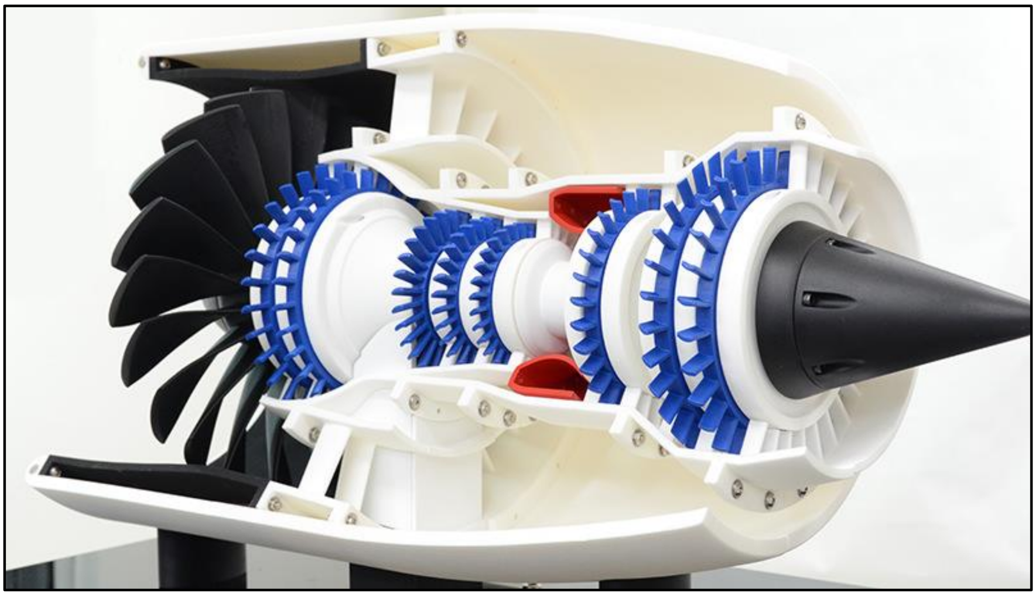
Limerick Institute of Technology Engineering Week Presentation 2016

Leaving Certificate Engineering prescribed topic 2016

"Basic principles of operation and applications of rapid prototyping processes"



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Basic Principles of Operation and Applications of Rapid Prototyping Processes

3-Dimensional printing was patented by Chris Hull in 1996 as a way of taking a 3-D model and turning that 3-D model into a physical object. Hulls process focused only on strereolithography (SLA) which is a fabrication process but there are many other types of 3-D printers which are regarded as rapid prototyping processes. The first patent application was filed by a Dr Kodama, in Japan, in May 1960 but a full patent was never filed.

Rapid prototyping has been developed to make a physical solid model of a part quickly so that it can be assessed and compared to the design ideas. Rapid prototyping is getting increasingly more accurate, more flexible, more economical, more resilient, and useful for prototyping or sample parts. Rapid prototyping is a disruptive technology as it opens up new possibilities and is revolutionising engineers approach to design and manufacture.

What is a prototype?

A prototype is usually a full scale model of a product, traditionally made using manufacturing processes such as milling, turning, fabrication, welding or other methods to create the first version of the product. 3-D rapid prototyping can produce complex prototype components or assemblies in a short time by comparison with making mass-produced parts but prototyping is vital part of design so that flaws or mistakes in finished parts can be avoided.

A rapid prototyped part is developed from a virtual or computer based three dimensional CAD drawing and is then converted into a real part in a matter of hours rather than weeks. These complex three dimensional CAD drawings or electronic models can be used to develop a solid part using a rapid prototyping machine. The most popular of these currently is a filament extrusion 3-D printer but there are other industry standard alternatives.

Material such as plastics, metals, ceramics, and sand and common materials used in 3-D printing for industrial prototyping and production. Generally speaking the more basic 3-D prototyping machines use:

- PLA (polylactic acid) which can be made from wheat or corn starch
    - glass transition temperature between 60-65 °C[1]
    - Melting temperature of 180-220 °C
- ABS (Acrylonitrile butadiene styrene) which is made from hydro-carbons. Both of these materials are thermoplastic materials. Lego block are made from ABS.
    - Its glass transition temperature is approximately 105 °C
    - Amorphous material with undefined melting temperature, ***Tm***[2], there is a large variation. For printing a temperature of around 230 °C is used

The melting temperature, T_m, is the temperature at which the polymer turns to a liquid.

[1] The glass transition temperature, T_g, is when a hard and relatively brittle state turns into a molten or rubber-like state. This temperature varies in different polymer materials.

[2] The melting temperature, T_m, is the temperature at which the polymer turns to a liquid.

Advantages and Disadvantages of Rapid Prototyping

Advantages of 3-D Printing

- High construction speed
- Creation directly from a 3-D model
- Many different materials can be used
- Large work areas possible
- Coloured parts can be created
- No tooling required
- No transportation between machines.
- One operation; no need of jigs and fixtures.
- CAD data files can be manufactured in hours.

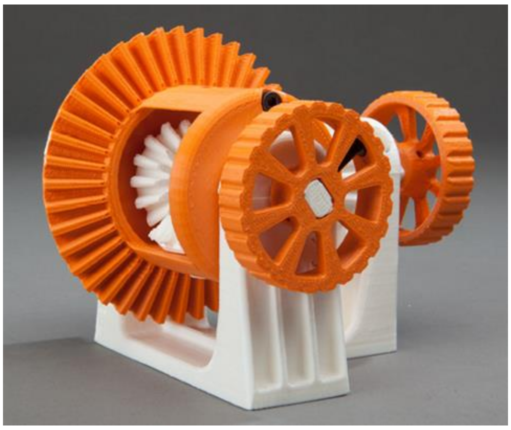

Figure 1 3D Printed Differential Gear system www.makerbot.com

Disadvantages

- Low surface quality; surface texture not a smooth as machining
- Lower mechanical properties than materials made from solid materials
- High cost per part
- Accuracy of parts not as high as machined equivalent except for high specification machines
- Limited range of materials available.
- Slow for mass production work

Comparison with traditional manufacturing processes

Subtractive vs Additive

Traditional machining processes are normally regarded as subtractive process.

A piece of material and excess is removed by machining until the finished shape or that is required by the customer and the drawing is achieved. A large amount of waste is created and while excess material can be recycled a lot of energy and time is spent creating the part.

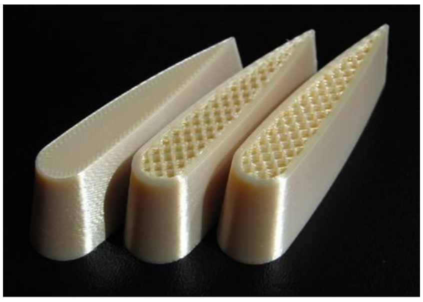

Figure 2. Printed honeycomb structure

Rapid prototyping is regarded as an additive process.

Layers of material are placed on top of one another to create the part. Waste is limited in this process but the part may not be a strong or reliable as traditional machining.

Additive manufacturing processes are based on the fundamental concept of building up parts layer upon layer to build up the part by generating individual layers.

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How are Rapid Prototype parts made?

Five step basic Rapid Prototyping process

1. Create a CAD model of the design
2. Convert the CAD model to STL format
3. Slice the STL file into thin cross sectional layers
4. Layer by Layer construction
5. Clean and Finish

Let’s look at each step in more details

Figure 3 Steps in Creating a 3-D Rapid Prototyped Part

1. Create a CAD model of the design

A 3-D printer or additive manufacturing machine needs a description of what you wish to build. Initial designs may start with a hand sketch or drawing that information must eventually be put into a Computer-Aided Design (CAD) programme so that a three-dimensional computer model of the part can be made.

Designing complex parts in three dimensions and using a CAD program is not easy and requires considerable time and learning as shown in (a) Powerful programs such as Solidworks, Autodesk or others are suitable for creating these models.

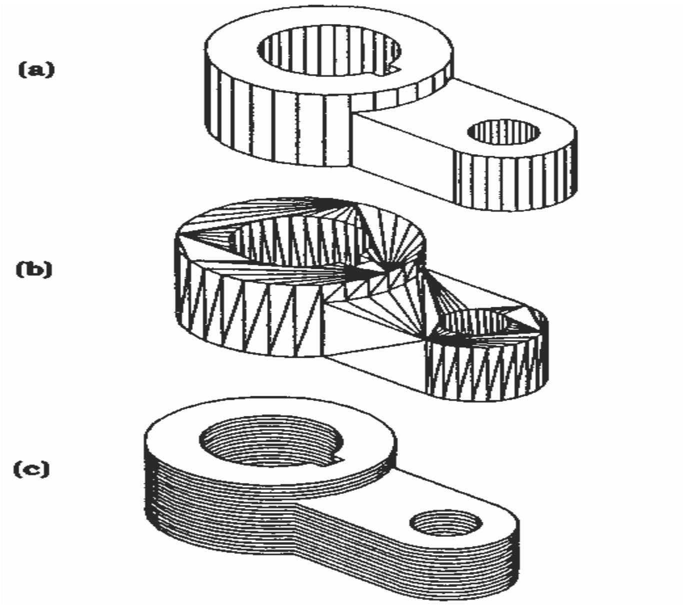


Figure 4. Conversion of a Solid Model to STL format

2. Convert to STL file format

Most CAD programs can generate an STL file automatically. An STL file is way of storing files geometry (shape) in a series of triangles. It was first used with 3-D Systems' Stereolithography machines from which the abbreviation is derived. The 3-D Systems' were the first commercial machines available and this file format is the standard for driving virtually all 3-D printers.

The STL file's description of the item to be 3-D printed is based on representing the surfaces of the original CAD object as a series of numerous triangular facets shown in (b). Objects can be scaled easily and the size of the triangles is usually chosen to be just slightly smaller than the resolution of the printer which makes them invisible in the final object.

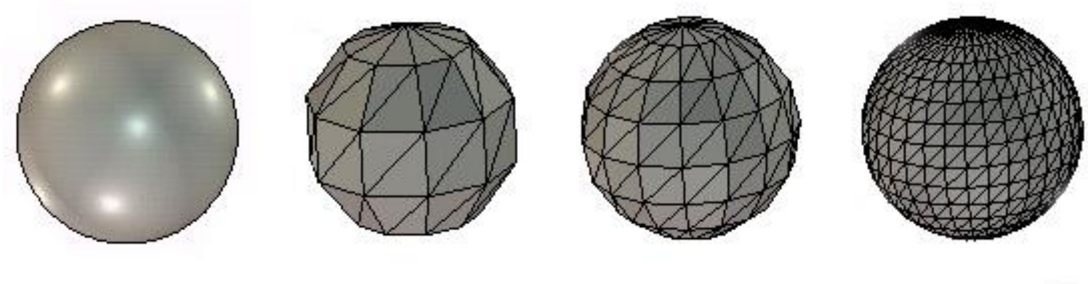


Figure 5. Conversion of a CAD model of a sphere to STL. The more triangles the more accurate the model (http://blogs.solidworks.com/tech/2015/05/preparing-solidworks-models-3d-printing.html)

It is possible to produce errors in converting the CAD file to the STL file. In some cases, and depending on the 3-D printing process used, such errors will make the object unprintable. It is important to spend time ensuring the STL files are correct to ensure printing is successful

3. Create the layers using a slicing Software and send to the 3-D printer

Once the STL file has been generated and any corrections made if necessary, it must be sent to the software that will run the 3-D printer. Professional-level systems have sophisticated user interfaces that allow you to manipulate, scale, slice and position the STL file within the build chamber of the printer.

For low cost systems this is typically a two-step process.

- One program is used to manipulate the STL file
- A second to issue commands to the machine in the form of so-called G-codes

G-codes provide very basic commands such as those used for actually positioning motors and for various settings. These are the same G-codes ass used in CNC lathes, and milling. The amount of code required can be very large for complex parts and writing this manually would take too long.

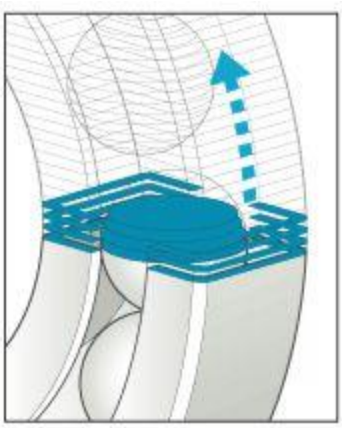


Figure 6. STL sliced for printing

It can take quite a bit of time for the software to process the STL file before the printer can make something. Twenty minutes is not unusual and an hour or more is

possible for a not so large object at higher resolutions. That processed file is then sent to the printer and it can finally get to work.

4. 3-D Print and Remove the Part

It can take hours and in some cases, days, to make a print. Assuming all goes well and the print is finally completed, the object can be removed from the machine. It may be necessary to work with various hand tools to free the object from a base upon which it was built and to which it is firmly attached, and you may have to refurbish the build surface before the next part is printed if you damage it, or it has reached the end of its life.

5. Clean and Post-process

With some 3-D printing methods some finishing is required to remove and recycle powder, or clean surfaces with solvents. It may be necessary to cut away support structures or dissolve them away if soluble support materials were used. Technologies that produce objects from light sensitive polymers (photopolymers) may require exposure to light for several hours to fully cure them.

3-D printed parts may also require additional finishing or processing to ensure the part looks like the intended finished object. This can include sanding to improve the surface finish, filing and painting or electroplating before the part can be used.

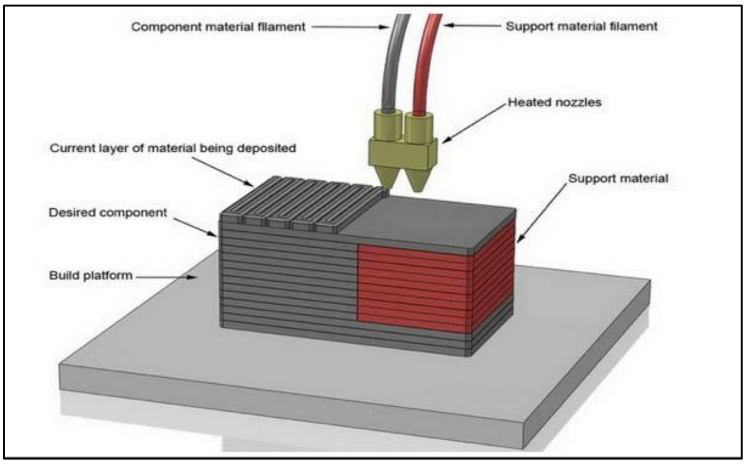


Figure 7. 3-D printing support material to be removed later.

Figure 8. MakerBot® Dissolvable Filament (http://www.makerbot.com/blog/2013/09/30/makerbot-filament-its-melting-its-melting)

Main methods for Rapid Prototyping

Rapid Prototyping can be classified into three basic methods for producing parts or assemblies; within these main methods there are various process. Five are listed here as good examples.

Method	Process	Material (examples)	Price
Liquid based	1. Stereolithography	Polypropylene (PP), Nylon	€75K – 800K
	2. Inkjet Printing	Polyester	€40K - €80K
Solid based	3. Filament Extrusion	ABS and PLA	€10K - €300K
	4. Laminated Process	Paper and adhesive	€10K - €300K
Powder based	5. Selected Laser Sintering	Titanium	€200K – €1Million

1. Liquid Based Rapid Prototyping Systems: Stereolithography.

This was the first rapid prototyping technology introduced. This is a process for making a solid plastic part out of a photosensitive liquid polymer using a laser beam of light to solidify the polymer.

- A laser beam is directed in the X-Y axes across the surface of the resin according to the 3-D data supplied to the machine (the .stl file),
- The resin hardens precisely where the laser hits the surface.
- Once the layer is completed, the platform within the vat drops down by a fraction (in the Z axis) and the subsequent layer is traced out by the laser.
- This continues until the entire object is completed and the platform can be raised out of the vat for removal.

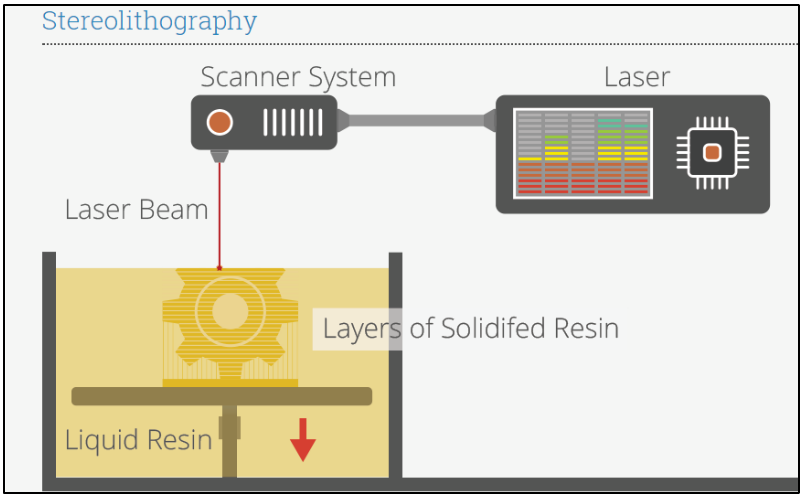


Figure 9. Stereolithography Process (The Free Beginner's Guide to 3d Printing, 3dprintingindustry.com)

2. 3-D Inject Printing

A 3-D printing process whereby;

- The actual build materials (in liquid or molten state) are selectively jetted through multiple jet heads (with others simultaneously jetting support materials).
- The materials tend to be liquid photopolymers, which are cured with a pass of UV light as each layer is deposited.
- The nature of this product allows for the simultaneous deposition of a range of materials
- A single part can be produced from multiple materials with different characteristics and properties.
- Material jetting is a very precise 3-D printing method, producing accurate parts with a very smooth finish.

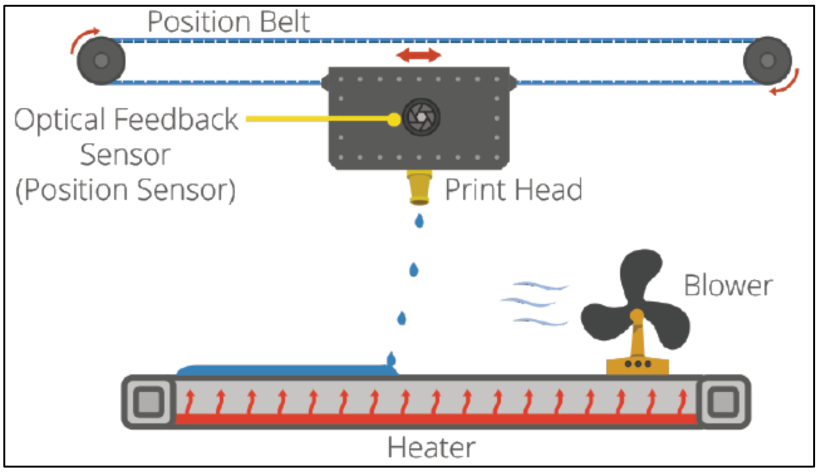
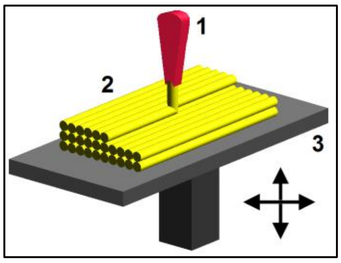


Figure 10. Inkjet Material Printing (The Free Beginner's Guide to 3d Printing, 3dprintingindustry.com)

3. Solid Based Prototyping Systems: Fused Deposition Modelling (FDM)

The Thermoplastic extrusion methods such as FDM have become the most widely used additive fabrication technologies. We will focus on the FDM 3-D printer construction later.



- A plastic filament is unwound from a coil and supplies material to an extrusion nozzle.
- The nozzle is heated to melt the plastic and has a mechanism which allows the flow of the melted plastic to be turned on and off.
- The nozzle is mounted to a mechanical platform which can be moved in both X and Y horizontal and Z vertical directions.
- As the nozzle is moved over the table in the required geometry, it deposits a thin bead of extruded plastic to form each layer.
- The plastic cools and hardens immediately after being squirted from the nozzle and bonds to the layer below.

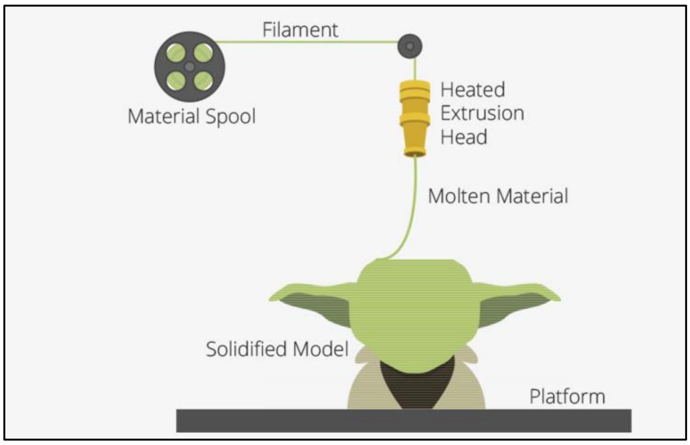


Figure 11. Fused Deposition Modelling process (The Free Beginner's Guide to 3d Printing, 3dprintingindustry.com)

In professional-level systems, to prevent warping of parts the entire mechanism is contained within a chamber which is held at a temperature just below the melting point of the plastic. Low cost hobby machines may simply use a heated table.

Several materials are available for the process including ABS and investment casting wax. ABS offers good strength, while polycarbonate and other materials have been introduced which extend the capabilities of the method further in terms of strength and temperature range.

- If the model being created cannot support itself during manufacture a support structure are usually fabricated for overhanging parts in a second, special water-soluble material.
- These supports can be easily washed away with a safe and benign water solution which is slightly basic.
- Breakaway support materials are also provided and removed by manually snapping them off the part.

Figure 12. 3-D printed objects with support structure need during printing (The Free Beginner's Guide to 3d Printing, 3dprintingindustry.com)

The method is quiet process and can be set up in workshops, design offices etc..

- Thermoplastic extrusion is fairly fast for small parts, or those that have tall, thin walls.
- It can be very slow for parts with wide cross sections
- The finish of parts produced with the method have been greatly improved over the years, but aren't quite as good as stereolithography.

4. Selective Deposition Lamination (SDL)

The closest technology competitor to FDM for functional and low-volume plastic prototypes is probably laser sintering. The SDL 3D printing process builds parts layer by layer using standard copier paper. Each new layer is fixed to the previous layer using an adhesive, which is applied selectively according to the 3D data supplied to the machine.

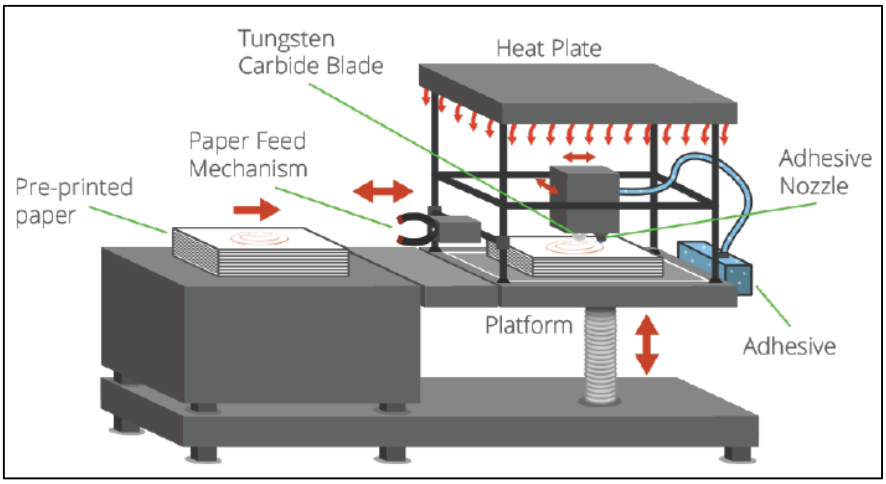


Figure 13. Selective Deposition Lamination (SDL) (The Free Beginner's Guide to 3d Printing, 3dprintingindustry.com)

- This means that a much higher density of adhesive is deposited in the area that will become the part, and a much lower density of adhesive is applied in the surrounding area.
- After a new sheet of paper is fed into the 3D printer from the paper feed mechanism and placed on top of the selectively applied adhesive on the previous layer,
- The build plate is moved up to a heat plate and pressure is applied.
- This pressure ensures a bond between the two sheets of paper.
- The build plate then returns to the build height where an adjustable Tungsten carbide blade cuts one sheet of paper at a time, tracing the object outline to create the edges of the part.

When this cutting sequence is complete, the 3D printer deposits the next layer of adhesive and so on until the part is complete.

5. Powder Based: Selective Laser Sintering

Laser sintering and laser melting are interchangeable terms that refer to a laser based 3-D printing process that works with powdered materials.

- The laser is traced across a powder bed of tightly compacted powdered material, according to the 3-D data fed to the machine, in the X-Y axes.
- As the laser interacts with the surface of the powdered material it sinters, or fuses, the particles to each other forming a solid.
- As each layer is completed the powder bed drops incrementally and a roller smooths the powder over the surface of the bed prior to the next pass of the laser for the subsequent layer to be formed and fused with the previous layer.

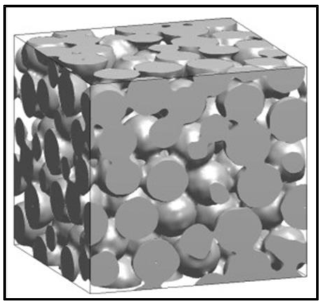


Figure 14 Example of a sintered component

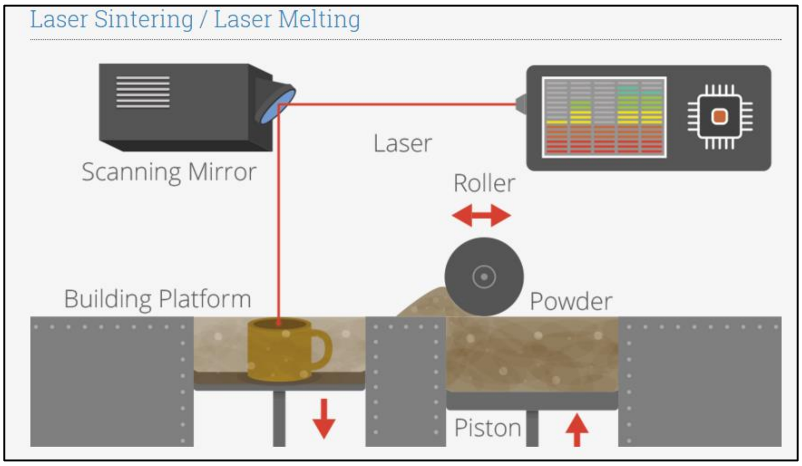


Figure 15. Laser Sintering process (The Free Beginner's Guide to 3d Printing, 3dprintingindustry.com)

Selective Laser Sintering offers better finishes, typically stronger parts, and a different and somewhat wider range of materials. Laser sintering equipment is also more expensive

Most **metals** are sintered at temperatures **of 70% to 80%** of their melting point

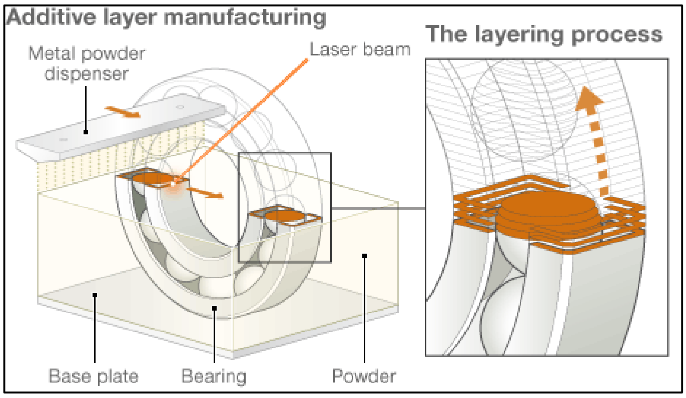


Figure 16. 3-D printed bearing. The parts could not be assembled if it wasn't 3-D printed. (The Free Beginner's Guide to 3d Printing 3dprintingindustry.com)

How does a 3-D Rapid Prototyping machine work?

X, Y and Z Movements

In order to control these axes, letters are used to identify each direction of the table movement. A 3-Printer has three directions of movement. Machine tool builders usually follow standards in designating axes (direction of machine movements). The primary axes are designated X,Y and Z and these apply to most machine tools. Each axis is perpendicular to each other and this can be explained by using the right hand rule to indicate each axis direction.

- A movement in the +Z direction is upwards, a -Z movement is downwards
- A movement in the X direction is horizontal. This is usually the longest movement or table travel
- A movement in the Y direction is also a horizontal movement.

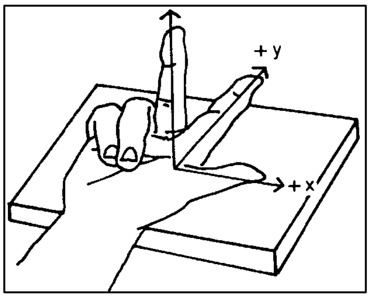


Figure 17. Right hand rule

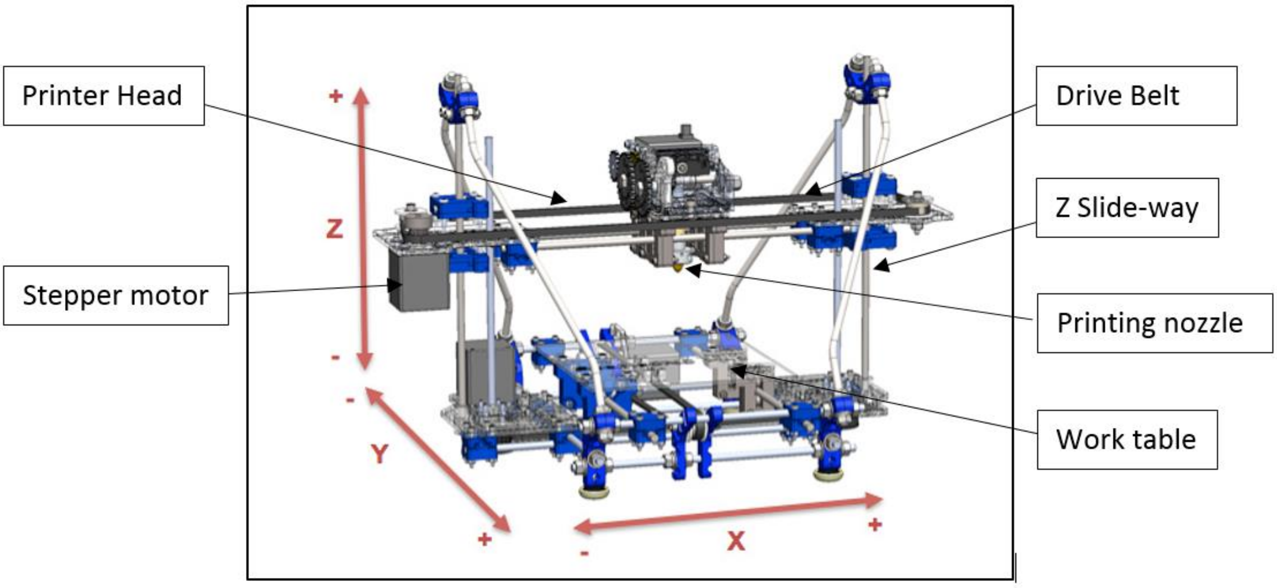


Figure 18. CNC X, Y and Z axis movements.

Stepper motors

Stepper motors are DC motors that move in discrete steps. They have multiple coils that are organized in groups called "phases". By energising each phase in sequence, the motor will rotate, one step at a time.

With a computer controlled stepping you can achieve very precise positioning and/or speed control. For this reason, stepper motors are the motor of choice for many precision motion control applications. Stepper motors come in many different sizes and styles and electrical characteristics.

What are stepper motors good for?

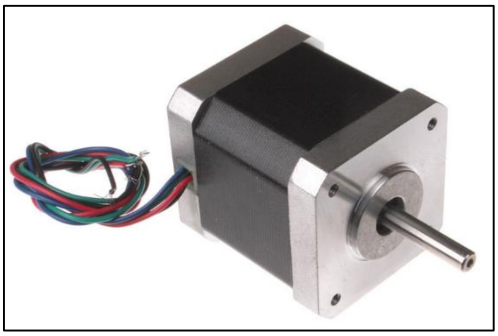


Figure 19. Stepper Motor (https://simple.wikipedia.org/wiki/Stepper_motor#/media/File:Nema_17_Stepper_Motor.jpg)

- **Positioning** – Since steppers move in precise repeatable steps, they are used in applications requiring precise positioning such as 3-D printers, CNC, and X, Y Plotters.
- **Speed Control** – Precise increments of movement also allow for excellent control of rotational speed for process automation and robotics. They can turn part of a revolution or run continuously.
- **Low Speed Torque** - Normal DC motors don't have very much torque at low speeds. A Stepper motor has maximum torque at low speeds, so they are a good choice for applications requiring low speed with high precision.

G Codes

G-code is a Computer Numerical Control (CNC) language used mainly for computer aided manufacturing (both subtractive and additive manufacturing). It is a language which tells a machine how to move. The G-codes are converted into electrical pulses and each pulse then turns the stepper motor by 1 step. This causes the table to move in either the positive or negative direction depending how the pulses are sent

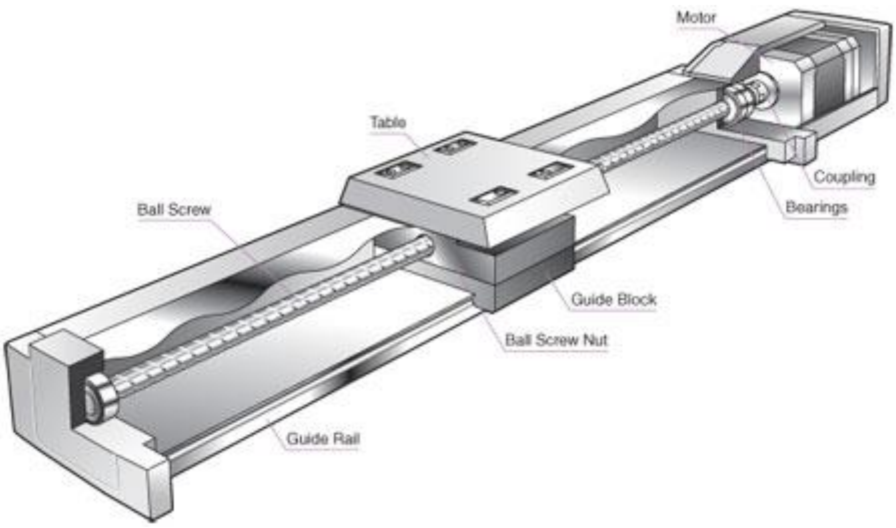


Figure 20. CNC axis movement in one direction

Without G-code there would be no way for the computer to communicate where to deposit, cure or sinter a material during the fabrication process. Programs such as Slic3r are required in order to convert 3-D model files into G-code.

Once the G-code is created it can be sent to the 3-D printer, providing a series of stepped movements to create the layers. These steps all add up to the complete fabrication of a physical object.

Printer head

The printer head for filament extrusion should be considered as a good example of engineering design.

- The feed mechanism is driven by a stepper motor and controlled by G-Code
- This feeds the filament through the head at the correct speed and into the hot end.
- This hot-end contains a heater that heats the material just above its melting temperature, T_m, so that it can have plastic flow
- The polymer is laid down in layers as the table is moved around by the stepper motors on the X and Y axis controlled by the G-Code
- The head is moved up (or the table is moved down) by the stepper motor on the Z axis so the next layer can be started.

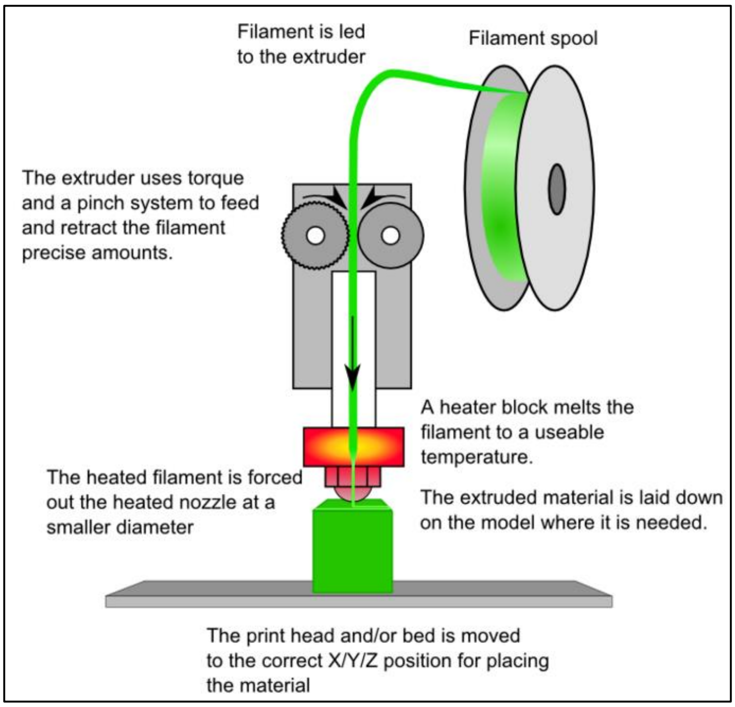


Figure 21. Filament Extrusion Process (3dprintingforbeginners.com)

Heated bed

Heat beds are used because **they dramatically improve print quality** by keeping the extruded plastic warm and thus preventing warping. Warping is a common condition caused by plastic on the edges of the part cooling down at an uneven rate when compared to the plastic inside of the part. The result is that corners warp up and deform your model.

The Future of 3-D Printing: Examples

3-D Printing is a disruptive process. It is changing the way parts and assemblies of parts are made. It is already moving away from a rapid prototyping process only and into a mainstream production process. Some examples:

Aviation/Aerospace

In manufacturing of parts for aviation it is not uncommon for 95% of the material to be machined away to create the final part.

- A 3-D printed part may only have 95% of the material.
- Weight reduced by 30 to 50% by changing the design.
- Structural stiffness increased by 30%

Figure 22. Airbus A380 part Aerospace part redesigned to be 3D printed (www.asme.org)

Medical/Bio Mechanical

3D printers offer many advantages for medical and Bio-mechanical applications. Each person is unique and the opportunity to make custom made parts for patients in areas such as prosthetics and implants is growing. 3D printing can also be used to make jigs and fixtures to hold and guide tools and instruments during surgery.

Surgeons are now 3D printing models of hearts before surgery so that they can plan their approach to complex problems before surgery begin. This helps to develop techniques for difficult situations or to even show the patient before surgery what the procedure will entail.

Figure 23 3-D printed Prosthetic leg (http://www.makepartsfast.com/)

Figure 24. 3-D printed model of a spine

City Planning

3-D printing of city and landscapes allow planners, architects or developers to visualise the effect of changes of new building on the landscape. For example, demolishing one building and replacing it with another building can now be planned and knowing the effect these changes will have on the surrounding areas.

One of the first cities to have a model created was San Francisco. The model was created to aid real-estate developer Tishman Speyer in telling the story of urban development in the rapidly changing SOMA neighbourhood. It can help with urban planning and building construction decisions that are better understood with the kind of physicality that only a real-world 3D replica offers compared to digital images or digital models.

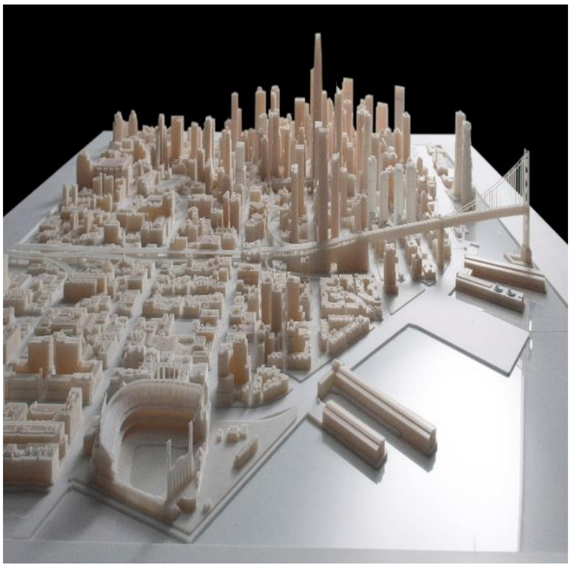


Figure 25. 3-D printed model of a cityscape (www.cgarchitect.com)

Summary: 3-D Rapid Prototyping can be summarised;

Parts are built up layer upon layer to form the final prototype product

1. The starting point is the three dimensional (3-D) computer aided design (CAD) model
2. The model is converted to an STL file
3. The STL file is broken down into individual layers, thereby reducing them to two dimensions, X and Y.
4. The data for the layers define the movements for the Computer Numerical Control programme for the machine used to make the prototyped part.
5. Different methods and materials can be used to create the product from layers
6. Layers are placed upon one another in the vertical direction which is noted as Z.

Sources:

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