**3-D PRINTING; SEEING THE WORLD IN A NEW DIMENSION**

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***Abstract--****In the early 1990’s the best way to properly visualize a three dimensional object was with a model.  Over the next two decades technology improved to the point where computer aided design and rendering became a practical alternative.  Despite these advances, sometimes a physical three dimensional model is still the most preferred representation.  Other outdated methods like carving or sculpting are an effective way to create a model, but these methods can create unnecessary waste and can be time consuming.  With the invention of three-dimensional printing both of these issues are diminished.  Compared to older techniques, three-dimensional printing produces little to no excess waste, and substantially reduces the time required to create models.*

*This paper will explore the development and applications of 3-D printing technologies starting from its origins. First, four different methods of 3-D printing will be analyzed, focusing on the advantages and disadvantages of each. The methods of Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), inkjet printing, and stereolithography will be analyzed. After looking at the various methods of 3-D printing, this paper will go into the specific uses of SLS in both the industry and for commercial use, specifically the manufacturing of custom parts. Finally, the potential benefits and drawbacks of future use will be discussed.*

*3-D printing will improve the way mankind visualizes and implements three dimensional models.  Selective Laser Sintering, with its level of precision and customizability, will offer much more detailed and unrestricted models than older methods such as metal casting.*

*Key Words--3-D Printing, Additive Layer Manufacturing, Direct Metal Laser Sintering, Powdered Materials, Rapid Prototyping, Selective Laser Sintering*

# What is 3-D Printing?

Three-Dimensional Printing is the future of visual aids, communicating ideas, prototyping, and implementing three dimensional models in everyday life. This method of model creation is fast. “Most prototypes require three to seventy-two hours to build, depending on the size and complexity of the object. This may seem slow, but compared to the weeks or months required to make a prototype by traditional means such as machining,” [1] 3-D printing is much quicker. Efficiency is another major benefit which shows how 3-D printing is superior to older methods. 3-D printing differs from some conventional methods of modeling in that it builds up the model layer by layer instead of slowly carving out pieces from a large slab of base material. Using these additive methods instead of subtractive methods reduces waste. “Born out of the rise of so-called rapid prototyping (RP) technologies in the 1990s and driven by the vision of a future where additive manufacturing could be as widespread and accepted as subtractive manufacturing methods are today, many people and companies around the world have developed ideas, prototype methods and commercial systems.” [2] Improvements in the field of 3-D printing have drastically changed this technology from an idea to a potential tool for both industrial and personal use.

  The process of creating the model using a three dimensional printing machine is quite easy. The user can either create a computer aided design (CAD), or obtain data from a three dimensional scan. From this data, a computer program chops up the computer model into two dimensional slices. This is the most effective way to transfer the data to the modeling machine because all three dimensional modeling machines print in layers and the data file is effectively feeding the machine one layer at a time.

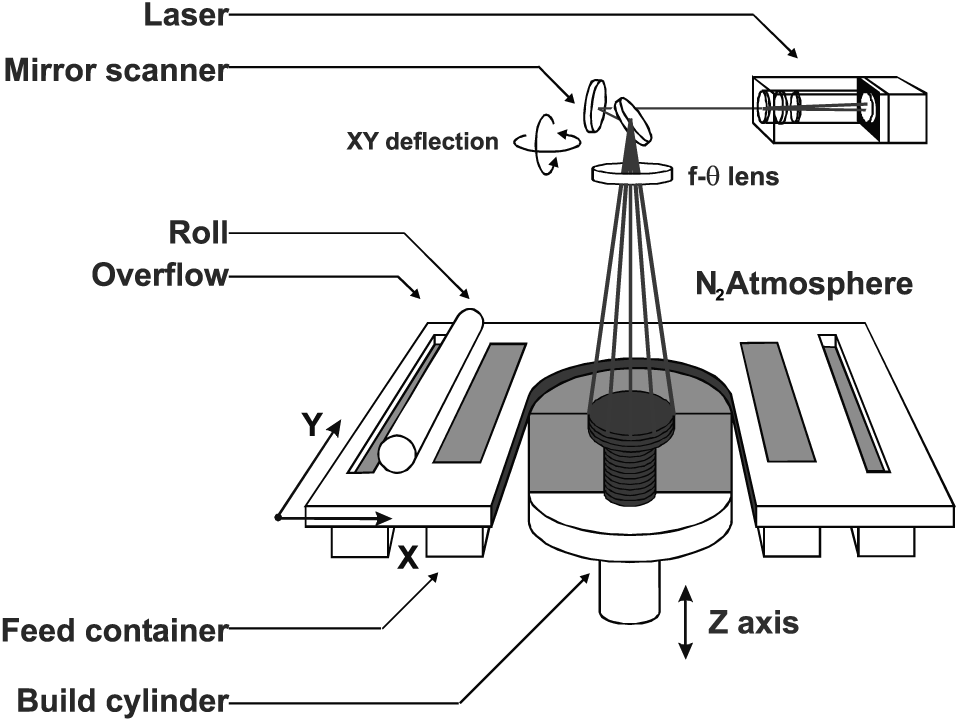
  As the computing power of computers has improved, better 3-D modeling programs have been created. Digital models can be made in programs such as SolidWorks. The SolidWorks program can output in the form of a STL file which is the file type accepted by most three dimensional printing machines.

   The four most prominent methods of three dimensional printing are Selective Laser Sintering, Stereolithography, Fused Deposition Modeling, and 3-D Inkjet Printing.  Stereolithography is considered to be the oldest, 3-D Inkjet printing is considered to be the most widely used, Fused Deposition Modeling is considered to be the simplest, and Selective Laser Sintering is the most versatile method of three dimensional printing. Because there are so many method of SLS printing, this research paper will delve deeper in to this method.

# Methods of 3-D Printing

Even though 3-D printing is based off of the additive method, there are many different approaches to making the final model. The following sections will give a brief overview of four main methods of 3-D printing; Stereolithography, Fused Deposition Modeling, 3-D inkjet printing, and Selective Laser Sintering. Each method has its own benefits and drawbacks that affect the qualities of the completed model.

Selective Laser Sintering

Selective Laser Sintering (SLS) is a method of 3-D printing that uses powders as the base material and a laser as a binding method. SLS starts with an application of powder onto a flat modeling platform, which may be heated to bring the powders closer to their melting point. A laser is then shot at the powder, causing it to undergo changes, depending on the intensity of the laser and the type of materials being sintered, and solidify to form the bottommost horizontal layer of the final model. The modeling platform is then lowered, another layer of powder is applied, and the process is repeated until the model is done. Once the model is done, the unsintered dust can be washed off and reused. Figure 1 shows an example of a SLS machine. Post-processing may involve shot-peening in order to strengthen the outermost layer. SLS can be further categorized depending on what kind of material is used (whether it’s a polymer, metal, wax, nylon, ceramic, or composite), exactly how the powdered materials interact with one another, and the degree to which the particles are melted. [3]

     The first subdivision of SLS is solid state sintering. Solid state sintering uses one kind of powder and a laser that heats the powder to between half the melting point of the powder and the melting point of the powder. At this range of temperatures, diffusion can occur, combining the powder particles into one mass. This method allows the use of a wide variety of materials. As long as the laser can provide enough energy, all kinds of powdered metals and polymers can be used in solid state sintering.

Figure 1: An example of a SLS machine. [3]

     Another subdivision of SLS is chemically induced binding. This type of SLS uses specific kinds of materials that partially form binding agents when heated. An example of this is SiC which forms SiO2 when heated. The binding agent (SiO2) mixes with the unreacted particles (SiC) to bind the whole structure together. This method only uses one type of material, which acts as both the structural material and the binding material. The problem with chemically induced binding is that it can only process certain materials which turn into binding agents when heated. This method is generally used to prototype ceramics.

     The third subsection of SLS is liquid phase sintering (LPS). This method relies on two or more different kinds of powder interacting to form the final structure. This method can be further divided into those methods based on whether the binder and structural particles are treated separately and exactly how those particles are arranged. In cases where the binder and structural materials are separate, the binder particles are generally much smaller than structural particles. This is due to the higher surface area to volume ratios of the smaller particles, causing them to heat up faster and melt first. The properties of the final model are influenced by exactly where the binder ends up within the structure, and how it has bound with the structural particles. These properties vary somewhat due to the random nature of heated particles. People have approached this problem by altering the powders themselves. The binder particles can be integrated into the structural particles by alloying the particles together. This is done by repeatedly melting together and breaking apart the component metals until the resultant particle is a mixture of both materials. This process results in a denser and smoother model than if the particles were simply mixed together. Another possibility is coating the structural particles with the binder material itself. In this configuration, the melted binder has to travel less in order to “glue” the structural particles together. This results in a more effective bonding between structural particles, creating a stronger and more coherent model. [3]

     When the distinction between binder and structural particles is not so clear, the powder may act as both the binder and the structural particles. This is similar to chemically induced binding, except the powders do not chemically react. The degree to which the materials melt provide another condition with which to differentiate between types of LPS. One type is called single-phase, partially molten sintering. A laser is directed at a particle causing the outer shell of a powder particle to partially melt, leaving the core intact. Then the outer layer acts as the binder between the solid cores, creating one mass. Another type, where the particles being sintered do change phases, is called fusing powder mixture. In this method, a powder consisting of multiple elements is melted. The different elements all melt at different temperatures, leading to a mixture with a variety of phases. Sintering with multiple materials allow the modeler to infuse the model with a variety of properties. For instance, adding Fe3P lowers the melting point of the entire powder. This makes the entire process require less energy and thus make it more efficient. Direct Metal Laser-Sintering (DMLS) is another type of LPS where metal powder is solidified directly into metal parts. (The principal application of DMLS so far has been rapid tooling.) This method has been reported to make nearly full-density tools. [2]

    A fourth subsection of SLS is called Selective Laser Melting (SLM). This differs from solid-state sintering by actually melting the metal powder, instead of merely heating it up. This ensures denser resultant models since more of the powder is melted and solidified. This method of SLS can form full dense objects with both polymers and metals. Theoretically, every metal is a potential material for this method of SLS; however processing specifications need to be determined experimentally for each metal due to their differences in structure. This is why there is still a rather limited selection of materials for this method. There are, however, commercially available materials in the form of steel and titanium.

    Apart from the specifications of the powdered materials, the type of laser and the method of powder application also influence the properties of the final model. Older DMLS machines used CO2 or Nd:YAG lasers, but more recent models use fibre lasers or disc lasers [2]. Fibre lasers and disc lasers have higher power intensities than CO2 lasers and are capable of faster melting times. The method of powder application onto the modeling platform also affects the quality of the final model. Factors such as the density, roughness, and overall stability are all related to how the powder is arranged on the modeling platform before sintering. If the added layer is too thick, then the laser may not completely melt the bottom of the new layer, causing higher porosity and incomplete binding. If the added layer is too thin, the final model would have a higher density and more stability, but the construction time may be significantly increased. The ideal layer thickness varies with different materials and the kind of method used. A balance between scanning speed and model accuracy should be found.

Stereolithography

Stereolithography uses a vat of light-activated polymers as the base material. This printing method starts with a layer of polymer liquid which is then treated with a light source to solidify the polymer. After a layer is solidified, the machine adds another thin liquid layer of the polymer by dropping the modeling platform a fraction of an inch lower into the liquid polymer vat. This allows the laser to treat another layer of polymer right on top of the first layer. When the entire model is solidified, the structure is lifted out from the vat of liquid and the excess liquid flows away from the model.

   There is more than one method for curing the photo-reactive polymer. The most common and widely used method involves a laser and a series of servos. The laser is mounted on a track in the same manner as a printing cartridge on a normal 2-D printer would be, but the setup can move the laser in two dimensions instead of just one. This allows the laser to print the two dimensional layer before the modeling platform drops the uncompleted model another fraction of an inch lower in to the vat of polymer. The other method uses a digital light projection system to deliver the light to the polymer. This method works much differently than the laser method. It uses a constant light source reflected off a digital mirror device. The digital mirror device has many pixels which ether deflect the light on target or deflect the light away from the polymer. This creates an image of light which solidifies each layer one “picture” at a time.

   Since the model is created using a photo-reactive polymer, an optional stroboscopic post-curing process can be done to improve mechanical properties of the model. This post curing process uses a series of ultraviolet lights to ensure that the photo-reactive reaction has gone to completion.

   The difference between stereolithography and Selective Laser Sintering, besides the materials used, is the laser is generally much more powerful in SLS. The laser used in SLS needs to be able to melt solids, and not merely activate polymers. Another thing to note is that SLS does not require part support structures that are needed in stereolithography since the unsintered particles provide enough support. This allows SLS to model overhangs and unsupported structures more easily than other methods.

  This method of three dimensional printing is easily the most climactic considering that the final product is effectively hidden in the vat of  liquid until it is finally lifted out and displayed when the modeling process is finished. [4]

  There are key differences between stereolithography and SLS that should be taken in to consideration when debating which method to print your model with. The first and most important factor to be considered should be the materials that the machines print with. Stereolithography machines print in a select variety of polymers because they have the strict requirement of being photo-activated. There are only a handful of photo-activated liquids and low viscosity gels that can be used, some of which are urethanedimethacrylate, diisopropyl acrylamide, trimethylolpropanetriacrylate, diisobutyl acrylamide, tetraethlene glycol diacrylate, and 2-( 2-ethoxy-ethoxy) ethyl acrylate. [4] Accuracy is another important factor. Stereolithography can create perfectly circular pillars at sizes smaller than 500 micrometers due to the fact that a point of energy in the form of a laser radiates outward to a specific distance creating a perfect circular shape. Figure 2 is an example of pillars formed with stereolithography. Figure A, on the right side, shows newly fabricated pillars, while B shows the same pillars after being exposed to body fluids for some time. In addition the surfaces tend to be smooth due to how the polymer is activated.  SLS also uses a laser, but it has a powder base.  The accuracy of an SLS model is highly dependent on the size and type of powder particles used.  The ideal particle size can range anywhere from 10-150 micrometers depending on what is being accomplished. [5] Since there are so many methods of SLS to consider, neither method is superior in every way.  Each method has its own benefits and detriments that should be taken into consideration when deciding which method of 3-D printing to use.

Fused Deposition Modeling

Figure 2: A close up of objects formed by stereolithography. [4]

Fused Deposition Modeling is a method of three dimensional printing that uses layered manufacturing. “Layered Manufacturing (LM) is a rapid Prototyping (RP) technique in which a part is fabricated by stacking layer after layer.” [6] FDM deposits melted lines of plastic onto a platform causing the plastic to rapidly cool and harden. Lines of plastic, called roads, are laid down in parallel. Once a layer is “laid” either the modeling deck is lowered by a fraction of an inch, or the extruding head is raised. The amount the extrusion head should be raised, or alternatively how far the modeling deck dropped, is determined by the thickness of the extrusion.

  The orientation of these roads can greatly affect the strength of the final model because the direction of the roads can cause great structural weakness in certain regions if the model is poorly laid out. Designers should take this into consideration when designing a model or product with the FDM method. For instance, if the model is going to need to resist a strong sheering force in a certain direction than the modeler should have the FDM machine lay the roads perpendicular to the sheering line. Figure 3 shows some examples of possible ways to lay a road. There is an inherent structural weakness in the road laying process. The fact that the extrusion is in a melted state is the only thing that attaches the roads to one another.

  It is very important to take the orientation of the model being printed in to consideration when using FDM. If printing a long thin rod is required, there are many different ways to orient it in a three dimensional printing space. The best option is to lay the rod on its side and allow the printer to print along the shape, but if you were to place it vertically than the machine would have to print thousands more layers and the entire print would take much longer even though it is the same model with the same dimensions.

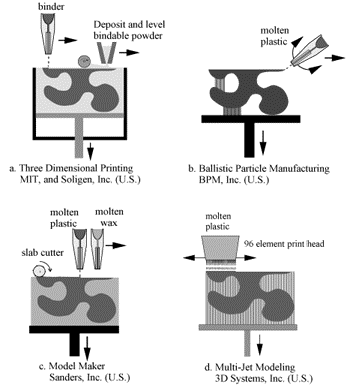
  There are key differences between Selective Laser Sintering and Fused Deposition Modeling worth considering. FDM uses extrusion to build models while SLS uses laser sintering. Extrusion has inherent size restrictions. The type of FDM machine controls the width of the roads being laid, and if there is a road with a width of 200 micrometers no part of the model can have a smaller thickness than that. The most precise FDM machines can print roads smaller than 100 micrometers. When considering accuracy and surface effects, there is a lot to consider.  With SLS, the most economic models will yield a sandy surface while the most economic FDM machines will yield a smooth ribbed surface. Alternately, given that money is not a factor, SLS machines with post-curing processes yield very hard, smooth surfaced highly accurate models.  FDM can yield much more accurate models, but there will always be a slight ribbing on the surface of the model. Each method has its own advantages. Although SLS can yield much higher quality models FDM is the economical option.

3-D Inkjet Printing

3-D inkjet printing uses the same method as many 2-D inkjet printers. In 2-D inkjet printing, a thin layer of ink powder is deposited on paper and then a binding agent is added in specific patterns, dictated by the schematic, in order to fuse the powder to the paper. Although the powder laying process and the binding agent process are almost simultaneous in 2-D inkjet printing processes, 3-D inkjet printers have a bit more down time between the completion of each process. 3-D inkjet printers lay the powder in an even coat, smooth the coat out, and then apply the binding agent. This is repeated until the model is complete. Figure 4 shows the four basic steps of 3-D printing.

Figure 3: Examples of two different road laying paths. [6]

    Given these guidelines for 3-D inkjet printing, quite a few companies have come up with different methods of implementing this technology in to 3-D inkjet printing machines. The first method follows the template of inkjet printing exactly. A powder is applied, a roller or similar device is used to smooth out the powder, and a print head applies the bonding agent. The second method is a little more advanced and does not even use a base powder. It simply has two print heads, one which prints in a thermoplastic, and the other which prints in a wax. The secondary wax print head is used for supports. This method is quite accurate because every time the construction of a layer is completed, a cutting tool mills the print surface down to a specified height for the next layer. This method allows the machine to check on the model and make sure that the accuracy is upheld. The third method of 3-D inkjet printing is very similar to the second method. There is no base powder to be bonded with a bonding agent, instead a linear array of extrusion heads print thermoplastic all at once. This method is very quick because “if the part is narrow enough, the print head can deposit an entire layer in one pass.” [1]

   After any method of 3-D inkjet printing is complete the model can be taken to a post-curing process. This process can do a number of things. The most common of these post-creation processes is a chemical bath which strengthens the model. Alternatively, “Finished parts can be infiltrated with wax, CA glue, or other sealants to improve durability and surface finish.” [1]

 3-D inkjet printing is one of the most popular methods used today and companies have modified the process to make it quite cheap relative to other methods of 3-D printing. In terms of accuracy and quality, 3-D inkjet printing is less accurate than SLS but with post-curing processes, it can have equally smooth and hard surfaces. The methods of each type of 3-D printing that have a powder base have the same grainy surfaces. 3-D inkjet printing is the method that is most widely sold in standalone units to consumers for personal use.

3-D Printing Today

3-D printing has many applications in both industrial and commercial sectors. Industrially, models of all shapes and sizes are being made with 3-D printing techniques. Some companies have made 3-D printers that are small, efficient, and office-friendly, similar to a 2-D printer. An example of this is the Objet 3-D printer line. [7] These products are able to print fully functional items, such as keys, using the PolyJet method, which is similar to stereolithography. On a larger scale, 3-D printing has been used in the manufacture of airplane parts. In 2011, Urbee [8] unveiled the world’s first 3-D printed car. 3-D printing has also become more accessible to the general public by companies such as Shapeways [9], which allow customers to send in their designs and receive the finished product in the mail. Shapeways has also made it possible to scan and upload player-created content from the game “Minecraft” [10] to print 3-D models. The companies mentioned above all use some form of 3-D printing or additive layer manufacturing, but the method may not be SLS. As of now SLS has limited capability to print in color, which is an important consideration for many products. SLS is however particularly suited to print metals in both industrial and commercial sectors.

Manufacturing

SLS, with its capacity to make metallic models, can be used in many parts of industry. One of these sections is the manufacturing of tools. DMLS has been studied and developed to make tools that are comparable to the tools being used today. Figure (#) shows a cross-sectional area of a part that has been fabricated using DMLS and then shot-peened, a process that causes the outside layer to undergo plastic deformation which increases the density and strength of a part. The top of this part has functionally full density (about 99.5%), while the lower section shows about 94% density. The outside layer of this tool needs to be near full density in order for it to polish well and have high hardness for wear resistance. The inside does not need to have as high of a density since the inside only needs to withstand load forces. Building the tool in this manner reduces the time it takes to build the inner structure to an eighth of the time it takes to build the outer layer. [2] If different metal densities are required, a DMLS machine can simply spend a different amount of time to alter the density of the model in certain places.

Figure 4: The process of 3-D inkjet printing. [1]

Bioengineering

Some applications of SLS in the field of bioengineering are the fabrication of tissue engineering scaffolds, drug delivery devices, and bone models. Tissue engineering scaffolds were developed to counteract the lack of tissues for use in grafting. Scaffolds are made using SLS and then implanted into a body as a basis for tissues to grow from. These scaffolds need to be biodegradable, and so biodegradable materials such as PCL, PVA, PLLA, and PLGA are used. Drug delivery devices are devices in which drug particles are absorbed and later released. The rate at which the drug diffuses from this device is an important factor in the design of these delivery systems. Sintering can reduce the rate at which a drug diffuses. SLS cannot always sinter drug particles directly into the device since some drugs are damaged by heat. In these cases, SLS can still build the device, the drugs are just loaded in later. SLS has also been used to make models of skulls and neuro-networks for neuro-surgeons to practice on. Information from MRI and CT scans can be used to make accurate models of a certain person’s anatomy. It has been reported that models generate with SLS has higher dimensional accuracy than models generated with other 3-D printing methods such as PolyJet. In addition to making training models, SLS can also be used to make specialized parts for individualized patients. SLS allows the fabrication of devices such as ankle-foot orthoses, which are “assistive or therapeutic devices to improve the gait performance of people with impaired lower limb function,” [5] directly from digital information on the patient’s body. Personalized parts are fitted to each patient’s body, ensuring a better fit and higher effectiveness. Improving 3-D printing technology can slowly decrease the monetary and time costs associated with fabricating medical equipment and training devices. This will improve humanity’s ability to provide more of its medical staff with higher quality equipment.

Electron Beam Melting

Additional advances in 3-D printing and rapid prototyping are continuing to decrease the time it takes to fabricate something. New methods of 3-D printing are being worked on all the time. In fact, another method of 3-D printing, similar to SLS, is called electron beam melting (EBM). Arcam AB [11], founded 1997, sells machines that use this method of rapid manufacturing. This method can also produce full density models. Instead of a laser, EBM uses an electron beam to heat up a layer of powder. An example of an EBM machine is the EBM-S12 system from Arcam AB. The beam source in this machine is mounted above a vacuum-filled building tank with a vertically adjustable building platform. Besides this platform are two powder hoppers and a powder rake, which apply and smooth out the applied powder. The powder is heated, to reduce the energy it takes to melt the powder. Then electrons are emitted by a tungsten filament and accelerated to speeds of 0.1 to 0.4 times the speed of light. These electrons are deflected onto specific points on the powder, which are determined by the uploaded schematic. These electrons hit the powder, releasing energy in the form of heat, and melt the powder. The building platform is lowered, another layer of powder is applied, and the process is repeated. [12] This method provides higher build rates than SLS systems, due to the electron beam’s ability to penetrate further into a layer of powder. Also some machines that use EBM have been modified to focus heat on multiple locations at once, greatly reducing the build time. However, there are still some significant problems with this method. An electron, travelling through the powder, requires multiple collisions before transferring all of its kinetic energy. This causes an uneven energy density inside the model, reducing the stability. This forms unwanted formations such as melt balls and delamination. Such formations can render a model or part unusable. [13]

Adding It All Up

Three dimensional printing is the future of the modeling industry. Whether a model is needed to better visualize a prototype, implement a prototype, or manufacture a large quantity of parts, 3-D printing can excel where older outdated methods fail. Within 3-D printing there are many different methods, each with their own benefits, but standing out among 3-D printers is a Method called Selective Laser Sintering. This method is the most versatile. Between the many different methods of sintering and the wide variety of materials that can be used, almost any type of model can be created. The main difference between SLS and the other three methods of 3-D printing is that SLS is more capable of processing metallic materials. Stereolithography, Fused Deposition Modeling, and 3-D inkjet printing do not typically print metals. 3-D inkjet printing could, in theory, print metal-like models, by substituting metal powders. However, since a binding agent is used, the density of the final model could not compare to the density of model produced by SLS. Also, the density of the final model in SLS can be somewhat controlled by limiting the time the powder is exposed to the laser sintering or by altering the composition of the component powders. Density  is important, especially in metals, since the density directly affects the strength of the final part. Although this technology has been around for two decades it is just starting to emerge as a prominent method of model fabrication and given more time, SLS, along with all of the other methods of three dimensional printing, will become the best, most efficient method of model fabrication.

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