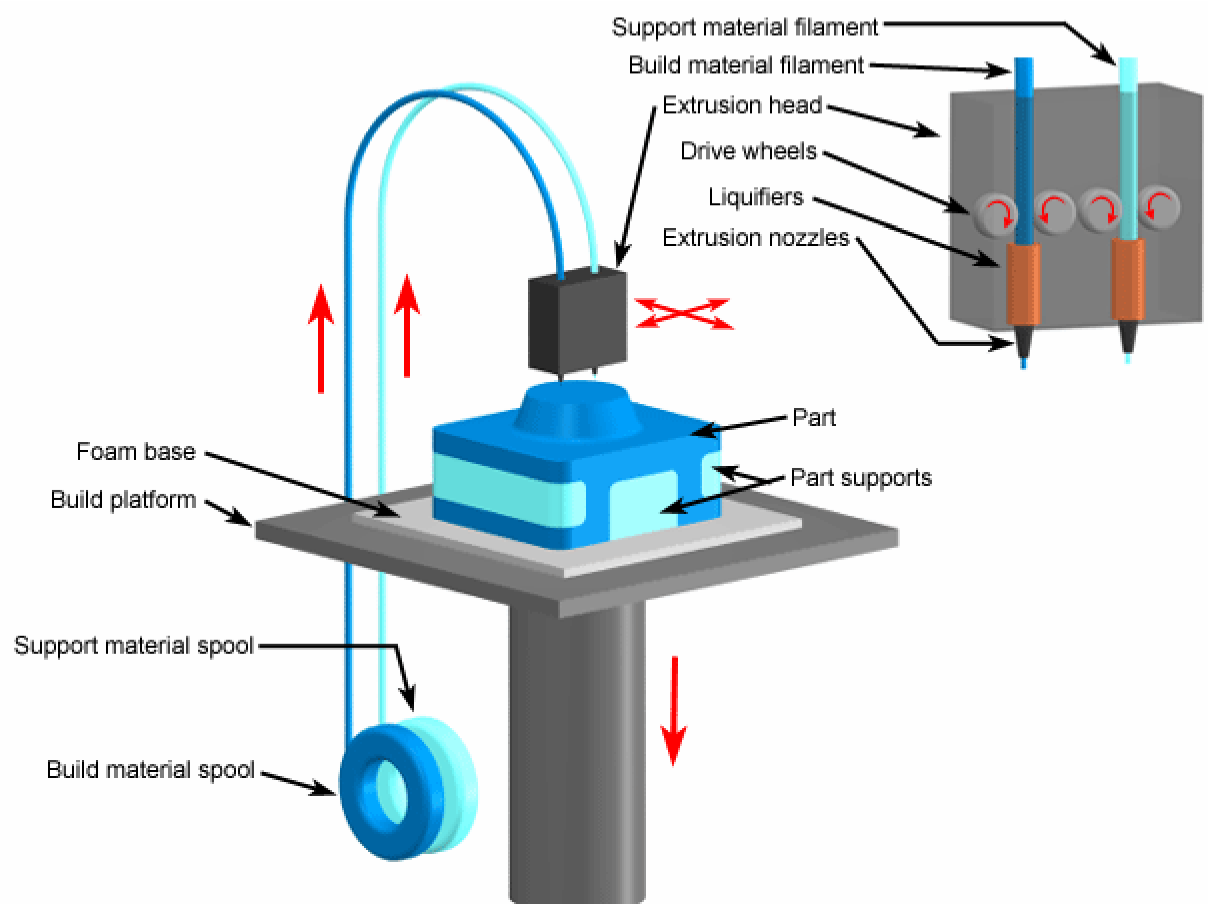


FIGURE 22: Fused Deposition Manufacturing

THREE DIMENSIONAL PRINTING:

Ink-Jet Printing, or 3-D 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. The ZCorp 3D printer, produced by Z Corporation of Burlington, MA (www.zcorp.com) is an example of this technology. As shown in Figures 21 and 22, parts are built upon a platform situated in a bin full of powder material. An ink-jet printing head selectively deposits or "prints" a binder fluid 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 is then removed from the unbound powder, and excess unbound powder is blown off. Finished parts can be infiltrated with wax, CA glue, or other sealants to improve durability and surface finish. Typical layer thicknesses are on the order of 0.1 mm. This process is very fast, and produces parts with a slightly grainy surface. ZCorp uses two different materials, a starch based powder (not as strong, but can be burned out, for investment casting applications) and a ceramic powder. Machines with 4 color printing capability are available.

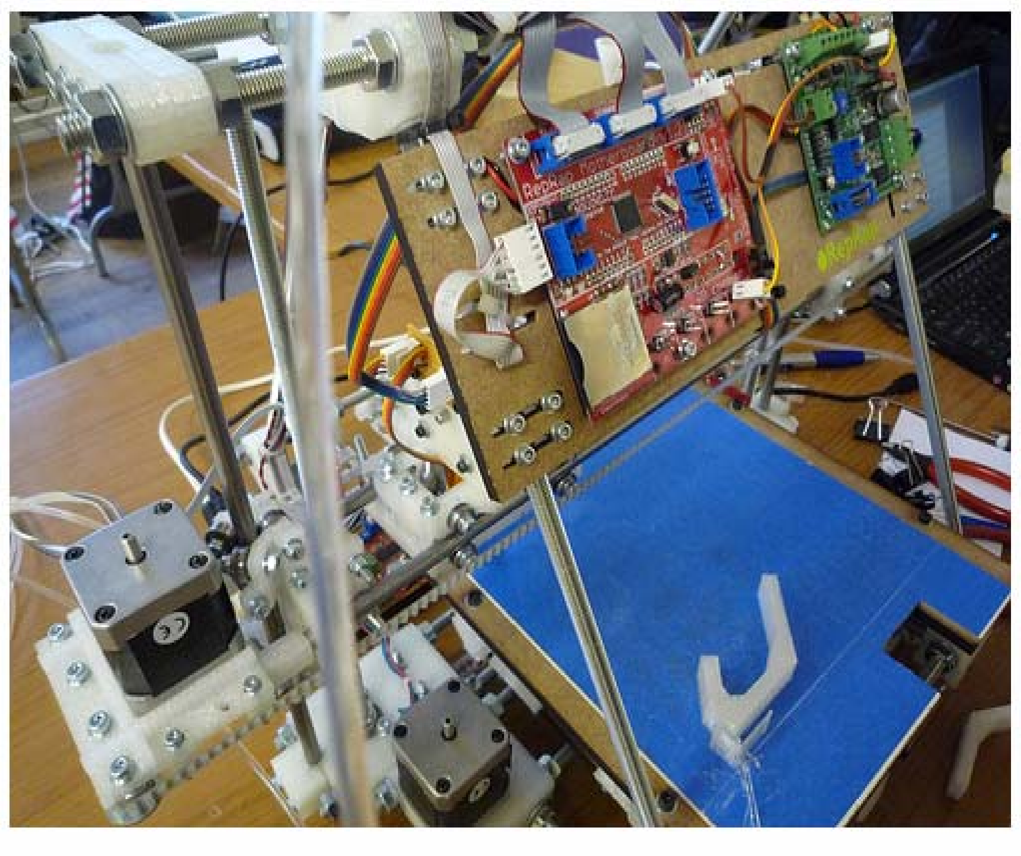


FIGURE 23: Three Dimensional Printing

3D printing is a form of additive manufacturing technology where a three dimensional object is created by laying down successive layers of material. 3-D printers are generally faster, more affordable and easier to use than other additive manufacturing technologies. 3D printers offer product developers the ability to print parts and assemblies made of several materials with different mechanical and physical properties in a single build process. Advanced 3D printing technologies yield models that closely emulate the look, feel and functionality of product prototypes.

A 3D printer works by taking a 3D computer file, using and making a series of cross-sectional slices. Each slice is then printed one on top of the other to create the 3D object. Since 2003 there has been large growth in the sale of 3D printers. Additionally, the cost of 3D printers has declined. The technology also is used in the jewelery, footwear, industrial design, architecture, engineering, construction (AEC), automotive, aerospace, dental and medical industries.

POLYJET PRINTING:

Objet's patented PolyJet inkjet technology works by jetting state of the art photopolymer materials in ultra-thin layers (16µ) onto a build tray, layer by layer, until the part is completed. The intuitive Objet studio™ software manages the process. Each photopolymer layer is cured by UV light immediately after it is jetted, producing fully -cured models that can be handled and used immediately, without post-curing. The gel-like support material, which is specially designed to support complicated geometries, is easily removed by hand and water jetting.

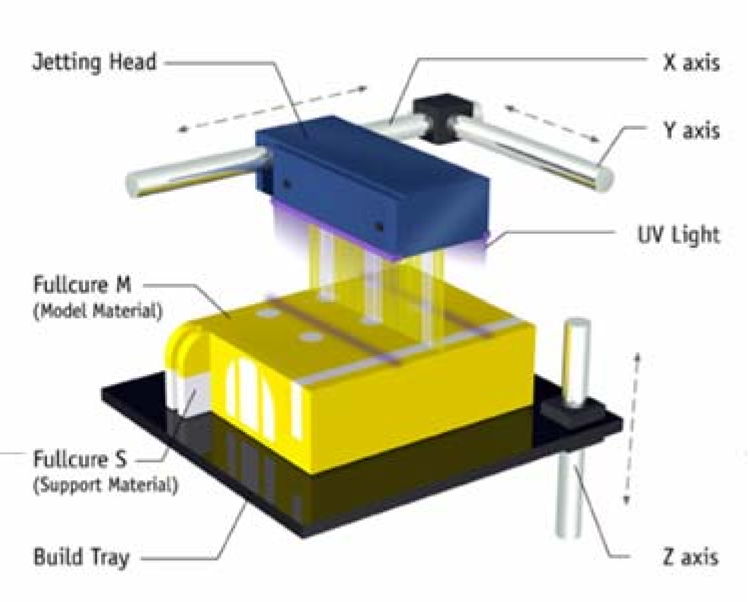


FIGURE 24: PolyJet Printing

CHEMISTRY AND SELECTED MATERIALS:

Improvements in the physical properties of materials used in RP&M technology have been instrumental in expanding the number and variety of new applications. These materials have allowed applications requiring very precise dimensional accuracy along with considerable improvement in mechanical properties. Of course these improvements are sought to fulfill very specific needs. New standards are required when "designing" materials to be used for RP&M. Individuals and companies within the industry are certainly contributing to the fast and continuous work, with clients, to improve the usefulness of materials available for a given methodology; i.e. SLA, LOM, 3-D Printing, etc. Most of these great improvements are "client driven". There is, or can be, a significant difference between the characteristics of a material chosen for RP&M vs. one chosen for a conventional process. When selecting a plastic to be used for an injection molding process, we look at injection conditions such as pressure, temperature and releasiblilty from the mold, etc. These characteristics do not apply when considering RP&M methodologies. **Each RP&M material has an inherent dimensional accuracy dependent upon the chemical or physical transformation associated with generating and adhering to the build layers.** RP&M accuracy depends greatly on the material. It is imperative that current and future users of this technology fully inspect the dimensional accuracy and mechanical properties actually achieved by the materials chosen in addition to the mechanical specifications and compare these with the required property specifications for their needs. Very, very important!

[1] **UV CURABLE PHOTOPOLYMERS:**

The first UV curable photopolymers were developed initially during the late 1960s as a way to reduce air pollution from solvent-based coatings. The chemistry was based upon acrylates, a class of chemistry known to undergo rapid photopolymerization when exposed to appropriate actinic radiation in the presence of free-radical photoinitiators. Today, acrylates continue to be the most popular and most widely used class of photopolymerization resin system in the UV coating and printing industry. Many types of acrylate monomers are commercially available.

Today most RP&M processes utilize lasers that emit light in the UV band although the use of lasers emitting at other wavelengths is not that unusual and certainly cannot be ruled out. It all depends upon the material and the mechanical system used. The ability to undergo photopolymerization by exposure to UV radiation is simply a prerequisite for current RP&M photopolymers. The laser wavelengths used for stereolithography (SLA) are 325 nm, generated from a helium-cadmium (HeCd) laser, or 351 and 364 nm, emitted by an argon ion laser. The latter system operates in either monochromatic or dual wavelength mode. This is quite different from the radiation sources employed in the conventional photocurable coating industry, which are typically UV lamps with a wide distribution of actinie output wavelengths ranging from 200 to 400 nm, as well as some wavelengths in the visible and IR bands. Relative to photocurable chemistry, the RP&M industry is one of the most exciting applications for material science. In the UV curable coating and printing industry, where the majority of commercial photopolymers are used, the applications are limited to the geometrical properties manipulation of essentially two dimensions. Consequently, the relevant physical properties of films and coatings are essentially limited to surface properties such as adhesion, wetting characteristics and scratch resistance. Now comes RP&M technology. With the advent of this exciting field, materials must respond to the need for growth of layer upon layer of the photopolymer. A huge difference relative to coating and printing. The product here is a three-dimensional model and not just a two-dimensional layer of paint. The object height is limited solely by the system-build envelope. These parts may be inches to tens of inches tall, generated by thousands of layers using the RP&M technology. The third dimension allows one to test the mechanical properties of the cured photopolymer. Provided the measurements are made under the same protocol, the properties of the cured photopolymer system can now be compared directly with various engineering plastics used in the marketplace today. Measuring mechanical properties is not very new for thermoplastics or thermosets; however, these measurements are relatively new for objects generated from multiple layers.

Many properties of multi-layered cross-linked polymeric materials, especially the various distortion mechanisms, are not fully understood. The interdisciplinary nature of the field is another characteristic of RP&M photopolymer technology. Specialty areas in the fields of surface, organic, photopolymer and physical chemistry must be pulled together to decipher the dynamic mechanisms underlying photopolymer behavior. These are some of the reasons why photopolymer development, initiated only about seven years ago, is a field breaking new ground.

The "official" definition of photopolymerization is as follows:

"***Photopolymerization is the process of linking small molecules (monomers) into larger molecules (polymers) comprised of many monomer units."***

The polymers used today are classified into one of three categories; 1.) Epoxy, 2.) Vinylether, and 3.) Acrylate. The respective advantages and disadvantages associated with each class may not always be true for all photopolymer formulations. Associating performance of a material used for the RP&M process simply with the class to which it belongs is not recommended. Classification is based upon the type of chemical reaction responsible for enabling cross-linking. This means that chemical links holding the monomers together are formed by the reaction of epoxy, vinylether or acrylate functional groups.

Vinyl monomers are broadly defined as monomers containing a carbon-carbon double bond. The vinyl group may be attached to another molecular structure and may contain one or more additional vinyl groups. This grouping is call multi-functional; difunctional, trifunctional, etc. Polymerization of mult-functional monomers results in a cross-linked polymer.

Acrylate monomers represent a subset of the vinyl family with high reactivity and versatility due to the carboxylic acid group (C00H) attached to the carbon-carbon double bond. Attachment of the various chemical segments is a relatively easy transformation which has led to the great variety of acrylate functional monomers.

Vinylether monomers were introduced by Allied Signal and represent a line of stereolithographic resins based upon vinylether monomers.

This was not intended to be a chemistry course, although the chemistry of the materials used in rapid prototyping is fascinating. We now want to look at that necessary process of "curing" the polymers.

CHEMICAL PROCESS:

*Photopolymers are materials th*at change from a watery liquid state to a strong, plastic-like solid almost instantaneously when light of the proper wavelength hits them. Since most of us never run across this sort of phenomenon in our daily lives, it's easy to assume that this must be something very new. But that's not true. Each of us sees photopolymers every day without recognizing them. Coatings on paper, wood and metals are very often based on photopolymers, as are many inks, paints and adhesives. If you've ever had your teeth bonded or appliances attached to them by a dentist, you're walking around with a mouthful of them. In fact, the earliest experiments in photography nearly 200 years ago were very likely based on these chemical reactions. Photopolymers have become important ecologically in recent times because they do away with the need for using volatile solvents in many industrial processes.

Polymerization is the process of building big molecules out of small ones. You're doing it right now as your body builds proteins out of the food, gases and liquids you take in. There are numerous ways that such reactions can be started, and they generally involve the application of energy. When light is the energy source, the process is called photopolymerization.

Composition

Photopolymers are basically a soup of ingredients that work in concert to make this process happen. They may contain a number of components, but there are just three main ones:

1) Binders or Oligomers

This material consists of long, chain-like, chemically-reactive molecules that give the final solid its mechanical and other properties. Examples include acrylates, epoxies and urethanes. Most of a photopolymer consists of these binders which might typically be in the range of 50 to 80% of the total weight.

2) Monomers

Monomers are small molecules that also enter into the reaction. They're used mainly to lower the viscosity because a soup made from binders alone would be very thick and not easy to spread or otherwise handle. Some monomers are multifunctional offering more than a single chemical route to polymerization. Some examples include vinyls and shorter acrylate molecules. Monomers may typically constitute 10 to 40% of the photopolymer.

3) Photoinitiators

Photoinitiators are molecules that can be split into two or more parts by exposure to light. At least one of these parts is capable of reacting with both the monomers and binders to link them together. Photoinitiators are only sensitive to specific wavelengths of light. While there are initiators that work with visible light, most of the ones used in additive fabrication are sensitive to ultraviolet radiation. The spectrum of the light source used must overlap that for which the initiator is sensitive. Both lasers and other types of light sources such as arc lamps may be used. Photoinitiators comprise just a few percent of the photopolymer mixture.

Changing Liquids into Solids

There are two major chemical schemes that are commonly used in photopolymerization, each requiring a specialized photoinitiators. In free radical polymerization a complex ion (radical) is split off the initiator by the light radiation and that combines with a monomer or binder molecule to start the reaction. In cationic polymerization, light causes a strong acid to be released by the initiator and that in turn starts the bonding process. Most photopolymers today are based on the free radical scheme, but more advanced materials use cationic polymerization which frequently offers better final solid material properties.

During the reaction, the molecules of binder and monomer not only combine to make longer chain molecules, but they also bond from chain to chain in a cross-linking process. Both the composition of the binders and monomers used and the way in which they bond together are responsible for the properties of the final solid material.

Once the polymerization process starts, it keeps right on going because it's a chain reaction. Each time monomer or binder molecules link to form a gelling solid, they liberate other radicals or acid molecules that in turn cause additional molecules to bond - and so on. In some cases the propagation can even proceed in the dark for a short time after the light source is removed.

The chain reaction continues to propagate until radicals recombine to form non-reactive products, or the ingredients needed for the reaction are no longer available in the correct proportions, or finally by trapping reactive molecules in the hardening matrix where they can no longer move into position to combine.

Using a chain reaction in the polymerization process is highly advantageous. It means that a relatively small quantity of light radiation energy can cause a large amount of the liquid photopolymer to solidify. The net result is that the effect of the light is multiplied hundreds of times. Nevertheless, not all the material is converted. Some free monomer is always trapped in the solid matrix. This can cause the properties of the solid to change over time and is an area where improvement continues to be made. In many cases "baking" or flooding the final part or object in a box where it's subject to intense UV light will affect a more complete cure and more stable properties. This is often referred to as post-curing.

The process of changing from a liquid to a solid provides many opportunities for errors and other problems. During the transition photopolymers may undergo shrinkage resulting in dimensional inaccuracies and part distortions such as curl. However, great progress has been made both in materials and the processes themselves over the years so that now these effects have been minimized or controlled. Today most photopolymer research is aimed at widening their properties to mimic engineering plastics more closely, or to provide innovative functionality.

SELECTING AN APPROPRIATE RP MATERIAL:

How can we select an RP&M material that will adequately approximate the production plastic? The process is straightforward and consists of four steps:

Step 1: Identify the Prototyping Situation. Clearly define the requirements for one aspect of design adequacy. Developing the CAD model will provide the prototyping situation and fully define the dimensions. The stated use for the part will define the need for a functional part or simply a visual representation.

Step 2: Determine the Key Material Properties for the Prototyping Situation*.* In each situation, there will be relatively few material properties that control the performance of the material in that situation. By examining the prototyping situation closely, we can determine what material properties control the performance of the material in that situation.

Step 3: Determine How Closely We Must Approximate Those Material Properties*.* It will be impossible to match material properties exactly in every case. However, if the properties of the RP material are close enough to those of the proposed plastic, we can still draw valid conclusions. The challenge is to determine how close we must be to allow valid conclusions to be drawn. Once determined, a range of values will be specified for each key material property. Any RP material that falls within that range can then be used to build a prototype valid for adequacy tests.

Step 4: Select a Rapid Prototyping Material and Process. Now that the bounds of the range of material property values are known, we can simply search the available RP materials, determine which are within that range and select one for the prototype build.

MECHANICAL PROPERTIES:

As you might expect, the need to produce a component from the rapid prototyping process must carry the minimal physical characteristics to make the sample usable. With this being the case, we will need to look at "typical" mechanical properties of the materials themselves. We do that at this time.

It is important to discuss a few cautions in using this process.

CAUTIONS:

- For some prototyping situations and materials, there will be no RP material that can sufficiently approximate the production material. Sometimes, it will be necessary to mold parts in the production materials for design verification.
- Many components will have several functional requirements and may require two, three, or more prototyping situations to completely test for design adequacy. In some cases, multiple RP materials will be required to approximate the production plastic over the range of prototyping situations.
- Careful considerations should be given to determining approximation requirements. It may be very difficult to predict ultimate loads by impressing moderate loads to components produced by RP&M methods. It is unlikely that RP parts will ever be able to predict failure loads of production parts. If we can adequately approximate material properties, we may be able to subject an RP component to a load of 20 pounds and conclude that the production component will withstand the same load. However, we can not increase the load on the RP part to failure and use that information to predict with any confidence the failure load of the production component. Differences in failure mechanisms and material behavior in the plastic region between the RP material and the production plastic can result in very different failure loads.
- It is also unlikely that we can predict life of the production part from testing RP parts. Differences in the material types, failure modes and aging mechanisms prohibit meaningful correlations.
- Material properties may not be the only consideration in the selection of an RP process to use for a particular project. RP systems vary significantly in the accuracy and surface finish they can provide. In many cases, accuracy and surface finish play a key role in the performance of the component. In such situations, they must also be a factor in the selection of an RP process for making design verification test components.
- It is also important to realize that unlike metals, material properties in plastics can vary with section thickness, load rate and other factors. Even if the properties of an RP material adequately match those of a plastic material under standard test conditions, they may not match under the load conditions and geometries of the actual design. In critical applications, it may still be necessary to verify the design with

molded parts. In spite of these limitations, using this process to select RP materials for functional prototyping will greatly extend the value and utility provided by rapid prototyping.

TENSILE AND FLEXURAL STRENGTHS:

We actually test the tensile strength of RP&M components according to ASTM D638 methods. Tensile strength data demonstrates that the stiff, but relatively brittle acrylate resins have the highest tensile strengths with numbers between 7,200 to 11,500 PSI. The urethane acrylate-based materials have the lowest tensile strengths with values around 5,000 PSI. These values are in the same range as acrylic plastics. Flexural strength is defined as the stress measured at the fiber strain of 5% in accordance with the criteria for flexural testing designated by ASTM D790. For the greatest majority of RP&M applications, flexural strength is actually more relevant because parts are more often subjected to bending loads rather than tensile loads. Urethane acrylates have the lowest strengths, for both tensile and flexural tests. Epoxy-based resins have significantly higher flexural strengths than tensile strengths.

ELONGATON:

The elongation-to-break data is obtained from testing against ASTM D638. The value for the flexible urethane-acrylate resins is the highest. Elongation values must be obtained from reliable material vendors.

IMPACT STRENGTH:

Impact strength measurements are accomplished using the ASTM D256 standard. The samples generally are notched samples. It is found that the impact strengths of the epoxy resins are comparable to medium impact polystyrene and are slightly greater than acrylic plastic. They also have impact strengths approximately three to four time that of acrylate resins.

VENDORS:

Following is a list of several vendors for materials that are actively, and on a daily basis, providing resins to companies producing parts using RP&M methodologies. This is just a partial list but does represent an excellent starting point for an engineer seeking the best material for a specific application.

<u>Polymers for Stereolighography:</u>

Adeka Corporation

DSM Somos

Esstech, Inc

Fiebing Company, Inc.

JSR Corporation

Huntsman Corporation

Nippon Kayaku

San Nopco

SIBCO

Shikoku Kasei Industry

Spectra Group, Inc

Takemoto Yushi Kabushiki Kaisha

American Dye Source

Polymers for Fused Deposition Modeling:

Bolson Materials Corporation

Kraftmark

RPM Products

SIBCO, Inc.

Polymers for Selective Laser Sintering:

Advanced Laser Materials, LLC

Praxair Surface Technologies

SIBCO, Inc.

Polymers for Laminated Object Manufacturing:

Cubie Technologies, Inc.

SIBCO, Inc.

Miscellaneous Materials:

Ballistic Fluid Technologies, LLC

Jet-Wax Laboratories

Machinable Wax.com

Open3DP

SIBCO, Inc

xlaForm, Inc

Let me state, the best source for specifications relative to materials is the company supplying those materials and / or the company you are dealing with to provide a rapid prototype of the component itself. You are after the most up-to-date declaration of material characteristics, the material specifications and the HAZMAT data. It is available. I have provided, in the Appendix to this document, examples of specification sheets existing for several materials used in the commercial market. Specifications sheets such as these represent the documentation you will get from your material supplier. Also, given below is a "cookbook" showing the type of information available to you. From this type of information, decisions can be made relative to materials for a specific use.

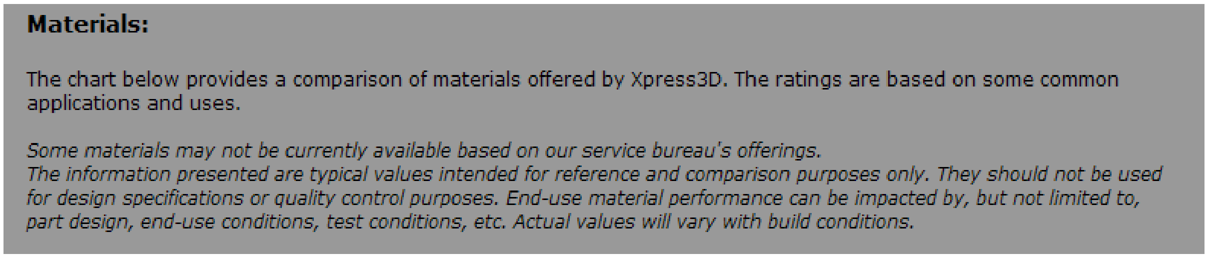
A= Acrylates
UA= urethane Acrylates
VE=Vinylethers

MANUFACTURERS	**Ciba-Geigy Citatool**								**DuPont** **SOMOS Photopolymer**		**Allied Signal** **Exactomer**	
NAME	5081-1	5131	5143	5149	5154	5170	5177	5180	2100/2110	3100/3110	2201	2202 SF
CHEMISTRY TYPE	A	A	UA	UA	UA	EPOXY	UA	EPOXY	A	A	VE	VE
LASER	HeCd	Ar	HeCd	HeCd	Ar	Ar	HeCd	Ar	Ar or HeCd	Ar or HeCd	HeCd	HeCd
SLA TYPE	250	400 500	250	250	400 500	190 250	250	500	250 400 500	250 400 500	190 250	190 250
							PHOTOSENSITIVITY PARAMETERS					
Dρ (Mil)	7.50	5.70	5.70	5.80	5.10	4.80	10.60	**5.20**	**8.5 or 4.7**	7.4 or 5.0	7.00	6.60
Ec (Mj/cm²)	6.60	3.90	4.30	5.50	4.20	13.50	11.20	16.20	2.9 or 3.5	4.0 or 2.5	27.00	8.50
							Liquid Properties					
Viscosity Centipoise 30 C	2400	2000	200	2000	2000	180	2000	187	3800	1000	205	230
Density (g/cm³) 25 C	1.21	1.21	1.20	1.20	1.20	1.22	1.20	1.22	1.20	1.20	1.16	
							CURED SOLID PROPERTIES					
Density (g/cm³) 30 C	1.21	1.21	1.20	1.20	1.20	1.22	1.20	1.22	1.20	1.20	1.16	
Tensile Strength (K lb/in²)	8.60	10.20	5.10	5.10	5.10	8.70	4.30	6.20	1.00	3.10	8.00	9.00
Tensile Modulus (K lb/in²)	435	508	138	160	573	154	391	5.4	120	211	201	

Elongation to Break (%)	2.50	2.50	20.00	10.00	10.00	19.00	12.00	16.00	46.00	9.20	6 to 10	7.00
Flexural Strength (K lb/in²)						15.60	8.60	12.70	0.08	3.00	6.20	
Flexural Modulus (K lb/in²)						430	203	366	2	94	325	
Impact Strength (ft-lb/in)	0.06	0.07	0.75	0.42	0.42	0.60	0.31	0.70	2.90	0.28	0.40	
Hardness (Shore D)	89.00	89.00	80.00	78.00	78.00	85.00	78.00	84.00	41.00	80.00	89.00	
Tg(º C)	150.00	150.00	80.00	83.00	83.00	83.00	72.00	80.00			65.00	

TABLE 2: Physical Characteristics of Selected Materials

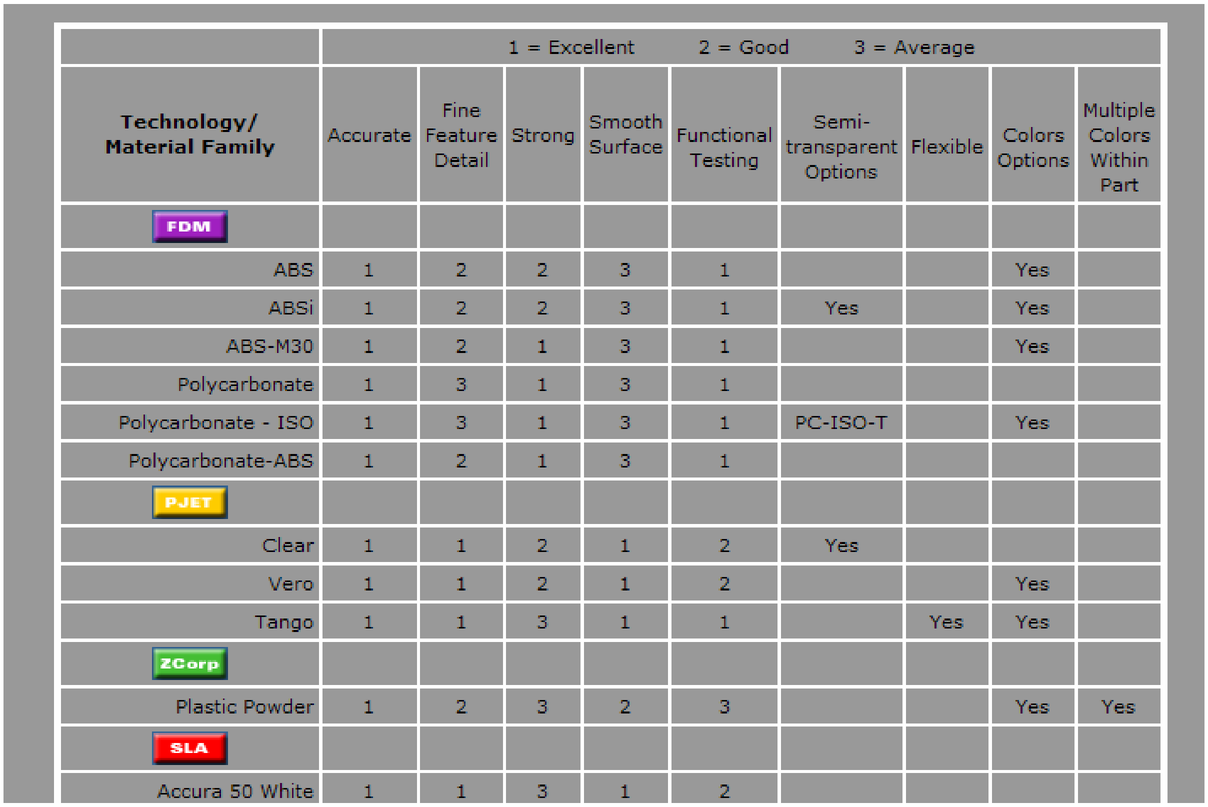
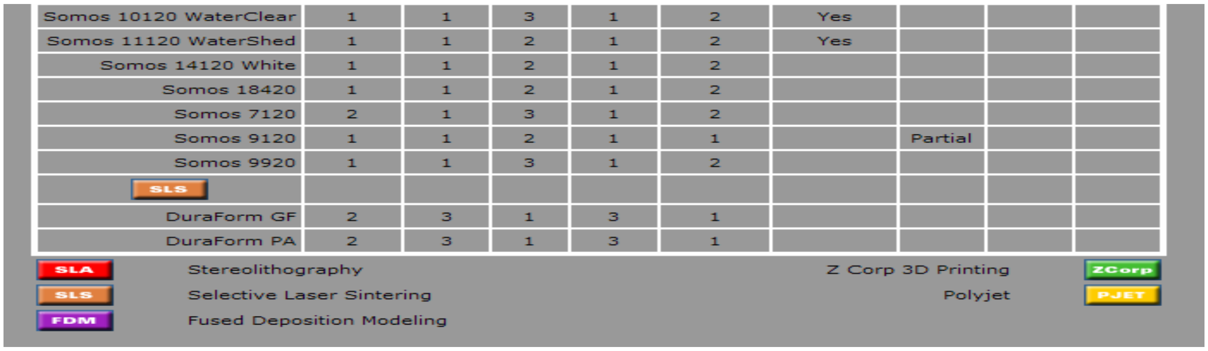
I will now like to show you another table, **TABLE 3:** below that represents a comparison of materials offered by a company called xpress3D. Each manufacturer will have information of this nature so the overall data is structured towards specific vendors. Please note the colored tabulations below that highlight the RP&M process relative to the various ratings for the physical characteristics.



Materials:

The chart below provides a comparison of materials offered by Xpress3D. The ratings are based on some common applications and uses.

Some materials may not be currently available based on our service bureau's offerings.
The information presented are typical values intended for reference and comparison purposes only. They should not be used for design specifications or quality control purposes. End-use material performance can be impacted by, but not limited to, part design, end-use conditions, test conditions, etc. Actual values will vary with build conditions.

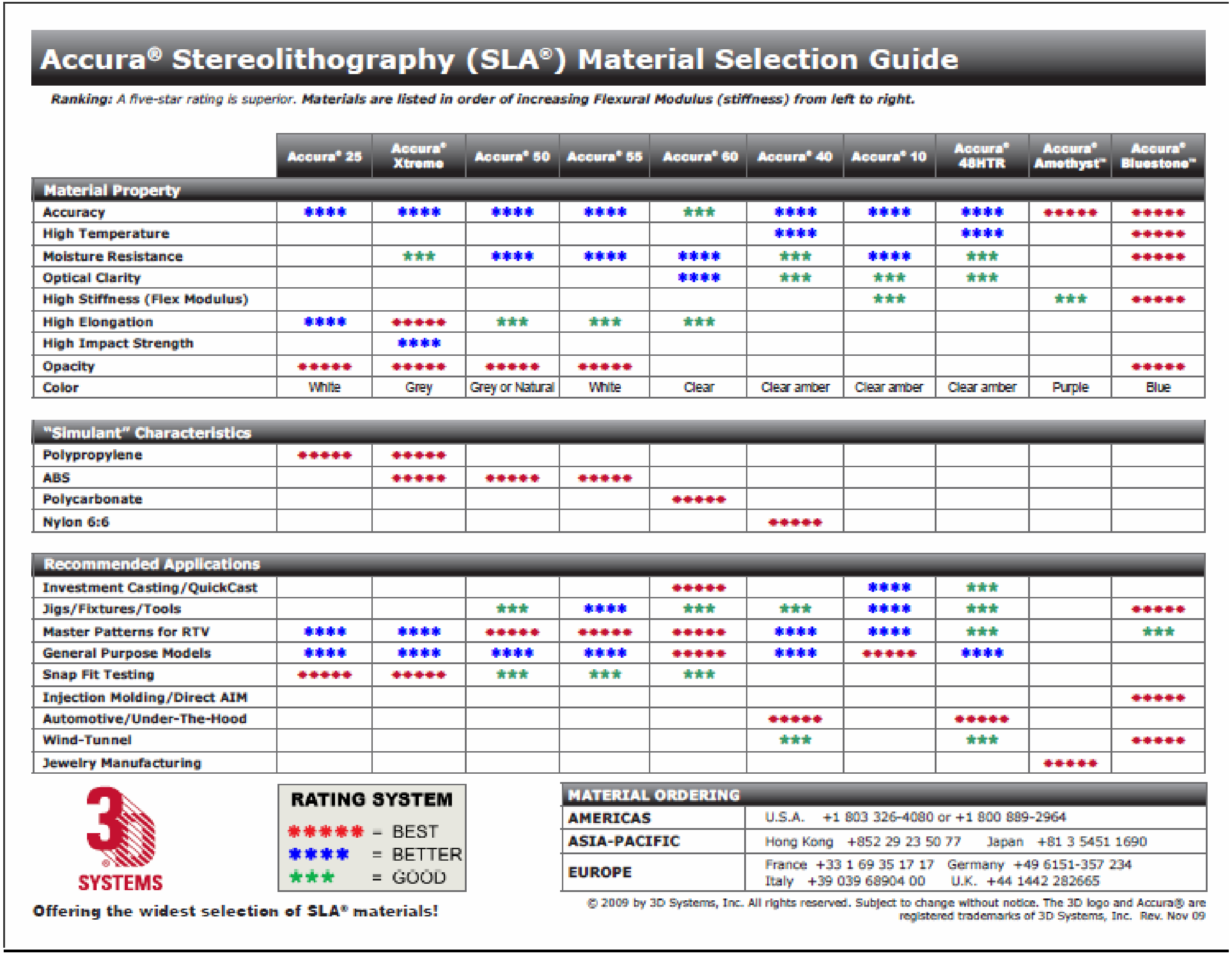
	1 = Excellent 2 = Good 3 = Average								
Technology/ Material Family	Accurate	Fine Feature Detail	Strong	Smooth Surface	Functional Testing	Semi-transparent Options	Flexible	Colors Options	Multiple Colors Within Part
FDM									
ABS	1	2	2	3	1			Yes	
ABSi	1	2	2	3	1	Yes		Yes	
ABS-M30	1	2	1	3	1			Yes	
Polycarbonate	1	3	1	3	1				
Polycarbonate - ISO	1	3	1	3	1	PC-ISO-T		Yes	
Polycarbonate-ABS	1	2	1	3	1				
PJET									
Clear	1	1	2	1	2	Yes			
Vero	1	1	2	1	2			Yes	
Tango	1	1	3	1	1		Yes	Yes	
ZCorp									
Plastic Powder	1	2	3	2	3			Yes	Yes
SLA									
Accura 50 White	1	1	3	1	2				
Somos 10120 WaterClear	1	1	3	1	2	Yes			
Somos 11120 WaterShed	1	1	2	1	2	Yes			
Somos 14120 White	1	1	2	1	2				
Somos 18420	1	1	2	1	2				
Somos 7120	2	1	3	1	2				
Somos 9120	1	1	2	1	1		Partial		
Somos 9920	1	1	3	1	2				
SLS									
DuraForm GF	2	3	1	3	1				
DuraForm PA	2	3	1	3	1				

SLA Stereolithography
SLS Selective Laser Sintering
FDM Fused Deposition Modeling
Z Corp 3D Printing ZCorp
Polyjet PJET

Table 4: is one more example of the comparisons available for material selection. As noted before, the very best source for mechanical and physical properties is the supplier of the material AND the vendor providing the prototype itself.

Mechanical Properties	Tensile Strength	Tensile Modulus	Tensile Elongation at Break	Flexural Strength	Flexural Modulus	Hardness	Izod Impact -Notched	Heat Deflection Temp
Test Method	ASTM D638	ASTM D638	ASTM D638	ASTM D790	ASTM D790	DIN 53505/2240	ASTM D256	ASTM D648
Units	psi	psi	%	psi	psi	Shore D	(ft-lb)/in	°F
ABS-Like								
White	6,100 -	316,000 -	8 - 16%	9,700 -	289,000 -	87 - 88	0.37 - 0.41	127 - 133°

(Std & High-Res) (Somos 18420)	6,400	336,000		10,200	309,000			
White (Std & High-Res) (Accura 55)	7,030 - 7,240	360,000 - 390,000	5.3 - 15.0%	10,400 - 11,200	320,000 - 340,000	86	0.31 - 0.51	120 - 127°
White (Somos 18120)	7,500 - 8,000	381,000 - 397,000	6 - 12%	11,900 - 12,200	275,000-348,000	86	0.83 - 0.91	124°
White (RenShape 7811)	5,200-7,400	260,000-348,000	10 - 20%	8,500-10,000	343,000 - 359,000	80 - 87	0.26 - 0.49	137°
Gray (Accura Xtreme)	5,510 - 6,380	260,000 - 287,000	14 - 22%	7,450 - 10,300	220,000 - 300,000	86	0.66 - 0.98	144°
Black (RenShape 7820)	5,200 - 7,400	274,000 - 348,000	8 - 18%	8,500 - 11,100	290,000 - 348,000	86	0.79 - 0.91	124°
High-Impact - White (Somos NeXt)	5,900 - 6,300	343,000 - 361,000	8 - 10%	9,800 - 10,300	350,000 - 366,000	82	0.88 - 0.97	131 - 134°
High-Temp (Accura Bluestone)	9,600 - 9,800	1,100,000 - 1,700,000	1.4 - 2.4%	18,000 - 22,300	1,200,000 - 1,417,000	92	0.24 - 0.32	149 - 151°
Durable, PP-Like								
(Std & High-Res)(Accura 25)	5,450 - 5,570	230,000 - 240,000	13 - 20%	7,960 - 8,410	200,000 - 240,000	80	0.4	136 - 145°
Rigid, PC-Like								
(Std & High-Res)(Somos 11122)	6,831 - 7,774	384,000 - 418,000	11 - 20%	9,152 - 10,756	296,000 - 344,000	N/A	0.4 - 0.6	115 - 130°
(Std & High-Res)(Accura 60)	8,410 - 9,860	390,000 - 450,000	5 - 13%	12,620-14,650	392,000 - 435,000	86	0.3 - 0.5	127 - 131°
Semi-Flexible, PE-Like								
PE-Like (Somos 8110)	2,600	46,000	27%	1,600	45,000	77	1.6	129°
	Varies Depending on Material Chosen							



Accura® Stereolithography (SLA®) Material Selection Guide

Ranking: A five-star rating is superior. ***Materials are listed in order of increasing Flexural Modulus (stiffness) from left to right.***

	Accura® 25	Accura® Xtreme	Accura® 50	Accura® 55	Accura® 60	Accura® 40	Accura® 10	Accura® 48HTR	Accura® Amethyst™	Accura® Bluestone™
Material Property										
Accuracy	****	****	****	****	***	****	****	****	*****	*****
High Temperature						****		****		*****
Moisture Resistance		***	****	****	****	***	****	***		*****
Optical Clarity					****	***	***	***		
High Stiffness (Flex Modulus)							***		***	*****
High Elongation	****	*****	***	***	***					
High Impact Strength		****								
Opacity	*****	*****	*****	*****						*****
Color	White	Grey	Grey or Natural	White	Clear	Clear amber	Clear amber	Clear amber	Purple	Blue
"Simulant" Characteristics										
Polypropylene	*****	*****								
ABS		*****	*****	*****						
Polycarbonate					*****					
Nylon 6:6						*****				
Recommended Applications										
Investment Casting/QuickCast					*****		****	***		
Jigs/Fixtures/Tools			***	****	***	***	****	***		*****
Master Patterns for RTV	****	****	*****	*****	*****	****	****	***		***
General Purpose Models	****	****	****	****	*****	****	*****	****		
Snap Fit Testing	*****	*****	***	***	***					
Injection Molding/Direct AIM										*****
Automotive/Under-The-Hood						*****		*****		
Wind-Tunnel						***		***		*****
Jewelry Manufacturing									*****	

RATING SYSTEM

***** = BEST
**** = BETTER
*** = GOOD

Offering the widest selection of SLA® materials!

MATERIAL ORDERING	
AMERICAS	U.S.A. +1 803 326-4080 or +1 800 889-2964
ASIA-PACIFIC	Hong Kong +852 29 23 50 77 Japan +81 3 5451 1690
EUROPE	France +33 1 69 35 17 17 Germany +49 6151-357 234 Italy +39 039 68904 00 U.K. +44 1442 282665

TABLE 5: Accura SLA Material Selection Guide

LASER:

Any course on rapid prototyping would not be complete without some discussion relative to the laser systems that drive the process. All rapid prototyping systems form solid parts as the result of sequential stacking of thin two-dimensional image lamina. Most of these technologies involve lasers and beam steering devices as well as computers, image generation, and manipulation software. At the present time, about ninety percent of all rapid prototyping and manufacturing systems worldwide are the stereolithography type. Most of these are sold by 3D Systems, Inc. Roughly, five percent are systems derived from SLA technology, such as those produced by Sony, Mitsubishi and EOS. All of these use helium-cadmium or argon lasers. The only RP&M systems that do not use either of these two laser types employ carbon dioxide lasers. DTM and Helisys use carbon dioxide lasers for their systems. Cubital, Stratasys, Percepton Systems and Light Sculpting use no lasers at all. These systems account for only five percent of the worldwide number of systems sold, so we will concentrate on those needing the laser to solidify the photosensitive materials.

The absolute key to the universality of the SLA system design concept is the ability to rapidly direct focused radiation of appropriate wavelength onto the surface of a liquid photopolymer resin, forming patterns of solidified photopolymer. The beam of a continuous wave laser emitting radiation of power P, at suitable wavelength, λ, is sent through a beam-expanding telescope to fill the optical aperture of a pair of cross-axis, galvanometer-driven beam scanning mirrors. The beam comes to a focus at a distance L, on the surface of a liquid photopolymer where the $1/e^2$ beam radius is W0. To obtain high speed, the galvanometer driven scanning mirrors must be of small inertia and small size. The source of radiation must have very high radiance to provide a tightly focused spot on the surface of the photopolymer located at a substantial distance. This explains the real need for the laser itself. It has become apparent that more raw power from lasers is not the best answer to faster, higher quality part building. The presumed advantage of greater laser power from visible lasers compared to UV lasers is not as important as originally thought for four very important reasons. These are as follows:

1. The trend toward thinner layers for greater part resolution has significantly reduced laser power needs.
2. New part building techniques utilize reduced cure depths.
3. The exposure varies exponentially with cure depth. The laser power requirements decrease exponentially with reduced cure depths.
4. Once it is recognized that lower exposure values are often adequate, higher laser poser can only be utilized if much higher scan speed galvanometers become available or if future photopolymers' sensitivity decreases.

The performance characteristics of a laser include: output power, wavelength, beam diameter, beam divergence, mode shape, optical noise, oscillation, bandwidth, input power, ruggedness, reliability and lifetime to some performance specification. Gas lasers are presently the primary source of UV radiation. A gas laser system generally consists of three parts or subsystems. These are as follows:

1. A laser head consisting of a gas discharge tube providing optical gain for the desired emission wavelengths, and a resonator structure which supports and maintains alignment of the mirrors at each end of the laser tube.
2. A heat exchanger for dissipating the waste heat generated by the laser tube.
3. A power supply for igniting, exciting and regulating the electrical current as well as the gas and metal vapor pressures within the laser tube.

Interaction between the various parts of the system establishes the ultimate performance of a laser. Basically, there are three types of laser systems used for the RP&M processes:

- Helium-Cadmium.
- Argon

- Carbon Dioxide

As mentioned earlier, stereolithography (SLA) RP&M systems dominate the “landscape”. The resins used with SLA are presently exposed used helium-cadmium lasers with output power levels up to about 40 mW at 325 nm and argon lasers with output power levels up to about 400 divided between 351 nm and 364 nm. The key advantages when using a HeCD system are low power consumption, long lifetime and low acquisition, installation and operating costs. The key disadvantage is low power output.

The key advantage of using an argon laser is higher UV power output. CO2 lasers are very high in efficiency, have high power capability and low acquisition, installation and operating costs. Although not useful for exposure of photopolymer resins, these lasers are effective in providing the focused heating necessary for sintering and cutting applications. The disadvantage of these lasers is their long wavelengths and inability to focus as tightly as the shorter wavelengths types. The table below will give you some indication as to the characteristics of each and some degree of comparison between the three systems.

LASER TYPE	**HeCd**	**Argon**	**Carbon Dioxide**
Emission Wavelength(nm)	325	351 & 364	10600
Power Output Range (mW)	20 to 40	100 to 500	25 to 50
Power Input Range (Kw)	0.60 to 0.80	10 to 20	0.3 to 0.60
Cooling Requirements	Air, 100 CFM	Water(20 GPM)	Air
Laser Head Size (cm)	15x18x84	18x13x114	8x8x50
Power Supply Size (cm)	33x10x36	43x15x48	20x20x30
Laser Acquisition Costs (K)	$15.00	$45.00	$15.00
Laser Installation Costs (K)	$0.00	$15.00	$0.00
Operating Costs per Month			
Laser Tube Wearout	$3.00	$12.00	$3.00
Electricity Cost	$0.05	$1.00	$0.05

TABLE 6: Characteristics of Powered Lasers

SOFTWARE:

Because the output of an RP&M system is a tangible object, the best representation of the object comes from those CAD systems which utilize the three-dimensional solid modeling approach. Unfortunately, these software packages represent a relatively small percentage of the total CAD systems in use today. This has definitely slowed the transition to RP&M systems and methodology. The RP&M system required data in a particular format. The original standard for system input is the StereoLithography file or (STL) format. This standard is based upon a mesh of connected three-dimensional triangles whose vertices are ordered to indicate which side of the triangle contains the mass. Most CAD companies with three-dimensional solid modeling packages provide the ability to output STL files. Currently, STL files have become the defacto standard for input into all types of RP&M

systems. 3D Systems has also announced development agreements with several other companies to accept other data format in addition to STL files. Companies such as Cubital, DTM and Stratasys also accept other input formats. Some of the industry standard file formats are as follows:

- Initial Graphics Exchange Specification (IGES, version 5)
- Numerical Control (NC) G-Codes
- Association of German Automotive Manufacturers-Surface Interface (VDA-FS, version 2)
- Hewlett-Packard Graphics Language 2 (HP/GL-2)
- Computerized Axial Tomography (CAT) Scan
- Nuclear Magnetic Resonance Imaging (NMRI or MRI)

STANDARDS:

A standard or standards for the Rapid Prototyping Industry represents a “work in progress” Mr. Kevin R. Jurrens from the National Institute of Standards and Technology, Manufacturing Engineering Laboratory has proposed a formalized standard for the industry. He has stated the following:

> This paper proposes that development of formalized standards for the rapid prototyping (RP) industry will help enable the continued growth and further advancement of RP technologies. Appropriate standards can provide common methods for measuring the benefits and limitations of RP, as well as facilitate the transition of current advanced rapid manufacturing capabilities from the research laboratory to commercial products. Results and recommendations from a prior RP industry workshop at the National Institute of Standards and Technology (NIST) in October 1997 form the basis for this discussion paper. This paper was presented as part of the 2nd Internet Conference on Rapid Prototyping to gather additional information and obtain further viewpoints regarding the need for and potential content of standards for the RP industry. An addendum is provided to summarize and analyze the results of the conference discussion.

There is no doubt that a formalized standard would benefit the industry and provide needed guidelines for companies doing business within the industry. The same may be said for any international standards, but at this time, an agreed upon standard is still a “moving target”.

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. [34] 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 will complement it.

SUMMARY:

Rapid Prototyping and Manufacturing methodology is a fascinating, relatively new, technology that is gaining strength year by year. In essence, we must answer several questions for the process to be greatly successful. These are as follows:

1. What is the end use for the prototype? This MUST be the very first question, even before the project begins.

2. Next, we must select the resin to be used in modeling the component. All vendors will aid your efforts in performing this task and make suggestions as to what material will be the very best for the component and the component need.

3. Select the RP&M system to be used; i.e. SLA, LOM, Sintering, etc. In doing so, you will, by default, have selected the vendor to perform the modeling itself.

4. Verify the part or object files. The proper question should be asked of the vendor so that the part receives the needed support. (NOTE: The design of supports for the component are extremely important. Multiple components produced together will have different supports than a single component.)

5. Support the STL files. The software generating the object file should be analyzed before proceeding.

The ultimate decisions when selecting a material and a process may seem very daunting at first, but there are many vendors and suppliers willing to aid your efforts with all of the tasks involved. Even though the technology is still in the developmental stages, there is a tremendous amount known and certainly enough to provide for the engineer or engineering manager a usable part and one that can meet all of your needs for rapid prototypes. Even though RP&M technology is still in the development stages, there is already a tremendous amount of knowledge to provide a usable part that meets all of the needs of the engineer. Rapid prototypes are here to stay—their future will reveal breakthroughs for better, easier, and faster technology.

APPENDIX

- GLOSSARY OF TERMS
- SPECIFICATION SHEETS FOR VARIOUS MATERIALS USED IN THE INDUSTRY
- REFERENCES

GLOSSARY OF TERMS

2D	Abbreviation for 2-dimensional. Often applied to the description of CAD systems (e.g. 2D CAD) indicating that the resulting file is a flat representation that has dimensions in only the x and y axes.
3D	Abbreviation for 3-dimensional. Often applied to the description of CAD systems (e.g. 3D CAD) indicating that the resulting file is a volumetric representation that has dimensions in the x, y and z axes.
3DP	See 3D printing.
3D Keltool®	An indirect rapid tooling process where powdered metals are formed against a pattern and sintered. This technology is owned and licensed by 3D Systems.

3D printing	1) Rapid prototyping processes that use systems that are low cost, small in size, fast and easy to use. Often suitable for an office environment. Original process and terminology developed at MIT (Massachusetts Institute of Technology); now commonly used as a generic term. 2) Collective term for all rapid prototyping activities.
3-axis	Devices that have simultaneous motion in the x, y and z axes.
5-axis	Devices that have simultaneous motion in the x, y and z axes and two rotational axes.
ACES	(Accurate Clear Epoxy Solid) Stereolithography build style that offered increased accuracy and improved surface finish, when compared to earlier build styles.
additive manufacturing	See rapid prototyping or rapid manufacturing.
alpha test	In-house testing of preproduction products to find and eliminate the most obvious design deficiencies. See also beta test.
ARP	(additive rapid prototyping) See rapid prototyping.
ASCII	Coding system for representing characters in a numeric form. ASCII (pronounced "asskee") files are text files that can be displayed on a screen or printed without special formatting or specific software program requirements.
aspect ratio	Relative relationship between height and width. Expressed in integer form (not percentage) as the ratio of height to width, where each is divided by the width to yield a ratio of X:1.
associative geometry	Placing and controlling graphic elements based on a relationship previously defined graphic elements. Elements placed associatively maintain the relationship an element is manipulated.
associativity	Operating under a single, integrated database structure. Allows changes in any application (i.e., design, drawing, assembly, mold, etc.) that are then reflected instantly throughout all associated applications as well as in every deliverable (e.g. drawings, bill-of-materials, NC tool paths)
axis (CAD)	Imaginary line segment upon which all measurements are made when creating or documenting a CAD model in 3D space. The complete Cartesian coordinate system is comprised of an x, y and z axis.
BASS™	Break-away support structure. A style of support structure for the fused deposition modeling process that is manually removed after prototype creation.
benching	For shop floor or model making operations, the process of finishing a part or prototype, typically with manual operations and hand tools. Examples: sanding, filing, joining and bonding.
b-rep	(boundary representation) CAD software methodology that defines the model as a set of vertices, edges, and faces (points, lines, curves and surfaces).
b-spline	(bi-cubic spline) Sequence of parametric polynomial curves (typically quadratic or cubic polynomials) forming a smooth fit between a sequence of points in 3D space.
beta test	

External operation of pre-production products in field situations to find those faults that go undetected in controlled in-house tests but may occur when in actual use. See also alpha test.

bezier curves

Quadratic (or greater) polynomial for describing complex curves and surfaces.

binary system

Numbering system in base two, using ones and zeros.

bit

Single digit number in base-2, or binary notation (either a 1 or zero). The smallest piece of information understood by a computer.

bitmap

Matrix of pixels representing an image.

blow molding

Manufacturing process in which plastic material, in a molten state, is forced under high pressure into a mold, causing the plastic to conform to the shape of the tool with a consistent wall thickness. Often used to produce hollow items such as bottles.

BOM

(bill of materials) Listing of all subassemblies, intermediate parts and raw materials that go into a parent assembly, showing the required quantity of each.

BPM

(Ballistic Particle Manufacturing) Rapid prototyping process where wax materials are deposited with a multi-axis, ink jet print head. Process is no longer available.

bridge tooling

Relating to molds or dies intended to fill demand between early prototype, or soft tooling, and production tooling.

build time

Length of time for the physical construction of a rapid prototype, excluding preparation and post processing time. Also known as run time.

CAD

(computer-aided design or computer -aided drafting) Software program for the design and documentation of products in either two or three dimensional space.

CAE

(computer-aided engineering) Software method using the design data of CAD for the analysis of mechanical and thermal attributes and behavior. This is accomplished through the use of finite element analysis (FEA) software for determining mechanical strength and thermal analysis.

CAM

(computer -aided manufacturing) Software program that uses the design data of CAD to build tool paths, and similar manufacturing data, for the purposes of machining prototypes, parts, fixtures or tooling.

children

1) Components of a design instance in a product structure tree. Also referred to as parts. 2) Nodes in a database tree structure that have a parent. 3) Also refers to features in parametric modeling. These features are dependent on others for establishing location in space. If the parent features are changed drastically, the children can become "orphans", or unassociated.

chord

Line segment that connects two distinct points on an arc.

chord height

Distance from the chord to the surface that the chord approximates. One of several terms that relate to the control and tolerance of the STL file.

CMM

(coordinate measuring machine) A device that determines 3D spatial coordinates from a physical part. The output is typically used for inspection and can be used for reverse engineering.

CNC

(computer numerical control) Numerical control (NC) system in which the data handling, control sequences and response to input is determined by an on-board computer system at the machine tool.

coincidence

Geometry that occupies the same spatial location. For example, coincident lines can have differing lengths while one occupies the same location as the other.

compression

Process of compacting digital data to reduce file size for electronic transmission of data archival.

computer model

Set of computer data representing a product or process and capable of being used to simulate the physical product or process behavior.

concept model

Physical model intended primarily for design review, not meant to be sufficiently accurate or durable for full functional or physical testing. Examples foam models, 3D printed parts, rapid prototype parts.

concept optimization / concept study

Research approach that evaluates how specific product benefits or features contribute to a concept's overall appeal to consumers. Product development tasks that help determine unknowns about the market, technology, or production processes.

concurrent engineering

Organization of product design, development, production planning and procurement that occurs in parallel rather than in series. The use of a project oriented team structure to include input from all concerned parties.

conformal cooling

Water lines in tooling that follow the geometry of the part to be produced, which creates higher cooling rates and lower cycle times. Unattainable prior to rapid prototyping techniques, significant research and development efforts are being made to understand and device optimal cooling strategies.

Cavity

Mold component that forms the exterior or external surface of the closure.

Core

Mold component that forms the internal surface of the closure.

CSG

(constructive solids geometry) CAD modeling technique that uses a hierarchical representation of instances of solids and combination operations (union, intersection, difference).

CT

(computed tomography) 1) Scanning system based on X-Ray technology used to reverse engineer or dimensionally verify physical parts. 2) X-Ray based volumetric scanning used for solid objects (e.g. bone in humans, but also industrial components) with internal features.

cycle time

Period between the start of an operation and the start of the next occurrence of the same operation.

Dp

Penetration depth. Variable for photocurable materials that specifies the depth of solidification at a known level of power input. Combined with Ec, these variables identify the photo speed of a resin.

design for manufacturability	Process to insure that a product or its components can be manufactured. The objective is to maximize the process rate and minimize the cost to produce.
DFA	(design for assembly) Application of a design philosophy to insure that parts and part designs are optimized for use in the assembly process. This step is important when automated assembly equipment is used to insure parts can be handled, oriented and positioned accurately.
DFM	See design for manufacturability.
die casting	Manufacturing process that produces metal components through the pressurized injection of molten alloys into a metal tool (die). Typically used for high volume production.
digital modeling	The concept of holding the master product design definition in purely digital form; the total information set required to specify and document the product. Related terms include virtual prototyping, virtual product development, soft prototyping and electronic product development.
direct	When applied to rapid tooling and rapid manufacturing applications, the production of a tool or part from a rapid prototyping devices without secondary manufacturing operations.
Direct AIM	Injection-mold tooling produced directly from a stereolithography process, where AIM stands for ACES Injection Molding. See ACES.
direct digital manufacturing	Application of additive technologies (rapid prototyping) to the production of finished goods without the use of tooling or secondary processes.
direct digital tooling	Application of additive technologies (rapid prototyping) to the creation of molds or dies without the use of secondary or intermediary steps.
Direct Metal Deposition (DMD™)	Proprietary rapid tooling process from Precision Optical Manufacturing (POM). Laser-based technology that produces fully dense metal tools. Often applied to tool restoration.
Direct Metal Laser Sintering (DMLS)	Rapid prototyping and tooling process from EOS GmbH that sinters metal powders.
Direct Shell Production Casting (DSPC)	Rapid prototyping and tooling process from Soligen based on MIT's 3DP technology. Ink jet deposition of liquid binder onto ceramic powder to form shell molds for investment casting.
DirectTool®	Trademarked rapid tooling process from EOS GmbH for the production of metal tools using the company's Direct Metal Laser Sintering technology.
DMLS	See Direct Metal Laser Sintering
drop-on-demand (DOD)	Ink jet methodology now incorporated in rapid prototyping systems, where the material is deposited in a non-continuous stream. Drops are produced and deposited only as required.
DOE	

(design of experiments) Methodology for running a statistically significant battery of tests (or computer simulations) on a design to determine its sensitivity to, or robustness for, design or manufacturing variations.

DPI

(dots per inch) Measure or resolution common to computer monitors and also applied to some raster-based rapid prototyping technologies where dots are equated to pixels or a single droplet of material.

DSPC

See Direct Shell Production Casting.

DXF

(drawing exchange file) File format that allows for transfer of CAD data among dissimilar systems. Originally devised by Autodesk for the AutoCAD software program.

Ec

Critical energy. A variable for photocurable materials that specifies the energy required to solidify a given thickness of material. Combined with Dp, these variables identify the photo speed of a resin.

EDM

(electrical discharge machining) Electric current passed through a graphite or copper alloy electrode that machines metal with spark erosion. The electrodes have the same geometry as the intended part or profile to be produced (machined).

early adopters

Customers who, relying on their intuition or vision, buy into new product concepts or new manufacturing processes very early in the product life cycle.

economies of scale

Achieving low per-unit costs by producing in volume, permitting fixed costs to be distributed over a large number of products.

economies of scope

Achieving low-per unit costs by computerizing production; allows goods to be manufactured economically in small lot sizes.

Electron Beam Melting

Proprietary rapid prototyping and tooling process from Arcam AB that solidifies metal powder with an electron beam.

element

The basic building block used in geometric modeling. Elements include points, lines, curves, surfaces, and solids.

enterprise prototyping center

Rapid prototyping devices characterized by higher throughput, larger physical size, increased operator control, improved accuracy and enhanced surface finish. Often operated by a dedicated staff in a lab-like setting.

epoxy tooling

Indirect rapid tooling process where the mold is created by casting an epoxy resin, usually mixed with aluminum powder, against a pattern. Suitable for injection molding in low quantities.

ergonomics

Interaction of technological and work situations with the human being. Also called human factors.

extrusion

Process where material, often in a molten or semi-molten state, is forced through an orifice that gives the material shape.

family mold

Tool that has cavities for two or more different parts.

facet

Polygonal element that represents the smallest unit of a 3D mesh. These elements can be either three or four sided. The mesh represents an approximation of the actual geometry. Three-sided (triangular) facets are used in STL files. Both three and four sided elements are used in finite element modeling.

facet deviation

Maximum distance between the triangular element of an STL file and the surface that it approximates. See also chord height.

FDM

See fused deposition modeling.

FEA

See finite element analysis.

feature

Discrete attributes of a model or prototype that include holes, slots, ribs, bosses, snap fits and other basic elements of a product design.

feature-based modeling

CAD modeling method defined by a series of rules that are used to describe how features interact with each other to construct a specific solid. Example, the through-hole feature understands the rule that it must pass completely through the part and will do so no matter how the part changes.

finite element analysis

Method used in CAD/CAE for determining the structural integrity of a part by mathematical simulation of the part and its loading conditions. Also used to predict the behavior of parts under a thermal load.

first-to-market

Initial product that creates a new product category.

fixture

Used to hold and position the workpiece for a manufacturing operation.

form & fit

Shape and size of a component and its relationship to mating components. Often used in the context of design analysis of the adequacy of a part in terms of its size, shape and conformance to constraints imposed by mating or nested components.

free-form fabrication

Alternative description of rapid prototyping. Intended to describe a broader base of application where components are generated directly from digital data. See rapid prototyping.

free-form surface

Contours that cannot be defined with simple linear or quadratic mathematical equations. Many natural shapes, such as the human face, are examples.

FTP

(file transfer protocol) Communication standard for transferring data over the Internet or internal networks.

functional testing

Evaluation of a prototype, in conditions similar to those that the product will experience, to determine its ability to operate as specified.

fused deposition modeling

Rapid prototyping process by Stratasys Inc. The process extrudes a thermoplastic material and deposits it on a layer by layer basis to form a part.

GARPA

(Global Alliance of Rapid Prototyping Associations) Alliance of rapid prototyping associations, such as RPA/SME, from around the world that fosters the transfer of information related to rapid prototyping.

gradient material

Graduated displacement of one material with another that yields a gradual transition between two materials.

gross profit

Financial measure that equals sales revenue less variable expense.

IGES

(Initial Graphic Exchange Specification) Standard format for the exchange of 2D and 3D CAD data between dissimilar CAD software systems.

indirect

When applied to rapid tooling and rapid manufacturing applications, the production of a tool or part from a rapid prototyping devices where secondary manufacturing operations are required between the rapid prototyping operation and the production of the desired item.

injection molding

Manufacturing process where molten plastic is introduced into a tool or die with the use of pressure. Commonly applied to both prototype and production requirements.

interference checking

CAD capability that automatically examines the intersection of objects within a 3D model.

investment casting

Manufacturing process, which utilizes an expendable pattern (the investment), to produce metal parts. A ceramic mold is made by repeatedly dipping the pattern in a ceramic slurry solution followed by fine grain silica sand. The pattern is then burned out in an autoclave or furnace, which simultaneously sinters and strengthens the ceramic shell. Molten metal is then poured into the shell. After cooling and solidification, the shell is destroyed to reveal the final metal part.

Keltool®

See 3D Keltool

kirksite

Low melting point metal used in the casting of large mold and form tools to produce low quantities of parts. This material is generally used to make large parts.

Laminated Object Manufacturing

Patented rapid prototyping system, originally from Helisys Inc. and now offered by Cubic Technologies, that uses a laser to cut a cross-section from sheet material. These cross-sections are stacked and bonded together to create an object.

LaserCusing

Derived from concept of fusing. Rapid prototyping and tooling process from Concept Laser GmbH that produces fully dense metal parts from powders that are fused with a high energy laser.

laser sintering

Rapid prototyping processes that use heat, often from a laser, to fuse powdered materials, including plastics and metals.

layer (CAD)

A logical separation of data to be viewed individually or in combination. Similar in concept to transparent acetate overlays.

layer (RP)

A thin horizontal slice of the STL file used to fabricate a rapid prototype. Typically between 0.001 and 0.010 in. (0.025 and 0.25 mm) in thickness. Also see slice.

layer thickness

Vertical dimension of a single slice of an STL file. Smaller dimensions often lead to smoother surfaces but may increase build time.

layer-based manufacturing

See rapid prototyping or rapid manufacturing.

LENS

(Laser Engineered Net Shaping) Rapid prototyping and tooling process that injects metal powder into a pool of molten metal created by a focused laser beam. Originally developed at Sandia and later commercialized by Optomec, Inc.

LOM

See Laminated Object Manufacturing.

LS

See laser sintering.

machining

General term for all manufacturing processes that produce parts or tools through the removal of material.

manufacturability

Extent to which a product can be easily and effectively manufactured at minimum cost and with maximum reliability.

mass customization

Method of production that stresses the manufacturing of small lots of customized goods rather than large volumes of standardized products.

mass production

Large-scale, high-volume manufacturing of standardized parts. Relies on "economies of scale" to achieve low per-unit costs.

mass properties

Characteristics of a solid that includes volume, weight, center of gravity, and moments of inertia.

MJM

See Multi Jet Modeling.

mold inserts

1) Components of a mold core or cavity used to change geometry features in the mold. Provides alternatives to making multiple molds. Or, it is used in the repair of hardened molds to prevent degradation of the surrounding metal if welding was used for the repair. 2) Used in insert molds to insert a complete core and cavity complete with ejector mechanism and cooling into a frame, which is then installed into a molding machine.

MRI

(magnetic resonance imaging) 1) used to generate cross sectional images of a solid part. Typically used for reverse engineering parts when 2D or 3D documentation is not available. 2) Used medically to can patients as a non-evasive method to check internal structure. 3) Process uses magnets to "align electrons" before creating a computer image. This image can be used to generate a 3D file then used to generate a rapid prototype. 3) Technique similar to CT scanning to examine internal geometry or structures.

Multi-Jet Modeling

Rapid prototyping processes from 3D Systems that use ink jet technology to deposit materials.

NC

(numerical control) Method of controlling the cutter motion of a machine tool through the use of numeric data and standardized codes. In contrast to CNC devices, NC tools offer automation with limited programming ability and logic beyond direct input.

neutral file

Format for electronic data that can be both imported and exported by dissimilar software programs. Examples include DXF, IGES, STEP and STL.

NURBS

(Non-Uniform Rational B-Spline) Mathematical description of a surface created by two or more b-splines.

OEM

(original equipment manufacturer) Company that uses product components from one or more other companies to build a product that it sells under its own company name and brand.

outsource

To subcontract services, such as prototyping, design or manufacturing, to an organization that is independent of the buying (requesting) organization.

Paper Lamination Technology (PLT)

Rapid prototyping process from Kira Corporation that laminates paper and then cuts the layer profile with a computerized knife.

parametric CAD

Type of CAD methodology that relates the geometry of different elements of a part such that the change of one element changes related features. The association is based on a predetermined correlation.

pattern

Physical representation of a design that is used to produce molds, dies or tools. Also called master pattern.

PDM

(product data management) Technology for managing and controlling all engineering and manufacturing data.

PHAST

Proprietary rapid tooling process developed by Procter & Gamble that was granted to The Milwaukee School of Engineering for further process development and refinement.

photopolymer

Liquid resin material that utilizes light (visible, ultra-violet) as a catalyst to initiate polymerization, in which the material cross-links and solidifies. This technique is used by various rapid prototyping techniques.

pipeline management

A process that integrates product strategy, project management, and functional management to continually optimize the cross-project management of all development-related activities.

pixel

Individual dot placed on a cathode-ray tube that, when combined with neighboring dots, creates an image (e.g. television or computer monitor).

plaster mold casting

Process for creating small quantities of metal parts in aluminum, zinc or magnesium. Often used as a prototype method for the simulation of die castings. The mold is created from a pattern, with several intermediate steps. Metal is cast into the mold, as with investment casting, the mold is destroyed to yield the metal casting.

PolyJet™

Rapid prototyping process from Objet Geometries that deposits photocurable materials through an ink jet process.

post processing

Common practice required with rapid prototype systems that refers to clean-up and finishing procedures on RP models after they are removed from the RP machine. May include mechanical or chemical removal of support structures, powder removal and surface finishing.

pre-production unit

Product that looks and works like the intended final product, but is made either by hand of in pilot facilities rather than by the final production process.

primitives

Lowest state of a solid model. A solid of surface that is not derived from other elements, such as a cube, cone, cylinder, or sphere.

product data

All engineering data necessary to define the geometry, the function, and the behavior of a product over its entire life span, including logistic elements for quality, reliability, maintainability, topology, relationship, tolerances, attributes, and features necessary to define the item completely for the purpose of design, analysis, manufacture, test, and inspection.

production tooling

1) Hardened tooling intended to create large volumes (quantities) of parts. The molds should last the life of the products produced. Typically machined from steel, it is used for the mass production manufacturing of wax, polymer or metal components.

ProMetal®

Rapid prototyping and tooling process commercialized by Extrude Hone, Inc. that is based on the MIT 3DP technology. The process generates a "green" part by solidifying metal powder with a binder. The green part is placed in a furnace to burn off the binder, sinter the powder and infiltrate with an alloy.

prototype

Physical model of a part or product during the product development process. Depending upon the purpose, prototypes may be non-working, functionally working, or both functionally and aesthetically complete. Derived from Latin term for "first form".

prototype tooling

Short life molds and dies used in the fabrication of molded, stamping and dies and other parts. This approach has a low life expectancy compared to hardened production tooling. May yield from one to as many as 50,000 parts depending on methods and materials utilized.

QuickCast™

A trademarked process of 3D Systems for a stereolithography build style that reduces the mass of the pattern to accommodate the investment casting process.

rapid manufacturing

Production of end use parts-directly or indirectly-from a rapid prototyping technology.

rapid prototyping

Collection of technologies that are driven by CAD data to produce physical models and parts through an additive process.

rapid tooling

Production of tools, molds or dies-directly or indirectly-from a rapid prototyping technology.

raster

1) A two-dimensional array of pixels which, when displayed, form an image or representation of an original document. 2) A scan pattern (as of the electron beam in a cathode-ray tube) in which an area is scanned from side to side in lines from top to bottom. Antonym - vector.

reaction injecting molding

Manufacturing process where thermoset resins are injected into rigid tools.

redlining

1) Facility for annotating on-screen documents by transmitting overlaid comments and sketches. 2) Process of marking documentation for requested changes to part, tooling or specification documentation.

rendering

Process of adding shading, colors, reflectivity, textures, and other visual elements to a solid model to make it appear realistic.

resin

General classification of non-metallic materials and compounds. For rapid prototyping, the term is most often associated with the liquid state of stereolithography photopolymers. For molding operations, the term is a reference to any thermoplastic or thermoset material.

reverse engineering

Process for the capture of the geometric definition of a physical part through scanning technologies. Resulting data, often a set of discrete points that are spatially oriented, is imported into a CAD system and used for further product refinement, prototype creation, tooling creation or manufacturing.

return on investment

Financial calculation that illustrates the value of an investment in a specific period of time. ((financial gain - cost)/cost) x 100%.

RFP

(request for proposal) Bid package, submitted to potential vendors, that solicits price and delivery information for a program or project.

RFQ

(request for quotation) Similar to an RFP, but generally used when requesting individual parts.

RIM

See reaction injection molding.

road

Term applied to the fused deposition modeling process that describes the extrusion of material in a single pass.

ROI

See return on investment.

RP

See rapid prototyping.

RPA/SME

(Rapid Prototyping Association of the Society of Manufacturing Engineers) Association dedicated to the collection and sharing of information on rapid prototyping. tooling and manufacturing.

rp-ml

(Rapid Prototyping Mailing List) Internet forum for the online discussion of topics related to rapid prototyping.

RTV molding

See silicone rubber molding.

rubber molding

See silicone rubber molding.

rubber plaster molding

See plaster mold casting.

sand casting

Manufacturing process for the production of metal, including gray iron, castings. Sand is packed against a form (tool) to create each half of the tool. After combining the tool halves, metal is cast into the cavity and allowed to cool. To remove the metal casting, the sand tool is destroyed.

Selective Laser Melting

Rapid prototyping and tooling process from F&S GmbH that produce 100% dense metal parts by melting a power with an infrared laser.

selective laser sintering

Rapid prototyping process, originally developed by DTM Corp and now owned by 3D Systems, which uses a CO_2 laser to fuse powdered materials, including plastics and metals.

service bureau

1) Company or group of companies providing engineering, prototyping or manufacturing support to other companies who do not have the capability. 2) For rapid prototyping, a commercial entity that specializes in providing rapid prototyping and peripheral services to a customer base.

SGC

See Solid Ground Curing.

short run tooling

Molds created for low volume (e.g. less than 100 samples) production.

silicone rubber tooling

Soft tooling technique that utilizes room-temperature vulcanized (RTV) rubber material to form molds that are cast from machined or rapid prototype patterns. Commonly used to produce small lots (25 to 100 pieces) in urethane materials.

sinter

Heating a material to a temperature below its melting point to causes it to fuse to create a solid mass.

SL

See stereolithography.

SLA

(StereoLithography Apparatus) A trademarked name by 3D Systems for the machines that use the stereolithography process. Also used interchangeably with SL.

slice

Single layer of an STL file that becomes the working surface for the additive process.

SLM

See selective laser melting.

SLS®

See selective laser sintering.

Solid Ground Curing

Rapid prototyping process that solidifies photocurable materials through a photo-mask. The use of the mask allows curing of a complete layer with one flash of UV light. Process is no longer available.

solid imaging

An alternative term for rapid prototyping.

solid freeform fabrication

An alternative term for rapid prototyping.

solid modeling

3D CAD technique that represents all physical characteristics of an object; including volume, mass, and weight.

Solid Object Ultraviolet -Laser Printer

Stereolithography process offered by CMET.

SOUP

See Solid Object Ultraviolet-Laser Printer.

spin casting

Process that uses rubber molds to create metal castings in low melting temperature alloys. The mold is rotated and material is poured into its center. Centrifugal force fills the mold with molten material.

Sprayform

A trade name and technology owned by the Ford Motor Company. This process uses wire arc spray of metal alloy onto a ceramic mold pattern to generate tooling.

spray metal tooling

Process for creating prototype or bridge tooling through metal deposition onto a pattern using wire arc spray, vacuum plasma deposition or similar techniques. After creation of the metal tool face, epoxy or other materials are used to backfill the tool to add strength. Often used for injection molds.

SRP™

(Subtractive Rapid Prototyping) Trademarked name of Roland Corporation used to identify rapid prototyping devices that remove material for prototype creation. Antonym - ARP (additive rapid prototyping).

stair stepping

Result of additive processes where surfaces that are neither vertical nor horizontal are not smooth, since they are approximated by individual layers.

STEP

(standard for the exchange of product model data). File format standard for the transfer of data between dissimilar CAD systems. Adopted by the International Organization for Standardization (ISO) in December 1994.

stereolithography

Process that builds an object, a layer at a time, by curing photosensitive resin with a laser-generated beam of ultraviolet radiation. Originally applied to 3D Systems' technology, the use of the term has broadened to include all technologies that process prototypes in this manner.

STL

Neutral file format is exported data from CAD systems for use as input to rapid prototyping equipment. The file contains point data for the vertices of the triangular facets that combine to approximate the shape of an object. The acronym is derived from the word STereoLithography.

surface

Boundary defining an exterior or interior face of a 3D CAD model.

surface normal

Vector that is perpendicular to a surface or facet in an STL file. For the facets of the STL file, the direction of the vector indicates the outward facing side of the facet.

surfaced wireframe

Method of 3D CAD modeling that represents part geometry with bounding edges and skins that stretch between the boundaries. The CAD model is defined by its innermost and outermost boundaries and does not contain any mass between these boundaries.

support structure

Common to many rapid prototyping processes. Scaffold of sacrificial material upon which overhanging geometry is built. Also used to rigidly attach the prototype to the platform upon which it is built. After prototype construction, these are removed in a post processing operation.

surface modeling

See surface wireframe.

TALC

(Technology Adoption Life Cycle) Business model that describes the adoption of technology through an analysis of purchasing traits.

thermoplastic

Plastic compound that is processed (molded) in a liquid state that is achieved with elevated temperatures. This class of plastic can be repeatedly cycled through a liquid and solid state. Common applications: injection molding, blow molding and vacuum forming.

thermoset

Plastic compound that is processed in a liquid state where two or more liquid components are blended just prior to molding. Upon blending, an exothermic, chemical reaction causes the liquid to change to a solid state. Unlike thermoplastics, once solidified these materials cannot be returned to a liquid state. Common applications: rubber molding and reaction injection molding.

time to market

Period to conceive, develop, manufacture and deliver a new product.

tooling

Generic term used to describe molds or dies used in the production of parts and assemblies. Examples include injection molds, blow molds, die cast dies, and stamping dies.

Ultrasonic Consolidation

Proprietary rapid prototyping and tooling process from Solidica, Inc. that ultrasonically welds sheet metal to deliver homogeneous material properties. After welding of the sheet material, the profile is CNC machined.

urethane

Thermoset material commonly used in rubber molding and RIM molding processes. Any of various polymers that contain NHCOO linkages and are used especially in flexible and rigid foams, elastomers, and resins.

UV

(ultraviolet) Light energy situated beyond the visible spectrum at its violet end -- having a wavelength shorter than wavelengths of visible light and longer than those of X rays Often used in the curing of photopolymer resins.

vacuum forming

Process for producing plastic parts by heating plastic sheet and drawing it against a form when air is pulled through the form.

virtual prototyping

Computer based generation of 3D geometry for analyzing product design features. Often associated with immersive environments where the digital data is presented with realism and offers an ability to interact with the digital design as if it were real. More commonly applied to computer-based testing and analysis methods such finite element analysis.

vector

Quantity that has magnitude and direction and that is commonly represented by a directed line segment whose length represents the magnitude and whose orientation in space represents the direction.

voxel

Volume cell. The 3D equivalent of the pixel.

WaterWorks™

Trademarked and patented process of Stratasys, used with the FDM rapid prototyping process, that allows models (or assemblies) to be made with movable parts already assembled. The support material is dissolved in a water-based solution.wireframe

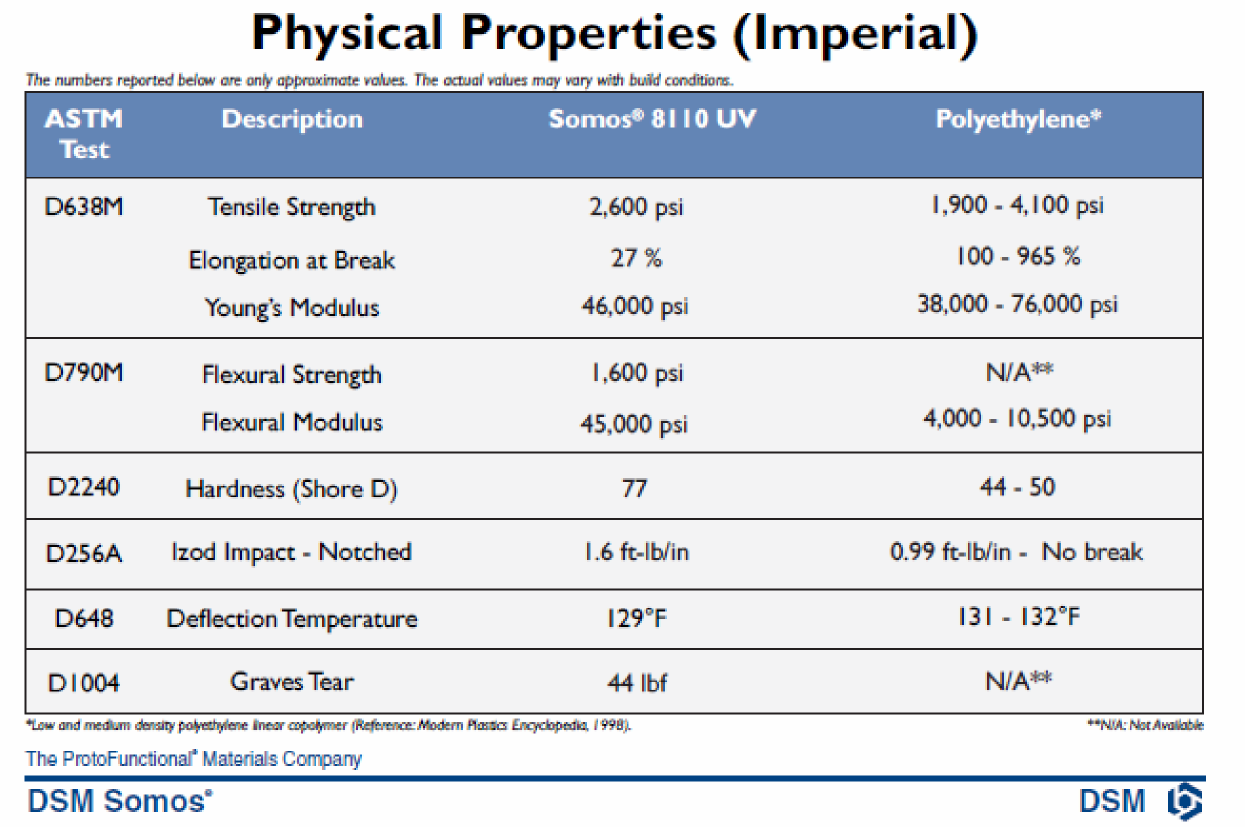
CAD modeling method that defines a part by its innermost and outermost boundaries. The model does not contain any mass between the boundaries nor any bounding surfaces.

SAMPLE MATERIAL SPECIFICATIONS

The material specification sheets presented in this section are merely to give the reader some idea as to what information is available from material vendors. I certainly would suspect that by the time this course is published the data will be somewhat outdated. For that reason, your source of CURRENT information must always be the supplier of the material itself.

Somos 8110

This material is particularly useful in applications where flexibility and impact-strength are critical requirements.



Physical Properties (Imperial)

The numbers reported below are only approximate values. The actual values may vary with build conditions.

ASTM Test	Description	Somos® 8110 UV	Polyethylene*
D638M	Tensile Strength	2,600 psi	1,900 - 4,100 psi
	Elongation at Break	27 %	100 - 965 %
	Young's Modulus	46,000 psi	38,000 - 76,000 psi
D790M	Flexural Strength	1,600 psi	N/A**
	Flexural Modulus	45,000 psi	4,000 - 10,500 psi
D2240	Hardness (Shore D)	77	44 - 50
D256A	Izod Impact - Notched	1.6 ft-lb/in	0.99 ft-lb/in - No break
D648	Deflection Temperature	129°F	131 - 132°F
D1004	Graves Tear	44 lbf	N/A**

*Low and medium density polyethylene linear copolymer (Reference: Modern Plastics Encyclopedia, 1998).

**N/A: Not Available

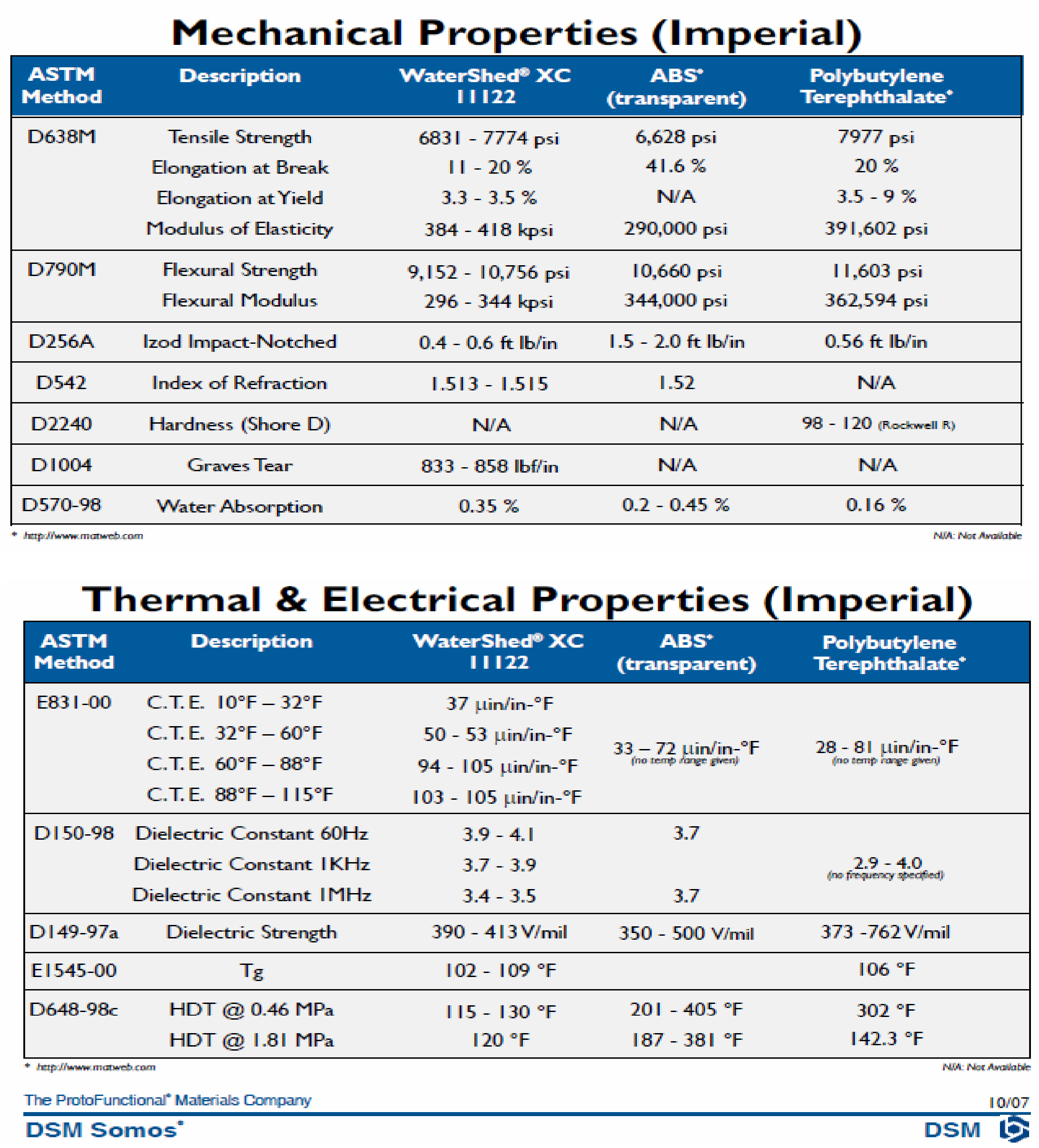
The ProtoFunctional® Materials Company

DSM Somos®

DSM

- **Somos 11122**

WaterShed XC is a low viscosity liquid photopolymer that produces strong, tough, water-resistant, ABS-like parts. Most importantly parts created with WaterShed 11122 are nearly colorless, and look more like true, clear
engineered plastic. In addition, WaterShed XC has been formulated with
the DSM Somos Oxetane Advantage™— an advanced chemistry platform that produces parts with outstanding water resistance and high dimensional stability.



Mechanical Properties (Imperial)

ASTM Method	Description	WaterShed® XC 11122	ABS* (transparent)	Polybutylene Terephthalate*
D638M	Tensile Strength	6831 - 7774 psi	6,628 psi	7977 psi
	Elongation at Break	11 - 20 %	41.6 %	20 %
	Elongation at Yield	3.3 - 3.5 %	N/A	3.5 - 9 %
	Modulus of Elasticity	384 - 418 kpsi	290,000 psi	391,602 psi
D790M	Flexural Strength	9,152 - 10,756 psi	10,660 psi	11,603 psi
	Flexural Modulus	296 - 344 kpsi	344,000 psi	362,594 psi
D256A	Izod Impact-Notched	0.4 - 0.6 ft lb/in	1.5 - 2.0 ft lb/in	0.56 ft lb/in
D542	Index of Refraction	1.513 - 1.515	1.52	N/A
D2240	Hardness (Shore D)	N/A	N/A	98 - 120 (Rockwell R)
D1004	Graves Tear	833 - 858 lbf/in	N/A	N/A
D570-98	Water Absorption	0.35 %	0.2 - 0.45 %	0.16 %

* http://www.matweb.com

N/A: Not Available

Thermal & Electrical Properties (Imperial)

ASTM Method	Description	WaterShed® XC 11122	ABS* (transparent)	Polybutylene Terephthalate*
E831-00	C.T.E. 10°F – 32°F	37 µin/in-°F	33 – 72 µin/in-°F (no temp range given)	28 - 81 µin/in-°F (no temp range given)
	C.T.E. 32°F – 60°F	50 - 53 µin/in-°F		
	C.T.E. 60°F – 88°F	94 - 105 µin/in-°F		
	C.T.E. 88°F – 115°F	103 - 105 µin/in-°F		
D150-98	Dielectric Constant 60Hz	3.9 - 4.1	3.7	2.9 - 4.0 (no frequency specified)
	Dielectric Constant 1KHz	3.7 - 3.9		
	Dielectric Constant 1MHz	3.4 - 3.5	3.7	
D149-97a	Dielectric Strength	390 - 413 V/mil	350 - 500 V/mil	373 -762 V/mil
E1545-00	Tg	102 - 109 °F		106 °F
D648-98c	HDT @ 0.46 MPa	115 - 130 °F	201 - 405 °F	302 °F
	HDT @ 1.81 MPa	120 °F	187 - 381 °F	142.3 °F

* http://www.matweb.com

N/A: Not Available

The ProtoFunctional® Materials Company

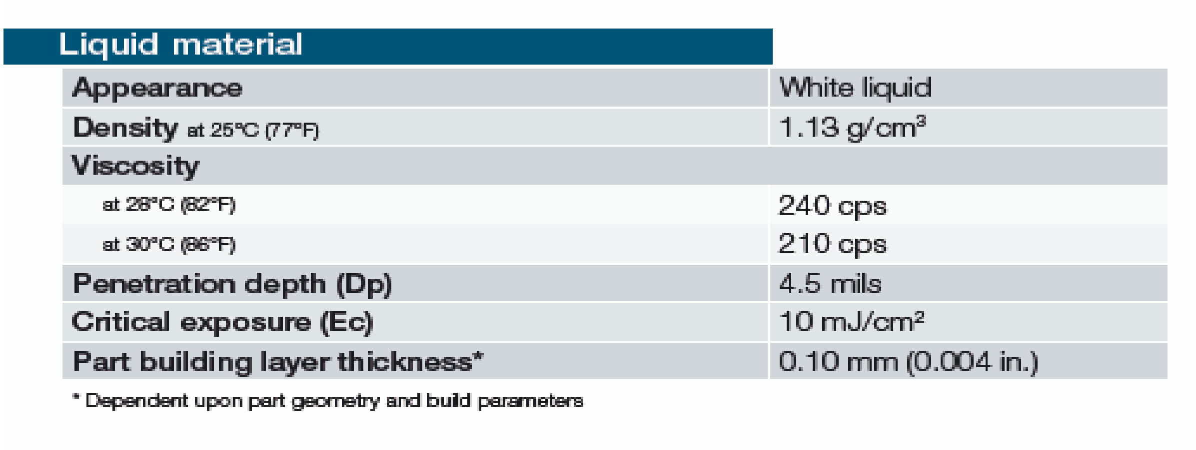
10/07

DSM Somos®

DSM

- **RenShape® SL 7820**

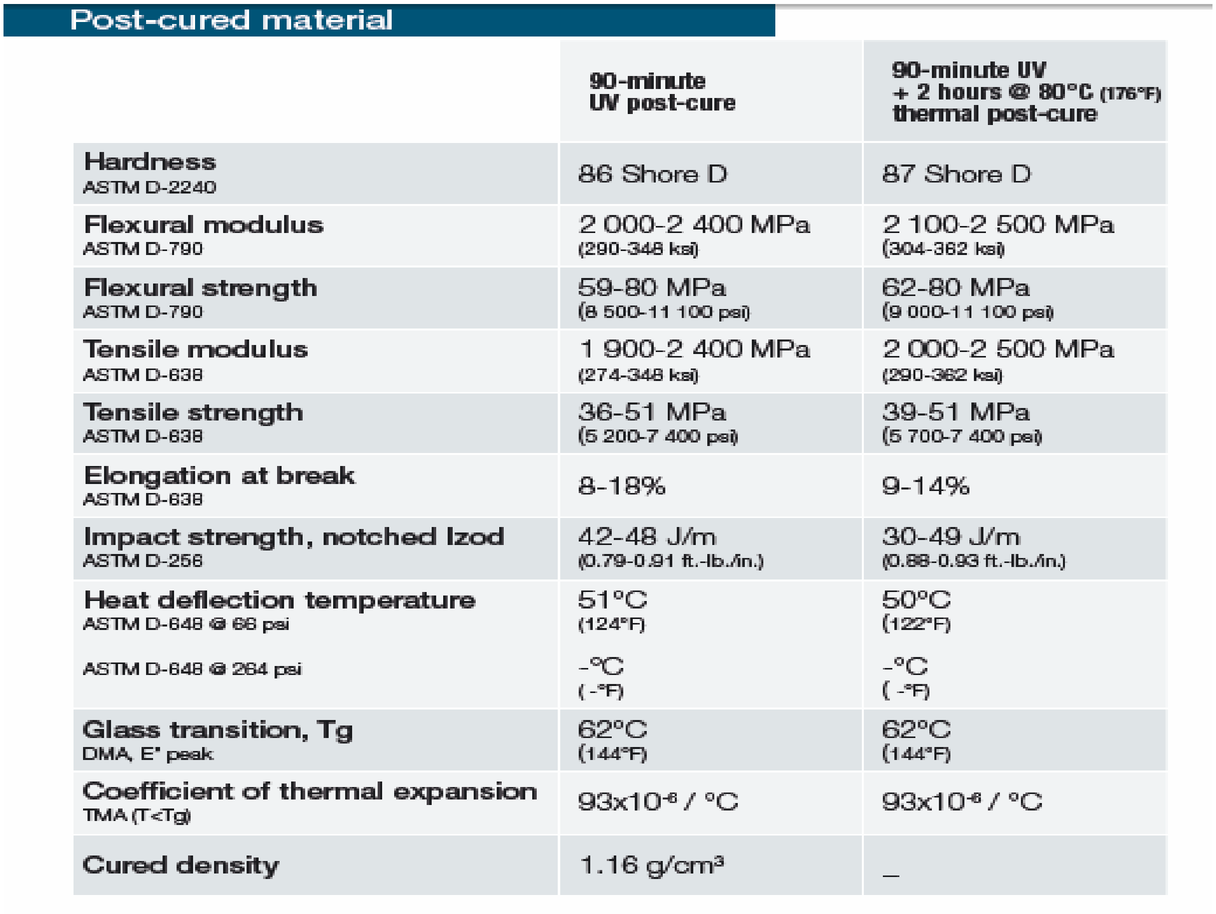
RenShape® SL 7820 stereolithography material is a white, low viscosity stable liquid that produces strong black models and prototypes with good surface finish and detail, an ABS-like appearance. The product is also well suited for building RTV patterns.



Liquid material

Appearance	White liquid
Density at 25°C (77°F)	1.13 g/cm^3
Viscosity	
at 28°C (82°F)	240 cps
at 30°C (86°F)	210 cps
Penetration depth (Dp)	4.5 mils
Critical exposure (Ec)	10 mJ/cm^2
Part building layer thickness*	0.10 mm (0.004 in.)

* Dependent upon part geometry and build parameters

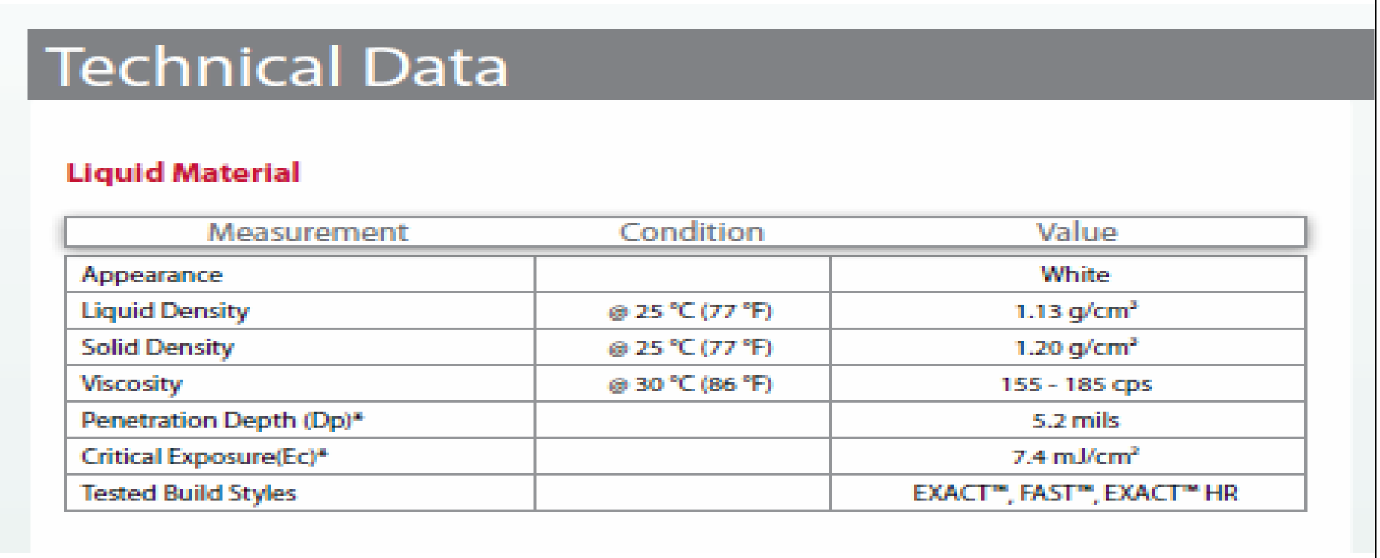


Post-cured material

	90-minute UV post-cure	**90-minute UV + 2 hours @ 80°C (176°F) thermal post-cure**
Hardness ASTM D-2240	86 Shore D	87 Shore D
Flexural modulus ASTM D-790	2 000-2 400 MPa (290-348 ksi)	2 100-2 500 MPa (304-362 ksi)
Flexural strength ASTM D-790	59-80 MPa (8 500-11 100 psi)	62-80 MPa (9 000-11 100 psi)
Tensile modulus ASTM D-638	1 900-2 400 MPa (274-348 ksi)	2 000-2 500 MPa (290-362 ksi)
Tensile strength ASTM D-638	36-51 MPa (5 200-7 400 psi)	39-51 MPa (5 700-7 400 psi)
Elongation at break ASTM D-638	8-18%	9-14%
Impact strength, notched Izod ASTM D-256	42-48 J/m (0.79-0.91 ft.-lb./in.)	30-49 J/m (0.88-0.93 ft.-lb./in.)
Heat deflection temperature ASTM D-648 @ 66 psi	51°C (124°F)	50°C (122°F)
ASTM D-648 @ 264 psi	-°C (-°F)	-°C (-°F)
Glass transition, Tg DMA, E" peak	62°C (144°F)	62°C (144°F)
Coefficient of thermal expansion TMA (T<Tg)	$93x10^{-6}$ / °C	$93x10^{-6}$ / °C
Cured density	1.16 g/cm^3	_

Accura® 55

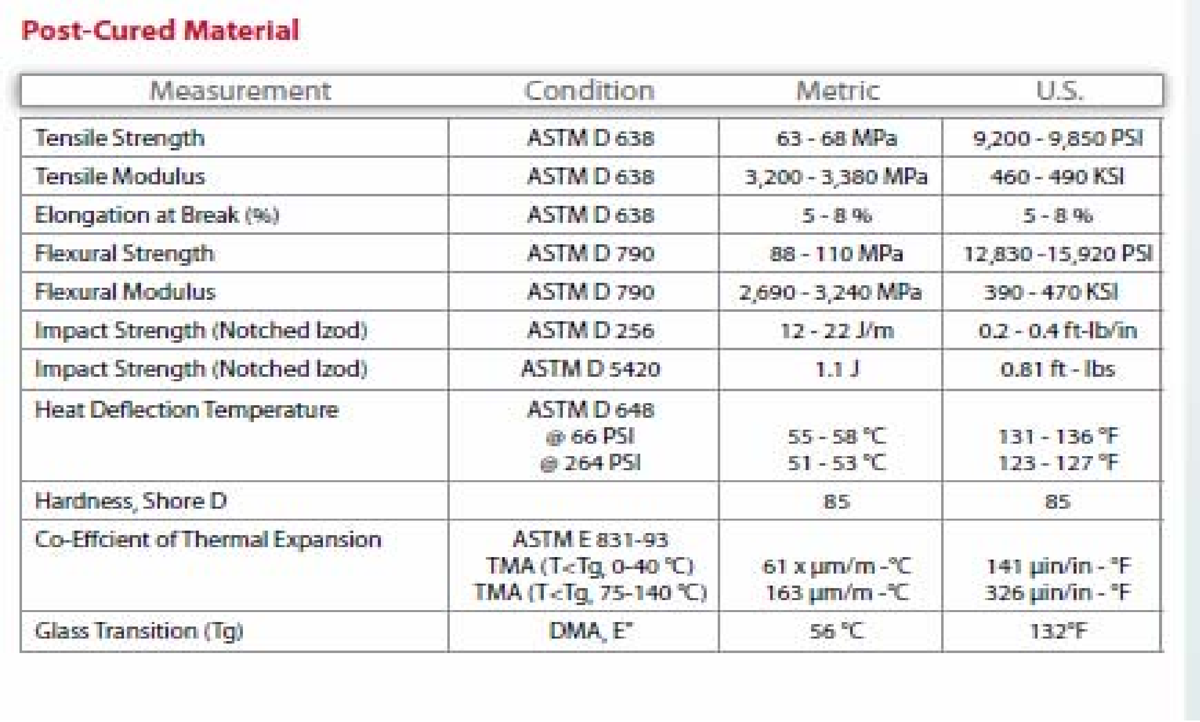
Functional components for assemblies and mock-ups. Look and feel like molded ABS, durable and rigid with high accuracy with less distortion.



Technical Data

Liquid Material

Measurement	Condition	Value
Appearance		White
Liquid Density	@ 25 °C (77 °F)	1.13 g/cm³
Solid Density	@ 25 °C (77 °F)	1.20 g/cm³
Viscosity	@ 30 °C (86 °F)	155 - 185 cps
Penetration Depth (Dp)*		5.2 mils
Critical Exposure(Ec)*		7.4 mJ/cm²
Tested Build Styles		EXACT™, FAST™, EXACT™ HR

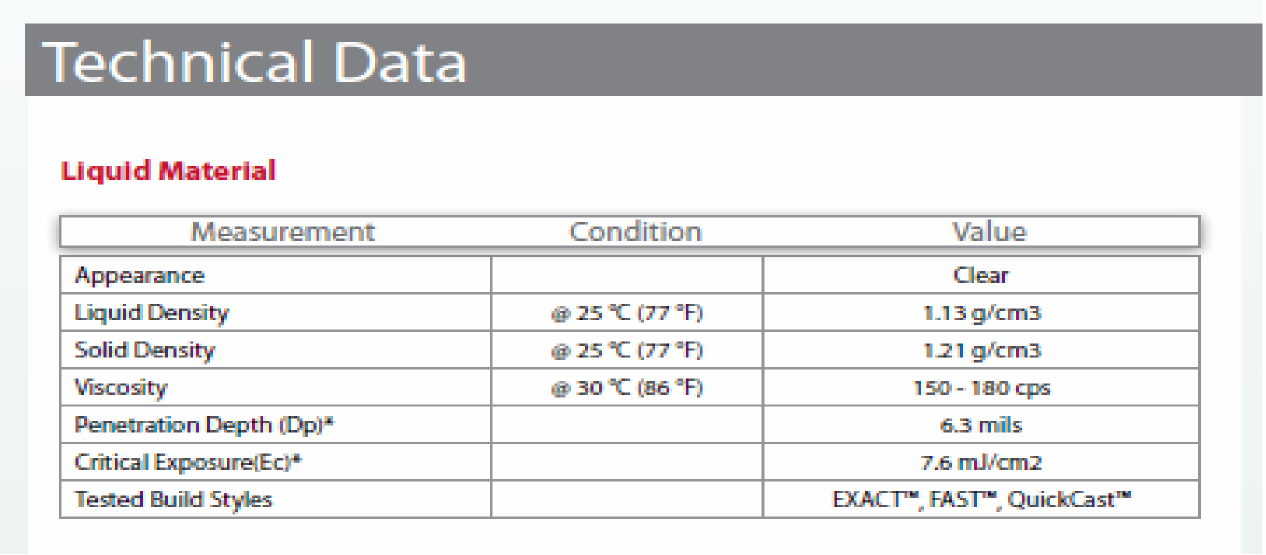


Post-Cured Material

Measurement	Condition	Metric	U.S.
Tensile Strength	ASTM D 638	63 - 68 MPa	9,200 - 9,850 PSI
Tensile Modulus	ASTM D 638	3,200 - 3,380 MPa	460 - 490 KSI
Elongation at Break (%)	ASTM D 638	5 - 8 %	5 - 8 %
Flexural Strength	ASTM D 790	88 - 110 MPa	12,830 -15,920 PSI
Flexural Modulus	ASTM D 790	2,690 - 3,240 MPa	390 - 470 KSI
Impact Strength (Notched Izod)	ASTM D 256	12 - 22 J/m	0.2 - 0.4 ft-lb/in
Impact Strength (Notched Izod)	ASTM D 5420	1.1 J	0.81 ft - lbs
Heat Deflection Temperature	ASTM D 648 @ 66 PSI @ 264 PSI	55 - 58 °C 51 - 53 °C	131 - 136 °F 123 - 127 °F
Hardness, Shore D		85	85
Co-Effcient of Thermal Expansion	ASTM E 831-93 TMA (T<Tg, 0-40 °C) TMA (T<Tg, 75-140 °C)	61 x μm/m -°C 163 μm/m -°C	141 μin/in - °F 326 μin/in - °F
Glass Transition (Tg)	DMA, E"	56 °C	132°F

- **Accura® 60**

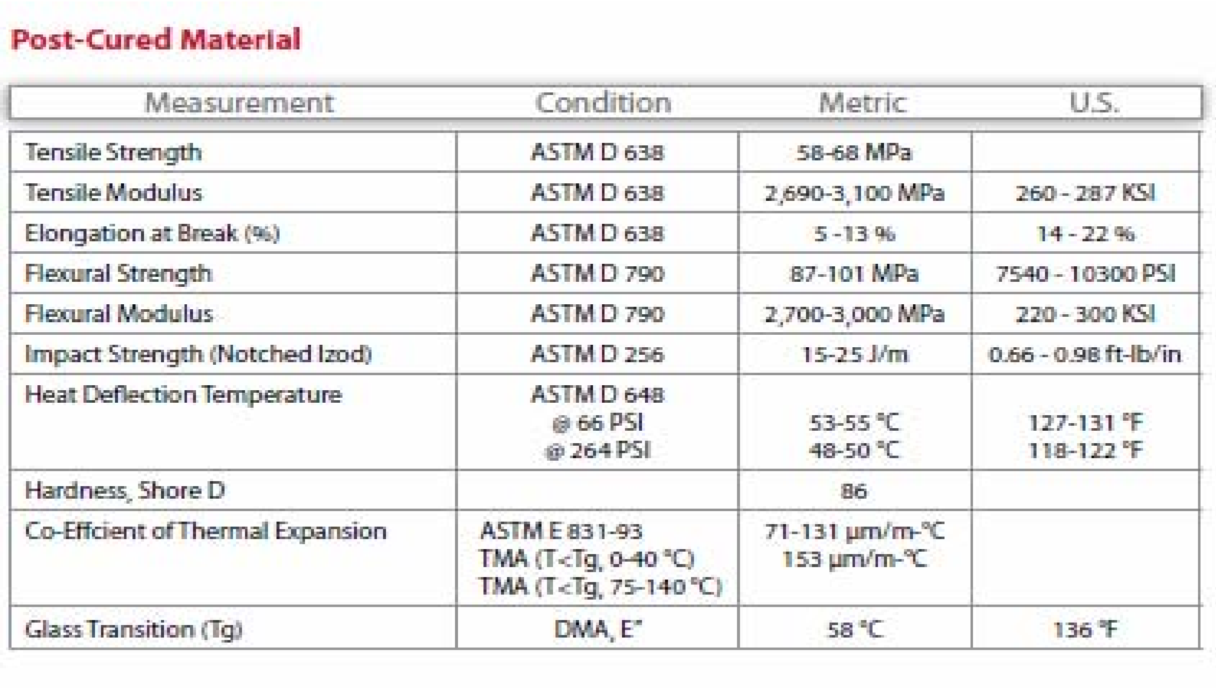
Simulates the properties and appearance of polycarbonate with this clear, rough plastic. Suitable for clear display models and transparent assemblies



Technical Data

Liquid Material

Measurement	Condition	Value
Appearance		Clear
Liquid Density	@ 25 °C (77 °F)	1.13 g/cm3
Solid Density	@ 25 °C (77 °F)	1.21 g/cm3
Viscosity	@ 30 °C (86 °F)	150 - 180 cps
Penetration Depth (Dp)*		6.3 mils
Critical Exposure(Ec)*		7.6 mJ/cm2
Tested Build Styles		EXACT™, FAST™, QuickCast™



Post-Cured Material

Measurement	Condition	Metric	U.S.
Tensile Strength	ASTM D 638	58-68 MPa	
Tensile Modulus	ASTM D 638	2,690-3,100 MPa	260 - 287 KSI
Elongation at Break (%)	ASTM D 638	5 -13 %	14 - 22 %
Flexural Strength	ASTM D 790	87-101 MPa	7540 - 10300 PSI
Flexural Modulus	ASTM D 790	2,700-3,000 MPa	220 - 300 KSI
Impact Strength (Notched Izod)	ASTM D 256	15-25 J/m	0.66 - 0.98 ft-lb/in
Heat Deflection Temperature	ASTM D 648 @ 66 PSI @ 264 PSI	53-55 °C 48-50 °C	127-131 °F 118-122 °F
Hardness, Shore D		86	
Co-Effcient of Thermal Expansion	ASTM E 831-93 TMA (T<Tg, 0-40 °C) TMA (T<Tg, 75-140 °C)	71-131 µm/m-°C 153 µm/m-°C	
Glass Transition (Tg)	DMA, E"	58 °C	136 °F

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