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Rapid Prototyping 101: A Primer on Additive Manufacturing Techniques and Procedures

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Additive manufacturing, commonly known as rapid prototyping, is becoming an extremely fast-growing manufacturing process, enabling the quick manufacture of complex parts at minimal cost. However, there appears to be a great deal of confusion and misinformation regarding process capabilities and uses. In this class we will help you to understand the information surrounding this significant manufacturing process. You will gain an understanding of the current 3D printing techniques, the capabilities and limitations of the technology, and the brief history of rapid prototyping.

Learning Objectives

- Gain a base-level understanding of current 3D printing techniques
- Gain a general understanding of the history of 3D printing
- Understand the capabilities of 3D printing
- Understand the limitations of 3D printing

About the Speaker

Drew Tucker is an Application Engineer with Tata Technologies, based out of southeast Michigan. He is focused on Autodesk Simulation products. Before coming to Tata, Drew spent 6 years in the automotive industry in various roles. In 2012 he obtained his bachelor's degree in Engineering Design Technology from Western Michigan University, with specializations in plastics manufacturing and rapid prototyping.

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What is Rapid Prototyping?

Simply put, rapid prototyping is the process of quickly creating a prototype from 3-dimensional CAD (Computer Aided Design) data, using a wide variety of techniques.

This task can be accomplished through traditional manufacturing or "subtractive manufacturing" as it has come to be known. Or, by the process of Additive Manufacturing, which will be our main area of discussion.

Additive Manufacturing vs. Subtractive Manufacturing

Subtractive Manufacturing

Traditionally, the manufacturing and prototyping parts is a subtractive process. This means that material is removed from a larger shape to create a part. CNC machining would be the best example of this, for the purpose of comparison to additive manufacturing.

Even today, subtractive manufacturing is used to prototype parts. There are some distinct challenges, however. Subtractive manufacturing for prototyping is expensive. There's a good amount of waste, secondary operations (any other manufacturing process required to finish a part) are almost always mandatory, it is time consuming, and part complexity is somewhat limited.

Additive manufacturing, on the other hand, manages to circumvent many of these issues. Though there are certainly challenges to overcome, which will addressed within each additive manufacturing technique section.

Additive Manufacturing

Additive manufacturing is the process of creating a part by laying down a series of successive cross-sections (a 2D "sliced" section of a part). It came into the manufacturing world about 35 years ago in the early 1980s, and was adapted more widely later in the decade. Another common term used to describe additive manufacturing is 3D Printing. A term which originally referred to a specific process (Inkjet 3D Printing. Further discussed in Granular Based Techniques section), but is now used to describe all similar technologies.

Additive Manufacturing and CNC subtractive manufacturing have many similar steps, and quite frequently, start in the same place. Both start with 3D CAD data.

Once a CAD model is created, it is run through a slicer software. This type of program cuts up a model layers, and generates a set of instructions for the machine to follow, known as a tool path. Most commonly, in the machining language, g-code.

Once the tool path is created, the file is loaded onto the machine, and a part is created by the successive layering of material (plastic, metal, paper, ceramic, etc.) along a specified path.

Stereolithography-(SLA)

What it is and how it Works

Stereolithography is the process of building an object by curing layers of a photopolymer, which is a polymer that changes properties when exposed to light. Usually, Ultraviolet light. Typically this causes the material to solidify, or cure.

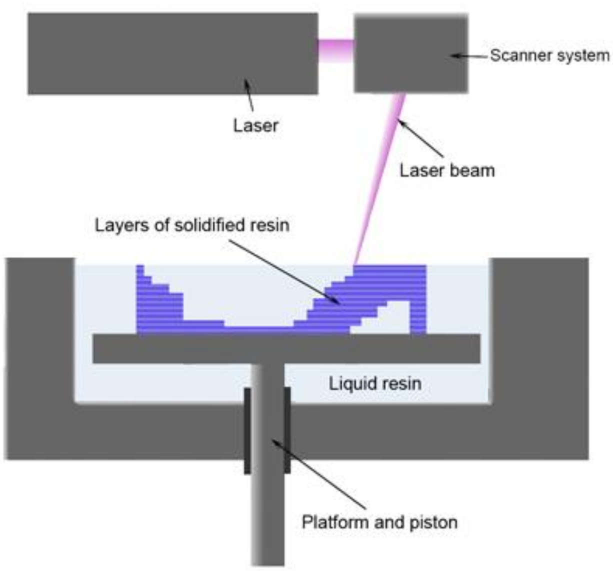

Diagram of Stereolithography Technique

This technique uses a bath or vat of material. An Ultraviolet Laser with cure a layer of photopolymer on a platform. The platform is then lowered into the bath, and another layer of material is cured over the top of it.

A variation on this technique, referred to as PolyJet printing, has a slight modification to the process. Instead of using a bath of material, PolyJet printing uses separate reservoirs of material, which are fed through a UV laser. The material reservoirs in this process are quite similar to inkjet printer cartridges, and function similarly to an inject printer. This technique was developed by Objet Technologies, which was acquired by Stratasys in 2012. Currently, Stratasys is the only manufacturer of these machines.

History

Stereolithography was the first commercialized form of Additive Manufacturing. The process invented by Charles W. Hull, cofounder of 3D Systems. Hull patent for stereolithography was published in 1986, and was commercialized his technology. He is also credited with commercializing the .STL or STereoLithography file format.

Advantages

Stereolithography is fast. Working prototypes can easily be manufactured within a short period of time. This, however, is greatly dependent on the overall size of the part.

SLA is one of the most common rapid prototyping techniques used today. It has been widely adopted by a large variety of industries, from medical, to automotive, to consumer products.

The SLA process allows for multiple materials to be used on one part. This means that a single part can have many several different structural characteristics and colors, depending on where material is deposits. In addition, all of the materials used in SLA are cured through the same process. This allows for materials to be blended during manufacturing, which can be used to create custom structural characteristics. Though, it should be noted that this is only available with PolyJet SLA machines.

Of the all the technologies available, SLA is considered to be the most accurate. Capable of holding tolerances under 20 microns, accuracy is one of the largest benefits to this technique.

Disadvantages

Historically, due to the specialized nature of the photopolymers used in this process, material costs were very high compared to other prototyping processes. They could be anywhere from $80 to over $200 per pound. The cost of a machine is considerably large as well, ranging anywhere from $10k to well over $100k. Though recently, a renewed interest in the technology has introduced more consumer grade SLA machines, which has helped to drive down prices. New material manufacturers have also appeared in recent years (spot-A Materials and MakerJuice Labs), which has cut prices drastically.

Stereolithography is a process that requires the use of a support structure. This means, any part produced with this technique will require a secondary operation, post fabrication.

Granular Based Techniques

What it is and how it Works

All granular based additive manufacturing techniques start with a bed of a powdered material. A laser beam or bonding agent joins the material in a cross section of the part. Then the platform beneath the bed of material is lowered, and a fresh layer of material is brushed over the top of the cross section. The process is then repeated until a complete part is produced. The first commercialized technique of this category is known as Selective Laser Sintering. As it is also the most common, it will be the primary focus of this section.

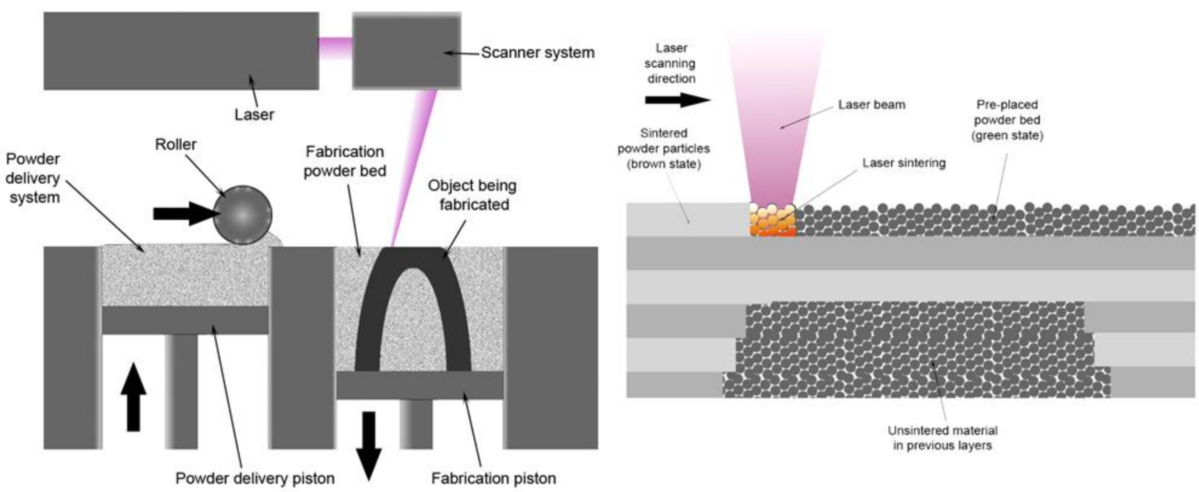

Diagram of Selective Laser Sintering Technique

Selective Laser Sintering (SLS)

History

The Selective Laser Sintering Technique was developed in the mid-1980s by Dr. Carl Deckard and Dr. Joseph Beaman and the University of Texas at Austin, under DARPA sponsorship. As a result of this, Deckard and Beaman established the DTM Corporation with the explicit purpose of manufacturing SLS machines. And, in 2001, DTM was purchased by their largest competitor, 3D systems.

Advantages

SLS is quick. It's one of the fastest rapid prototyping techniques. Though, relatively speaking, most techniques are fast. SLS also has the widest array of useable materials. Theoretically, just about any powdered material can be used to produce parts. In addition, it can potentially be one of the most accurate rapid prototyping processes. The major limiting factor being the particle size of the powdered material.

Because parts are created in a bed of material, there is no need to use support structures, like in other forms of rapid prototyping. This helps to prevent secondary operations and machining.

Another advantage of the material bed is the ability to stack multiple parts into the build envelope. This can greatly increase the throughput of a SLS machine.

Disadvantages

Of the commercially available rapid prototyping machines, those that use the Selective Laser Sintering technique tend to have the largest price tag. This is usually do to the scale production these machines are designed for, making them much larger than others.

SLS can be very messy. The material used is a bed of powdered material and, if not properly contained, will get EVERYWHERE. In addition, breathing in powdered metals and polymers can potentially be very hazardous to one's health. Though, most machines account for this, it is certainly something to be aware of when manufacturing.

Unlike other manufacturing processes, SLS limits each part to a single material. This means parts printed on SLS machines will be limited to those with uniform material properties throughout.

As materials aren't fully melted in this process, full density parts are not created through this process. So, parts will be weaker than those created with traditional manufacturing processes. Though full density parts can be created through similar manufacturing processes, such as Selective Laser Melting.

Other Granular Based Techniques

Direct Metal Laser Sintering (DMLS)

DMLS is the same process as SLS, though there is an industry distinction between the two, so it is important to know. DMLS is performed using a single metal, where SLS can be performed with a wide variety of other materials, including metal mixtures (where metal is mixed with substances like polymers and ceramics).

Selective Laser Melting (SLM)

Instead of the substrate being sintered, it is melted to fuse layers together. This is typically done in a chamber with an inert gas (usually Nitrogen or Argon), with incredibly low levels of oxygen (below 500 parts per million). This is to prevent any unwanted chemical reactions when the material changes its physical state. This technique yields higher density parts than any sintering process.

Electron Beam Melting (EBM)

Electron Beam Melting is very similar to SLM, though there are a few distinct differences. EBM uses an electron beam to create a molten pool of material, to create cross sections of a part. The material solidifies instantaneously, once the electron beam passes through it. In addition, this technique must be performed in a vacuum. This is one of the few additive manufacturing techniques that can create full density parts.

Powdered Bed & Inkjet 3D Printing (3DP)

Invented in 1993 at Massachusetts Institute of Technology, it was commercialized by Z Corporation in 1995. This technology uses a powdered material, traditionally a plaster or starch, and is held together with a binder. Though, more materials are available now, such as calcium carbonate and powdered Acrylic. These parts are typically very fragile after initial production and require a coating, usually in epoxy.

Though 3DP is a granular (or powder) based technique, it does not use a laser to create a part. Instead, a glue or binder serves to join the part.

This process is one of the few Rapid Prototyping Techniques that can produce fully colored parts, through the integration of inks in the binders. It is also worth mentioning that this type of technique is where the term 3D Printing originated from, as it uses an Inkjet style printing head.

Filament Extrusion

What it is and how it Works

Filament extrusion techniques all utilize a thin filament or wire of material. The material, typically a thermoplastic polymer, is forced through a heating element, and is extruded out in 2D cross section on a platform. The platform is lowered and the process is repeated until a part is completed. In most commercial machines, and higher end consumer grade machines, the build area is typically kept at an elevated temperature to prevent part defects (more on this later).

The most common form, and the first technology of this type to be developed is Fused Deposition Modelling, or FDM. As such, the majority of this section will focus on FDM.

Fused Deposition Modeling (FDM)

History

The Fused Deposition Modeling Technique was developed by S. Scott Crump, co-founder of Stratasys, Ltd. in the late 1980s. The technology was then patented in 1989.

The patent for FDM expired in the early 2000's. This helped to give rise to the Maker movement, by allowing other companies to commercialize the technology.

It should also be noted that Fused Deposition Modeling is also known as Fused Filament Fabrication, or FFF. This term was coined by the RepRap community, because Stratasys has a trademark on the term Fused Deposition Modeling.

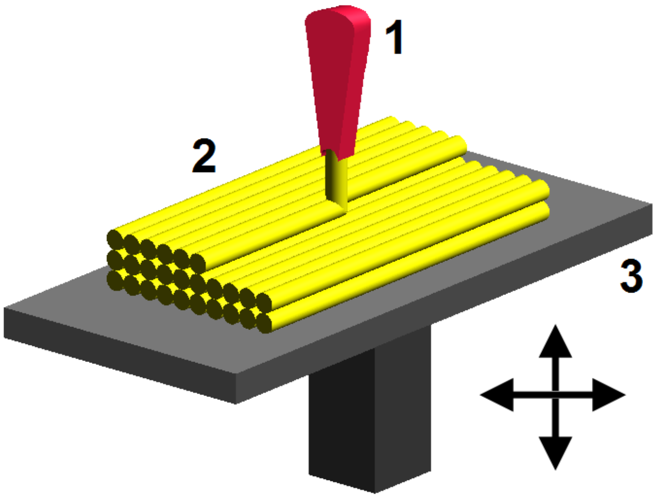

Diagram of Fused Deposition Modeling Technique

Advantages

Fused Deposition Modeling machines, by far, are among the most affordable of rapid prototyping machines. They constitute the vast majority of commercially available small scale machines. This is, again, partly due to the expiration of the patent on this technology, allowing many new entrepreneurs to enter the field.

This technology is also widely used. It is very common in many different industries, though is primarily used small to medium scale businesses and home inventors.

There are many different types of materials that can be used with this technology. Allowing for a wide range of different part properties.

A unique advantage of this technique is the ability to reduce part weight by creating partially hollow parts. Instead of printing a solid core, a cross-hatched pattern can be used instead. This allows for weight reduction and decreased print time, without drastically compromising structural integrity. However, this is largely dependent of the user defined specifications.

With the use of multiple extrusion heads, multiple materials can be applied to a single part. Though this is primarily used to build supports, it can also be used to give a part different structural characteristics.

Disadvantages

One of the major limiting factors of parts produces using an FDM technique is the orthotropic part properties. That is to say, the part will have different structural properties in different directions. For example, the material will be much weaker in the Z direction as opposed to the X and Y directions. The Z high being the direction of the layers. This can be a major issue if these prototypes need to be used in any kind of testing.

Dimensional accuracy with this process, while it can be very accurate, is limited by the thickness of the filament. So, the FDM process can be less accurate that other prototyping techniques.

Any type of filament extrusion will also require the use of supports. This can either be a separate material (printed with a second extrusion head) or a lattice structure using one material. This adds a mandatory secondary process and waste whenever a part is produced.

Another issue exclusive to this application is the curling of material. This is when the part begins to warp and bow towards the top of the machine. This can completed ruin a part, depending on the severity. This phenomenon can be attributed to the shrinkage of the material during the cooling process. More specifically, uneven shrinkage. The effects of curling can be lessened by encasing the print area and elevating the temperature, to insure the part cools at an even rate.

Electron Beam Freeform Fabrication (EBF^3)

Another form of filament extrusion worth mentioning, is Electron Beam Freeform Fabrication. Electron Beam Freeform Fabrication, or EBF^3 is one of the newest forms of rapid prototyping. This technique is performed with a focused electron beam and a metal wire or filament. The wire is fed through the electron beam to create a molten pool of metal. The material solidifies instantaneously, once the electron beam passes through, and is able to support itself (meaning support structures generally aren’t required). This entire process must be executed under a high vacuum.

Pioneered by NASA Langley Research Center, this process is capable of producing incredibly accurate parts at full density (other additive manufacturing techniques have trouble achieving, or require secondary operations to achieve similar results). This is also one of the only techniques that can be successfully performed in zero gravity environments

Laminated Object Manufacturing (LOM)

What it is and how it Works

Laminated Object Manufacturing or LOM works by joining Layers of material (usually paper or plastic sheet with an adhesive, while a knife or laser cuts cross sections to build a complete part. Parts are typically coated with a lacquer or sealer after production.

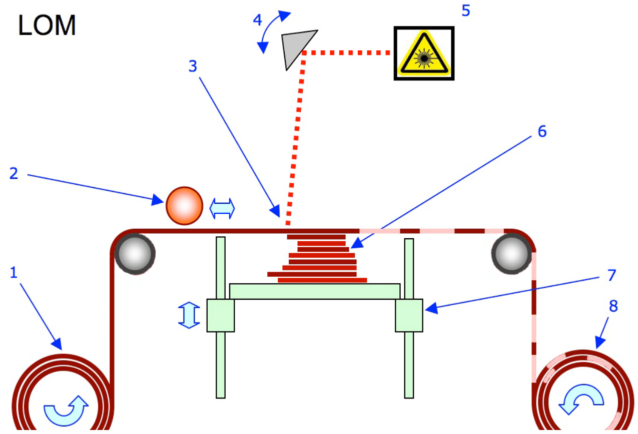

Diagram of Laminated Object Manufacturing Technique

Advantages

Developed by Helisys Inc. (now Cubic Technologies), has some distinct advantages. It is the only additive manufacturing technique that utilizes paper. This means that material costs for LOM machines is very low. Some machines can even use standard office printer paper. Parts printed with paper exhibit material properties similar to wood, and can be machined and handled in a similar fashion.

Disadvantages

The accuracy of LOM is slightly less than SLA or a granular based technique. Which, isn't to say this technique doesn't produce accurate parts, though other techniques can achieve more accurate results. In addition, this technique tends to produce a fair amount of waste. More so than many other techniques. This is due to the unique support structure LOM machines use (a cross-hatched pattern cut into the remaining parts of the sheet, after the cross section of the part has been cut). While the supports are easily removed, they are still waste.

Laminated Object Manufacturing is far less common than other commercialized additive manufacturing techniques, though it is beginning to gain popularity within the Maker Movement.