RUNNING HEAD: 3D PRINTING

3D Printing Concrete within the Construction Industry

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# Abstract

3D printing is an enabling technology that emboldens and promotes innovation with the freedom of designing intriguing objects with reduced cost and a tool-less process. 3D technology is an emerging technology that is energy-efficient as it provides environmental efficiencies not only in the manufacturing process but throughout the manufactured product operating life. It utilizes almost 90% of the material required to construct an object. 3D printing technology facilitates in designing several components of the objects precisely that in turn bypass the assembly requirements of the components. Thus, various sophisticated geometrical shapes can be created with much ease with no additional costs. Previously, this technology was only limited to the industrial prototyping and manufacturing processes. However, as modern life spins around the elements of technologies making it an indispensable part of our lives, 3D printing has also become more accessible to the wider audience. As the use of 3D printing technology is increasing day by day the exponential adoption rate of this technology growing tremendously. This thesis will explore the background of 3D printing, its working mechanism, and issues associated this technology along with its role in the construction industry mainly focusing on the use of concrete as a building material.

Keywords: 3D printing, construction, concrete, manufacturing, building materials

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# Chapter 1

# Introduction

The 3D printing is an umbrella term that is comprised of variety of processes during which a specific material is joined under computer control to generate a three-dimensional object. Various styles of objects can be created with the computer-aided design model that is also known as CAD (Kamran, 2016). Owing to the process of creating several geometrical shapes by layering the material this process is also known as addictive manufacturing. Generally, the two fundamental innovations that 3D printing has brought with itself are object manipulation into their digital format and object manufacturing by layering the materials. While constructing a porotype it is necessary to have an idea of the tools that are required to construct objects. Also, it is important to consider the availability of tools in the market. Typically, the production of porotypes falls into three categories that are 3D printed parts, Injection molded parts and CNC machined parts. 3D printing has always been a top priority for rapid porotype development. However, due to several advancements in the technology 3D printing has a major impact on the manufacturing world as well. Especially, many medical devices are constructed using this technology. Additionally, 3D printing has also paved its way in the construction field as well because of the utilization of build materials like concrete and cement. Hence, this technology has changed the dimensions of how objects used to be manufactured in the past.

# 1.1 Historical Background

The process of making physical objects from a three-dimensional digital model by layering a specific material is called 3D printing. The earliest idea of 3D printing became visible in the late 1980’s. During this time several addictive materials and equipment’s were developed. Although, at that time this technology was termed as Rapid Prototyping. The reason why this technology was termed as rapid prototyping was due to its ability of creating cost-effective and fast porotypes of the products used in the industry. In May 1980 the first patent application for rapid prototyping technology was filed by Dr Kodama (Wohlers, and Gornet, 2014). He presented two methods that can be used to fabricate three-dimensional models by using photo-hardening thermoset polymer. He utilizes scanning fiber transmitters to control the area of UV exposure. Even though, he filed application first yet he failed to file the detailed specification within the given dead line. Therefore, the origin of 3D printing can be tracked back to 1986 when Charles Hull filed a patent for a stereolithography fabrication system (Savini and G, 2015). According to his system layers are added by preserving photopolymers with ultraviolent light lasers. Charles was also the inventor of SLA machine which was invented in 1983. His contributions include STL file format and digital slicing. He also cofounded a 3D system corporation which is one of the largest and most reputed organization that is operational in the 3D printing sector today. In 1987 first commercial rapid prototyping system was introduced which after passing through several testing was sold in 1988. Even today most of the 3D printers use fused deposition modeling which is a special application of plastic extrusion that was developed by Scott. SLA was not the only technology that was in the development phase at that time because in 1987 Carl Deckard a member of University of Texas also filed a patent for selective Laser Sintering rapid prototyping process. Despite filing patent in 1987 the patent was issued to him in 1989. Later SLS was licensed to DMT Inc which was then acquired by 3D systems (Horvath, 2014).

In the context of 3D printing, 1989 was considered as the year of Scott who was the cofounder of Stratasys Inc. because during this year he filed a patent for Fused Depositing Modelling. FDM is a technology that still being used by many entry-level machines. FDM machine was first marketed in 1992 (Wohlers, and Gornet, 2014). During 1980s and 1990s AM process such as selective laser sintering and selective laser melting, etc went by their own names. Additionally, all metalworking was done by the process that are now known as non-additive processes. Despite applying automation to several technologies such as robot welding, the concept of tool moving through a 3D work envelope altering a raw material in to desired geometric shapes with toolpath was typically associated with processes that removed metal. For instance, CNC milling and EDM, etc. In the same year at Stanford University, several metal deposition techniques such as micro-casting were developed.

Due to the increasing demand of SL processes EOS focused heavily on laser sintering process that is still in use. In 1990 EOS sold its first Stereos system and made its name in the top industrial prototyping applications of 3D systems. During these days’ various 3D printing technologies were emerging. The most prominent were Ballistic Particle Manufacturing that was patent by William Masters, Solid Ground Crucing Patent by Itzchak and three dimensional printing patent by Emanuel. Thus, one can say that nineties witnessed an increasing number of numerous competitive companies yet only three of them exists today. The companies that still exists today are EOS, 3D systems and Startasys. The term 3D printing was coined after the development of custom inkjet print head by MIT in 1993 the term 3D orienting. In 1995 selective laser melting was developed by was developed by Fraunhofer Institute (Su & Al'Aref, 2018).

. However, in terms of commercial operation several companies such as sanders Prototype was established in 1996 while Arcam was established in 1997 and Objet Geometries was established in 1998.

In the year 2000 SLM technology was introduced by MCP technologies. These companies played avital role in growing the Western companies operating all over the world. During this time the high end 3D printing was at its peak although it was very expensive and was used to design high value sophisticated engineering parts. Even today 3D printing is used the complex engineering parts yet several other applications of 3D printing such as aerospace, medical, fine jeweler and automotive design are now being learned. Owing to various applications of 3D printing many manufacturers were focused on to improve functional prototyping to make cost-effective and user-friendly systems. Although, today the price is affordable but in the past 3D printing was way too expensive. Even in the year 2007 the accessibility of 3D printing technology was way beyond the reach of common people and even many industrialists. In 2009 FDM patent was expired yet during this time the first commercially available 3D printer was offered for sale. The year 2010 was the year that has seen the growth of metal end use parts in job production as well. In 2012 Filabot designed a system that enabled FDM or any other 3D printer to print with different types plastics (Horvath, 2014). This year is also known as the year of alternative 3D printing process. During this year more people were interested to know what 3D printing is. Even several media channels also highlighted the 3D printing technology. The popularity of this technology increased even in the year 2013. During this year the acquisition of Makerbot by Stratasys took place. In the year 2014 the first multi-material and vertically integrated printed electronic platform for additive, manufacturing was demonstrated by Dr. Benjamin. This platform allows 3D printing of functional electronic operating up to 40GHZ. Since 2013 the progress in the 3D printing technology was remarkable (Su and Al'Aref, 2018). In 2019 as well 3D printing is widely used and is less expensive. Also, using 3D printing concrete is considered by many construction companies. Thus, 2D printing concrete is expected to change the dimension of construction business.

# Current industry uses of 3D printing

Owing to the immense benefits that 3D printing is offering, its use in several industries is also growing day by day. Many industries are there that use 3D printing technology to make a variety of products that are high in demand. This innovative technology allows industrialist to make products that are used in every field of like. Some of the most common industries that use 3D printing technology are as follows:

## 1.2.1 Aerospace and defence

Aerospace and defence industry is considered as one of the earliest industry to use 3D printing. Several functional prototypes and lightweight components can be built by using this technology. In the aerospace industry, the use of 3D printing is not limited to only making prototypes buy it is also used to make various real-life components that can be used in the aircraft (Gutierrez and Holzer, 2018). Using 3D printing in the aerospace industry is very helpful in producing low-volume highly complex parts. Due to 3D printing, the aerospace industry does not have to buy expensive equipment to manufacture various materials.

In aerospace space industry weight is the most important factor that affects the performance of aircraft and planes, etc. Weight is interrelated to carbon-dioxide production. Thus increasing weight will increase the amount of carbon dioxide emission. 3D printing can facilitate in making lightweight complex geometric designs thus reducing carbon dioxide emission. Additionally, 3D printing allows for repairing several aircrafts components as well.

## 1.2.2. Automotive

The trend of using 3D printing in the automotive industry is growing tremendously. Specifically, in racing cars and motorsports, the 3D printing is used to not only several components but are used to design sophisticated parts as well. Prototyping facilitates in testing how the components will work after they are manufactured. 3D printing is a cost-effective way to manufacture porotypes. Also, it is the fastest way of manufacturing prototypes (Nematollahi & Sanjayan, 2017)

In the automotive industry, every automobile needs a specific design. Due to the ability to customize any component or art 3D printing is considered an effective way to customize components as per the requirement. Additionally, the complex geometry that every part of the automobile possesses can also be made by using 3D printing technology.

## 1.2.3. The dental and medical industry

The dental and medical industry is one of the fastest-growing adopters of using 3D printing. The 3D printing technology facilities in making implants and several dental appliances that are cost-effective (Ventola, 2014). Additionally, the detailing that is required I making implants can be attained by using 3D printing techniques. Recently, several prosthetics are also made using 3D printing that facilitate lots of patients. Due to immense benefits researchers are focused more on using a material that is safe and does not emit toxins. With the help of non-toxic material, the use of 3D printing in the medical and dental industry will increase more.

## 1.2.4. Consumer goods

Since the evolution of 3D printing, the competition in the market has increased. Due to this reason, consumers’ goods industry is also using 3D printing technology. Specifically, consumer electronics are made using 3D printing. Before the launch of the product, it is necessary to validate the design that whether it will be able to meet consumers’ needs or not. As 3D printing technique makes prototypes efficiently, this technique is used to test the design of a product before manufacturing and launching it. Moreover, the customized products can also be made using 3D printing in a very short time (Lee and Chua, 2017).

## 1.2.5. Construction industry

Owing to the materials such as concrete and various types of plastics, 3D printing is widely used in the construction industry. Not only making walls or ceiling of the houses, but this technology is also used in making architectural designs as well. Many artists use 3D printing using concrete to design sculptures and statues (Thomas and Claypole, 2016).

# 1.3. Common Issues/downfalls of 3D Printing

Despite having several advantages some issues are associated with this technology.

The most common issues are listed below:

## 1.3.1. High energy consumption

3D printing requires the melting of powders and build materials. To melt the material a lot of energy is required. According to several studies, 3D printing consumes 50-100 times more energy than any traditional manufacturing does. In an era where people are already suffering from an energy crisis, the use of 3D printing is increasing the crisis (Oropallo and Piegl, 2016).

## 1.3.2. Environmental hazards

Materials such as plastics and metals that are used in 3D printing, during melting produce toxic compounds that may pollute the environment. Additionally, most of the materials are on-recyclable that also play a key role in damaging the ecosystem. Although researchers are trying to build material that is ecofriendly yet still most of the 3D printing techniques use plastic which is very harmful to the environment (Ionita et al., 2014).

## 1.3.3. 3D printing and weaponry production

As this technology is used widely people are using it make weapons such as knives, explosives and guns. Due to wide availability criminals can use this technology to make as many weapons as they want that is one of the major disadvantages of 3D printing (Oropallo and Piegl, 2016).

## 1.3.4. Construction industry issues

Scale and size limitation is one the major issue that 3D printing technology is facing. The printers cannot print giant walls or a whole house, therefore, it cannot replace traditional manufacturing methods. Also, to print walls and ceiling it is necessary to take the machine on the construction site. However, transporting a machine and then operating on site is nearly an impossible task to do (Bos and Salet, 2016).

# Chapter 2

# 3D printing technology

3D printing also referred to as additive manufacturing is a process of in which materials are layered to achieve the desired physical object. To start this process, the first step is to construct a digital model. This model can be created using a variety of software that is available online. For industrial use, the software is 3D CAD while for makers and consumer several simple software are available online. After designing the model, the next step is slicing during which the design is converted into a file that is readable by 3D printer. The material that is to be used to construct the object is processed and layered according to the design. Every 3D printing technology has a unique way of processing the raw material. Nowadays metals, functional plastics and metals, etc are used widely in the industrial prototyping industry. Due to the increasing demand for this technology researchers are now focused on to use biomaterials for 3D printing making this process environment-friendly. Despite these efforts plastic is currently the most used material in 3D printing.

# 2.1. 3D printing working mechanism

## How it Works

As mentioned different types of 3D printers use completely different technology to process material. Some 3D printers use powdered materials such as nylon, ceramic and plastics by utilizing light source to melt or fuse the powder to turn to into the preferred shape. On the other hand, many 3D printers use polymer resin materials. Although they also use a light source to solidify the resin in several ultra-thin layers. As parts in 3D printing are printed directly it is possible to construct sophisticated and intriguing objects with built-in functionality (Kamran, 2016). Even though the process looks simple yet several complications are involved while designing an object for 3D printing. The process is also very time consuming and extremely complicated especially engineering designs require lots of efforts during the build process. However, whatever procedure a 3D printer utilizes the basic method is usually the same.

## 2.2.1. Steps involved in printing

Regardless of what type of 3D printer is being utilized the main process remains the same. Below are the steps that are involved in the process of 3D printing (Wohlers, T. and Caffrey, 2011)

## Step 1

In the 3D printing process, the first step is to design a digital model. There is a variety of software, present in that help in designing a digital model yet the computer-aided design CAD is the most common method used for designing the objects. With the help of scientific data this software also gives some hints regarding the structure of the finished products. The scientific data regarding the material that is being processed to design an object can facilitate in creating virtual simulations of how an object will behave under certain conditions. There are a variety of CAD programs that are compatible with 3D printing. While constructing an object it is necessary to evaluate several design considerations. Determining the geometry limitations or escape-holes requirements while designing a model for 3D printing will help in creating a stable model.

## Step 2

After designing a model, it is necessary to convert it into STL format. STL is an acronym for standard tessellation language. A conversion of the CAD model to STL distinguish the additive manufacturing from traditional manufacturing methods. STL file format was developed by SLA machines in 1987. Most 3D printers are compatible with the STL file format. STL utilizes polygons to demonstrate the surface of a model. To convert the file design into STL it is necessary to understand the STL resolution. As this process involves a series of triangles to determine the surface of the model so increasing the resolution will result in increasing the STL file size. In contrast in the case of low resolution, the triangles will be visible once the object is printed making it less desired. After choosing an appropriate resolution it is necessary to select the right exporting parameters. Most CAD software utilizes two main parameters that are chord height and angle to help in identifying the STL resolution. Although, it is recommended that the chord height should be 1/20 of the 3D printing layer thickness. Thus, it is necessary to evaluate all the necessary recommendation while converting a digital model to the STL file format. After the generation of the STL file. The generated file will be imported into a slicer program where it will further be converted to G-code. The G-code is used in computer-aided manufacturing that facilitates in controlling automated machine tools. G-code is a numeric programming language. The slicer program allows the designer to customize the design according to his or her requirements (Wohlers and Caffrey, 2011).

## Step 3

After importing a file to the slicer program the next step is to transfer the file to an AM machine. This stage involves STL file manipulation where a designer can modify the STL file according to the requirements. After modifying the file the STL file is copied by the user to the computer that is operating a 3D printer. At this stage, the object size and its orientation for printing are determined. This process is similar to that of the 2-D printing process where before printing the size and orientation of the material to be printed is determined. Also, the printer is installed in the computer the same way as in 2-D printer.

## Step 4

To prepare a machine for a new print job every printing machine has its own set of requirements. While setting a 3D printer it is necessary to focus on every detail. Therefore regular maintenance and correct calibration are critical to producing precise and multifaceted prints. Typically, setting up a printer for a new print job involves series of steps such as refilling polymers and maintaining binders, etc. specifically, discussing 3D printers the raw material used in the printing process has a limited shell life and therefore careful handling is required. Although, several materials can be recycled yet using the same material over and over again make material lose its original properties. Generally, 3D printing machines do not require regular monitoring as the process is automated. However, issues may arise during printing if the material is not provided adequately or there is an error in the software.

## Step 5

As mentioned earlier the build process is automatic and therefore does not require monitoring. In this step, the printer will start producing the object according to the digital design that was provided. Typically, the thickness of each layer is 0.1 mm. However, in many cases, the thickness may differ based on the design requirement. Owing to the complexity of the design and material used for printing the desired object, the process of 3D printing can be very time-consuming. It can take days to fully build an object. In many cases, if the design is not complex and the material is also easy to process 3D printing can take a few hours to print an object. It is recommended to check the machine to avoid any errors.

## Step 6

After the printing of the object is completed it is necessary to carefully remove the printed object from the printing platform. However, the industrial 3D printing or the printing of various engineering parts are highly complex. So the removing of complex designs comprises precise extraction of the print while it is attached to the printing platform. Therefore, highly skilled machine operators are required to remove the printed object from the printing platform. Additionally, removing process is critical o it is highly recommended to take precautionary measures to protect yourself from toxic chemicals and extremely hot surface to avoid injuries.

## Step 7

For every 3D printer, the post-processing is also different. Typically, post-processing involves removal of powder residue or removal of water-soluble support. The newly printed object may be weak and therefore require some time to cure. The SLA components can be cured under UV and if the printed material used was metal then it will require stress relieve in the oven. On the other hand, FDM parts do not require cure and can be handled right after printing. There are many post-processing techniques such as tumbling, colouring and high-pressure air, etc that are to be used to prepare a printed object for the end-user.

## Step 8

Following all the above-mentioned steps the object is finally ready to use.

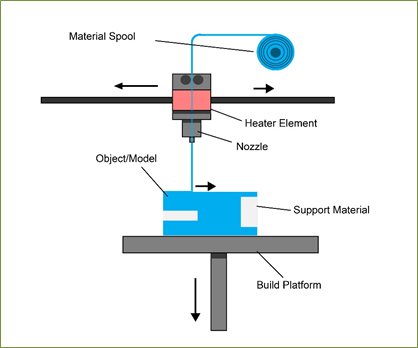
# Chapter 3

# 3. 3D printing methods

Since 1970s several 3D printing processes have been invented. Previously, 3D printers were very expensive and were larger in size as compared to the printers used today. Several additive processes are available now as compared to the past. The only difference between the processes is due to the method of layers’ deposition to constructs different objects and in the raw material used. For instance, to produce layers many methods melt the materials while some methods in spite of melting the material just cure liquid materials to create objects. Similarly, many 3D printing companies use polymers and plastic for constructing an object while others use off-the-shelf business paper for manufacturing an object. Several factors are involved in while choosing the type of process such as speed and cost, etc. Typically, printers that use metals are a bit expensive as compared to the printers that use different materials. The processes that are used currently in 3D printing are as follows:

## 3.1. Material Extrusion

It is a 3D printing process in which filament of solid thermoplastic material is melted with the help of heated nozzles. The process of material extrusion is explained with the help of figure below:



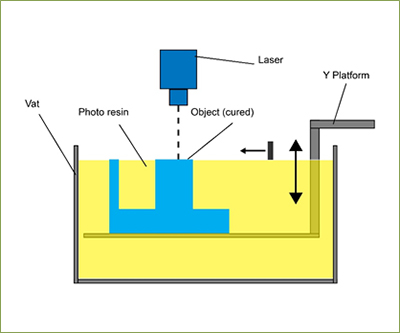
**Figure 1 Parts of printer used in material extrusion (Lboro.ac.uk, 2019).**

As shown in the figure the nozzle head is used to heat the material and switch the flow on and off. To control the flow, stepper motors are employed that facilitates in moving the extrusion head. After the material is being melted the printer will deposit it on a build platform. At the build platform, the filament is then solidified to form an object. Fused pellet deposition is another technique that is developed recently where pellets of plastics replace filament usage.

Generally, this process uses plastic as a raw material to build an object. Although, different types of polymers such as polycarbonate, high-density polythene and high impact polystyrene, etc are also used as well. Due to the ability to withstand high temperature, materials such as fluoropolymers can also be used. Additionally, metal and glass can also be used but are typically very expensive and only reserved to be used for artworks. After the development of WAAM, the cost of using metal for the purpose of 3D printing has reduced significantly. The types of 3D printing technology that use the process of material extrusion are FDM. The main advantage of this process is that it provides the best surface finish. While the disadvantage of this process is that the printed object is inelastic and is brittle (Gonzalez and Holzer, 2018).

## 3.2. Vat polymerization

The process of vat polymerization is explained with the help of figure below:



**Figure 2 Parts of printer used in vat polymerization (Lboro.ac.uk, 2019).**

As shown in figure above a Vat polymerization is a 3D printing process where a photopolymer resin is cured by the light of a specific wavelength. Due to this exposure a chemical reaction occurs that solidifies photopolymer resin. This process only occurs when photopolymers comprise of chromophores. In the absence of chromophores, photosensitive molecules are used to react with the solution to initiate the process of polymerization. The process of polymerization facilitates in creating polymers that change the property of a solution. The build plate is then moved downwards where the liquid polymer is visible to light. This process is repeated until the object has been constructed completely. Typically, inkjet printers spray photopolymer material in ultrathin layers on a build tray. In this case, as well the photopolymer is exposed to the light. Another type of inkjet printer that prints a polymer with intermediate light curing is also available in the market. This method is used to make ophthalmic lenses. The types of 3D printing technology that use the method of Vat polymerization are SLA and DLP. The advantage of using this method is that it provides that have a smooth surface finish with fine detailing of the object features. The disadvantages of this method are that it is not suitable for constructing mechanical parts (Gibson and Stucker, 2015).

## 3.3. Powder Bed fusion

It is another 3D printing technique in which a thermal source of energy is utilized to induce fusion between the particles of plastic or metal powder that are present in the build area to construct a solid object. The process of powder bed fusion is explained with the help of figure below:

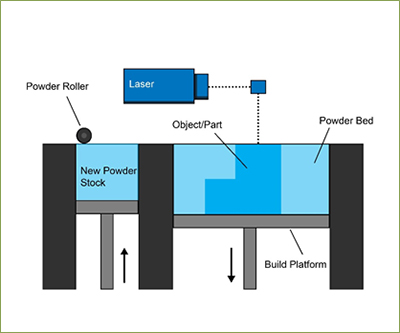


Figure 3 Parts of printer used in powder bed fusion (Lboro.ac.uk, 2019).

In this technique, parts of the layers are fused until the object has been built. Most of the powder-based fusion technologies use the mechanism for spreading thin layers of powder due to which the constructed object is encapsulated in powder after the construction is completed. As this technique utilizes the unfused medium to support thin parts that are being constructed, the need for temporary support for the part that is constructed is not needed anymore. All the PBF technologies use the same process yet they vary because of the different energy source and powders that are used in the process.

The types of 3D printing technologies that use the method of powder bed fusion are SLM, SLS and EBM. The main advantage of this method is that it can be used to make complex geometrical objects and several functional parts. The disadvantage of this technology is that it is very costly and required a lot of time to build an object (Duda and Raghavan, 2016).

## 3.4. Material jetting

It is a 3D printing process in which the droplets of material that is used for the manufacturing of an object are deposited and cured on a build platform. The process of material jetting is explained with the help of figure below:

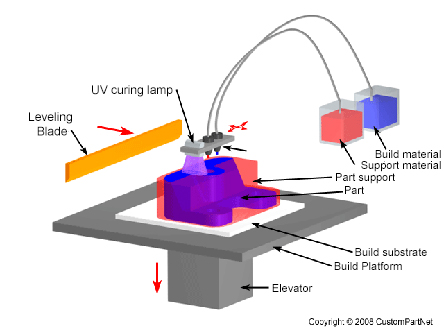


Figure 4 Parts of printer used in material jetting (Lboro.ac.uk, 2019).

This technique helps in the printing of different materials in the same object. This method is similar to standard inkjet printer where multiple layers are assembled upon each other to construct a solid part. After jetting hundreds of photopolymer droplets the print head then solidifies the droplets with the help of UV light exposure. This process is repeated until the whole design is completely constructed. Objects that are printed using this technique requires support.

The types of 3D printing techniques that utilize this method are MJ and DOD. Like other methods discussed above this method also provides the best surface finish. However, this method is different from other methods because the printers that use this method are able to construct objects made from full-colour. It also offers multi-material printing. Additionally, the printer that uses this method is faster than other types of 3D printers. The disadvantage of this method is that it is not suitable for constructing mechanical parts (MacDonald and Wicker, 2016).

## 3.5. Binder jetting

It is a 3D printing process in which a binding agent is deposited on a powder bed to build one layer at a time. The process of binder extrusion is explained with the help of figure below:

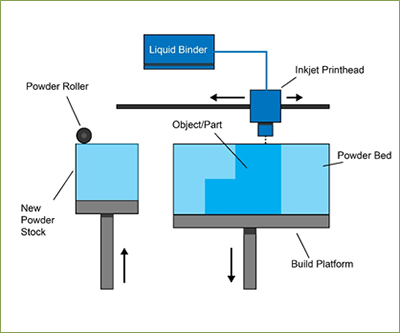


Figure 5 Parts of printer used in binder jetting (Lboro.ac.uk, 2019).

In this process, layers formed in the process will bind together to form a solid component. The materials used in this process can be metals or ceramics. This method is also called as called an inkjet 3D printing system. The printer builds an object by utilizing a print head that moves over a build platform and deposits one layer at a time. Layers can be deposited by spreading powder and printing binder using an inkjet-like process. This method is similar to a type of 3D printing technology that is SLS. As SLS technique also requires an initial of powder to construct an object on a build platform. However, there exists one dissimilarity between the binder jetting process and the SLS. In SLS to sinter powder, a laser is used while in binder jetting a print head is used to deposit binder droplets. Typically, the diameter of the droplets is 80 microns. After a layer has been printed the powder bed is then lowered and the process is repeated to until an object is formed. To gain strength the object is left in the powder. After the object is cured the powder is then removed using compressed air. The type of 3D printing technique that uses this method is BJ. The main advantage of this method is that it is low cost and can build functional effectively. It also allows the printing of coloured prototypes. The disadvantage of this method is that it is that its mechanical properties are not as good as compared to the powder bed fusion method (Lv and Liu, 2019).

## 3.6. Direct energy deposition

It is a 3D printing process in which parts are created with the help of melted powder material. The process of direct energy deposition is explained with the help of figure below:

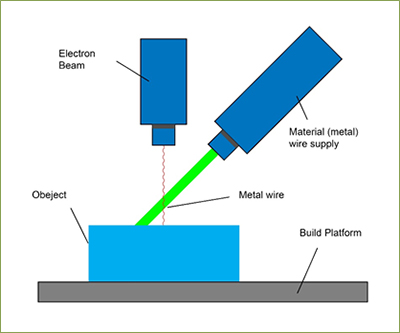


Figure 6 Parts of printer used in direct energy deposition (Lboro.ac.uk, 2019).

In this method, materials are fused using thermal energy. The thermal energy facilitates in melting a material while they are deposited in the form of powder or wire on a build platform. This method is also known to utilize the robotic welding process that helps in high rate deposition however the resolution is typically very low. This technique can be considered as a mixture of both material extrusion technique and powder bed fusion technique. A DED printing machine consists of a nozzle head that helps in depositing material in multiple directions. This is because the nozzle head can move around a fixed object. After the deposition of the first layer, the nozzle head moves upward and start preparing to deposit another layer of the material until an object is formed. Generally, DED systems use plasma and laser beam to melt the material that is used to construct an object. The main advantage of this technique is that it helps in repairing and improving the preexisting parts. This technique is widely used in the medical fields. The types of 3D printing techniques that use this method are DLF, DLD, DMD and EBDM (Gibson and Stucker, 2015).

## 3.7. Other processes

The above-mentioned processes are the most common processes that are used in 3D printing. However, there still exists some other processes as well that are also used in 3D printing. Liquid additive manufacturing is another method that is used in the process of 3D printing. In this process, a liquid or a viscous material such as liquid silicon is deposited on a build platform to create an object. The liquid material is then solidified by utilizing heat. Another process used in 3D printing is lamination. It is the most commonly used low-cost 3D printing process. The paper is used as a building material (Chia and Wu, 2015). The ultrasonic consolidation is also a 3D printing technique that is a printing technique for metals.

# Chapter 4

# 3D printing Techniques

3D printing can be done by utilizing various techniques. Some of the widely used techniques are listed below:

## 4.1. SLA

Stereolithography is the world’s first and the most widely used 3D printing technology that was invented in 1986 by Chuck Hull. This type of 3D printing utilizes the Vat polymerization method. The machine that uses this technique is known as a stereolithograph apparatus (SLA). Generally, all the 3D printing techniques follow the same printing process yet the difference occurs in the type of material and methods that are being used to construct an object. Likewise every other 3D printing types, SLA also requires a computer-aided design file that contains all the necessary information regarding object orientation and measurements. The CAD file is then converted to STL and then it is sent to the computer that is linked with the printer. Typically, printers eject some amount of ink to the surface however, SLA requires liquid plastic that after some time solidifies to form an object. The object that is built by using 3D printing techniques have smooth surface yet the quality of the object depends upon the quality of the SLA machine that is being used.

SL can be described as a laser-based process that works with photopolymer resins. The photopolymer resins react with a laser to form multiple layers on the build plate. After the layering depositions, the layers are cured to form a solid object. The resulted object is precise and sophisticated. SLA utilizes a build platform that is immersed in a translucent tank that is packed with liquid photopolymer resin. After the immersion of a platform, a laser that is located inside the SLA machine maps a layer of a digital model through the bottom of a tank to solidify the material. After solidifying the first layer the platform is lifted and start preparing for a new layer of resin that will flow beneath the first layer. The process is repeated several times until all the layers are deposited, forming a complete object. After the construction of the object, an object is then cured with the exposure of UV light. This will help in refining the mechanical properties of the object (Griffey, 2014).

### 4.1.1. SLA machine parameters

SLA machines have fixed parameters that are designed by the manufacturer. These parameters cannot be changed. Typically, the layer height used in SLA is 25-100 microns. The build size, however, depends upon the SLA machine that is being used. SLA machine setups can be categorized into two setups. The first one is a top-down setup in which the laser is placed above the tank due to which parts are built in the upward direction. The main advantage of this setup is that it has faster build time and provides with large build size. The disadvantage of this setup is that it is expensive and require a professional operator. The second setup is a bottom-up setup in which the laser is placed under the translucent laser tank. After the deposition of every layer, the resin is cured and is removed from the bottom of the tank. The main advantage of this setup is that it is not expensive and is available widely while the disadvantages include small build size and need for extensive support.

## Support structure

The objects build by utilizing SLA require support due to which the support structure is built with the parts. After the construction is complete the support is manually removed. The support structure is different for top-down and bottom-up SLA printers. In top-down SLA printers, it is necessary to print accurately the overhangs. However, the orientation of the parts can vary and the objects are printed flat that help in minimizing the need for support. In bottom-up SLA printers’ overhangs need full support (Griffey, 2014).

## 4.2. FDM

(FDM) fused deposition modelling is a type of 3D orienting technology was developed in 1980 by Scott Crump. It is a technique that utilizes the extrusion of thermoplastic material. It is also known as fused filament fabrication (FFF). The FDM process is also similar to the SL. Firstly a design of an object is made by using CAD. Then the design is cut into several layers by using special software. This helps in calculating the way through which a printer extruder will build each layer. In this technique, the pats are built using strings of a thermoplastic material. This material comes in the form of filaments. The filament is melted when it is passed through the heated nozzle. The printer then continuously moves around to deposit the material at a precise location following the digital design. After the deposition of the material is completed the material is then left to cool. After cooling the material solidifies forming a complete physical object. FDM facilitates in printing not only the functional prototypes but also the final end-users’ products. It is the only 3D printing technology that can build parts with production-grade thermoplastics. The objects that are printed using this technique possess excellent mechanical and thermal qualities. The main advantage of FDM is that it uses thermoplastic material for construction that is widely available and can be used for both industrial purposes and commercial purposes. The disadvantage of FDM is that the printed objects have the lowest dimensional accuracy. Additionally, the printed objects have visible layers’ line and therefore requires post-processing to achieve a smooth finish (Kun, 2016).

## 4.2.1. FDM printer parameters

Unlike SLA printers FDM printers allow the changes in parameters. It not only allows to change the temperature of the nozzle but the height of the layers can be changed as well. The speed of a cooling fan and build form can also be adjusted. Typically, the build size is 200 x 200 x 200 x mm for the desktop 3D printer while the build size of the FDM printer used for industrial purposes can be up to 1000 x 1000 x 1000 mm. The height of the layer that is mostly used ranges from 50-400 microns. However, smoother geometric parts can be created by using reducing the height of the layers. For industrial purposes, the larger height layers are used as it facilitates in printing the pats faster thus reducing the overall cost of the process.

## 4.2.2. Warping

FDM technique faces a major issue that is called warping. This defect occurs because the thermoplastic material when cooled results in decreased dimensions. The reason for the decrease in dimension is because while depositing the layers, each layer cools at different rates. Although, warping can be prevented by closely monitoring the temperature and increasing adhesion between the build platform and printed parts. It is therefore recommended to avoid the large flat area while designing a model to prevent warping. Also, adding fillets to the sharp corners also help in avoiding warping.

## 4.2.3. Support structure

The objects that are printed using the FDM technique requires support especially for the applications that use overhanging geometry. This is because melted thermoplastic used for the construction in the FDM technique cannot be deposited on thin air and therefore requires support. It is recommended to design a model that requires less support. To provide support a water-soluble material is used that can easily be washed once the objected is printed completely. On the other hand, if a breakaway material is used for support then it can easily be removed manually. The water-soluble material is typically used by industries only as it is very costly (Guo and Leu, 2013).

## 4.3. SLS

Selective Laser Sintering (SLS) is a 3D printing type in which an object is created by using a polymer powder and the powder bed fusion technology. In this technique, a laser is used as a power source. This technique was invented the 1980s by Carl Deckard and Joe Beaman. This technique is different from SLA as instead of using liquid resin it uses powdered material to build an object. Like all the process mentioned above, this process also starts by designing a model using CAD. The file created in the CAD is converted to STL format and then transferred to the computer that is linked with the printer. In this technique, a thermoplastic material is heated and then a wiper blade deposits the powder in a thin layer on the build plate. Only one layer is deposited at a time. After the deposition of the first layer on the build plate, the cross-section of the part is then sintered by a laser. This help in solidifying a material. The process is repeated until all the layers are deposited. The powder that is not sintered during the process helps in providing support to the printed object. The main advantage of this technique is that it does not require a support structure. This is because when an object is printed it is surrounded by un-sintered powder. This un-sintered powder is removed after the process is completed. SLS can be used to manufacture functional parts that are complex in design. The making of complex functional parts requires a lot of time, therefore, SLS require longer lead time. Also, it is very expensive as compared to the FDM technique.

This technique is commonly used by the manufacturers because it requires high-powered lasers due to which the cost of the printer is very high. However, to make this printing technique more accessible to the masses researchers are trying to make low cost SLS printing machines by using a material that is cheaper than thermoplastic material used for industrial purposes (Kruth and Rombouts, 2005).

## SLS printer parameters

In SLS printers all the parameters are already predefined. The default height of the layer is 100-200 microns. As this technique does not require support, it can be used to make freeform geometries that are nearly impossible to create by using any other type of 3D printing techniques. Another point that should be taken into consideration is that the height of a bin used in the printer is predetermined. The time required to print a part depends upon the height of a bin, not on the number of parts that a bin contains. This is because the total processing time depends upon re-coating steps. Thus, the packaging of bin affects the time required to complete small orders.

## Warping, Shrinking and Over-sintering

While printing an object using the SLS technique, high temperature is required to melt the material used for manufacturing an object. After the layers are deposited they are let to cool for some time. During this time layers’ experience warping and shrinking. To prevent shrinking the dimensions are increased by 3-3.5% before printing. The increase in the dimensions before printing does not affect the design of the object. To prevent warping ribs are added to increase the stiffness of the objects. On the other hand, over-sintering occurs when the un-sintered powder is fused around the features of the object. This can affect the detailing of the small features of an object. Over-sintering is dependent on the wall thickness and size of a feature being printed. It is therefore recommended to select the thickness and size precisely so that the end product can be without any imperfections (Kruth and Rombouts, 2005).

## 4.4. SLM/DMLS

Selective laser melting is a 3D printing technique that made its first appearance in 1995. This technique is also known as direct metal laser sintering (DMLS). In this technique, a digital model is converted into a physical object by using a high-power laser beam. The laser beam melts and fuses metallic powder. Like many other techniques mentioned above, this technique also follows similar steps. First, a design is made using CAD which is then converted to STL file format. The file is then sent to the computer that is attached to the printer. The fine metal powder is distributed evenly on the plate after which the digital model is fused by applying high power laser. As soon as the laser beam hits the powder it joins the particles of the material together. After depositing the first layer the process is repeated until the object is completed. After the completion of the process, the excess and unused powder are removed manually. The metals that can be used for SLM are stainless steel, aluminium and titanium. SLM is often considered as a category of SLS however they both are different techniques. This is because in SLM the powder is melted completely while in SLS the powdered material is melted partly. SLM is used for making complex geometric objects. Specifically, the aerospace industry uses this technique in their projects. As this technique is costly it is not popular among the masses however it is widely used in not an only aerospace industry but also medical orthopedics industry (Yadroitsev and Smurov, 2007).

## 4.4.1. Printer parameters

The printing parameters in SLM are predefined by the manufacturers. Typically, the height of the layer in SLM is 20-50 microns while the build size is 250 x 150 x 150. The main advantage of this technique is that the material used is recyclable with less than 5% is wasted. The waste is due to the material used for a support structure

# 4.5. DLP

The direct light processing (DLP) is a type of 3D printing technique that was created by Larry Hornbeck in 1987. The technique is very identical to SLA. This is because DLP also works with photopolymers. However, both the techniques are different because both use a different source of light. DLP utilizes light projectors screens that help in flashing a single image of each layer at once. Each layer image is made up of square pixels that result in a layer that is formed from rectangular bricks known as voxels. DLP technique uses a conventional light source, for instance, DMD or crystal display panels. The light source is then applied to the surface of the building material. DLP uses liquid plastic resin as a building material. This material is placed in a translucent container. After the light source is applied to the material it solidifies quickly. DLP printing technique is typically faster than SLA printing. This is because in the DLP technique the entire layer is exposed at once. DLP printing provides excellent resolution and is robust. Additionally, DLP requires less material to construct an object as compared to SLA printing. Due to the usage of less material, DLP is less expensive than SL. DLP also produces highly precise parts with excellent resolution (Olmos, 2017).

## 4.5.1. DLP projection system

Colours in DLP can be projecting by using two primary methods that are single-chip projectors and three-chip projectors. The single-chip projectors produce colours by placing a colour wheel in between the DLP chip and white lamps. The colour wheel contains multiple sections. The first section contains primary colours while the other contains white colour. Another method through which single-chip projectors produced colours is by using an individual light source. This light source helps in producing primary colours. To display any colour the synchronization of the DLP chip and colour wheel is necessary. The DLP projectors also have the ability to produce a rainbow effect. For this purpose the need a mechanical spinning colour wheel is required. On the other hand, the three-chip projectors utilize prism to split light. After splitting each colour is routed to DMD chip. Generally, three-chip projectors are widely used in higher-end home theatres and digital movie theatres.

## 4.5.2. Continuous DLP

Continuous DLP is also known as CLIP that is an acronym of continuous liquid interface production. It is similar to DLP yet the only variation is that in CLIP the build plate is continuously in motion. This helps in faster build time because in this process there is no need to stop the printer for separating the parts from the build plate (Mu and Wang, 2017).

# 4.6. LOM

Laminated object manufacturing (LOM) is a type of 3D printing that was developed by Helisys. Inc. This technique is considered as an affordable technique of 3D printing. Like every other 3D printing technique this technique also uses the same steps. First, a CAD file is designed which is then converted to STL file format. The STL file is then sent to a computer that is connected with the printer. After connected to a printer the layers of plastic or paper are fused by heat and pressure to build an object. After the fusion of the material, the layer is cut using a computer-controlled laser to get the desired design. After one layer is deposited the platform moves down to prepare for another layer. Excess material is also removed using the sharp laser. This will help in easy removal of the object once it is completed. The process is repeated again and again until the object is completely built. However, if in spite of plastic, the material used for building an object is paper then the object needs to be protected from moisture. Due to this reason, the object is covered in paint or lacquer. As this technique use paper and plastic as a raw material to form an object it is less expensive as compared to other 3D printing techniques. This is because plastic and paper are widely used and are easily available. This process is not so popular today as 3D printing has improved a lot as many other techniques are available that facilitate in providing extremely complex geometric objects. Despite, not being used today this technique is still the fastest 3D printing technique. Large objects can be built by using this technique. As this technique is low-cost many architects and artist use this technique to build objects of their choice. The disadvantage of this technique is that when a paper material is used to build an object the accuracy and stability of the end product is not good. Also, the object lacks stability (Xia and Sanjayan, 2016).

# 4.7. Photopolymer phase change Inkjets

Photopolymer phase change inkjets is a type of 3D printing technology in which objects are created by the deposition of several layers using the inkjet head. This technique was developed in 2000 by a company named Object-Geometrics and named this technique as Polyjet. Later the right of this printing technique was taken by Stratasys in 2011 with the same name. Polyjet printing is similar to the material jetting process. A Polyjet printer comprises of a material container, jetting print heads, and a build platform. To start the process first a container is filled with photopolymer material. After this, the material is heated. The heating of material facilitates in attaining the desired viscosity. The print heads then jet the resin across a build platform in a form of droplets. After the droplets are jetted they are exposed to the UV light that helps in curing the droplets and converting them into a solid object. The process is repeated over and over again until an object is fully constructed. After the object is fully constructed material is removed from the building plate. The removal of a material can be done by using hands or by water (Udroiu and Braga, 2017).

Due to the presence of multiple print heads, different materials can be printed at once. Thus, making this technique the only technique that can support multiple building materials. Also, the support material is built along with the object so there is no need for extra support. Ever Polyjet printed excellent precision along with smooth surface and fine detailing on the object. This technology is considered as the most powerful 3D technique as complex geometric shapes can be achieved by using this technique. It also incorporates a variety of colours and materials. Recently, bio-resins are being used as a construction material. Another feature of this technique is that it can stimulate plastic and rubber material to human tissues.

# 4.8. Plaster based 3D printing

Plaster based 3D printing is a type of printing technique in which plaster is used as a building material. Even the SLS printer also used plaster as a building material. Z printer is a company that held the patent of this technique. However, several open-source printer models are available online as well. To attain full-colour 3D models this technique is often combined with inkjet technology. The mixture of water and dry powder forms a paste known as plaster. To harden the plaster heat is applied due to which some amount of water is evaporated from the paste. At first, the plaster particles are spread over the build plate, then with the help of print adhesives, the particles are fused to form an object. After one layer is deposited the printer starts preparing for the next layer and the process continues until an object is fully formed. This technique does not require support while building an object as overhangs are typically supported by the powder. As this technique uses plaster so it requires post-processing as well. Another advantage of this technique is that it supports full-colour printing. The main disadvantage of this technique is that the object formed at the end is not smooth as the plaster is brittle naturally. This technique is used by artists. This type of printing is usually used for display purposes (Guo and Leu, 2013).

# 4.9. Other techniques

## 4.9.1. SDL

Selective deposition lamination (SLD) is a 3D printing technique that is similar to LOM. This technique uses paper as a building material. In this process layers of paper are glued together by utilizing a heated roller. The pressure is then applied to the glued papers to ensure a bond between the sheets of paper. After the layers are glued they are cut to the desired shape by a laser cutter. The process is repeated until the object is fully constructed. The build size is limited in SDL. As this technique uses paper, it is relatively low in cost and is popular among the masses. SDL technique can also be used to produce full-colour components. To produce full-colour, the SDL use CYMK colour palette. Additionally, no post-processing is required and the process is eco-friendly (Crawford, 2005).

## 4.9.2. EBM

Electronic beam melting is another type of 3D printing in which a high energy beam is utilized to induce fusion between the metal powder and particles. The difference between SLM and EBM is the power source utilized by both techniques. SLM uses a high power laser while EBM uses an electron beam. To start a printing process an electronic beam is focused upon a thin layer of powder. The beam scans the thin powder layer that causes the powder to melt. Generally, the process is conducted under a high-temperature environment. After the powder is melted it solidifies and the process is repeated again and again until the object is completed. EBM is faster than SLM due to higher energy density. This technique is widely used in the aerospace and medical industry. This technique can create fully-dense parts it can facilitate in building fully functional parts (Tan and Chua, 2014).

## 4.9.3. DOD

Drop on Demand (DOD) is also a 3D printing technology in which two inkjets are used. The purpose of using two inkjets is because one inkjet is used to deposit the built material while the other facilitates in dissolving support material. The build material is a wax-like material. Like every other 3D printing process DOD also follows the same steps. Metal is melted in a heated chamber of a print head to form a metal liquid. The liquid metal is then manipulated electromagnetically to form a droplet that is ejected with precision through a ceramic nozzle. In this technique, a material is deposited on the build platform to construct several components of an object. The printers that use DOD technique use a fly-cutter that scans the build area after the deposition of each layer to ensure a flat surface. DOD is considered as a variation of MJ 3D printing method (Dong and Morris, 2006).

# Chapter 5

# 3D Printing Materials

Due to the increase in the use of 3D printing researchers are focusing more on incorporating as many materials as possible to print different kinds of objects. Some of the most common materials that are used in 3D printing are as follows:

## 5.1. Plastic

It is the most common material that is used in 3D printing. This material is used widely and is not limited to industrial use only. It is firm, strong and provides several color options that make it an ideal printing material. A variety of products such as household fixtures, utensils, and toys, etc can be printed using this material. It has the ability to combine with powdered aluminum to produce material for sintering known as alumide. Typically, FDM printers use plastic as the build material (Ngo, 2018). The table below contains types are that are widely used in 3D printing.

Table 1 Types of plastics used in 3D printing (Ngo, 2018)

|  |  |  |  |
| --- | --- | --- | --- |
| Sr.No | Types | Advantages | Disadvantages |
| 1 | PLA | Easy to print and is eco-friendly | Texture is not smooth |
| 2 | ABS | Non-toxic and is very strong | Very high melting point |
| 3 | PVA | Water soluble | Expensive and is toxic |
| 4 | Nylon | Less expensive and strong | Require extremely high temperature |
| 5 | PETT | Food safe and is transparent | Requires lot of time to print |
| 6 | HDPE | Easy to dissolve | Require high temperature |
| 7 | Metal filament | Metal like finish | Very expensive |
| 8 | Wood filament | Similar to wood | Very expensive |
| 9 | Conductive filament | Excellent conductor | expensive |
| 10 | Carbon fiber mix | Lightweight and is similar to carbon in texture | expensive |

## 5.2. Metals

It is the second most common printing material in the 3D printing industry. It is used by the DMLS printers. Aluminum and cobalt are the most common metals that are used in the process of 3D printing. However, titanium is another metal that is supplied in the form of powder is also used as the 3D printing build material. Metal can be used to make jewellery, components of air-travel equipment and many more. As the objects that are printed by using metal as a building material are strong it is widely used in industries. Metal is used in the form of dust which is then fired to achieve the desired hardness. After the printing of an object is completed, the object needs to be electro-polished before it is released to the market (Lee and Chua, 2017). The types of metals that are most commonly used in 3D printing are as follows:

## 5.3. Stainless- Steel

It is ideal for printing several households’ items such as cookware and utensils, etc.

Gold

It is used in making jewellery that includes bracelets, necklaces, etc. It is also an expensive metal.

Bronze

It is cheap metal and used to print object-like vases and fixtures.

Aluminum

Highly recommended for making thin objects.

Titanium

It is the most preferred metal for 3D printing as it is very strong. It is used for industrial purposes.

## 5.3. Ceramics

Ceramics are not as popular as plastic and metal yet they are still used in 3D printing. However, objects made from ceramics using 3D printers also have to go through the same process that is glazing and firming as the ceramics do in traditional methods (Stansbury and Idacavage, 2016).

## 5.4. Paper

It is the most cost-effective material that is used in 3D printing. Mcot. technologies who use the SDL technique for 3D printing required. Designs printed using paper helps a lot in illustrating what a realistic prototype of any component will look like. This material is environmentally safe as it is recyclable. Additionally, objects printed using paper as build material do not require post-processing (Chia and Wu, 2015).

## 5.5. Powders

Powdered materials are used widely in 3D printing. The powder is melted and deposited layer by layer on the build plate evenly. After the deposition of layers, the material is left to cool down after which it solidifies creating an object (Lee and Chua, 2017). The powder can come from several sources yet the most common sources of powder used in 3D printing are as follows:

Alumide

A mixture of polyamide and grey aluminium is used in 3D printing. The objects that are made from this powder are very strong. Several industrial prototypes are created by using this powder mixture.

Polyamide

It is also known as nylon. Polyamide is typically very flexible yet strong due to which they are used to make detailed and complex 3D printed objects. Polyamide powder is used for joining pieces in 3D printed models.

## 5.6. Resin

Resins are also used as 3D printing material yet the use is very limited. The material offers limited strength and flexibility. Resins are made up of liquid polymer and the object printed using this material are cured by UV light exposure. Usually, resins are found in black and white colours yet so of them also provide red and orange shades of colour as well (Xia and Sanjayan, 2016). The types of resin material used in 3D printing are as follows:

High-detailed resins

This type of resin is used to print small objects that require sophisticated details.

Paintable resins

This material helps in providing smooth-surface 3D prints. Specifically, figurines that require precise facial details also used this type of material.

Transparent resin

It is the strongest resin as compared to high-detailed and paintable resin. It is used to print models that require transparent appearance and smooth surfaces.

## 5.7. Carbon fibre

Carbon fibre is a type of material that is used for top-coating plastic material. It helps in making plastic stronger. It is also considered as an alternative to metal material that is used in 3D printing (Van et al., 2016).

## 5.8. Biomaterial

Since the awareness regarding environmental issues, people are more concern regarding the material used in 3D printing. For this reason, researchers are working on making biomaterial that is eco-friendly. Specifically, in medical application, the need for biomaterial for 3D printing is very necessary. Therefore, researchers are considering to make material that does not produce toxins during the manufacturing process that may harm the environment (Ventola, 2014).

# Chapter 6

# 6.1. Introduction

The popularity of 3D printing leads to the advancement of this technology significantly. Researchers are not only focused on improving this technology but to use a variety of materials for printing an object. Recently, 3D printing has made its way to even the construction industry as well. Construction 3D printing is a type of 3D printing in which components used in the construction industry are built. Specifically, discussing the construction scale, 3D printing has various methods. These methods are 3D printing concrete, 3D printing wax and additive welding (Buswell and Dirrenberger, 2018). This chapter will focus on 3D printing concrete along with a brief history, methods, advantages and disadvantages. Also, potential improvements in the 3D printing concrete will be discussed that will facilitate in mitigating issues associated with this type of printing.

# 6.2. 3D printing concrete

Since the invention 3D printing has seen several revolutions in the context of the material being used for creating an object. Specifically, the use of concrete as a building material is emerging these days. 3D printing presents itself as a promising tool that facilities in the construction industry. Building an object using concrete is expensive and time-consuming however researchers are focused on to develop tools that may facilitate in making an object with concrete much faster and cheaper (Bos and Salet, 2016). Additive manufacturing is a technique that is used by 3D printers when using concrete as a building material. The figure below shows some design that are printed by 3D printer using concrete as a build material. 

Figure 7 Design that are printed by 3D printer using concrete as a build material (Bos and Salet, 2016).

# 6.3. History

To facilitate building process tests regarding automated construction were made quite early. In the early 1960s, an automated machine was developed that uses pumped concrete. In 1995 two techniques were developed one which utilizes sand as a building material while the other was contour crafting (Bogue, R., 2013). The First method was invented by Joseph Pegna. In his proposed method sand or cement use steam to join the layers of material to form a solid object. However, this technique was never validated. The second method that is contour crafting was developed by Behrohk in which cranes that are controlled by computers to construct objects rapidly and efficiently. After several years, in 2000 many new construction techniques were developed due to which there was a need to incorporate concrete as a building material with these new techniques. In 2003 Rupert store planned to build a 3D printer that uses concrete as a building material. After several attempts, in 2008 3D concrete printer was developed and started printing at Loughborough University. Since then many companies have built 3D printers that require concrete/cement as a building material to build components that are used in the construction industry (Wohlers and Gornet, 2014).

# 6.4. Working mechanism

Concrete 3D printers working mechanism to the FDM printers. As both the printers are controlled by g-code which is a machine language used for directing print head. Concrete 3D printers also use the x, y, z-axis. To start a process a block of concrete is mixed with water to form a paste. This paste is then pumped to the hose which is connected to a printer head. At the nozzle, the pressure will be applied to the concrete mixture by the pump that pushes the mixture towards the printer head. The printer head is connected to the nozzle from which the filaments of concrete leave the printer. It is recommended to adjust the nozzle size appropriately as the diameter of a nozzle depends upon the flow-ability of the concrete mixture. As if a diameter of a nozzle is increased the flow-ability of a mixture should be decreased to get the desired object (Tay and Leong, 2017). Typically, 3 D printer concrete requires continuous monitoring and control of the material during the printing to attain the desired object. This is because in concrete 3D printing lacks a support framework and therefore concrete that is used traditionally in making buildings cannot be used directly. Due to lack of support, there is a high chance of deformation in the layers that were deposited by the printer while printing. It is therefore recommended to use low viscosity concrete as this will provide ease of pumping material to the print head. Also, while using low viscosity concrete it is important to use chemical accelerator at the nozzle. This will ensure a quick setting of the material once it is printed upon a building surface. Another important feature of 3D printing concrete is that it provides a small resolution to attain 3D freedom that facilitates in controlling complex internal and external geometries (Kreiger, and M.P, 2015).

# 6.5. 3D printing concrete advantages

3D printing is considered economical as less material is used to build an object rather than traditional manufacturing processes. While discussing the overall manufacturing process the cost of a machine is an important factor to consider. Generally, machine cost plays a very small part of the total cost of the construction process. It is difficult to create parts in the industrial environment with high precision because a lot of energy is required to create a design. However, there is a freedom of creating a complex and intriguing design that can be developed in less time (Rael and San Fratello, 2011). Thus, the total cost of a machine is counterbalanced by the savings made during the construction process. Another advantage of this technique is that it helps in reducing labour cost. In traditional construction process many people are required to operate machines to build a single part but in 3D printer require only one operator. Additionally, material cost is also reduced in 3D printing concrete rather than the traditional manufacturing process.

One major advantage of 3D printing concrete is that less time is required to build an object as compared to the traditional methods. Typically, after constructing a component by traditional method requires days until the concrete solidifies and sets completely. However, in 3D printing, an object or part can be created in very less time. Also, 3D printed structures are strong that can be helpful to combat any disastrous situation.

It is not new that while providing instructions regarding the design of an object a miscommunication can occur. Due to which the completed object can be completely different from what it was expected to look like. As 3D printing can create an object timely the chances of error are reduced. Also, alterations can be made during the manufacturing process. Additionally, a fully customized design can be created by using 3D printing concrete (Mpofu and Mukosera, 2014).

3D printing concrete is considered as a solution to the housing crisis. Many construction companies are now considering to use 3D printing concrete to create homes and other buildings. A company named WASP, which is an Italian company has now developed a 3D printer large enough to build a home. Not only homes 3D printing concrete is used in the construction of bridges. Another advantage of 3D printing concrete is that it can be used to make sophisticated architectural designs. Recently, NASA has launched a program named as printed habitat challenge in which using 3D printing concrete homes are built in space so that people in future can explore space.

# 6.6. Challenges associated with 3D printing concrete

Despite having several advantages 3D printing concrete face several challenges as well. The first and foremost challenge is the maintenance of the printer. To operate a printer that uses concrete as a building material an operator is required that possess a special set of skills. However, a construction labour shortage is already an issue that many construction companies are facing. So, it is a great challenge to find an operator for a printer. Another challenge that is faced by 3D printing concrete technique is quality. While printing it is necessary to take all the precautions to avoid any errors but if not monitored properly the result can be a very expensive mess (Oropallo and Piegl, 2016).

Specifically, discussing building houses, a house consists of many parts. These parts are a foundation, walls, ceiling, etc. A 3D printer concrete is not able to build a house entirely rather it can print walls only. To start a construction process, large printers begin printing individual parts of a building. These parts are then assembled. However, to construct walls a large printer is required. So, if a construction company wants to use a 3D printer that uses concrete as a building material they have to place a printer at a construction site which is not possible. It is extremely difficult to transport a printer to a construction site and operate it. As mentioned in the earlier chapters that to initiate the 3D printing process there is a need to design a model in the CAD. To build a house it is necessary to consider both internal and external factors that might impact a construction process. So to design a precise and sophisticated that incorporate all needs it is necessary to hire an expert that knows all the software specifications which is another challenge. Despite knowing the software specifications a designer can't incorporate all the external factors. This makes design vulnerable. Also, in the traditional construction process before processing, the workers measure the resistance and other external factors. While using, 3D printing concrete to construct a building it is not possible to take into account the external factors as it requires testing. Thus, testing the material resistance and then constructing a building is very costly.

Another issue that is faced during the construction of a building arises is the horizontal structure of floor slabs and ceiling. While creating horizontal structure support is necessary. Typically, printing horizontal slabs using plastic can resolve the issue as plastic support can be removed easily. However, while using concrete as a building material support will also be made up of concrete and removing concrete after the building process is complete is nearly impossible. Moreover, wet concrete solidifies after some time and therefore while printing details of components or parts the solidification of concrete results in wastage of building material (Ionita et al., 2014).

# 6.7. Recommendations and Solutions

Some recommendations may help in overcoming the challenges that 3D printing concrete is facing. Most of the people have concerns regarding the stability of a printed wall or other building components. To address this concern it is necessary that before extrusion the consistency of the concrete paste must be considered. A concrete paste that can be pumped easily to the print head will remain stable after it solidifies. Wet concrete is key to an excellent print. When concrete is mixed with water it loses its workability which is another major challenge that construction companies face while printing. So, to overcome this challenge, water-reducing admixtures can be added so that the concrete workability is maintained for a long time. Another challenge that was highlighted in the previous section was deformations of the printed object. Generally, when weight is put on a wet concrete it tends to slump. However, this issue can be resolved by adding a no-slump concrete mix that will facilitate wet concrete to withstand the weight. Filament cracking is another challenge that is faced while constructing an object. This challenge can be resolved by monitoring the nozzle speed. If the movement around the corners is increased then there is less chance of filament cracking (Thomas and Claypole, 2016).

While constructing parts of a building there is a need for a digital design that can be made with CAD. If not a professional person is hired to design a model, then a design can be turned into a disaster. However, several online software is present that can help in creating a design so this issue can be resolved by utilizing the research conducted on the design of an object. Thus, the design accuracy of the printer can be improved if the abovementioned recommendations are followed.

# Chapter 7

# 7.1. Conclusion and future work

Technology has become an indispensable part of our lives. People regardless of their age rely more upon technology. 3D printing is an innovative technology that enables people with the freedom of designing highly sophisticated and intriguing design objects. Due to the wider accessibility of 3D printing technology the exponential adoption rate of this technology is increasing remarkably. Owing to the advancements in the technology 3D printing has a major impact on the manufacturing world as well. Especially, many medical devices are constructed using this technology. Additionally, 3D printing has also paved its way in the construction field as well because of the utilization of build materials like concrete and cement. Despite immense benefits, there are some issues associated with this technology that cannot be neglected. Many researchers are trying to improve 3D printing to make it more environment-friendly by using biomaterial rather than toxic materials and increase its scalability. Thus, it is without any doubt that in coming years’ 3D technology will evolve more and people will be able to get benefits from this technology.

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