THE MATERIALS ADVANTAGE OF THE SLS™ SELECTIVE LASER SINTERING PROCESS

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Introduction

The rapid prototyping market continues to progress in terms of processes and materials used for the creation of conceptual and functional parts and prototype tooling. As this market continues to mature, the market leaders will be able to offer rapid prototyping processes and materials that provide parts which are accurate, have good surface finish, and provide properties which support functional applications. The materials used for these parts will be polymers, metals, and ceramics. The strength of the SLS™ Selective Laser Sintering Process is the potential to use a wide variety of powdered materials for the creation of models, patterns, and some forms of prototype tooling. This paper will cover the types of materials currently used in the SLS process and their inherent advantages and discuss current research into the development of new materials.

Powdered Materials

The use of powdered materials in the SLS process has several inherent features that address the basic requirements for fast modeling, prototyping, and pattern-making within almost all industries. These include:

1) Speed;
2) The additive-layer nature of the part building process; and
3) The ability to employ a variety of heat-fusible powdered materials.

Speed

The main factor affecting the speed at which a part can be built is the thickness of the layers being sintered. A part which is being sintered with a layer thickness of 0.005 inch (0.125mm) will take approximately twice as long as a part being sintered with a layer thickness of 0.010 inch (0.25mm). This is due to the total number of layers needed to manufacture the part. At 0.005 inch (0.125mm)it will take 200 layers to build 1 inch of part height. Using a 0.010 inch (0.25mm) layer thickness, the 1 inch part will require 100 layers to build the part.

The time needed to scan a layer of a part is determined by the area of the layer, the complexity of the layer, and the number of parts being built simultaneously. As the size, complexity, and number of parts increase, the time needed to complete a layer in the process increases.

The type of material will also greatly affect the time needed to complete a part. The wax requires more time to process since a cool down time is added to each layer at the end of the scanning process. This cooling period may be from 1 to 30 seconds depending on the geometry and size of the parts. Typical build times for materials used in the SLS process are:

Wax build rate of 0.125 to 0.5 inch (3.125 to 12.5 mm) of vertical height per hour
Thermoplastic build rate of 0.2 to 1.0 inch (5.0 to 25.4 mm) of vertical height per hour.

To further increase the overall speed, the SLS process software performs concurrent slicing of the part geometry files while processing of the object is taking place. Moreover, no post-production curing is necessary with the SLS process when using wax or thermoplastic.

An Additive Layer Process

The additive-layer nature or layered manufacturing technique of the SLS process also allows for the creation of very complex parts without the need for external support structures or fixtures, clamping, or repositioning of specific portions of the design geometry. This is possible because the unsintered powder that surrounds the fabricated part during the SLS process provides a customized support structure that is easily removed upon part completion. Designs with internal cavities, overhangs, undercuts, and other intricate geometries, which are difficult to achieve through other processes, are easily produced using the SLS process. In short, the SLS process allows a degree of total design freedom never before realized because of the constraints tooling placed on designs.

Multiple Materials

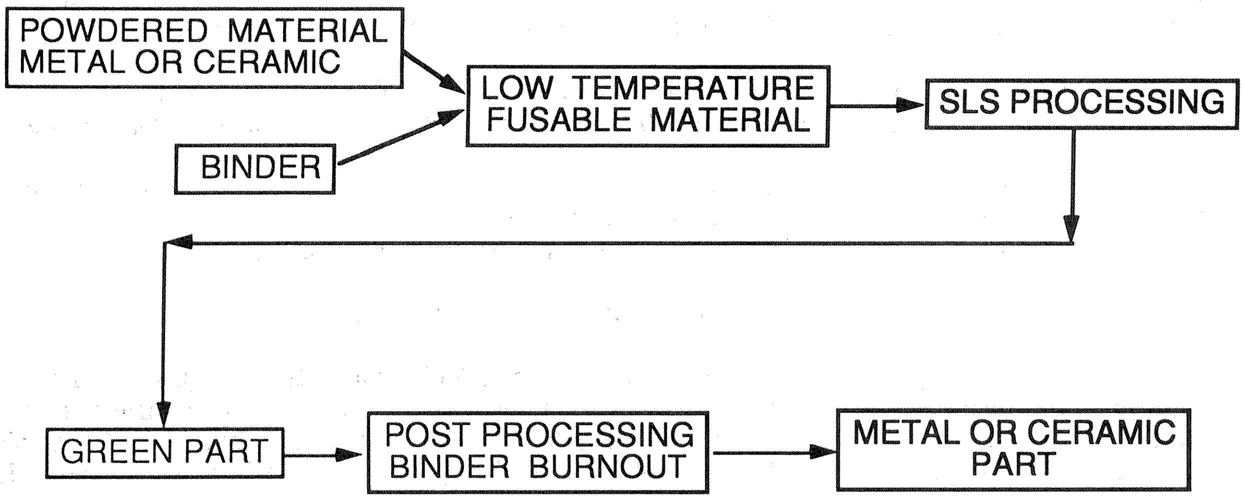
The SLS process can use a variety of materials. In fact, virtually any material that softens and has decreased viscosity upon heating or that can sinter with the application of heat can potentially be used. Materials currently available include: investment casting wax, polycarbonate, and nylon. Other thermoplastics that have shown potential as powdered materials in the SLS process include polyester, polyurethane, and a glass filled nylon.

The natural evolution of the SLS technology is also heading toward the use of powdered metals and ceramics. Current market research indicates that this capability will have widespread application throughout manufacturing industries, primarily because more than 80 percent of all design prototypes are currently made from various metals using conventional processes.

Metals and Ceramics

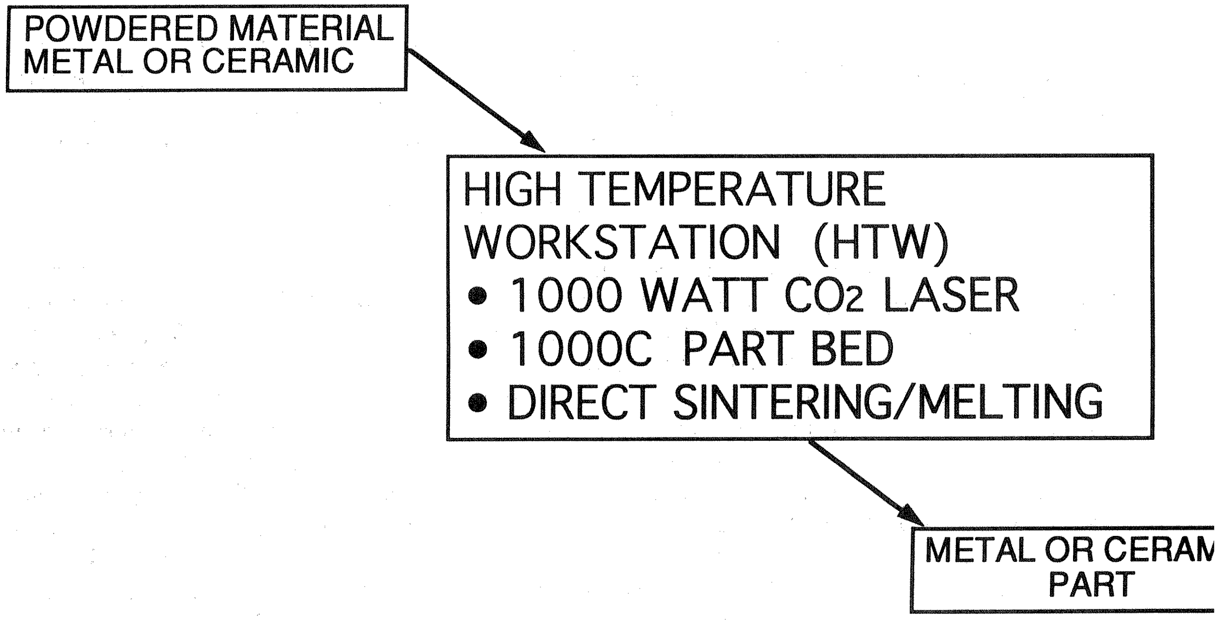
In response to these market requirements for metals and ceramics, DTM is currently funding research using powdered metals and ceramics with the SLS process. This research is focused in the areas of direct and indirect sintering using the SLS process. The indirect method involves combining a low temperature binder with a powdered metal or ceramic to form a powdered material which can be fused into a "green shape" using a low temperature SLS process. The green part is then removed from the SLS process and placed in a high temperature furnace. Temperatures in the furnace are sufficient to burn off the binder and sinter the metal or ceramic particles together. This process is analogous to metal or ceramic injection molding. Early tests have focused on polymer coated copper, alumina, glass, and zircon and inorganic binders such as ammonium phosphate and boron oxide have been used with alumina. Already verified in practice on the existing Sinterstation™ 2000 System product platform, materials such as copper mixed with binders have been fabricated to produce EDM electrodes. Alumina ceramic molds for investment casting have also been produced in the same low temperature process. The process of indirect sintering is shown schematically on the following page.

Indirect Sintering



Direct Sintering

The direct method of Selective Laser Sintering involves using a higher temperature process chamber and a higher wattage laser to fuse metal and ceramic particles. This process is being used on an experimental basis at The University of Texas in Austin. The University, through DTM funding, has constructed an High Temperature Workstation (HTW) which employs a 1000 watt laser and a process chamber capable of reaching 1832 °F (1000 °C). Using the direct method of sintering, no post-sintering is required to complete the parts. The goals of this research program are the determination of the optimum process parameters for materials used in the next generation of SLS systems that will sinter metals and ceramics for future applications that include the direct manufacture of prototype tooling and complex parts.



The areas of current research with metal and ceramics are summarized in the following table:

	Sintering Method	
Material	Indirect	Direct
Metal	Polymer Coated Copper	Cobalt-Tungsten Carbide Copper-Nickel Aluminum-Silicon Carbide
Ceramic	Polymer Coated: Alumina Glass Zircon Alumina/Ammonium Phosphate Alumina/Boron Oxide	Aluminum-Aluminum Oxide

The addition of metals and ceramics to the SLS process will greatly enhance the possible applications of the process. It may be feasible in the future to directly sinter a number of metals into 3-D solid shapes. Using a pure copper or copper-tungsten powder in the process may allow EDM electrodes to be made directly in the SLS process. This will significantly reduce the time required to generate EDM electrodes which have complex shapes for mold building.

Using select metals, it may be possible to generate core and cavity inserts for injection molds. Because of the unlimited design potential of the process, these molds may have water-cooling channels and bubblers that are curved to accommodate the core and cavity surfaces. This would allow for a uniform temperature distribution across all mold surfaces, which is not easily obtainable with conventional mold-building techniques.

Investment Casting Wax

The investment casting wax used in the process is an investment casting wax that The BFGoodrich Company purchases then powders in a patented process. This material has been in use for over 18 months and has gone through several improvements. The patterns made from this investment casting wax go directly into the investment casting process and can follow the procedures normally used for patterns generated via molding wax. Thus the problems of long burnout cycles associated with photopolymer resins are eliminated. Other benefits of the SLS process with investment casting wax include:

- Accuracy within the specifications of most investment casting applications. The average tolerances range of wax patterns made in the SLS process range from ±0.002 to ±0.010 inches (±0.04 to ±0.25 mm). This meets the accuracy requirements for most investment casting applications.

- A surface finish that is suitable for most investment casting applications, typically 100 to 120 average micro inches RMS. When smoother finishes are required, secondary polishing and finishing may be employed.

- Eliminating the tooling stage translates into numerous benefits for investment casters, including minimized up front tooling costs and significant time savings for prototypes and the ability to produce complex shapes that were previously too difficult to produce via simple tooling.

Most parts made of wax in the SLS process have very complex geometries and are typically produced in very small quantities, typically less than 10 pieces. Some sample applications include:

- Aerospace parts produced in titanium or other exotic alloys which are difficult to machine. The use of the investment casting process with the SLS process to quickly produce wax patterns allows for the rapid prototyping of parts which would normally take months to manufacture.
- In the transportation industry, wax patterns are used to quickly produce functional metal prototypes for use on the engine or drive train. These pieces would be time consuming to prototype via traditional methods.
- In medical prosthetics industry, custom made prosthetic implants can be quickly made in investment casting wax from CAT scan data then cast in the alloy of choice.

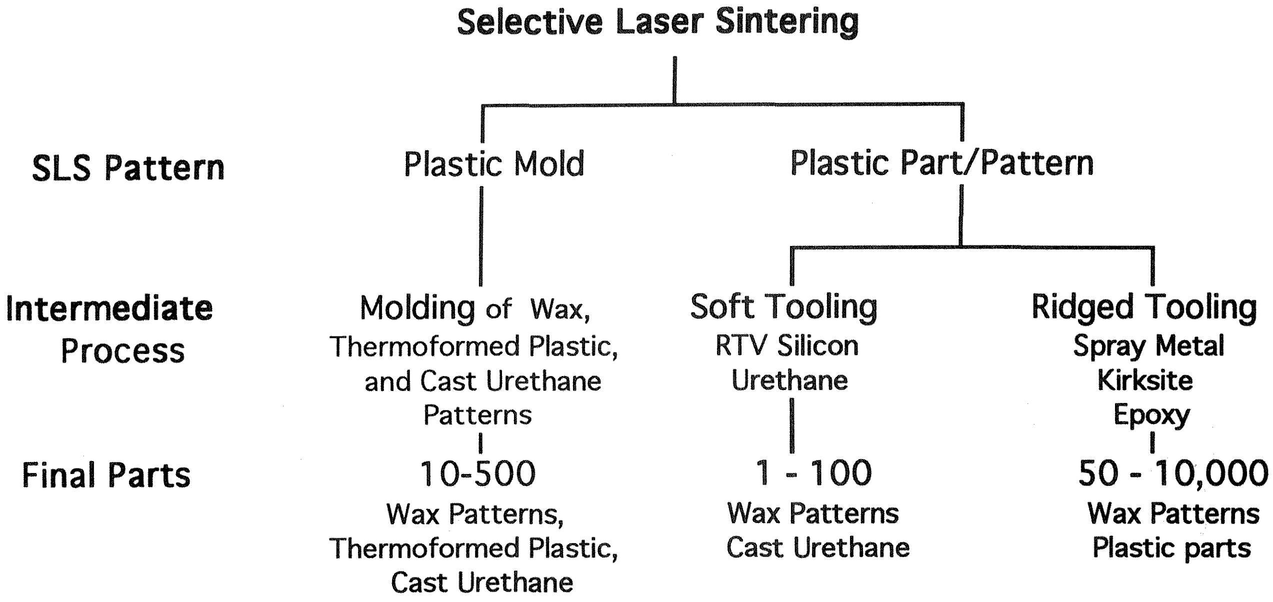
Polycarbonate

Polycarbonate has been used in the SLS process for a variety of purposes, ranging from functional models to patterns for tooling to an actual tooling material. Currently, the most common use of the material has been for the development of functional models. The advantages of the SLS process are significantly impacting product design capabilities in the plastics industry, resulting in shorter design cycles and superior design. The process allows the designer to make a part directly from a 3-D CAD design for visual inspection of form and fit and also allows the designer to perform some limited functional testing. Applications for these functional models span almost every industry. In effect, the use of the SLS process serves as a time-saving, communications-enhancing bridge between design and manufacturing. Thus, it is an excellent tool to aid in concurrent or simultaneous engineering efforts. Every market segment that produces parts via injection molding has used the SLS process. Some of the more common uses are listed here:

- Computer housings and printers have been prototyped using the SLS process. The parts for these housing have been assembled and tested for form, fit, and some functional testing. The SLS generated parts may be painted to give the appearance of an injection-molded part.
- Toys have been made for test marketing purposes. If there is large market acceptance, then a mold is made and the item is produced in large quantity.
- Automotive electrical components are built to assess fit and function and to verify the design. In some cases, these parts are finished to give the appearance of an injection-molded part.
- Electrical enclosures are made to give the designer and manufacturer information on how efficient the design will be and how easily it may be manufactured.
- Power tools are prototyped to provide an operating model and to allow manufacturing, tooling, and assembly operations to review the parts and make recommendations on improving or adjusting the design before hard tooling is built.

All of these markets have one thing in common: There is a requirement to evaluate the plastic part before making large commitments in terms of time and money for production tooling.

The functional models may also be used as patterns to generate prototype tooling in a variety of ways. There are three categories of molds that can be made when using the SLS process. They include mold patterns which are used for the direct manufacture of prototype parts and part patterns which are used as a master for both rigid and soft tooling.



Prototype molds made of polycarbonate in the SLS process may be used in a variety of processes. These include molds for wax injection which will produce patterns for investment casting, thermoforming tools, and patterns for sand casting. The thermoforming or vacuum-forming molds are used for materials with a forming temperature of less than 170^{o}C (338^{o}F). Materials that are formed below this temperature include polypropylene, polyethylene, polystyrene, and ABS.

Rigid tooling is used where a small number of injection molded samples are required. The most popular method of making these molds currently is the TAFA spray metal process. It consists of defining a parting line on the pattern then spraying a low temperature molten metal over the pattern to build-up a core or cavity detail which may be approximately 6.3mm (0.25 inch). These shells are then backed with a low-melting-temperature metal or a metal-filled epoxy. Ejector pin holes are added and the mold is assembled.

Other methods for building ridged tooling include nickel vapor deposition, metal plasma deposition, Kirksite casting, and epoxy casting. The number of parts obtainable from any of these ridged tooling techniques depends on the type of material being injected into the mold. As a general rule, materials which process at higher temperatures, require greater pressures, and are filled, will shorten the life expectancy of the mold.

For a very limited number of parts, soft tooling may be used. These are molds generated in RTV silicone or a flexible urethane. These molds may be used to generate parts from cast urethane materials or from wax to be used in the investment casting process.

Nylon

The latest material being added to the line of SLS materials is a Nylon. This material was selected based on its performance in early testing. It offers improved toughness and strength over polycarbonate and will expand the number of functional applications for SLS-generated parts.

Since the material is a crystalline polymer, it offers improved chemical resistance over the polycarbonate and has successfully been used in high temperature caustic plating baths.

New applications include:

- Functional automotive components with the thermal properties to withstand the on-engine temperatures and the chemical resistance for use as a functioning prototype.
- Connectors with the detail and functionality to be used as prototypes.
- Prosthetic devices that can be custom made and used directly from the SLS process.

New Material Development and Characterization

When a material is selected for use in the SLS process, safety is a primary concern. The first step in the safety process is to review the MSDS sheets to ensure that the material is safe for the operator to handle. If the material is non toxic and safe, then it is reviewed to ensure that it will not cause a safety hazard in the machine. Once safety criterion are met, then the material will be tested via a single layer test to begin to understand how it sinters on a layer basis before multi-layer tests begin.

Further testing will include a 10 hour normal run test that will be used to collect gas data and determine if any gasses are being generated in a normal running mode.

Another test performed on a new material is called an upset test which is designed to determine what happens to a material exposed to high temperatures in the SLS process. This 90 minute test is performed by running the heaters at a high temperature with no nitrogen flowing through the system. The laser power is set at 100% to further degrade the material. Again, gas samples are collected and analyzed to determine if any harmful materials are begin emitted from the system.

Process Developments and Improvements

With the development of new materials, the sintering process is continually enhanced and refined to produce quality parts specific to each new materials. Since this is a thermal process, the distribution of heat across the machine is critical and the design improvements in the Sinterstation 2000 have been to provide a uniform thermal distribution across the part bed. Currently, DTM is using thermal imaging to study temperature distribution in the SLS process chamber. Again, these improvements in the process will lead to improvements in the strength, surface finish, and accuracy of the parts.

Other improvements to the process over the last year include:

- The addition of a beam off setting software to improve the accuracy.
- A redesign of the SLS model 125 into the Sinterstation 2000 System that offers improvements in powder handling, laser delivery, and a graphical user interface.

Summary

The SLS process is a viable time and money saving method for generating complex prototype parts in the plastics and metals industries based on the materials employed in the system. The benefits of using the system include:

The ability to use a variety of materials and the future ability to expand the variety of materials which will work in the process. Current materials include investment casting wax, polycarbonate, and nylon. Future materials will include additional thermoplastics and the addition of metal and ceramic parts made with binders in an indirect sintering process and the direct sintering of metals and ceramics in a high temperature SLS process.

The ability to generate very complex parts using powdered materials. This can be accomplished since the powder acts as a natural support structure during the build process. With some materials and some designs, the fabricated parts may require the use of a base grid to minimize distortion of the part.

A process which is very fast. The powder is fused together in a thermal process and there is no need for secondary curing.

The wax patterns made in the SLS process can be used directly in the investment casting process. This eliminates the need for excessive burnout cycles normally associated with photopolymer based systems. The process can be used to effectively generate small quantities of parts (1 to 20 pieces) without the need for expensive and long lead time tooling.

In the plastics industry, the process can be used to generate functional models from three-dimensional CAD models to visualize part form, verify fit, and test some aspects of the function. These functional models are and excellent aid for concurrent engineering because they clarify the communication between the designer, manufacturing, and marketing departments.

Prototype tooling may be generated by a variety of techniques using SLS generated part patterns and mold patterns. These prototyping techniques include generating the mold pattern using a powdered polycarbonate material. These mold patterns may be used for wax injection applications. From this SLS-generated part pattern, prototype soft or rigid molds may be produced using secondary processes such as RTV molds and spray metal tooling.