Unit III : Extrusion and Energy Based Techniques [08 Hr.]

Introduction, Process and mechanism, Materials, Process Physics, Parameters, Benefits, Drawbacks, Limitations and Applications of

Extrusion-Based Deposition: Fused Deposition Modeling (FDM), Fused Filament Fabrication (FFF), Direct Ink Writing (DIW), Robocasting, Bio-printing.

Inkjet(droplet)-Based Deposition and Fusion: Multi-jet Modeling (MJM), Polyjet Printing, Nanoparticle Jetting, Binder Jetting, Multi-Jet Fusion, Color-jet Printing (CJP), Energy Deposition Techniques: Plasma/TIG/MIG/Arc Deposition, Electron Beam-based DED, Direct Metal Deposition (DMD)

UNIT III

EXTRUSION AND ENERGY BASED TECHNIQUES

3.1 INTRODUCTION

- Material extrusion technology is similar to cake frosting the reservoir is pushed out by the nozzle when pressure is applied. If pressure remains constant, then the resulting extruded material (commonly referred to as like a "road") will flow at a constant speed and remain a constant cross-section diameter. This diameter remains constant if the nozzle path through a the storage area is also maintained at constant speed corresponding to the flow rate.
- The material being extruded must be in a semi-solid state when it comes out of the nozzle. This material must solidify completely while remaining in this shape. In addition, the material must combine with material that has already been extruded to form a solid structure. Since the material is extruded, the AM machine must be able to scan in a horizontal plane as well as starting and stopping the flow of material during scanning.
- Once the layer is complete, the machine must index up or move the part downwards so that another layer can be created. There are two primary approaches when using the extrusion process. The most commonly used approach is to use temperature as a way of checking the condition of the material. The molten material is liquefied inside reservoir so that it can flow out through the nozzle and connect with the adjacent material before solidification. This approach is similar to conventional polymer extrusion processes, except that the extruder is mounted vertically on the rendering system rather than remaining in a fixed horizontal position.

3.2 Extrusion Process

3.2.1 Working Process

- Extrusion is a simple process of forming metals by pressure. In this process, a piston or plunger is used to apply a compressive force to the work piece. These processes can be summarized as follows.
  - ➢ The first billet or ingot (metal work piece of standard size) is produced.
  - ➢ This billet is heated during hot extrusion or remains at room temperature and placed in an extrusion press (Extrusion press is like a piston cylinder device in which the metal is placed in a cylinder and pushed by a piston. The top of the cylinder is provided with a die).
  - ➢ A compressive force is now applied to this part by means of a plunger embedded in the press, which pushes the billet toward the die.
  - ➢ A die is a small hole of the desired cross-section. This high compressive force allows the machined metal to pass through the die and be converted into the desired shape.
- Now the extruded part is removed from the press and heat treated for better mechanical properties. This is the basic operation of the extrusion process.

Extrusion Materials :

- Extrusion is the most important process in which a billet is pushed and/or pulled by a die to form a rod or tube in a specific shape. This process is also used to develop Poly Vinyl Chloride (PVC), aluminium and other profiles/components that are used to make windows and doors.
- The extrusion process is done with the help of various extrusion machines such as extruder, PP / TQ film plant, extrusion lamination plant, synthetic string plant and others. There are mainly two types of extrusion processes, hot extrusion and cold extrusion.

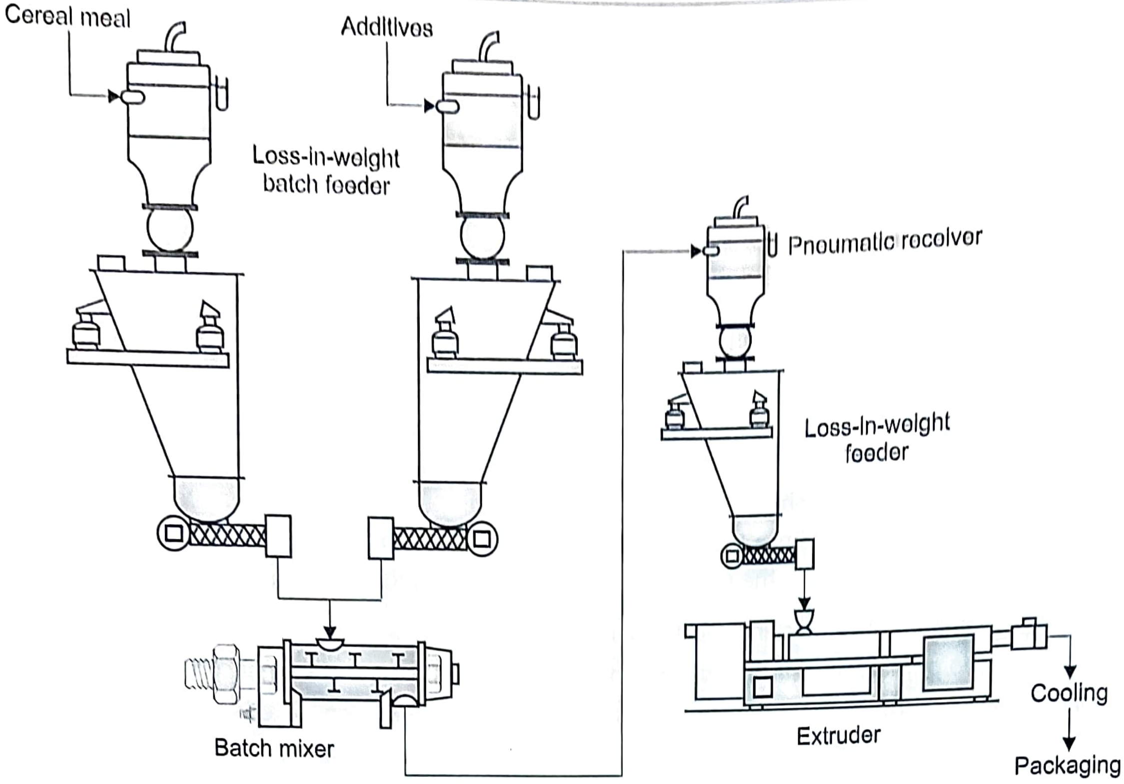


Fig. 3.1

- In the **hot extrusion** process, different products are made using different materials, which are also called extrusion materials. The extrusion materials used mainly include aluminium and copper together with their alloys. Some of the other quality extrusion materials that are extruded through the hot extrusion process are as follows:
  - Magnesium
  - Steel
  - Titanium
  - Nickel
  - Refractory alloys
- Similarly, the **cold extrusion** process develops different products from a range of materials. Some of the main extrusion materials include:
  - Copper
  - Lead
  - Tin
  - Aluminium alloys
  - Titanium
  - Molybdenum
  - Vanadium
  - Steel
- Extrusion occurs by the process of first preparing the material to be extruded. This can be done by preparing dough, melting metal or plastic, or simply preparing a hopper of material, such as pouring in plastic pieces. After this the material passes through the extruder. The exact parts of an extruder can vary depending on the type of extruder, but generally the components consist of :
  - Container for the material.
  - A ram or punch to push the material inside.
  - A matrix to create the final shape.

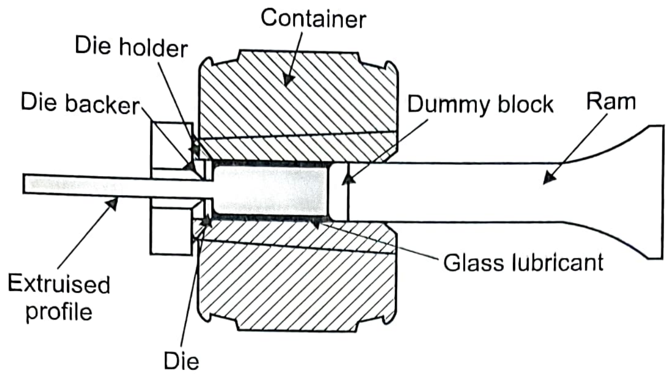


Fig. 3.2

- The material is generally pushed through the container, usually using a ram or punch. Sometimes the vessel is lubricated to minimize the friction. Sometimes heating is done to melt or cook the material before (or during) extrusion. Sometimes the container is pressurized or unpressurized to change the final consistency of the required product. The material finishes up pushed through a matrix. The cutter cuts the shaped material in the required width precisely.
- The shape of the final product can be changed based on:
  - ➢ Cube shape.
  - ➢ The amount of pressure in the vessel.
  - ➢ Temperature (hot vs. cold) or container and material.
  - ➢ The amount or type of force used to push the material inside.
  - ➢ Friction size in the container.

Extruders:

- It is necessary to measure important process parameters in order to know what is happening in the extruder and to be able to control the process. The most important process parameters are melt pressure and melt temperature. They are generally the best indicators of how well or poorly the extruder is performing. Another important process.

  Parameters are:
  - ➢ Screw speed
  - ➢ Engine load
  - ➢ Barrel temperatures
  - ➢ Temperatures
  - ➢ Power of various heaters
  - ➢ Cooling speed of different cooling units
  - ➢ Vacuum level in vented extrusion

Advantages of extrusion

- Low cost per part.
- Flexibility of operation.
- With hot extrusion, post-production adjustments are easy because the product is stationary in a heated state.
- Continuous operation is done.
- High production volumes needed.
- Different kinds of raw materials can be used.

- Good mixing (folding).
- The obtained surface treatment is good.
- Good mechanical properties can be obtained by cold extrusion.

Disadvantages of Extrusion

- Differences in product size can be seen
- Product limitation due to only one cross-section type can be obtained at a time only
- High initial costs

Applications of Extrusion Process

- Electrical wires, bars and tubes are some of the items produced by **hot extrusion** etc.
- Collapsible tubes, gear blanks, aluminium cans, cylinders are some of the items produced by the **cold extrusion** process.

3.2.2 Fused Deposition Modelling (FDM) and Fused Filament Fabrication (FFF)

- Fused deposition modeling is an additive manufacturing technology that creates 3D components using a continuous thermoplastic or fibrous composite material in the shape of fibers.
- The extruder feeds the plastic filament through an extrusion nozzle where it is melted and then selectively deposited layer by layer onto the assembly platform in a predetermined automated path process.

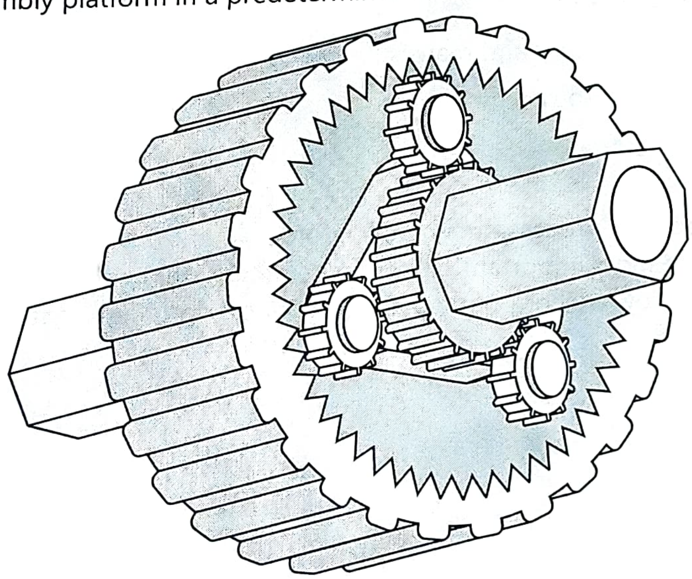


Fig. 3.3

- FDM, additionally referred to as Fused Filament Fabrication (FFF), is a material extrusion technology, it is one of the seven main sorts of main additive manufacturing technologies. FDM is the maximum huge 3D printing technique with the biggest quantity of 3D printer users international and is commonly the primary 3D printing era humans are exposed to.
- Scott Crump pioneered this procedure within the 1980s under the registered term fused deposition modeling (FDM). Stratus's Inc, a business enterprise co-based by using Scott Crump, owns the FDM (fused deposition modeling) trademark and its acronym FDM.
- Fused Filament Fabrication (FFF) is one of the popular additive manufacturing processes. In this technology, a polymeric material in the form of a wire is fed into a hot chamber and a melt of this material in the form of a wire is deposited in a layer-by-layer manner using a tool path obtained from a solid model of the part.

- Fused Filament Fabrication (FFF), additionally called fused deposition modeling (trademarked FDM), or known as Filament Freeform Fabrication, is a 3D printing system that makes use of a continuous filament of thermoplastic Fabric. Filament is fed from a huge spool through a moving heated print extruder head and deposited onto the developing cloth. The print head actions beneath the computer manipulate to define the printed shape.
- Typically, the pinnacle moves in two dimensions to apply one horizontal plane or layer at a time; the activity or print head is then moved a small amount vertically to begin a new layer. The rate of the extrusion head can also be managed to forestall and begin the utility and create an intermittent plane without threading or bleeding among sections. "Fused Filament Fabrication" become coined by using participants of the Riprap assignment group to present an acronym (FFF) that could be legally not restricted in its use.
- Fused filament printing is now the most famous method (by using a number of machines) for amateur 3D printing. Different techniques such as image polymerization and powder sintering can provide better consequences but are extra costly.

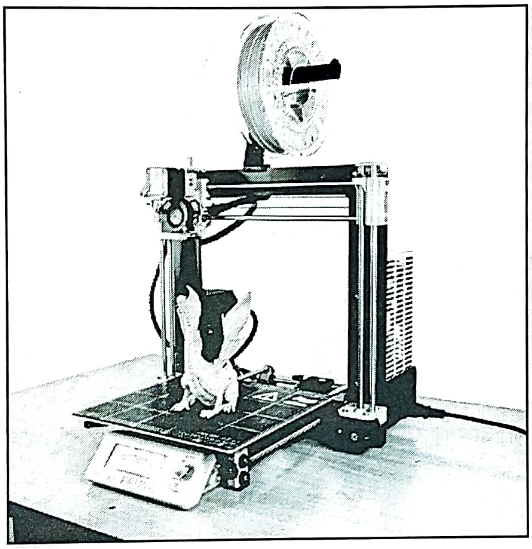


Fig. 3.4

3.2.3 Direct Ink Writing (DIW)

- Direct Ink Writing (DIW), also called Direct Write Fabrication, Robo Casting or robot-Assisted shape Deposition, is a way associated with the extrusion group of materials.
- It was initially mounted by Caesarean Et Al. at Sandia country wide Laboratories in 1997 to produce focused substances together with ceramic pastes with a positive share of organic binder. This approach is a clean, adaptable and cheaper methodology appropriate for an extensive range of materials like ceramics.

Direct Inkjet Writing of Alumina-Based Materials

- Aluminium oxide (Al_2O_3) is a ceramic material that has top notch mechanical and bodily houses including wonderful compressive energy, top notch modulus of elasticity, at the side of outstanding resistance to corrosion and wear, and notably, thermal and chemical stability at improved temperatures.
- These superior residences set it apart from the alternative lessons of substances: polymers and metals, making it suitable for a wide variety of programs including aerospace and automotive.

Direct Ink Writing of Other Ceramics

- Similar to the a hit printing of ceramic structures based on alumina and zirconium, the capability of the DIW method has been explored in lots of other structural and functional ceramics, including glass, clay sulphides, borides, phosphates, and nitrides.

- The multi-material DIW approach became correctly utilized by Chao Xu Et Al. to produce complex steel systems by way of growing a removable provider made of copper (low melting point than metal) and alumina.

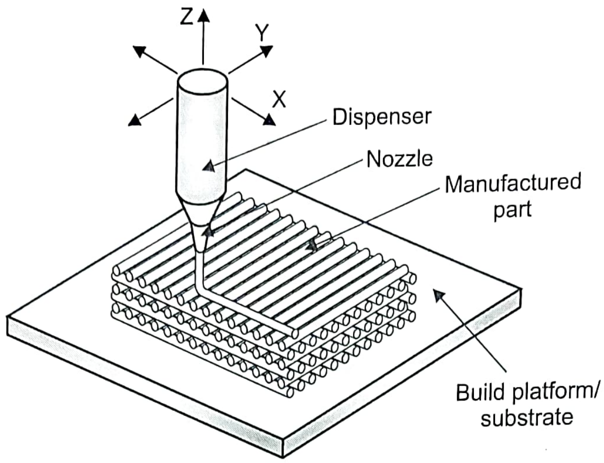


Fig. 3.5

3.2.4 Robo Casting (RC) / Direct Ink Writing (DIW)

- Robo Casting (RC), also referred to as Direct Ink Writing (DIW) and much less usually as Direct-Write meeting (DWA) or Micro robotic Deposition (μRD), is an additive manufacturing generation primarily based on the direct extrusion of slurry-based totally inks. Robo casting changed into the time period used by the original inventors of the method and has found specific resonance inside the ceramic AM community due to its one-word simplicity and similarity to different traditional slurry-based ceramic processing strategies together with slip casting, tape casting, and many others.
- The method was first developed at Sandia national Laboratories in 1996 as a technique without cost-forming gadgets with low binder content (U.S. Patent 6,027,326). In extra detail, this approach consists of the robot application of incredibly concentrated (~35-50 vol%) colloidal suspensions of ceramic powders in water (generally), that are capable of assisting their very own weight for the duration of assembly due to carefully tailor-made composition and viscoelastic homes.

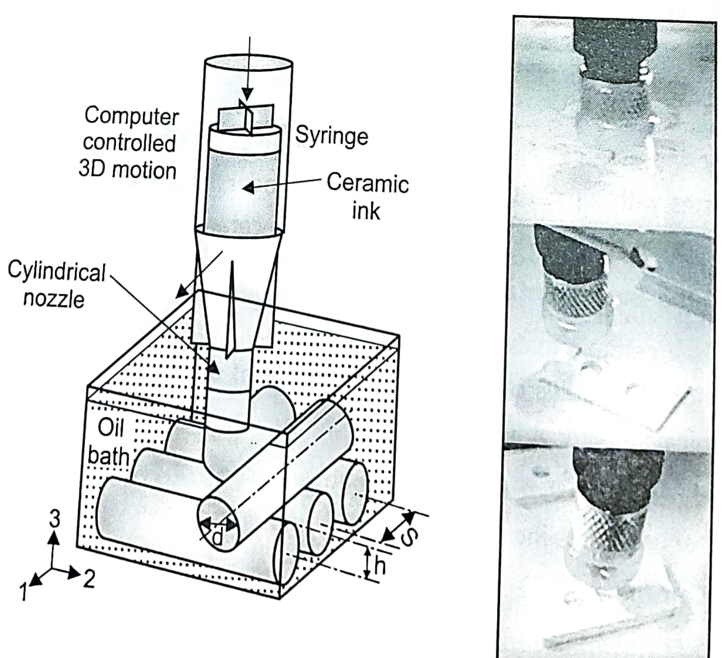


Fig. 3.6 **: Schematic illustration and in-situ images of the Roboocasting process within an oil bath**

- An ink with appropriate rheological homes for Robo casting need to be able to go with the flow through the nozzle (i.e. have fantastically low viscosity under stress) and feature great capacity to retain form (i.e. excessive modulus/flexibility and high yield pressure) whilst carried out. Because of this shear thinning rheological behaviour, the ink behaves as a pseudo-strong after deposition and form retention does not rely on solidification or drying of the raw fabric as in other techniques (e.g., soften deposition modeling and so forth).
- The education of colloidal inks for Robo Casting commonly includes two steps:
  (i) preparation of a low-viscosity but focused suspension the use of normally anionic polyelectrolyte as dispersants;
  (ii) the induction of a drastic rheological exchange to transform the suspension right into a pasty gadget with tuned elastic residences thru a alternate in pH or temperature or by way of the addition of salts or cationic components.
- After the desired rheological behaviour is executed, the ink is placed in a syringe and extruded through a generally conical/cylindrical nozzle (inner diameter, d typically ≥ 100 μm) with the aid of a laptop-controlled robotic application gadget (Fig. 3.6).
- The nozzle role is moved according to the CAD model previously designed inside the managed software program to create the preferred part line by means of line and layer by using layer. The ink flows through the nozzle on the quantity drift rate required to preserve a regular linear deposition price normally among 1-100 mm s-1. lower speeds generally provide higher shape tolerances at the rate of longer print times.
- Line separation 's' and layer height 'h' proven in (Fig. 3.6) in addition to the raster sample also are critical parameters in figuring out the microstructure and houses of a published ceramic component. With a suitable design, no interlayer defects are created and the interfaces among the individual layers are indistinguishable inside the microstructure. With a view to keep away from choppy drying of the structure throughout assembly, the utility process can be executed in a tank of paraffin oil (Fig. 3.6) or in a moist environment, despite the fact that direct printing in air is truly feasible and in some cases also suitable for printing of bulk components.
- After meeting, the uncooked sample is normally eliminated and dried underneath ambient conditions for 24 hours and warmth dealt with beneath suitable conditions to get rid of the binder and sinter the ceramic element.

Advantages

- The shortage of a powder mattress may be considered one of the advantages of this approach, as it permits constructing three-D structures the usage of a minimal amount of fabric, minimizing waste and warding off the want to implement extra techniques to reuse extra powder. This is specially useful when printing high priced and uncommon materials which includes those developed in research sports.
- Some other gain of the use of excessive solids ceramic slurry for additive manufacturing is its potential to provide bulk samples with an excessive preliminary uncooked fabric density, typically exceeding 50% of the theoretical cloth density. For those dense components, it's also possible to similarly increase the density of the raw material by using isocratic bloodless urges.
- In addition to the manufacturing of bulk ceramic elements, the high storage modulus of Robo casting inks can bridge gaps within the underlying layers which might be often the diameter of the filament.

Disadvantages

- This is also the case for different extrusion-based totally AM strategies including FFF/FDM. Among other options, graphite-primarily based inks were proposed as suitable options for this cause, due to the fact carbon may be without problems eliminated with the aid of warmness remedy at 800 °C, that is much less than standard sintering temperatures for ceramics. Printing with such assist structures requires using two print heads as shown in Fig. 3.7.
- However, the absence of a helping powder bed approach that when printing complex elements with massive overlaps or internal gaps the use of Robo Casting, a secondary help structure should be built from sacrificial material (Fig. 3.7).

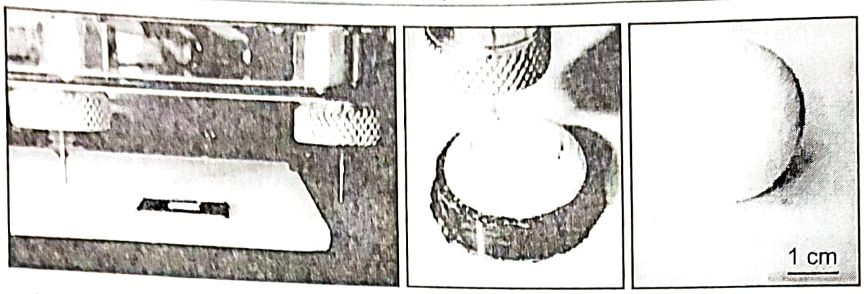


Fig. 3.7 : Robocasting complex structures with overhangs require co-printing a fugitive ink (with a dual-head) to generate a support structure that is eliminated during heat treatment.

Applications

- It is a specially useful method for the fabrication of porous structures that have been widely used as catalyst helps, filters, acoustic metamaterials, photonic crystals, and scaffolds for tissue engineering and different biomedical packages.
- Superior load bearing composites can also be created with the aid of infiltrating Robo casting porous structures with molten polymers, glasses or metals.

3.2.5 Bioprinting

- Bioprinting is described as the location of biochemicals, organic materials, and living cells to generate bioengineered systems (i.e, additive production) of biological and biologically relevant substances, the use of computer-aided transfer and constructing tactics..
- Typical 3D printing techniques have similarly evolved with the advent of sacrificial resin melds for the introduction of 3D scaffolds from organic substances. The improvement of solvent-loose water-based structures has facilitated the printing of biomaterials into 3D scaffolds that may be used for transplantation with or without seeded cells. Any other milestone was 3D bioprinting, particularly the creation of tissue engineering structures.
- Bioengineering techniques for the construction of artificial blood vessels were studied with the aid of numerous agencies. Successful tissue regeneration has been associated with cellular seeding, scaffolding, and engineering technologies.3D printing and electrospinning technology can help speedy and unique fabrication of scaffolds for cellularization with vascular progenitors or combinations of mature human vascular cells to obtain bioengineered blood vessels.
- Advances in 3D bioprinting are driven with the aid of the growing need for alternative layout processes to broaden tissues and even organs, as to be had traditional methods are not able to produce materials and constructs with the important structural, mechanical, and biological houses, inclusive of biocompatibility and complexity.
- In general, 3D bioprinting is based on an appropriate placement of organic components, biochemical and residing cells layer with the aid of layer by way of spatially controlling the position of practical additives of the manufactured 3D structure. Three-D bioprinting is based totally on three simple approaches: (i) Bio mimicry or bio mimetic, (ii) Independent self-meeting and (iii) Mini tissue constructing blocks.

3.3 DEPOSITION AND FUSION BASED ON AN INKJET PRINTER (DROPLET)

3.3.1 Multi-Stream Modeling (MJM)

- A 3D printing method known as Multi Jet Modeling (MJM) is where layers of photopolymer are placed on top of each other and cured using UV light. This method is also widely known as the Inkjet or Polymer method. During the printing process, the 3D object is created layer by layer using the print head.
- Multi Jet Modeling allows you to create objects that are rich in detail and have a smooth surface. The way it works is comparable to a regular inkjet printer. At least two print heads are used for printing, so that additional support elements can be built in. Thanks to this, it is possible to create overlaps on the object without any problems. Layers of the object are gradually added, alternating between building and supporting materials.
- The carrier material that surrounds the model during the printing process is completely removed when the part later goes through additional processes. The carrier material is either removed by a stream of water or can be dissolved in water. The material used is a photopolymer, which is cured by exposure to UV radiation.

Disadvantages

- The disadvantage of photopolymers is that their strength changes over time as the UV light contained in sunlight eventually changes the material.
- Thanks to the layering method, different components can be built into each other even during the printing process. It is immaterial whether the materials differ from each other aesthetically, physically or haptically.

Advantages

- The advantage of Multi Jet Modeling is that, depending on the equipment used, different materials can be mixed in the jet, so that completely different color shades or degrees of hardness can be achieved on parts that can later be painted, cut or sanded in the finishing process.

Applications

- Multi Jet Modeling is ideal for industries where objects must be designed in great detail:
  - Prototype construction
  - Models with thin walls
  - Model making
  - Precision moulds and casting templates
  - Models with subtle design.

3.3.2 Poly Jet Technology

Poly Jet is a powerful 3D printing technology that produces smooth and precise parts, prototypes and tools. With the microscopic layer resolution and accuracy down range to 0.014mm, it can also produce thin walls and complex geometries using the widest range of materials available with any available technology.

Advantages of Poly Jet

- Create smooth, detailed prototypes that express the aesthetics of the final product.
- Produce precision moulds, jigs, fixtures and other manufacturing tools can be obtained.
- Complex shapes, intricate details and fine features can be made.

Poly jet & Multi jet Modeling (MJM)

- Poly jet is a remarkable rapid prototyping generation. Poly jet combines excessive precision (up to 16 μm layer top and tight tolerances) with the capability to combine more than one material in the identical print. Furthermore, it's viable to dynamically blend substances to create "digital substances" with new residences. For example, it's far possible to print rubber-like substances targeting a particular Shore A hardness.

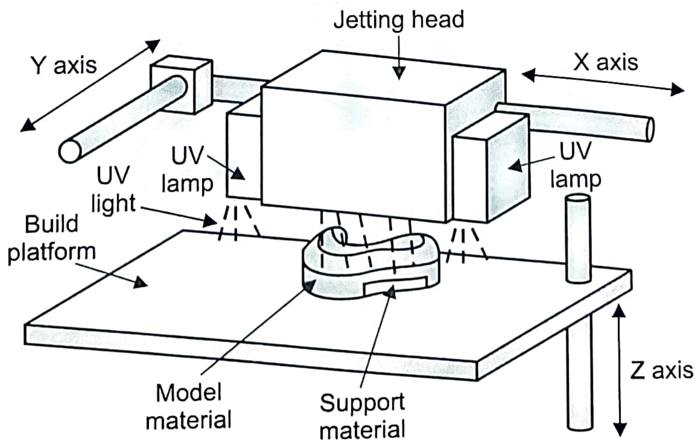


Fig. 3.8

- Another key feature of the Poly jet is the potential to print with an obvious resin (known as Vero clear). A popular use case is printing awesome white or black systems in an obvious package. A beneficial way to visualize complicated organic systems or the internal workings of complicated prototypes.

3.3.3 Nano Particle Jetting (NPJ)

- NanoParticle Jetting (NPJ) is a 3D printing procedure advanced by way of Xjet. It's a fabric blasting technology that uses a suspension of powder material to construct parts.
- The NPJ jets a liquid that includes nanoparticles of metal or ceramic material in suspension to shape the element even as concurrently jetting the service material. The technique takes a region in a heated bed maintained at 250°C, which lets in the liquid to vaporize as it jets, so the particles adhere to all instructions. The resulting 3D object has simplest a small quantity of binder in its body and supports.

Materials :

- The X jet helps NanoParticle Jetting with 316L stainless steel and two ceramic materials, zirconia and alumina. The material is established into the machine using a cassette without the need for processing or managing.

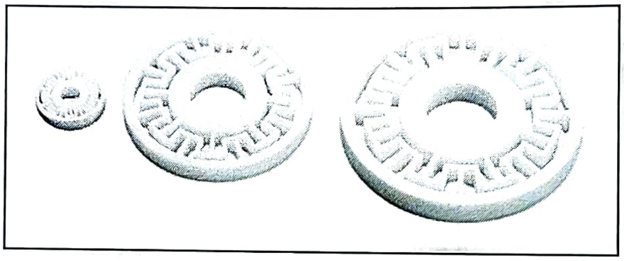


Fig. 3.9 : Ceramic Parts made with NanoParticle Jetting

Post Processing

After printing, NPJ components nonetheless maintain a small amount of binder and may have help structures. The provider material is water soluble and may be dissolved in a water bathtub. The inexperienced parts are about 60% dense and durable, sufficient to be machined or polished at this stage if necessary.

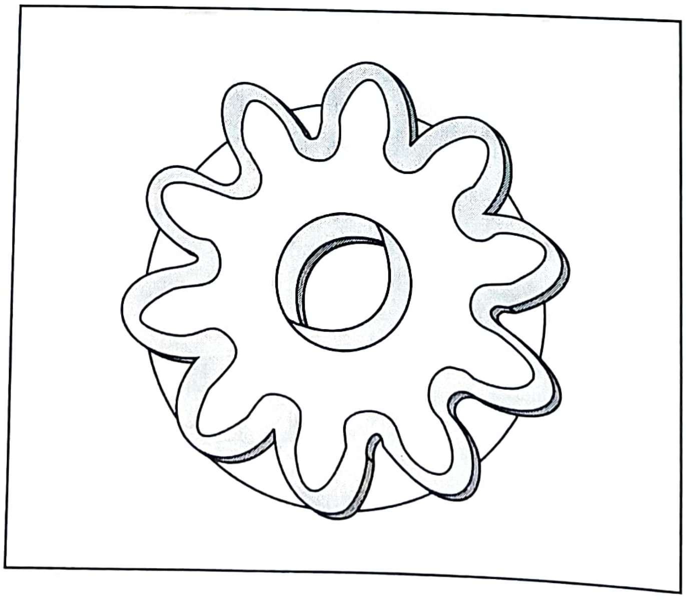


Fig. 3.10 : Part made via NPJ with the soluble support material still intact.

- The elements are then sintered in a furnace to remove the final binder. The sintering technique results in about 13% linear and isotropic shrinkage for metal elements and 17.8% in line with dimension for ceramics.

Advantages

- NanoParticle Jetting is able to produce many small components straight away. The cloth jetting process can be controlled drop by way of drop inside ±25 microns for small components and ±50 microns for large MIM/CIM components, consistent with X Jet. The minimal function size is 100 microns and the layer height may be 8 to 10 microns, allowing high-quality elements.
- Because NPJ makes use of material in suspension, screening and different steps required in powder-based processes are eliminated. The fabric may be printed in an everyday atmosphere without the want for gas, vacuum or strain and can be effortlessly recycled.
- Applications for nanoparticle jetting include listening to aids, surgical gadgets, crowns, bridges, and drill guides for the clinical enterprise; components immune to excessive temperatures and friction for the aerospace and automobile industries; and sensors for the electric industry.

3.3.4 Binder Jetting

- Binder jetting is a 3D printing manner that makes use of a liquid binder (think: glue) carried out to a build platform to bond layers of powder cloth collectively to create an element.
- First, the coating blade applies a thin layer of powder to the device's build platform. Next, the print head (a carriage with ink jets, just like those utilized in computing device second printers) precisely jets the binder into the powder in line with the geometry of the component.

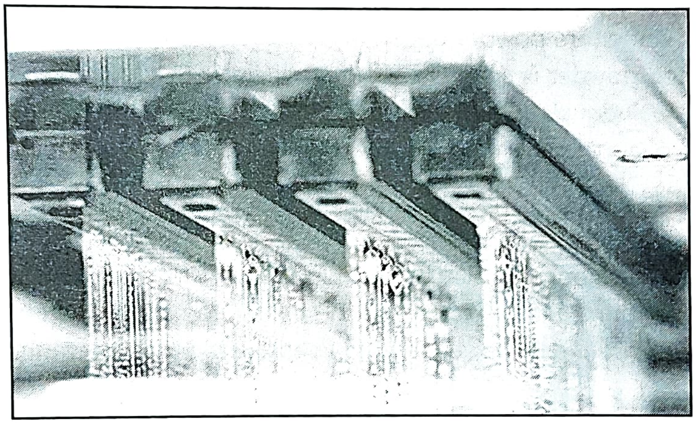


Fig. 3.11

- The print head is a carriage with inkjet nozzles, similar to those used in desktop 2D printers. It deposits the binding agent.
- When the binder layer is complete, the build platform is lowered and the recoating blade applies a fresh layer of powder over the platform and the top of the published part. The print head applies some other layer and this technique repeats until the part is entire. Sooner or later, the element is cured at the same time as still powder lined. The complete building box is then removed from the system and the loose powder is blown off with compressed air in a managed environment. These green components may be in addition processed to provide them the desired porosity and mechanical properties.
- Because the rubbing of the binder is achieved at room temperature, the system avoids dimensional deformations which can be not unusual in high-temperature three-D printing processes, consisting of warping or curling. If sintering is needed, only the bonded powder that makes up the additives is exposed to the heat of the furnace, so the last bulk powder can be recycled without worry of deterioration.

Advantages

- Binder injection moulding machines provide larger construct volumes than many powder bed 3D printing technologies and permit multiple layers of components to be stacked on top of every different in a build box. components produced in this way can be nested in all three dimensions of the printer meeting volume, allowing for the parallel manufacturing of multiple elements at the same time.

- Substances utilized in binder blasting tend to be more lower priced and less difficult to recycle than substances utilized in different powder-based AM procedures, which translates into cost savings and competitive parts expenses. The era is also specific and repeatable, making it suitable for mass production of small precision components.

Applications

- Binder jetting may be used to print a variety of materials together with metals, sands and ceramics. Markets for this technique include commercial programs, dental and scientific devices, aerospace components, casting components, luxury packages etc.
- Binder jetting 3D printing structures includes machines from desktop steel, digital steel, ExOne, GE Additive, HP (called metal Jet Fusion), Viridis3D and Vox eljet. Binder blasting services are also available from 3DEO, the developer of its personal blasting era (known as wise Layering), in addition to the various carriers referred to.

3.3.5 Multi Jet Fusion

Multi Jet Fusion is an commercial 3D printing system that produces functional nylon prototypes and very last production elements in as low as 1 day. The very last parts showcase a best finish, pleasant feature resolution and extra constant mechanical properties as compared to techniques which include selective laser sintering.

- Multi Jet Fusion uses an ink array to selectively deposit fixative and detailing retailers onto beds of nylon powder, which might be then melted with the aid of heating factors into a strong layer. After each layer, the powder is applied to the bed and the procedure is repeated until the part is entire.
- After production is complete, the entire powder bed with encapsulated components is moved to a processing station, wherein most of the unfastened powder is eliminated with an included vacuum. The elements are then shot blasted to dispose of any ultimate residual powder before sooner or later entering the finishing department wherein they're painted black to decorate the beauty look.

3.3.6 Color Jet Printing (CJP)

Color Jet Printing (CJP) is an additive production technology with two predominant additives: a core material and a binder. The core material is rolled onto the development platform in thin layers. After every layer is applied, a color crimson binder is selectively ejected from the inkjet print heads to purpose the center to solidify. The construct platform lowers to allow every subsequent layer to be unfold out and revealed, ensuing in a full-colour three-dimensional version.

Applications :

- Architectural models
- Demonstration models
- Conceptual models

Advantages :

- Enables full colur 3D prints
- Cost effective technology
- No support structures are required

Disadvantages :

- Fragile, low mechanical strength
- It cannot be used for functional prototypes because the abrasion is too great and the material breaks easily
- It is not waterproof

3.4 ENERGY DEPOSITION TECHNIQUES

3.4.1 Directed Energy Deposition (DED)

- Directed Energy Deposition (DED) directs energy into confined and concentrated areas to heat the substrate while simultaneously melting the material and substrate that is deposited into the substrate melt bath. The focused heat source used in this process is commonly an electron or laser beam.

- Each path of the DED head forms a path of solidified materials, and layers can be formed by connecting lines of material. A multi-axis deposition head or support material is required for complex 3D geometry. In this process, an inert gas is supplied to deliver the powders to the substrate and protect the deposit from oxidation.

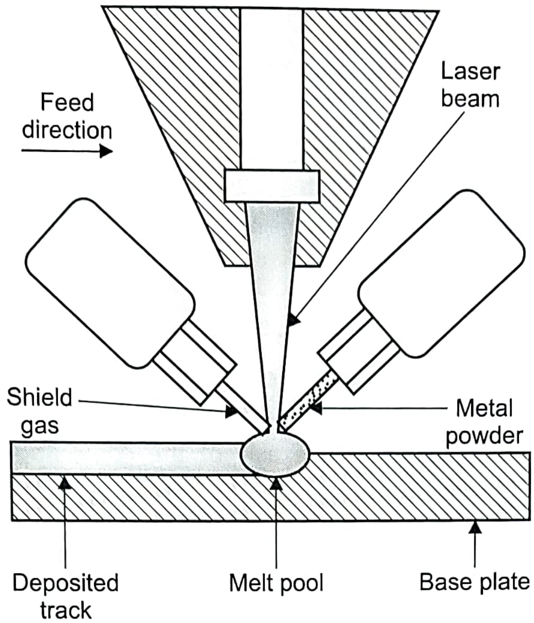


Fig. 3.12 : Schematic representation of directed energy deposition process.

- DED produces parts in a layer-by-layer manner like other 3D printing techniques. In this technique, two- or three-axis systems have a static base plate, so the nozzle moves upward as each layer is applied. In four-axis or five-axis systems, the nozzle and base run simultaneously and remain independent of each other. It also allows you to create more complex geometries. This process does not necessarily require a flat starting surface, so DED is suitable for attaching new material to existing components. This new material can also be applied to damaged parts for repair purposes. In general, the manufactured parts are in the shape of a near-net mesh and require a final machining step.
- The DED technique can process starting materials in the form of powder and wire with its own advantages and limitations. Powders are a multipurpose raw material in which most ceramic and metal materials are available in powder form. In addition, the powder form allows for easy reorientation between layers, as the presence of excess powder flow ensures dynamic equalization of the melt bath and deposit thickness in each region of the deposited layer. However, not all powders can be captured in the melt bath, so excess powders are needed. If recycling is desired, excess powders must be recaptured in a clean state, but this is not always easy.
- The advantage of the wire shape is that the raw material capture efficiency is almost 100%, because the deposit volume is almost similar to the amount of the feed wire. The wire is suitable for simple geometries, block geometries without many transitions, thin and thick, or with surface treatment. For a complex, large and dense model, process parameters such as layer thickness, wire diameter and wire feed speed should be carefully controlled to achieve the correct deposit size and shape.

3.4.2 Direct Metal Deposition (DMD)

- Direct steel deposition (DMD) is a powder jet additive manufacturing (AM) approach that can be used for low-price meeting, repair, welding and reconfiguration of forging dies. This approach has additionally been used to add features such as flanges and spigots to cast components to improve their capability.

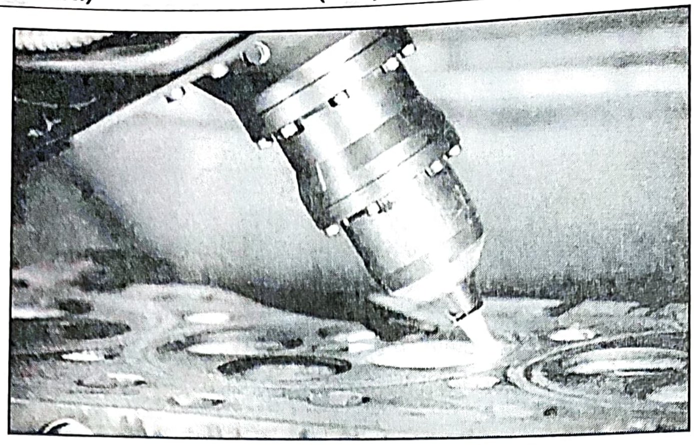


Fig. 3.13

- The success of the Direct metal Deposition (DMD) method lies in the design of the powder, protecting fuel and laser nozzle (Fig. 3.13). The powdered metallic is guided into the cone in order that its tip intersects the substrate. An excessive-powered laser beam is directed across the axis of the cone, imparting energy to melt and soften the powdered steel to the substrate. A barrier of protective gas is formed around the metal, which protects the melt bath from atmospheric gases.

EXERCISE

1. What is Robo casting and Bio print explain it with suitable example.
2. Explain with neat diagram FDM technology.
3. Explain Advantages and disadvantages of Ink jet Based technologies (i.e. CJP, MJM etc.)
4. Enlist several inkjet based technologies and explain binder jetting.
5. Explain energy deposition techniques.
6. What is Bioprinting?
7. Explain Nano partical Jetting (NPJ).
8. Explain Direct Ink writing in Detail.
9. Write short note on Extrusion. Give its advantages and disadvantages.

Unit IV : Materials and Design for AM **[08 Hr.]**

Introduction, Materials: Metals, Polymers, Ceramics & Bio-ceramics, Composites, Hierarchical Materials, Biomimetic Materials, Shape-Memory Alloys, 4D Printing & Bio-active materials, Material selection,

AM Material Specific Process Parameters: Processes, Heat or Chemical Treatments, Phase Transformations, Process Selection for various applications,

DfAM: Process specific strategies, Rules and Recommendations,

Quality Considerations and Post-Processing techniques: Requirements and Techniques, Support Removal, Sanding, Acetone treatment, Polishing, Heat treatments, Hot isostatic pressing, Materials science, Surface enhancement Techniques and its Material Science Analysis of AM's error sources

UNIT IV

MATERIALS & DESIGN FOR ADDITIVE MANUFACTURING

4.1 MATERIALS

4.1.1 Polymers

- Common plastics can be used in 3D printing, including ABS and PC. Common structural polymers can also be used, as can a variety of waxes and epoxy resins.
- A wide range of structural and aesthetic materials can be created by mixing different polymer powders.
- The following polymers can be used:
  - ➢ ABS (Acrylonitrile Butadiene Styrene)
  - ➢ PLA (Polylactide), including soft PLA
  - ➢ PC (Polycarbonate)
  - ➢ Polyamide (Nylon)
  - ➢ Nylon 12 (tensile strength 45 Mpa)
  - ➢ Glass filled nylon (12.48 Mpa)
  - ➢ Epoxy resin
  - ➢ Wax
  - ➢ Photopolymer resin

4.1.2 Metals

- A range of metals can be used, including a number of options suitable for structural and integral components.
- Commonly used metals: steel, titanium, aluminum, cobalt-chromium alloy.
  - ➢ Martensitic steel 1.2709(tensile strength 1100 Mpa)
  - ➢ Titanium alloy Ti6AI4V (tensile strength: 1150 Mpa)
  - ➢ Stainless steel 15-5ph (tensile strength: 1150 Mpa)
  - ➢ Cobalt chromium alloy, Co28Cr6Mo (tensile strength 1300 Mpa)
  - ➢ Aluminum alsi 10 mg (tensile strength 445 mpa)
  - ➢ Gold and silver

4.1.3 Ceramics

- Additive Manufacturing (AM) has the potential to disrupt the ceramics industry by offering new opportunities to produce advanced ceramic components without the need for expensive tooling, reducing manufacturing costs and lead times and increasing design freedom.
- While the development and implementation of AM technologies in the ceramic industry has been slower than in the polymer and metal industries, there is now considerable interest in developing AM processes capable of producing flawless, fully dense ceramic components.

- A wide variety of AM technologies can be used to shape ceramics, but mixed results have been obtained so far. Choosing the right AM process for a given application depends not only on the requirements in terms of density, finish, size and geometric complexity of the part, but also on the nature of the particular ceramic being processed.
- This article provides a detailed overview of the current state of the art in AM ceramics through a systematic evaluation of the capabilities of each AM technology, with an emphasis on reported results in terms of final density, surface finish, and mechanical properties. It also provides an in-depth analysis of the opportunities, challenges, benefits and limitations arising in the processing of advanced ceramics with each AM technology.

4.1.4 Bio-ceramics

- Bioceramics are a popular class of materials used in biomedical applications due to their mechanical stability and biocompatibility. They exist in various fields including hip joints for orthopedics, dental fillings for dentistry and scaffolds for tissue engineering; however, the standard processes currently used to produce these ceramic products can be time-consuming and expensive.
- In response, current literature alternatively proposes additive manufacturing (3D printing) strategies to produce bioceramic materials in a cost-effective and efficient manner. Here we briefly cover five common processes and materials used in additive manufacturing of bioceramics: fused deposition modeling, material jetting, binder jetting, powder bed fusion, and tank photopolymerization.
- We further discuss the potential of these 3D printed ceramic structures when applied to various biomedical technologies such as bone tissue scaffolds and structural implants.

4.1.5 Composites

- Composites typically contain a core polymeric material and a reinforcing material such as chopped or continuous fibers. The composite material offers higher strength and stiffness compared to unreinforced polymers.
- In some cases, it can even replace metals such as aluminum. These improved material properties make composites sought-after materials for tooling and end-use applications in a variety of industries such as aerospace, automotive, manufactured goods, and oil and gas. The streamlining and cost reduction of traditional composite manufacturing is one of the key factors in the growth of composite 3D printing.
- In addition to 3D printing, there are a number of methods for manufacturing composite components. However, most of them have a number of disadvantages: the need to manually lay down the layers of the composite and the use of expensive curing equipment and tools such as molds.
- This makes the traditional composite manufacturing process very labor, resource and capital intensive. intensive, which means it can be difficult to scale to large volumes. 3D printing, on the other hand, enables the automation of the manufacturing process, as the entire process is controlled by software and requires manual input only during the post-processing stage.

4.1.6 Hierarchical Porous Material

- Hierarchical porous materials are widespread in nature and find an increasing number of applications as catalytic supports, biological scaffolds, and lightweight structures. Recent advances in additive manufacturing and 3D printing technologies have enabled the digital fabrication of porous materials in the form of grids, cellular structures and foams in various lengths.
- However, current approaches do not allow the rapid production of bulky porous materials with pore sizes that range widely from macroscopic dimensions to the nanoscale. Here, ink compositions are designed and investigated to enable 3D printing of hierarchical materials exhibiting nano, micro and macro scale porosity. The pores are generated after removing the nanodroplets and microtemplates present in the initial ink. Using particles to stabilize droplet templates is the key to obtaining Pickering nanoemulsions that can be 3D printed using direct inkjet writing.

- The combination of such self-assembled templates with the spatial control offered by the printing process enables the digital production of hierarchical materials exhibiting hitherto inaccessible multi-level porosity and complex geometries.

4.1.7 Biomimetic Material

- Over millions of years of evolution, nature has created organisms with astonishing performances thanks to their unique materials and structures, providing us with valuable inspiration for the development of next-generation biomedical devices.
- As a promising new technology, 3D printing enables the production of multi-scale, multi-material and multi-functional three-dimensional (3D) biomimetic materials and structures with high precision and great flexibility.
- The challenges of manufacturing biomedical devices with advanced biomimetic materials and structures for various applications have been overcome with the booming development of 3D printing technologies.

4.1.8 Shape Memory Alloys

- "Shape memory alloys are smart materials that remember their shapes at high temperatures," said Lei Xue, first author of the paper. "Although they can be used in many ways, making shape memory alloys into complex shapes requires fine tuning to ensure the material has the desired properties."
- This technique uses a laser to melt metal or alloy powders layer by layer to produce objects with complex geometries that traditional manufacturing prohibits.

4.1.9 Bio Active Material

- The creation of scaffolds by three-dimensional printing in the field of tissue engineering has supported groups of doctors and patients in response to the shortage of organ implants.
- Traditional scaffolding methods have many complications associated with poor mechanical and architectural properties. 3D printing provides a huge platform for solving these problems; the problem arises in the selection of the material that should be printable, meeting the requirements of the scaffold, the acceptability of these printed scaffolds after insertion into the host body.
- This review summarizes relevant work and progress with respect to the following areas, representing bioceramics, their material and printing characteristics, discusses current issues and further enhancement of materials using enhancers to improve the overall properties of scaffolds for biomedical applications.

4.1.10 4D Printing

- 4D printing refers to single-material or multi-material printing of a device or object that can be transformed from a 1D source to a pre-programmed 3D shape, from a 2D surface to a pre-programmed 3D shape, and is capable of transitioning between different dimensions.
- Such transformations are facilitated by e.g. heating, light or swelling in a liquid, electrochemically and by programming different sensitivities to e.g. swelling into different parts of the designed geometry.
- These techniques offer adaptability and dynamic response for structures and systems of all sizes, and promise new possibilities for building programmability and simple decision-making into non-electronic-based materials.
- Potential applications include; robotic-like behavior without relying on complex electro-mechanical-chemical devices, as well as adaptive products, clothing or mechanisms that respond to user demands and changing environments. The basics and laws governing 4D printing, the materials that are used in 4D printing, with applications such as soft robotics, and the challenges that need to be overcome in order for 4D printing to evolve as a manufacturing technology.

4.2 AM MATERIAL SPECIFIC PROCESS PARAMETERS

- Each product manufactured by AM has its own unique set of product requirements.
- The selection of process parameters to meet these product requirements is complicated by an incredible number of process parameters.

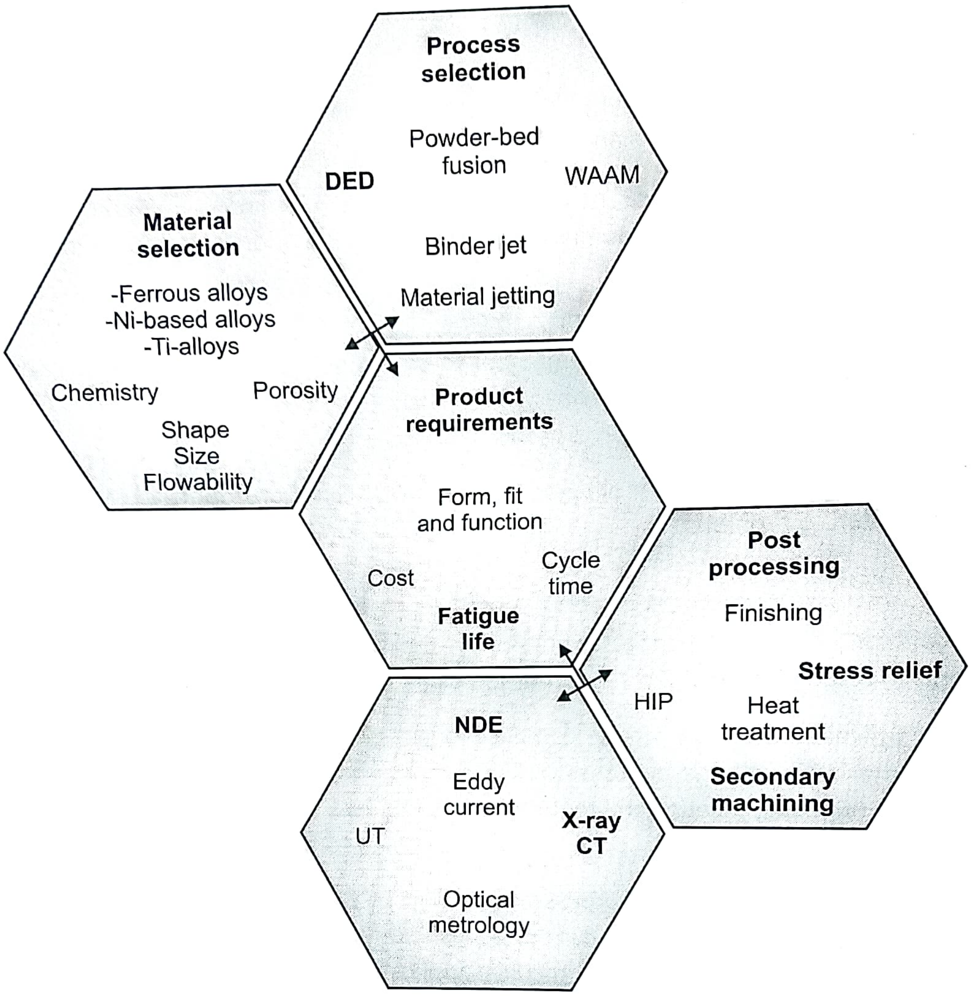


Fig. 4.1 : Specific process parameters

- Here is a step-by-step procedure to help you choose the optimal process parameters:
  1. Set your product requirements and understand the trade-offs
  2. Select the AM method
  3. Change the configuration of your method
  4. Select and qualify your raw materials
  5. Choose process parameters and understand the trade-offs
  6. Verify your process parameters
  7. Helps you identify a press partner on the scale (if needed)

Six Different AM Processes

- Additive manufacturing is a method of applying 3D printing in industrial production, which makes it possible to produce products without joints and with minimal post-processing.
- More materials can be used during this process, making it easier to create new products with minimal waste and lower material costs.
- Seven additive manufacturing techniques are available. Each of them differs in materials, layering and necessary machine technology.

1. Powder Bed Fusion :

This method of additive manufacturing uses either a laser or an electron beam to melt and fuse powdered material together to make products. Here are the differences between the two forms of powder bed fusion:

(i) Laser Powder Bed Fusion : Laser powder bed fusion uses a laser to heat powder material into 3D objects. After the powder layer is indexed, a new powder layer is applied to continue the process. Ultimately, the laser powder fusion technique does not require the support of other methods.

(ii) Electron Beam Powder Bed Fusion : This type of powder bed fusion is used to fuse particles together in specific areas. The beam can be manipulated very quickly, which speeds up the overall process by allowing multiple melt baths to occur simultaneously.

2. Thermal and Chemical Treatments

- Polylactic Acid (PLA) is one of the predominant filaments used in the 3D printing process, which is a type of Additive Manufacturing (AM) technology in which a printer prints semi-molten filament onto a bed, layer by layer, forming a part of the desired dimension.
- Final 3D printed parts generally have lower mechanical properties than conventional manufacturing techniques such as injection molding.
- The primary reasons for comparatively poor mechanical properties are poor bond formation between inter-fibers and residual thermal stresses induced by the temperature difference during 3D printing of the fiber.
- Heat treatment of a 3D printed part can significantly reduce the internal stress generated during the printing process and also improve the formation of bonds between interfilaments.
- The mechanical properties of PLA, especially the tensile properties, can be improved to about 80% by heat treatment at about 100°C for 4 hours. The Heat Distortion Temperature Test (HDT) is used to analyze the heat resistance of samples.
- The HDT test also showed an improvement in heat resistance of heat-treated parts compared to non-heat-treated parts by about 73%. It is the heat treatment of parts for 3D printing that significantly improves the mechanical properties compared to parts that have not been heat treated.

3. Phase Transformation :

- There are many valuable process transformation opportunities when implementing 3D printing into your manufacturing operations.
- Traditional manufacturing processes are usually cumbersome, inefficient and full of obstacles at all stages. Projects get stuck due to unfeasible designs, inadequate prototyping and long supplier delays. Such inefficiencies can quickly lead to exorbitant manufacturing costs or even costly product failures.

- Implementing 3D printing into your manufacturing operations can significantly streamline and improve your processes at all stages of product design, development and manufacturing. Here are a few ways 3D printing can optimize your manufacturing and provide valuable process transformation.

4. **Design Phase Transformation :**

- Moving to using software 3D printing technology in your product design process will allow you to create a product design that is the closest representation of how the final part will actually turn out in real-world production.
- The 3D printing design process uses software like BCN3D Stratos to input your CAD files and make any necessary adjustments. This advanced software adjusts printer settings and prepares design files for optimum quality printing.
- The main advantages of implementing a solution like Stratos in the design phase include:
  - ➢ Create prints with a higher level of detail
  - ➢ Have your prints customized to your exact specifications
  - ➢ Gaining more design freedom and flexibility
  - ➢ Easily explore a wealth of ideas and aesthetics
  - ➢ Ability to iterate designs faster
  - ➢ Transformation of the development phase

5. **Development Phase Transformation :**

- A successful development process involves choosing the right materials for your project and verifying the functionality of the parts. 3D printing technology provides several advantages for optimizing the development phase, resulting in time and cost savings.
- For example, the innovative shoe company Camper was able to streamline its development process and bring new collections to market faster by implementing 3D printing. Moving from outsourced prototyping to in-house 3D printing prototyping allowed Camper to reduce the turnaround time for a prototype iteration from two weeks to less than 24 hours.
- The main advantages of implementing 3D printing technology in the development phase include:
  - ➢ Ability to create more creative designs
  - ➢ Validate your designs quickly and easily
  - ➢ Easily test a large number of different materials
  - ➢ Accurately assess the quality of the part
  - ➢ Make sure the part meets all specifications

6. **Transformation of the Production Phase :**

- Because IDEX technology allows you to print using a dual extrusion system, it is possible to double the productivity of your production. BCN3D printers are able to handle a large print volume and easily produce large prints both in a short time frame and at a low cost.
- For example, the 420 × 300 × 400 BCN3D Epsilon W50 print volume allowed the ELISAVA team to create several large end-use parts for a mountain rescue motorcycle. 3D FFF printing technology has also made it easier to produce parts with complex geometries that other manufacturing processes could not provide.

- CIM UPC calculated that it was able to save between 3000 and 8000 Euros by producing a series of waterproof tanks for a client using FFF 3D printing technology. With FFF printers, they could produce parts in less than 48 hours at a lower cost per part than other manufacturing methods and still use materials equivalent to those used in injection molding.
- Automaker Nissan has achieved a process transformation of its assembly line and dramatically reduced costs by 3D printing more than 700 tools, fixtures and fixtures in-house instead of outsourcing.
- Their prototype manufacturing timeline was reduced from one week to one day, at a cost about 20 times lower than traditional methods such as CNC and drilling.
- The main advantages of implementing dual extrusion technology in your production phase include:
  - ➢ Functionality for fast production of even large prints
  - ➢ Flexibility in the production of parts with complex geometry
  - ➢ Increased efficiency of the production process
  - ➢ Significant cost savings by producing more parts in less time
  - ➢ Additional cost savings through reduced equipment needs

The 3D Printing Process Transformation :

- By implementing 3D printing technology, many advantages can be achieved in the stages of design, development and production.
- Streamlining the production process in turn leads to faster time-to-market and the creation of better quality products. Thanks to 3D printing, a valuable process transformation is now within reach.

4.3 DFAM

- DfAM is the method, science and skill of designing or redesigning parts, products and components to be additively manufactured using 3D printers. As any engineer can tell you, how something is made greatly affects its initial design. The part or product must meet the limitations and match the strengths of the chosen manufacturing process.
- For example, if you need to produce 500,000 car door handles, injection molding may be the most cost-effective way. You would design the handle for injection molding considering that the structure must have an opening to allow the molten plastic to be injected into the mold cavity.
- This is a classic Design for Manufacturing Process (DFM); where the product design is optimized to be created more cheaply and easily based on the best manufacturing process for the product.
- Similarly, Design for Additive Manufacturing (DfAM) is a set of principles where the design of a product is optimized to make it better and easier based on the constraints and attributes specific to 3D printing (additive manufacturing).

4.3.1 Rules and Recommendations

- Anything can be designed in the digital space, but not everything can be 3D printed. When you are designing a part for 3D printing whether for prototyping or for manufacturing final products certain limitations apply. These limitations have to do with the basic mechanics of any additive manufacturing process.
- In this we summarize the most important rules and process limitations to keep in mind when designing parts for each of the major 3D printing processes. We also describe the key strengths and limitations of each technology to help you get the most out of your designs.

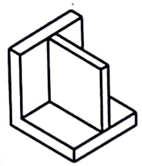
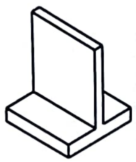
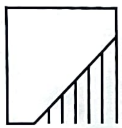
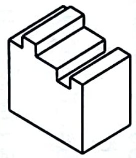
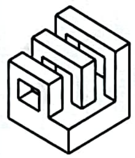
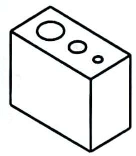
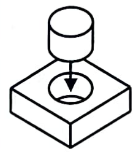
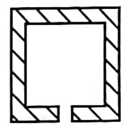
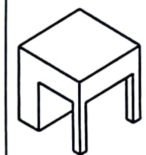
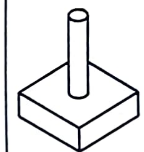
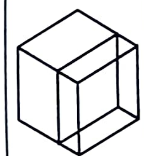
	Supported walls	Unsupported walls	Support & overhangs	Embossed & engraved details	Horizontal bridges	Holes	Connecting /Moving parts	Escape holes	Minimum features	Pin diameter	Tolerance
	Walls that are connected to the rest the print on at least two sides.	Unsupported walls are connected to the rest of the print on less than two sides.	The maximum angle a wall can be printed at without requiring support.	Features on the model that are raised or received below the model surface.	The span a technology can print without the need for support.	The minimum diameter a technology can successfully print a hole.	The recommended clearance between two moving or connecting parts.	The minimum diameter of escape holes to allow for the removal of build material.	The recommended minimum size of a feature to ensure it will not fail to print.	The minimum diameter a pin can be printed at.	The expected tolerance (dimensional accuracy) of a specific technology.
											
Fused deposition modeling	0.8 mm	0.8 mm	45°	0.6 mm wide & 2 mm wide	10 mm	Ø2 mm	0.5 mm		2 mm	3 mm	± 0.5% (Lower limit ±0.5 mm)
Stereo lithography	0.5 mm	1 mm	Support always required	0.4 mm wide & high		Ø0.5 mm	0.5 mm	4 mm	0.2 mm	0.5 mm	± 0.5% (Lower limit ±0.15 mm)
Selective laser sintering	0.7 mm			1 mm wide & high		Ø1.5 mm	0.3 mm for moving parts & 0.1 mm for connections	5 mm	0.8 mm	0.8 mm	± 0.3% (Lower limit ±0.3 mm)
Material jetting	1 mm	1 mm	Support always required	0.5 mm wide & high		Ø0.5 mm	0.2 mm		0.5 mm	0.5 mm	± 0.1 mm
Binder jetting	2 mm	3 mm		0.5 mm wide & high		Ø1.5 mm		5 mm	2 mm	2 mm	± 0.2% for metal & ±0.3 mm for sand
Direct metal laser sintering	0.4 mm	0.5 mm	Support always required	0.1 mm wide & high	2 mm	Ø1.5 mm		5 mm	0.6 mm	1 mm	± 0.1 mm

Fig. 4.2

Designing for FDM :

In Fused Deposition Modelling (FDM), an object is built by selectively depositing melted material in a predetermined path layer by layer. The materials used in FDM are thermoplastic polymers that come in a filament form.

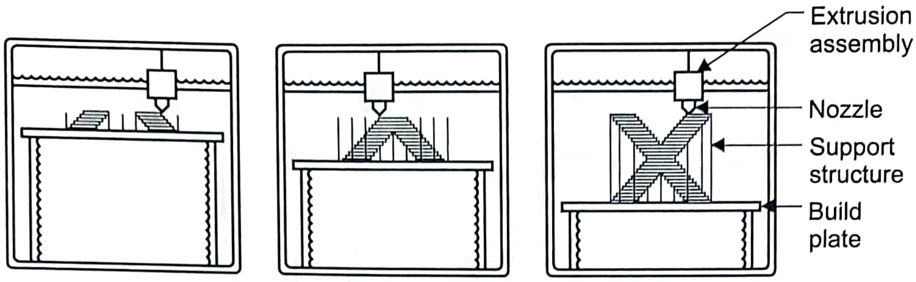


Fig. 4.3

The FDM 3D Printing Process :

- The main design limitations in FDM come from the shape and size of the deposited molten strings of plastic material.
- These have a typical width of 0.4 to 0.5 mm and a typical layer thickness of 100 to 300 μm. Recommended minimum FDM wall thickness is 1mm, but protrusions and pins must be larger (recommended minimum is 2mm and 3mm).
- Another limitation of FDM is the need for support structures: molten material cannot be stored in air. Any wall that slopes more than 45° from the vertical must be supported. Support structures are usually printed from the same material as the base part, but dissolvable supports are increasingly common, which give a better result.
- Surfaces printed on support structures usually have a lower surface finish than the rest of the part, so it is recommended to avoid them completely if possible and to think about the orientation of the part on the machine when designing.

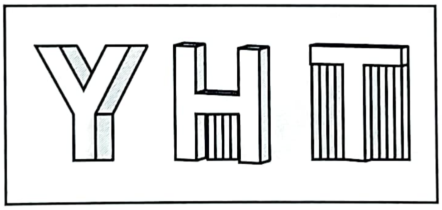


Fig. 4.4

- Remember the Y, H, and T's of FDM support when you design parts for this process
- A common misconception about FDM is that lower layer thickness is always better. A smaller layer thickness than the standard (which is 200 μm) should only be used when designing parts with very small features or with significant curvature, as this reduces the "stair-stepping" effect.
- Here is a important FDM printer parameters:
  - ➢ Typical build size: 200 × 200 × 200 mm (up to 1000 × 1000 × 1000 mm)
  - ➢ Typical layer thickness: 50 to 400 μm
  - ➢ Support structures: mandatory (critical angle 45°)
  - ➢ FDM materials: Thermoplastics (PLA, ABS, Nylon, PETG, ULTEM - see more)

Designing for SLA/DLP :

- In Stereolithography (SLA), an object is created by selectively curing a polymer resin layer by layer using a UV laser beam. Direct Light Processing (DLP) is a similar technology that uses a projector instead of a beam.
- The materials used in both SLA and DLP are photosensitive thermoset polymers that come in liquid form.

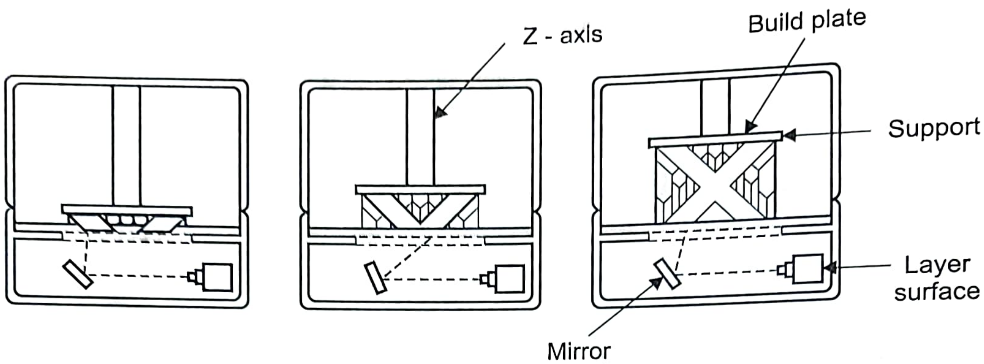


Fig. 4.5 : SLA process

The SLA 3D Printing Process :

- SLA and DLP can produce some of the most accurate 3D printed parts with very fine detail because the light source can solidify the material very precisely. This process can produce elements with dimensions of up to 0.2 mm and walls with a thickness of 0.5 mm (sometimes less).
- SLA and DLP are also known for producing parts with a very smooth finish that resembles injection molded parts. However, keep in mind that support structures are required here as well (the critical angle here is again 45°).

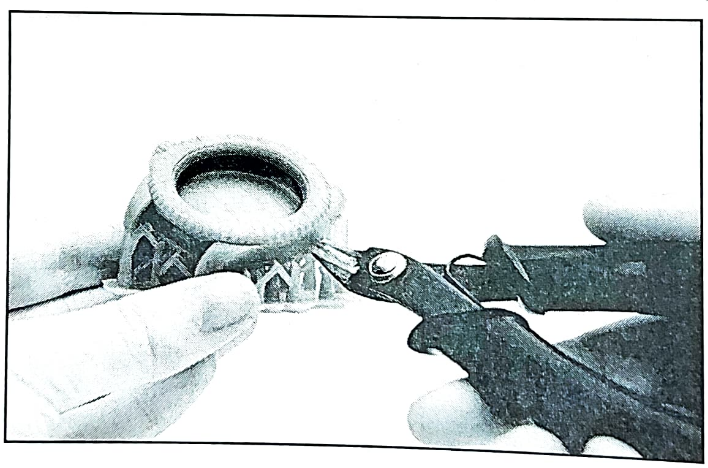


Fig. 4.6

- Support in SLA/DLP has a tree structure. Small marks will be visible on the part at the points of contact and manual post-processing is required to remove them.
- For this reason, keep all features that require the highest dimensional accuracy on the same side of the part if possible.

Removing the support structure from an SLA part

- Here is a important SLA/DLP printer parameters:
  - ➢ Typical build size: 145 × 145 × 175 mm (up to 1500 × 750 × 500 mm)

- Typical layer thickness: 25 – 100 μm
- Support structures: Always required
- SLA materials: Thermoset resins (standard, ABS-like, PP-like, rubber-like - see more)

Designing for SLS

In Selective Laser Sintering (SLS), a laser passes through particles of polymer powder, bonding them together to form the part layer by layer. The materials used in SLS are thermoplastic polymers that come in powder form.

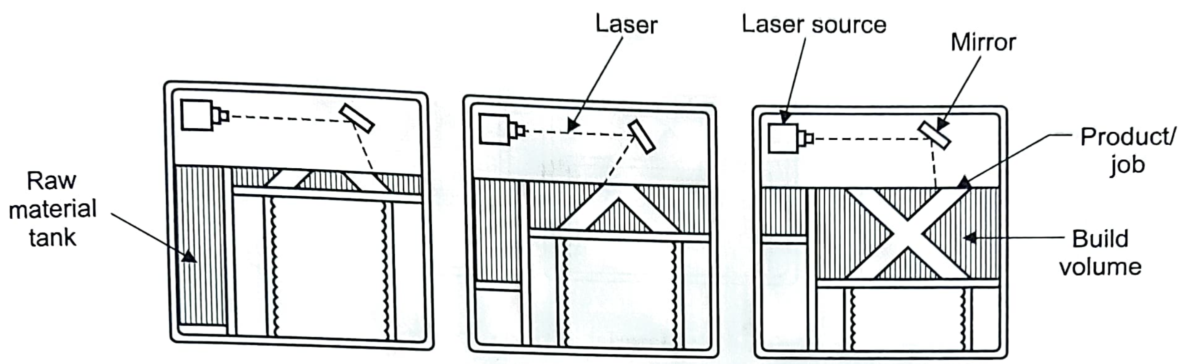


Fig. 4.7 : SLS process (Selective Laser Sintering)

The SLS 3D Printing Process :

- SLS can produce parts with good detail and high precision: the minimum feature size that can be produced with SLS is 0.7 to 0.8 mm. However, the holes must have a minimum diameter of 1.5 mm to prevent excessive sintering.

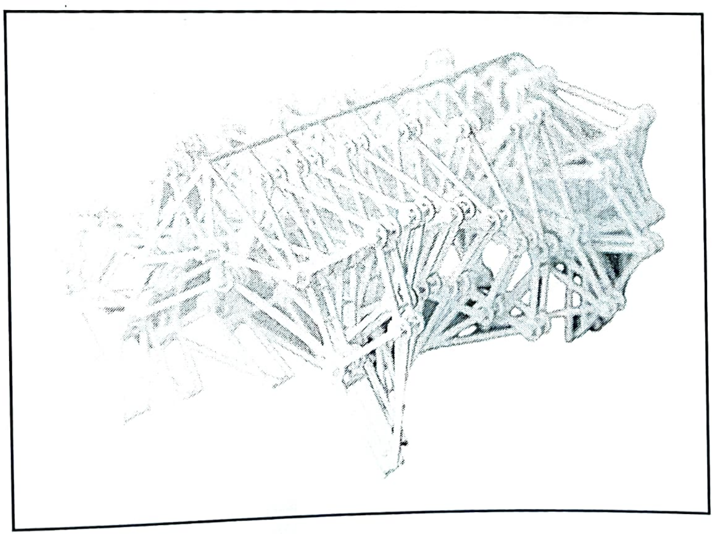


Fig. 4.8

- A key advantage of SLS is that it does not need any support structures. The unsintered powder provides all the necessary support to the part. Because of this, SLS can be used to create free geometries or interlocking assemblies that cannot be produced by any other method (leave a gap of 0.3 mm between moving parts).
- However, be aware that warping is a problem in SLS, so 3D printing large aspect ratio parts with SLS is not recommended. SLS part printed as a single assembly.

- Here is a important SLS printer parameters:
  - ➢ Typical build size : 300 x 300 x 300 mm (up to 750 × 550 × 550 mm)
  - ➢ Support structures : Always required
  - ➢ Typical layer thickness : 25 - 100 μm
  - ➢ SLS materials : Thermoplastics (Nylon, TPU, composites - see more)

Designing for Material Jetting :

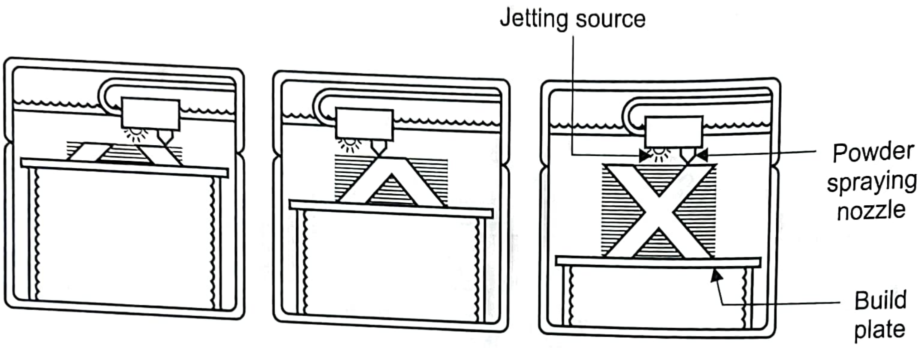


Fig. 4.9 : Material jetting process

- In Material Jetting, a printhead (similar to printheads used for standard inkjet printing) dispenses droplets of photosensitive material that solidifies under Ultra Violet (UV) light.
- The materials used in Material Jetting are thermoset photopolymers (acrylics) that come in liquid form.

The Material Jetting 3D printing process :

- In Material Jetting, a printhead (similar to printheads used for standard inkjet printing) dispenses droplets of photosensitive material that solidifies under Ultra Violet (UV) light. The materials used in Material Jetting are thermoset photopolymers (acrylics) that come in liquid form.
- A key benefit of Material Jetting is the ability to produce accurate multi-material and multi-color prints that accurately represent final products.

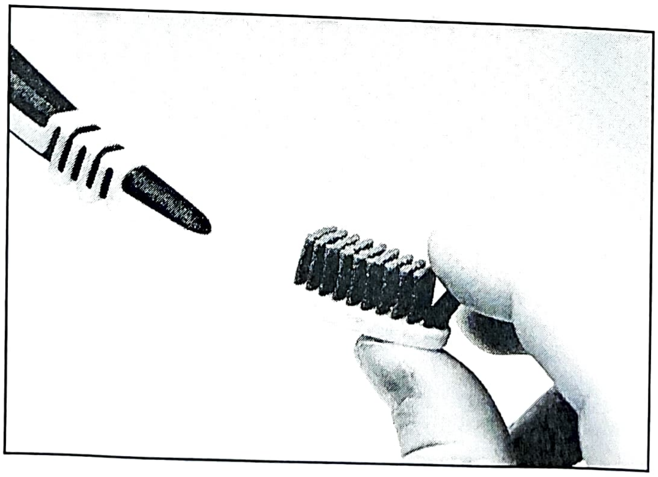


Fig. 4.10

- To designate certain areas of the part as a different material or color, the model must be exported as separate STL files (for one color/material) or accompanied by an OBJ or VRML file (when mixing colors).

Multi-Material Part Printing with Material Jetting

- Here is a important parameters of the Material Jetting printer:
  - ➢ Typical build size: 380 × 250 × 200 mm (up to 1000 × 800 × 500 mm)
  - ➢ Support structures: Always necessary (but dissolvable)
  - ➢ Typical layer thickness: 16 – 32 μm
  - ➢ Materials Blasting materials: Thermoset resins (similar to ABS, PP, rubber - see more)

Designing for DMLS/SLM

Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM) are similar technologies that use a laser to scan and selectively fuse (or fuse) metal powder particles and bond them together. The materials used in both processes are metals that come in powder form.

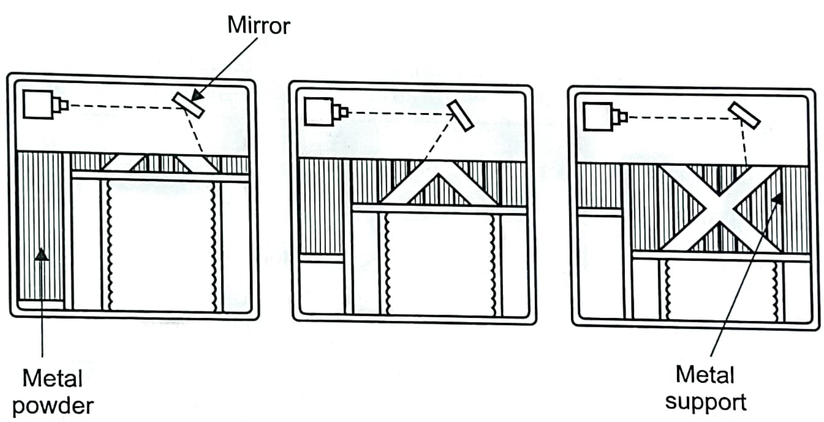


Fig. 4.11

The DMLS/SLM 3D Printing Process :

- DMLS and SLM machines are high-end industrial systems that have great precision. The minimum achievable wall thickness and element size are 0.4 and 0.6 mm.
- Support structures are always required in metal 3D printing to prevent warping and anchoring of the part to the platform, and are printed from the same metal material as the base part.
- Simulation and topology optimization algorithms using specialized software are often used to minimize the amount of support because it is difficult to remove.
- Since DMLS/SLM requires significant engineering effort and high cost, it is currently mainly used in high-end applications. The key advantages of this technology lie in the possibilities of manufacturing highly optimized lightweight structures and the consolidation of multiple assembly components into one part.

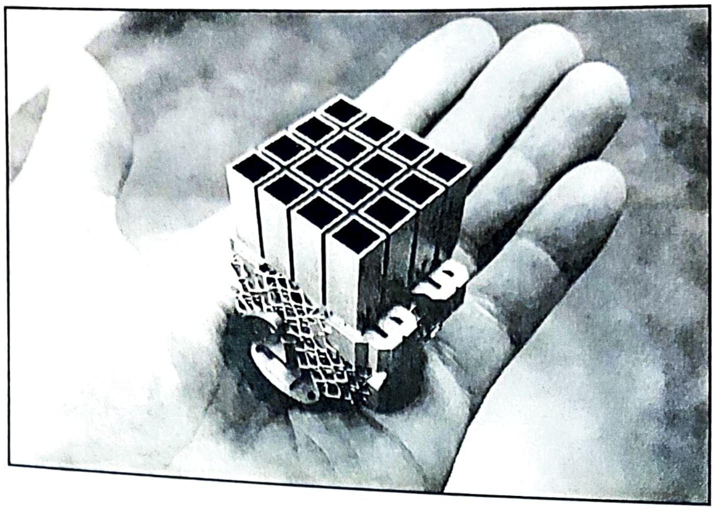


Fig. 4.12

Topology optimised satellite antenna manufactured using DMLS. Courtesy

- Here is a important DMLS/SLM printer parameters:
  - ➢ Typical build size: 250 × 150 × 150 mm (up to 500 x 280 × 360 mm)
  - ➢ Support structures: Always required
  - ➢ Typical layer thickness: 20 - 50 μm
  - ➢ SLM/DMLS materials: Metal and alloys (stainless steel, aluminum, titanium - see more)

Designing for Binder Jetting :

- In Binder Jetting, an adhesive binder is selectively applied to the powder bed and bonds the particles together one layer at a time to form a solid part.
- The materials used in Binder Jetting are metals, sand, ceramics or polymers that come in powder form.

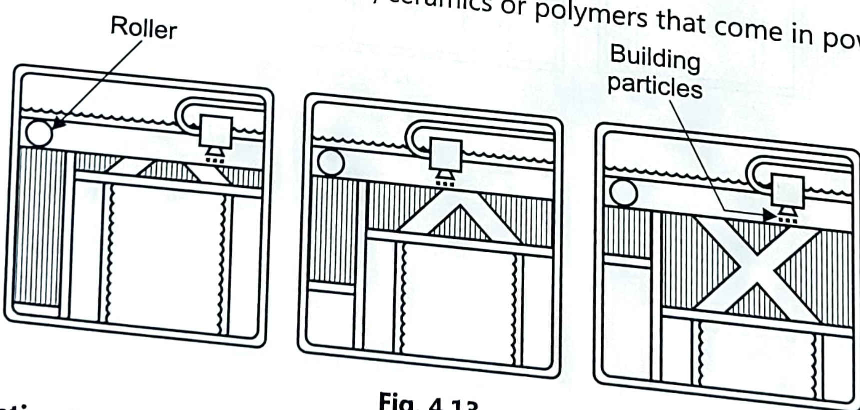


Fig. 4.13

The Binder Jetting 3D Printing Process :

- Binder Jetting is not recommended for the production of parts with fine elements and small details (recommended minimum wall thickness is 2 mm). This is because the printed parts are fragile and must be strong enough to survive the post-processing step before they get their good mechanical properties.
- Binder Jetting's strengths lie in the fact that printing takes place at room temperature: thermal effects such as distortion are not a problem here, so very large parts can be produced.

Binder Jetting does not require support structures, which leads to higher productivity, especially compared to other metal 3D printing technologies.

New metal binder jetting systems, scheduled for release in 2018, are expected to advance the technology's capabilities.

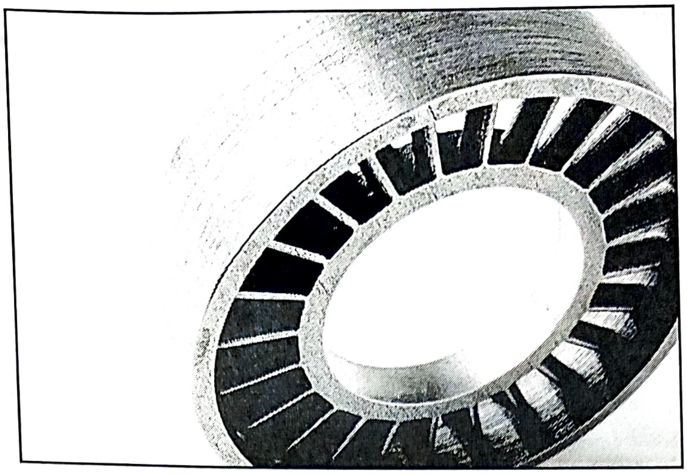


Fig. 4.14

- A stainless steel part manufactured with Binder Jetting
- Here is a important parameters of the Binder Jetting printer:
  - ➢ Typical build size: 400 × 250 × 250 mm (up to 800 × 500 × 400 mm)
  - ➢ Support structures: Not required
  - ➢ Typical layer thickness: 50 – 100 μm
  - ➢ Binder Jetting materials: Metals, full-color sandstone, silica sand - see more.
- Designing for a particular 3D printing technology requires knowledge of the basic mechanics of each process.

4.4 QUALITY CONSIDERATIONS AND POST-PROCESSING TECHNIQUES

- Additive manufacturing is revolutionary in many ways. Few other manufacturing methods have the design freedom and digital workflows that this collection of technologies offers.
- As a result, you can print complex and lightweight parts with optimal geometric properties in breakthrough materials that outperform traditionally manufactured parts.
- From a cost-effective perspective, waste reduction compared to subtractive processes can provide manufacturers with significant raw material savings, not to mention time and labor savings.
- And now, after many years of research, development and innovation, 3D printing is finally crossing that threshold from prototype to production.
- However, there are still several challenges that prevent AM from being fully adopted in the manufacturing industry. The biggest: standardized quality measures and quality control.
- These are essential for repeatability, consistency, scalability and overall confidence in the process.
- You need data to meet the requirements of any particular manufactured product.
- In order to obtain GD&T (Geometric Dimensioning and Tolerances) measurements, investing in high-precision metrology equipment for your specific purpose is a must.

What is Post Processing?

- Post-processing is the basic phase of additive manufacturing.
- It is the final step in the manufacturing process where parts receive finishing touches such as smoothing and painting.

Why is Post-Processing Important?

- Post-processing improves the quality of parts and ensures they meet their design specifications.
- The finishing process can improve a part's surface properties, geometric accuracy, aesthetics, mechanical properties, and more.
- With samples and prototypes, it can mean the difference between a sale or a loss. For production parts, finishing creates a part that is ready for use.

Post-Processing Capacity

- When placing an order, it is important to consider the additive manufacturer's finishing capacity. Some companies dedicate only a small area of their facility to finishing work.
- This can lead to costly post-processing, outsourcing or bottlenecks in the final stage of production. It can also be an incentive to finish in a hurry.

Common Finishing Processes

- There are many different post-processing techniques. Additive manufacturing companies often specialize in certain types of finishing and may even have their own proprietary finishing process.
- Below are common finishing techniques as well as proprietary techniques found only in ProtoCAM. These techniques can be slightly modified for special materials.
- We can identify 5 steps in post-processing, although not all steps are required for all projects:
  1. Cleaning
  2. Repair
  3. Curing or Curing
  4. Surface finish
  5. Coloring
- Also note that the post-processing technique may vary depending on the printing process used to create the model.

1. Cleaning :

(a) Removal of support material (FDM and Material Jetting)

- When printing overhanging models with FDM or other material jet technologies, support structures are needed to hold overhanging elements.
- These support structures can be printed using the same material as the model itself. However, if the machine allows printing on multiple materials, a special support material can be used. However, any time a supporting structure is required, some post-processing will need to be done.
- There are two types of carrier material: (i) Soluble and (ii) Insoluble (usually the same material that the model is printed with).

(i) When using a soluble carrier material, there is a lower risk of damage to the model. The support structures can be dissolved in water or with a chemical called limonene. Examples of soluble materials are HIPS (used as a carrier with ABS material) and PVA (used as a carrier with PLA material).

(ii) The insoluble material is quite firm and can only be removed with tools such as knives or pliers. This must be done carefully and there is a risk of damaging the model or unintentionally removing small elements.

(b) Powder Removal (SLS and Powder Bed Fusion)

- Models printed using powder fusion (SLS, etc.) are produced using plastic or metal powders. Powder residue can stick to or remain in the model, such as in holes or more complex internal channels inside the model.
- Excess powder can be removed manually, but automated solutions have arrived on the market that vibrate or rotate to remove access powder. This 3D printing post-processing technique works like a sort of centrifuge that spins the part in all 3 dimensions.

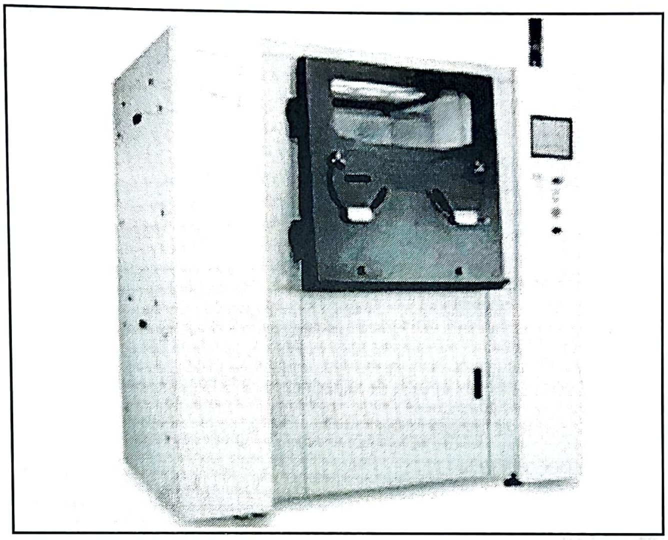


Fig. 4.15 : Industrial SLS machine

- SFM-AT800S depowdering machine by solukon Maschinenbau GmbH in collaboration with Siemens

(c) Washing (SLA and Photopolymerization)

- Parts that are printed with SLA or other photopolymerization can be easily cleaned after printing. The two companies have added post-processing washers that are seamlessly integrated into their range of printing processes.
- FormLabs has added Form Wash, which uses Isopropyl Alcohol (IPA) to clean parts. Carbon developed the Smart Part Washer for cleaning.

2. Fastening / Repair :

Sometimes minor repairs are needed to fill small holes or cracks, or even to join parts that were printed separately.

(a) Fulfillment :

When fillers and hardeners are used to repair unwanted holes or cracks in a printed object.

(b) Bonding and welding :

Used when separately printed parts need to be attached together. ABS prints can be welded or glued using acetone.

3. Curing :

- Just like French fries, baking the models after printing improves the mechanical properties (crunchiness of the French fries) of the material.
- Formlabs and Carbon have added UV light curing to their printing process (SLA and CLIP, both photopolymerization processes). After the model is printed, special curing machines heat the model to bring the part to optimal mechanical

properties. Curing therefore differs from other post-processing options in that it improves not only the aesthetic properties but also the physical quality of the model.

4. Surface Treatment :

After washing, cleaning, removing support or excess material and curing, various processes are available to make the model look more aesthetically pleasing. This is especially important when models are aimed at consumer markets.

(a) Grinding :

- Lines of layers or contact points where the support structure was attached to the model can be removed by carefully sanding the surface of the model using sandpaper with different grits from low to high for finishing.
- In addition to being labor intensive, manual sanding can lead to inconsistent results. This can be avoided with automatic polishing.
- Layer lines are particularly visible on 3D models made using layering techniques (such as FDM).

(b) Steam or Chemical Smoothing :

- Sometimes chemicals are used to smooth the surface of the model. The vapors react with the outer layer of the object. The layer lines melt away to leave a smooth outer layer while giving the model a glossy look.
- For PLA and ABS printed models, acetone or the chemical reagent Tetrahydrofuran (THF) is often used.
- The problem with this technique is that it cannot be controlled: small elements that should remain can be melted. Vapors can also be harmful if inhaled. This can be avoided by using closed chemical cleaning machines.

5. Dyeing :

In some cases, 3D models can be printed using colored material, and multi-material printing can produce (multiple) colored prints. But one can also opt for dyeing during the post-processing phase.

Painting and Varnishing :

The parts that need to be colored would ideally be printed using white stock. A coat of primer is usually applied before painting the model. Painting can be done by hand using a brush or spray. There are machines that automate the injection molding of parts.

4.4.1 Support Removal

Remove Breakaway support

Prints using support material will require additional processing to remove the support structures. This can be achieved by breaking out the supporting structures from the building material.

1. **Tear up the inner support structure**

   Start by removing the walls of the supporting structure using the pliers. This allows you to quickly tear off most of the internal support structure.

2. **Pull the Breakaway support out of the building material**

   After most of the supporting structure is removed, the remaining part(s) can be pulled out of the building material. Using the pliers, grab the Breakaway support in the corner and try to carefully get under it, then bend it up. Repeat this process for several corners to release the support from the model around the corners. Then pull the Breakaway support out of the model.

3. **Peel off the last traces from the model**

Sometimes after the Breakaway support is pulled from the building material, the last layer of support material remains. If this happens, use a pair of pliers to pry it away from the loose edge. Any residue on the model can be removed with tweezers.

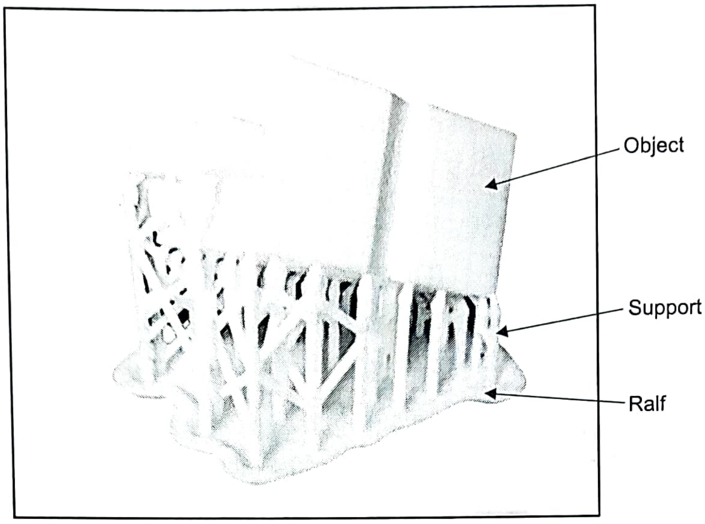


Fig. 4.16

4.4.2 Sanding

- A project fresh off the 3D printer may look great from a distance, but a closer look will likely reveal an uneven surface marked by visible layer lines. Removing these coarse details is practically a requirement if you are looking for 3D prints with a more professional finish. This will take some work.
- One of the simplest options for post-processing, although tedious and laborious, is grinding. Simply put, you take a piece of sandpaper and go to town on the surface of this finished 3D print. However, you will need to be a bit more subtle depending on what type of filament material you are working with.

Which filament materials can be sanded?

If you are looking for a professional look, the first thing you need to know is that not all filament materials are gentle on the mechanical smoothing process of sanding. The sandpaper essentially sands the surface of the print, removing much of the plastic and creating a smooth surface. So the hardness and density of the material play a role in how easily it can be sanded. Here are some of the fiber materials that are good candidates for grinding:

PLA :

Sanding is the best choice for smoothing PLA prints, mostly because there aren't really any alternatives. It is also one of the easier to grind fiber materials because of its low strength.

PETG :

PETG is slightly more flexible compared to ABS and PLA. This ductile or flexible nature means that PETG is much more difficult to grind. Still, sanding PETG prints is easier than any other alternative – either heat treatment with a heat gun or a solvent bath using toxic solvents.

In terms of quality, brushed PETG prints are on par with any other filament material. PETG is slightly more thermally stable than PLA, so you won't need to handle it as carefully during sanding.

ABS :

Although the acetone steam bath method is the preferred technique for smoothing ABS prints, ABS actually responds very well to sanding. ABS is known to be a high strength and wear resistant material, so honing its rough properties will require quite a bit of effort.

The best thing about grinding ABS is that it is very stable when exposed to high temperatures. If you sand by hand, it would be almost impossible to generate the amount of heat that would cause the ABS to warp. That's lucky, because you'll probably need a lot of pressure to succeed at grinding ABS.

Composite PLA :

- By far the easiest material to sand is composite PLA. These are basically PLA fibers filled with solid materials such as wood, metals, marble or carbon fibers. Composite filaments are extremely popular due to their unique visual appeal and appearance that deviates from the typical "plastic" look.
- What makes PLA composite fibers easy to sand is the fact that they retain the ease with which PLA can be sanded, but are much less prone to warping. Some composite fibers look downright beautiful when sanded, especially those impregnated with wood powder.
- If there is a fiber that cannot be ground, it would be a truly flexible fiber like TPU.

Acetone Treatment :

- Layer smoothing is one of the most popular methods to remove layer lines on 3D prints, improving their finish and appearance. One common method of smooth layering is to use acetone, which only works on parts printed in ABS, ASA and similar filaments.

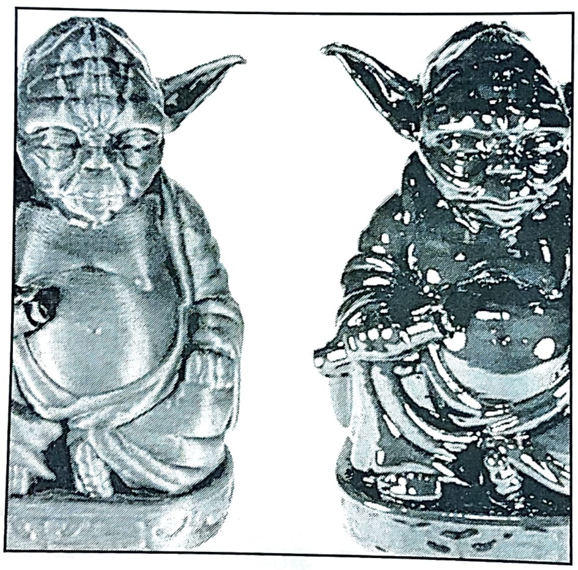


Fig. 4.17 : Texture after post processing

- Acetone, which most people are familiar with for its use in painting, is a solvent that can dissolve some plastics, including ABS. Acetone smoothing can be done by applying acetone vapor or liquid to the printed part, which dissolves the many 3D printed layers. This "bonding" of the layers is what gives the shiny and smooth surface.

Vertical Strength :

- As most people might think, parts that are treated with acetone are vertically more robust because the horizontal lines of the layer have dissolved and joined vertically. This concept was proven by a study that measured the material toughness (MPa) of acetone-treated and untreated parts. An acetone-treated, vertically oriented 3D printed part was found to be stronger than one that was not treated (see bar graph above).

Horizontal Strength :

- *It is a mistake to assume that parts treated with acetone are stronger overall. Michael Graham's study confirms the findings of a previous study - that parts treated with acetone are vertically stronger - but provides new evidence regarding their horizontal strength.*

- Graham's intensive study was conducted using a machine that tests the tensile strength of acetone-treated and untreated parts both horizontally and vertically. In other words, the pieces were subjected to stress tests in both horizontal and vertical orientations.
- When the results were recorded, you can see that the acetone-treated parts were weaker than the untreated parts when subjected to a stress test horizontally. The data revealed that they were 9% weaker horizontally than untreated sections. However, parts treated with acetone were 31% stronger vertically than untreated

4.4.3 Hot Isostatic Pressing (HIP)

- Hot Isostatic Pressing (HIP) has been used for many decades as a method of consolidating metal powders and metal matrix composites to produce fully dense parts, to remove porosity from sintered parts, to produce diffusion bonded parts, and to remove casting defects. HIP now also plays an important role in ensuring and enhancing the quality of critical components produced by powder additive manufacturing.
- Hot Isostatic Pressing (HIP) has been used for many decades as a method of consolidating metal powders and metal matrix composites to produce fully dense parts, to remove porosity from sintered parts, to produce diffusion bonded parts, and to remove casting defects.

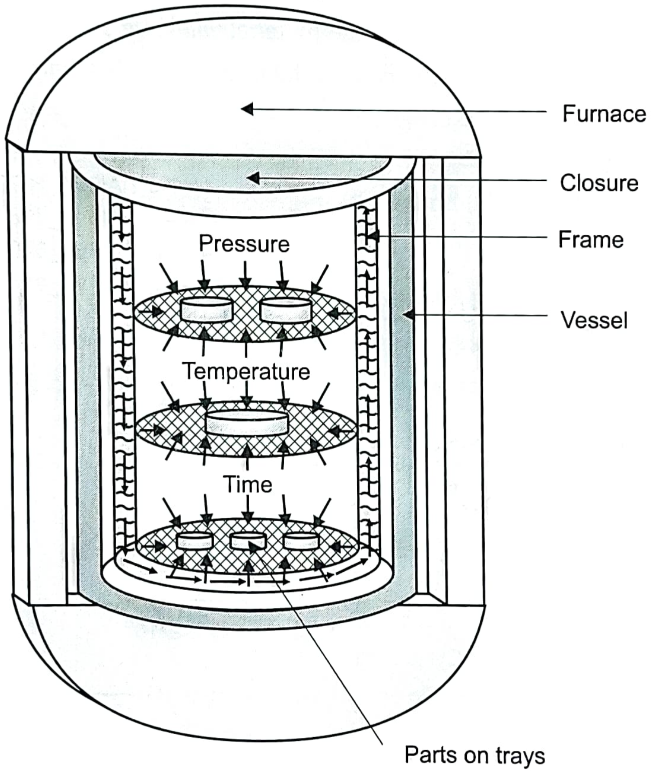


Fig. 4.18

- HIP now also plays an important role in ensuring and enhancing the quality of critical components produced by powder additive manufacturing.
- Hot isostatic pressing is a process used to consolidate metal powder or remove defects in solids such as pores, voids and internal cracks, compacting the material to 100% of theoretical density. When bulk metal powders are consolidated by HIP, or when previously densified parts with surface porosity need to be fully densified, the HIP cycle must be performed in gas-tight capsules made of sheet metal or glass.
- Previously densified parts that do not have surface-bound porosity, such as gas-tight surface products, can be HIPed without the need for encapsulation. The process involves high temperature and high isostatic gas pressure, which

means that pressure is applied to all surfaces of the part in all directions, resulting in densification. The mechanisms of densification during HIP are plastic deformation, creep and diffusion.

- Initially, plastic deformation is the dominant driving mechanism because the applied external pressure is higher than the yield strength of the material at the HIP temperature, causing the voids in the material to collapse. After initial plastic deformation, it contributes to creep densification and diffusion.
- These mechanisms not only collapse and close the pores, but completely eliminate them, creating a defect-free material. This process has been used successfully for many decades to both manufacture and densify critical components for industries such as aerospace, medical implants, power generation, and oil and gas extraction. Fig. 4.18 shows a schematic diagram of the HIP process.

HIP for Metal Additive Manufacturing

- Although the relative density of AM powder material is often very high, material defects such as pores and internal cracks cannot be guaranteed. Defect types, size and occurrence are determined by powder and print parameters.
- These defects negatively affect the mechanical properties of the material, especially the fatigue behavior. By using HIP for AM materials, these defects can be removed and the material will have 100% relative density. The most significant benefit of removing printing defects with HIP is that fatigue properties can be improved because the stress concentrations from the defects are eliminated.

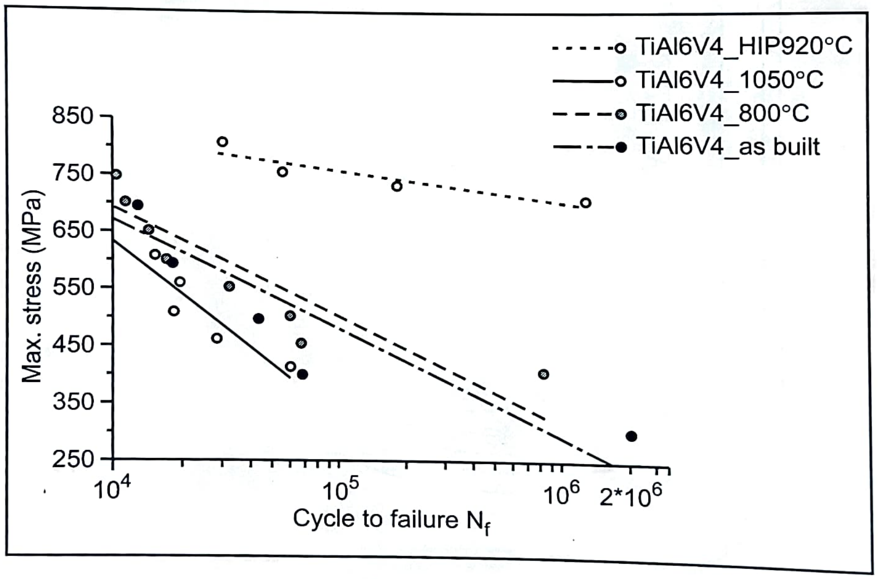


Fig. 4.19

- As reported by Stefan Leuders, the fatigue properties of SLM Ti-6Al-4V were shown to be improved compared to printed material and solution annealed material with a large increase in fatigue life and also a decrease in fatigue slope, see Fig. 4.19. This is an important factor for components in highly demanding applications such as aerospace components and medical implants.
- One thing to note from the research done by Leuders is that the yield strength actually decreases in the annealed and HIP processed SLM Ti-6Al-4V compared to the printed material, but instead a much better ductility is produced, see Fig. 4.20. This change in properties is explained by the fine microstructure in the printed SLM material, which is generated by a very high cooling rate in the printing process of several thousand degrees per second and provides a high yield strength in the printed state.

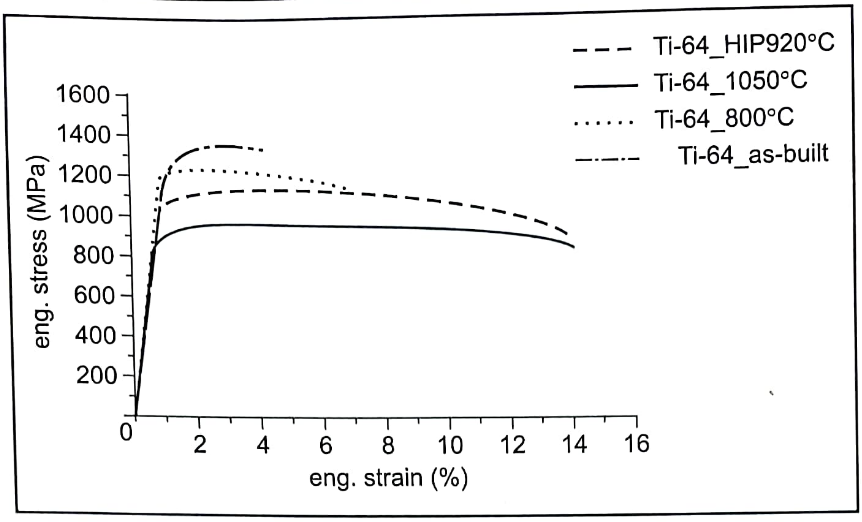


Fig. 4.20

- When additional heat treatments with more conventional cooling rates such as HIP and annealing are added, the microstructure is roughened resulting in a lower yield strength, but ductility is improved due to the removal of any porosity.
- With typical pressures from 400 to 2,070 bar (5,800 to 30,000 psi) and higher temperatures to 2,000°C (3,632°F), HIP can achieve 100% of maximum theoretical density and improve the ductility and fatigue resistance of critical, high-performance materials. 3D printed components regardless of method (EBM, SLM, etc.) benefit greatly from isostatic hot pressing.
- Hot isostatic pressing (HIP:ing) is used successfully by manufacturers worldwide. HIP:ing is used to remove pores and remove defects ie nitrides, oxides and carbides to dramatically increase material properties. Ingredient Manufacturing (AM), also known as 3D printing, is rapidly gaining ground in demanding markets such as aerospace and medical implants.

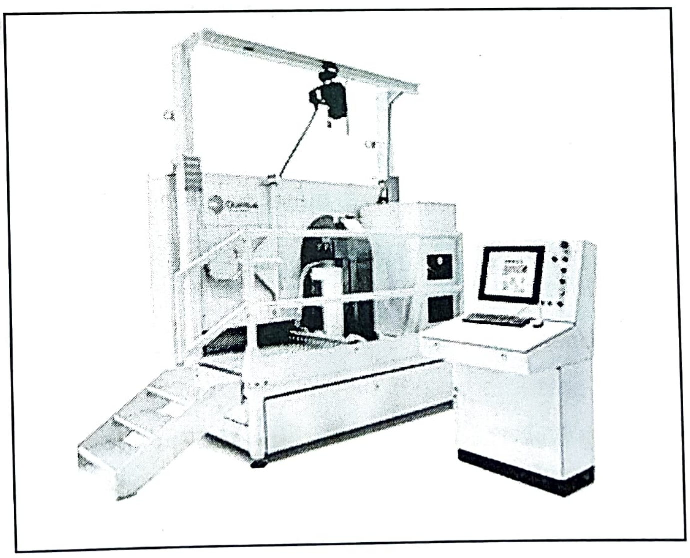


Fig. 4.21

- The combination of hot isostatic pressing and heat treatment removes pores, thereby increasing the ductility and fatigue resistance of parts that are often critical to safety and quality. The aerospace industry plans to use additive manufacturing for the mass production of critical metal alloy parts.

Surface Enhancement Techniques

- To obtain the desired surface finish, several attempts have been made by optimizing process parameters such as component orientation, embedment orientation, layer thickness and the use of post-processing operations such as machining operations (turning, milling, CNC machining), abrasive machining, chemical machining, laser operations surface treatment and abrasive flow machining.
- Since there is much more work involved, optimization of the process parameters such as controlling the orientation of the part at the initial stage by various combinations with respect to the STL file is done to obtain the desired output. Control of built-in orientation of parts in the machine and control of layer thickness.
- The final surface quality of AM-ed parts is greatly influenced by print parameters such as build direction, laser parameters (e.g., laser power, scan strategy, scan speed, etc.), layer thickness, and powder properties. One of the most direct methods for improving surface finish is to optimize print parameters.
- However, optimizing print parameters for the best surface finish may not achieve the desired mechanical properties or microstructures of AM-ed parts and may even lead to print failure.
- In addition, inappropriate construction direction may result in additional support structures that cannot be removed, or worse surface quality after removal of the support

4.5 SURFACE FINISHING TECHNIQUES

Laser Polishing/Remelting Laser Polishing :

- Also known as laser remelting, it is a thermal energy based process that is often used to achieve a high quality surface finish by remodeling the topographical profile of the workpiece through laser material interaction.
- During laser remelting, the laser beam includes only a microscopic layer of material and affects only the topography of the surface while maintaining the shape accuracy of the workpiece.
- Meanwhile, irregularities and high unevenness are smoothed out during the liquefaction process. Due to the advantageous possibilities of automation using multi-axis CNC assemblies, excellent controllability of process parameters and "zero" tool wear, laser polishing technology has been intensively investigated on components of various materials and geometries, assessing surface finish, surface hardness, microstructure, chemical composition, etc.
- Process parameters such as is laser power, laser spot size, pulse duration, offset, feed rate, tool path trajectory, overlap percentage, etc., can be fine-tuned to achieve sub-microscopic surface finish and homogeneously improve surface hardness for most metals and alloys investigated.
- In recent years, laser polishing has been explored as a finishing process for Additively Manufactured (AM-ed) metal components.

Chemical and Electrochemical Polishing Electrochemical polishing (ECP) :

- Electrolytic Polishing (EP) is a chemical finishing process that gradually removes material from a metal part by anodic dissolution. The workpiece, which is the anode, is immersed in an electrolyte and connected to the positive polarity of the power supply, while the cathode tool is placed close to the anode with a specified interelectrode gap.
- As the voltage increases, etching, passivation, polishing, and gas release processes will gradually occur on the workpiece. In this polishing process, the ions from the high roughness of the anode dissolve faster than the pits, allowing for excellent surface smoothing of the workpiece. However, the intrinsic mechanism of ECP material removal is still unclear.

- ECP is suitable for finishing parts of complex geometry with sharp corners that are accessible to liquid electrolyte.
- The main process parameters include electrolyte temperature, electrolyte composition, polishing time, initial surface roughness, electrode rotation speed, inter-electrode gap, workpiece microstructure, current density, etc.
- A detailed representation of these process parameters can be found in Ref. Due to the excellent availability of the liquid electrolyte and excellent surface quality, ECP has been preliminarily applied to the surface treatment of various AM-ed materials and components of complex geometry.

Abrasive Based Finishing :

- Abrasive finishing is a well-established and widely used finishing technique in various industries. A key characteristic of these processes is the use of abrasive particles as tools to improve shape accuracy and/or surface finish. According to Hashimoto et al. abrasive finishing techniques can be characterized as bonded abrasive finishing (eg grinding and honing) and non-bonded abrasive finishing (eg blasting, jet finishing, abrasive flow machining and magnetic abrasive finishing).
- Bonded sanding is usually used to correct form errors and improve dimensional and shape accuracy, while non-bonded sanding is preferred for surface finishing. The Preston equation is commonly used to characterize the Material Removal Rate (MRR) for unbonded abrasive finishing.

$$MRR = kPV \qquad \text{... (4.1)}$$

where k is a coefficient related to the properties of the polishing tool and workpiece material, P and V are the contact pressure and relative velocity between the polishing tool and the workpiece, respectively

- Abrasive Flow Machining/Finishing (AFM/AFF) is typically used to finish internal surfaces and complex external surfaces. In AFM high viscosity. Abrasive media flows back and forth across the surface of the workpiece under high pressure to remove burrs and improve surface quality.
- This process has been widely used in many industries since the mid-1960s. Recently, researchers have used AFM to complete AM-ed components. DuvalChaneac et al. polished 300 SLM high strength steel cylindrical parts with four media with different abrasive concentration (35%, 50% and 65%) and media viscosity (low viscosity-LV and medium viscosity-MV). A progressive reduction of the surface roughness was recorded during the AFM process and the residual stresses were measured before and after the AFM process

4.6 ADDITIVE MANUFACTURING ERROR SOURCES

Choice of Material :

- Choosing the right material for your prints is an important step in ensuring fit, shape and function. The two primary materials for personal 3D printing are Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA). ABS is a petroleum-based plastic that is suitable for applications requiring strength.
- PLA is a natural corn-based plastic that lends itself well to visual or decorative objects due to its high-resolution capabilities. Regardless of the plastic raw material, 3D printers should be operated in a ventilated area, as plastic can release fumes.
- A paper published in the journal Atmospheric Environment states that 3D printers can be classified as "high emitters" with emissions of ultrafine particles greater than 1010 particles/min. In terms of emissions, running these printers in unventilated areas is like grilling food on a gas or electric stove at low power.

Design Considerations :

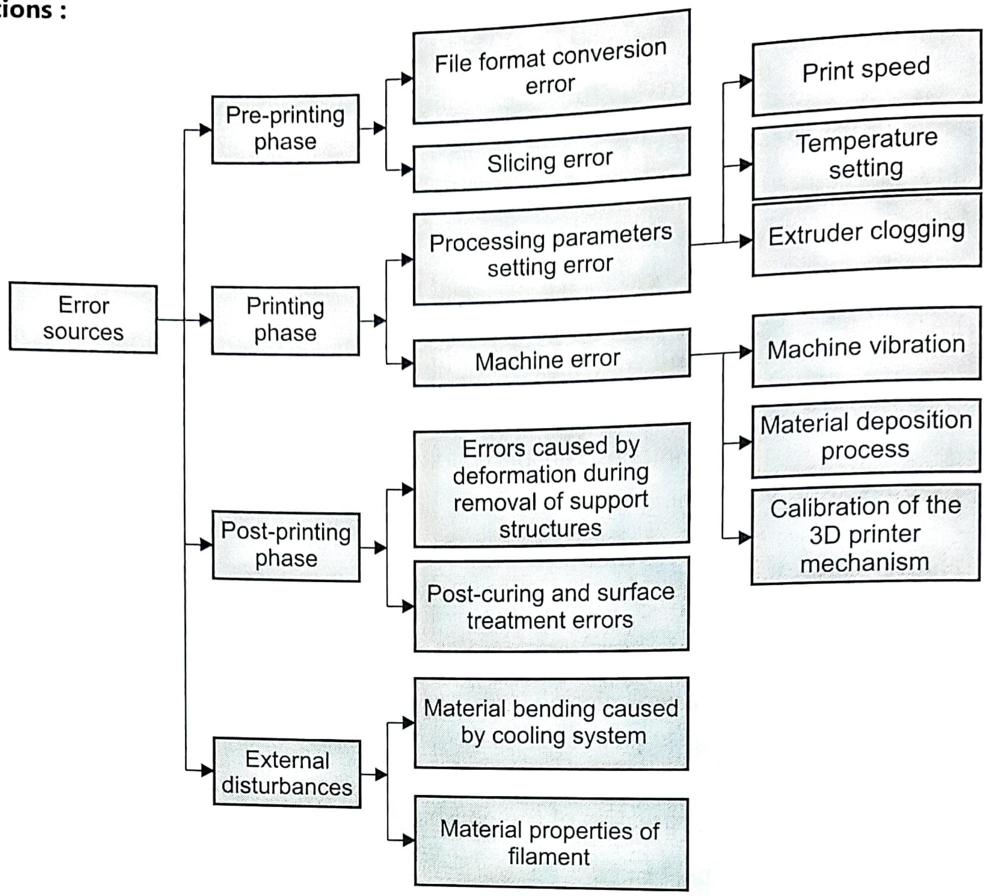


Fig. 4.22

- Most 3D printer manufacturers relate tolerance to the word resolution. A high-resolution 3D printer will most likely specify the tolerance in Dots Per Inch (DPI) as the build unit rather than inches.
- 3D printer manufacturers also use metric units for most of their specifications. Either way, a typical minimum model wall thickness is roughly 0.6 mm and the accuracy of the printed part is ± 0.2mm.
- Another design aspect is the support material. A model with large overhang angles will collapse or buckle on its own if printed without support material. Fortunately, support material can be automatically generated in 3D printing software.
- The software prevents over-supporting the part and thereby wasting material, but also allows the user to control the angle at which the support will be generated. The recommended angle of the supporting material is 10 to 30°.

EXERCISE

1. Enlist different types of materials in 3D printing with examples.
2. Write short note on 4D printing.
3. Example importance of Bio-active materials and state its application.
4. Write short note on chemical treatments and thermal treatment.
5. Explain different quality considerations in A.M.
6. Explain sanding, Acetone Treatment and polishing.

Unit V : Hardware and Software for AM

Construction of Basic AM Machines: Equipment Layout and sub-system Design, Construction, Working, Equipment Topology/Layout Frame Designs, 3D Printer Design Considerations (Filament, Frame, Build Platform, Extruder Design, Nozzles, Print Bed, Heated build/Base Plate, Heater, Dispenser, Optical system, Cooling system, Gas Recirculation System, Laser controller, Gas Filtration, Inert Gas Cooling system, Powder Handling System, Loading/unloading System, Moving Parts and end stops, Sensors, Actuators, Motors and Control Electronics, Power supply, Machine Tool Peripheral), Raw Material Manipulation

Software and Controller: Types of In fill, Types of slicing, Software Integration (with Process, Slicing, etc), Control system (PLC and safety PLC, micro control/ Microcontroller, Micro-processor control), CAD Software and Controller Interfacing, CURA Software, Relevant G/M Codes, Standard firmware (Merlin Software, etc), In-process Monitoring, Calibration

UNIT V

HARDWARE AND SOFTWARE FOR AM

5.1 CONSTRUCTION OF BASIC ADDITIVE MANUFACTURING MACHINES

5.1.1 Equipment

- 3D printing techniques are in use of a computer, 3D modeling software (Computer Aided Design or CAD), machine equipment and layering material.
- Once a CAD sketch is done, the AM equipment reads in data from the CAD file and lays downs or adds consecutive layers of liquid, sheet material, powder, or other, in a layer-upon-layer fashion to fabricate a 3D object.
- The term AM encompasses many technologies including subsets like 3D Printing, Rapid Prototyping (RP), layered manufacturing and additive fabrication.

Layout

- The term additive manufacturing encompasses several manufacturing technologies that manufactures part layer-by-layer.
- Each vary in the way they produce metal and plastic parts and can differ in selection of material, surface finish, durability and manufacturing cost and speed.
- There are several types of 3D printing, which include:
  - ➢ Stereolithography (SLA).
  - ➢ Selective Laser Sintering (SLS).
  - ➢ Fused Deposition Modeling (FDM).
  - ➢ Digital Light Process (DLP).
  - ➢ Multi Jet Fusion (MJF).
  - ➢ PolyJet.
  - ➢ Direct Metal Laser Sintering (DMLS).
  - ➢ Electron Beam Melting (EBM).

1. **Cartesian FDM 3D Printers**

- Cartesian 3D printers are the most common FDM 3D printer used in the market. Based on the Cartesian coordinate system in mathematics, this technology uses three axis: X, Y and Z to state the correct direction and positions of the print head.
- In this type of printer, the printing bed usually moves only on the Z-axis, where the print head is working two-dimensionally on the X-Y plane.
- Two well-known brands within the consolidated Deposition Modeling market that use Cartesian technology for his or her FDM 3D printers are MakerBot and Ultimaker. It should even be noted that there are some variations in however the printing bed moves; on the coordinate axis.

2. **Delta FDM Printers**

- More often delta type printers are seen with FDM technology. The recent addition was developed by two Swiss students, which is included of a six-axis 3D printer that was based on the Delta technology. These machines operate with Cartesian co-ordinates.

- This involves a round printing plate that is in combination with an extruder that is fixed at three triangular points. Every axis (i.e. X, Y, Z) then moves up and down. Determining the position and direction of the print head is completely dependent on X-Y movement.
- Delta printers were designed to increase the speed of the printing process. However, many believe that delta type printer is not so accurate like a conventional Cartesian printer.

3. **Polar 3D FDM Printers**

- Polar 3D printers' positioning is determined by an angle and length and not by X, Y, and Z coordinates, this means that the plate moves and rotates at the same time, with the extruder moving in up and down direction.
- The main advantage of Polar FDM 3D printers is they only have two engines, whereas Cartesian printers need at least three. The polar printer has greater energy efficiency and can make larger objects while using less space in coming future.

4. **FDM 3D Printing with Robotic Arms**

- In large automotive plants robotic arms are most commonly known for assembling components on industrial production lines.
- Nowadays 3D printing has begun to incorporate robotic arms into their manufacturing process, most notably seen in the 3D printing of buildings and homes, this technology is still in the development stage.
- Though it is not a commonly used printing process for manufacturing, FDM printing method is now in demand. This is because the process is not fixed to a printing build plate, making it much more portable.
- In addition, thanks to the flexibility when positioning the FDM 3D printer head, it is easier to create complex structures. It should be noted, however, that the final print quality is not as good as conventional Cartesian printers.

5.1.2 Sub-Systems Design

Dynamic (UV) Additive Manufacturing

- The Dynamic Projection Systems LRS-MCx series can be combined by synchronizing with precise x or x-y scrolling movement systems. This allows scaling up the total build area while maintaining the high power output and high resolution of the projector.
- The LRS-MCx allows for combining number of vats in the same machine, thereby utilizing the dynamics and power to create high resolution build area. This is done without changing the speed of printing per area.

Dynamic (IR) Additive Manufacturing

- Stereolithography 3D printing by using a UV-reactive process has limited source of materials for high volume production. On the other hand, additive manufacturing using IR light sources for melting plastic materials increases the material availability on large scale.
- Rigid and hard materials like PEEK can be melted and extruded to any 3D shape, keeping the material properties. Thus creating a sophisticated, durable, and strong parts is now possible. Further, this process does not require the same level of costly post-processing.

5.1.3 Working and Construction

Let's find some common plastic 3D printing processes and discuss when each provides the most value to product developers, engineers, and designers.

1. **Stereolithography (SLA)**

- Stereolithography (SLA) is the first industrial 3D printing process. SLA printers enhances at producing parts with high levels of detail, tight tolerances and smooth surface finishes.
- The quality surface finishes on SLA parts, will only look nice, and also aid in the part's function –testing the fit of an assembly, for example. It's widely used in the medical industry.

2. **Selective Laser Sintering (SLS)**

- Selective laser sintering (SLS) melts together nylon-based powders to convert it into solid plastic. Since SLS parts are made from genuine thermoplastic material, they are durable, suitable for functional testing, and can support snap-fits and living hinges.
- In comparison to SLS, parts are stronger, but have rougher surface finishes. Many SLS parts are used to prototype designs that will be injection-molded for fast production.

3. **Digital Light Processing (DLP)**

- Digital light processing is similar to SLA the main difference is projector light is used to cure the resinn instead of LASER source. The primary difference between the two technologies is that DLP uses a digital light projector screen whereas SLA uses a UV laser.
- This states that DLP 3D printers can image an entire layer of the build all at once, resulting in more faster build speeds. While mostly used for rapid tooling, rapid prototyping, the higher throughput of DLP printing makes it suitable for low-volume production runs of plastic parts.

4. **Fused Deposition Modeling (FDM)**

- Fused deposition modeling (FDM) is a common desktop 3D printing technology used for plastic parts. An FDM printer produces a product functions by extruding a plastic filament layer-by-layer onto the build platform.
- It's a Quick and cost-effective method for producing physical models. There are some cases when FDM can be used for functional testing but the technology is limited due to parts having relatively rough and hard surface finishes and less strength.

5. **Direct Metal Laser Sintering (DMLS)**

- Metal 3D printing opens up new possibilities for metal part design. The process used to 3D print metal parts is direct metal laser sintering (DMLS). It's often used to reduce metal, multi-part assemblies into a lightweight parts or single component with internal channels or hollowed out features.
- DMLS is viable for both production and prototyping since parts are as dense as those produced with traditional metal manufacturing methods like casting forging or machining.

5.1.4 3D Printer Design Considerations

There's rarely a simple answer when selecting a 3D printing process. It's difficult to assist customers evaluating their 3D printing options; we can typically point out five key criteria to determine what technology will fulfill their needs:

1. Budget
2. Mechanical requirements
3. Cosmetic appearance
4. Material selection
5. Geometry

Following are the ten steps which briefly specifies all the steps considered while designing a 3D printer :

Step 1: Printer Specification

(i) Speed

- When all the three parameters are considered it is very much difficult to optimize all three. One of the three is sacrificed for the rest. There are some parameters inversely proportional to each other to some limit.
- When speed is increased Quality is sacrificed, similarly if speed is reduced we will achieve the quality but not within the given cost mostly. That is the only reason it is job dependant thing to select a combination.

(ii) Quality and Cost

- Quality and cost are directly proportional to each other. When quality increase cost will increase due to various parameters in any kind of manufacturing. In the example of 3D printing if we will reduce the speed to get the better quality of surface finish we will need to spend more cost.
- Another key demand was reliability to make a machine that might with confidence accept to make in specific elements that look nice. It means that machine wasn't designed to cut prices where attainable so a number of the elements can be sourced cheaper however at a lower quality or with a lower factor-of-safety.

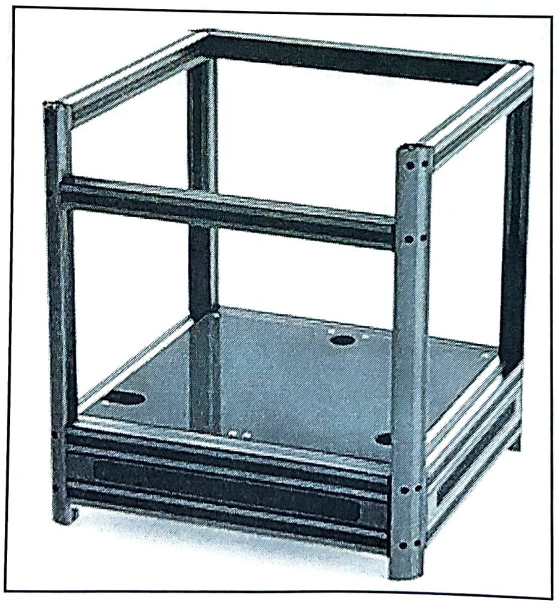
(iii) Build Volume

- Most parts that print are engineering prototypes and typically fall into a small build volume. Having owned both a 300 mm^3 and 220 mm^3 printer for several years and never having printed anything larger than 100 mm^3 it seemed obvious to build a smaller printer and take advantage of some of the benefits this can deliver such as shorter belt runs, a more rigid frame and most importantly a smaller footprint. For that reason, the printer will be made around a $200 \times 200 \times 200$ mm build volume.

(iv) Printer Size

- Desk assets could be a massively valuable artifact in offices and workshops.
- A most size demand is 450×450 metric linear unit. Conjointly wished the physics to be connected to the printer and safely contained to stop harm to them and to stay the machine tidy.

Step 2: Chassis



- The chassis is the fundamental structure that holds the printer together, mounts all of the sub systems, and gives it the much-needed rigidity that is intrinsically tied into good quality prints.

(i) Aluminium Extrusion

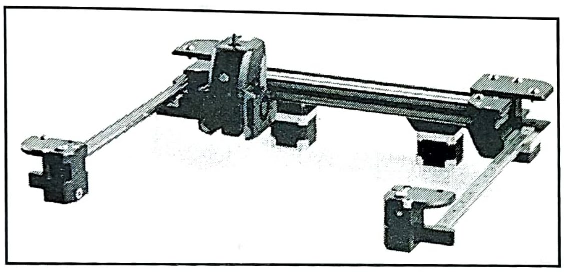
- To create something easy to build with relatively less tools and equipment but without incurring high sub-contract costs for contract machining.
- The only answer to this was aluminum extrusion profiles which are popular among the maker and engineering communities thanks to their 'lego-like' quick assembly with minimal cost of processing.
- As aluminum is easily available in market, machining people for aluminum are also easily available in the market.

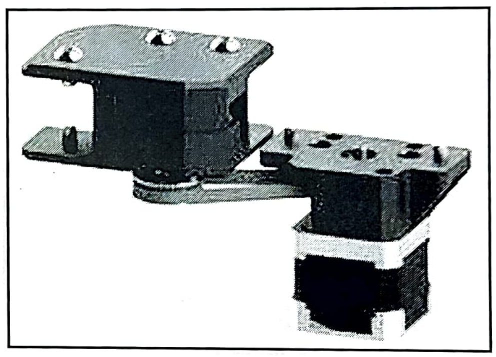
- Aluminium extrusion may be anodized in a range of colors but clear (silver) and black are the most common and cheapest. Purchase plastic pieces that fit into the gaps of the extrusion which tidies up the look and allow to use the extrusion channels for running cables.

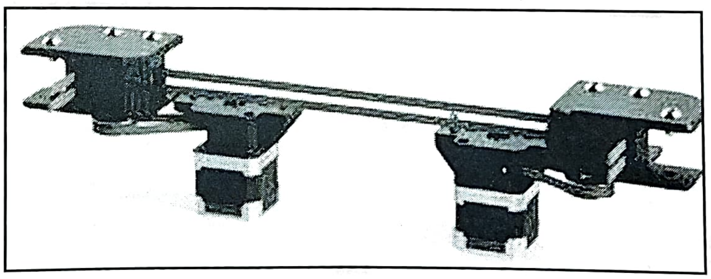
(ii) Blind Joints

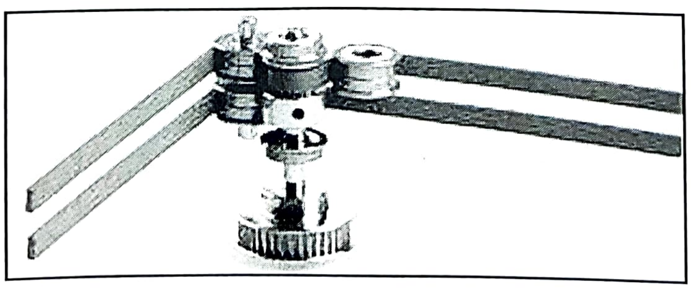
- Aluminium extrusion can be connected in a huge range of ways including (but not limited to) various angle brackets, hinges, pivots, extenders and blind joints. Blind joints involve tapping (cutting a thread into) the end of the extrusion and using a button head bolt to clamp the two extrusions together at right angles.
- They reduce the part count (reducing cost), reduce the number of tolerances to control (easily get a square frame with a strong metal-to-metal joint) and permits to connect frame members at any point.
- This type of joint does require a simple cross hole to be drilled to permit Allen key access for tightening the button head bolts but fortunately many sub-contractors will also drill these cross holes for a small fee. Using blind joints throughout the entire frame there is no plastic that can introduce flexible nature in the frame and creating an extremely rigid chassis.

Step 3: Motion Platform









- The XY motion platform is used for the XY movements of the printer. There are many different popular motion assemblies each offering pros and cons.
- The main kinematics are Cartesian, Delta and Core XY each with their own subtle pros and cons.

Linear Rails

- The X and Y axis need a linear sliding element for smooth operation of a motion. Linear bearings assembled on circular rods are the most common setup for liner rail 3D printers, but the rods are poorly supported along their length.
- While the Chinese manufactured rails are certainly lower quality, they are still more than suitable for a 3D printer and come at a particular cost reduction.

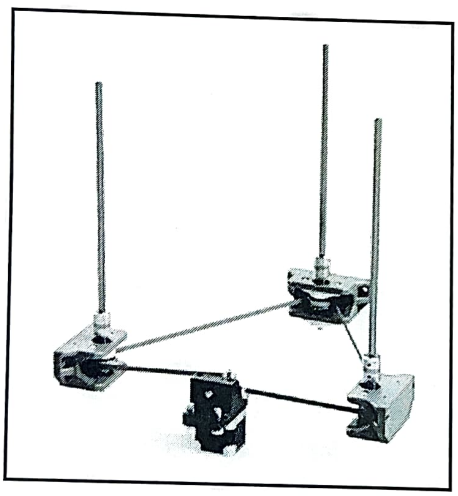
X and Y Axis

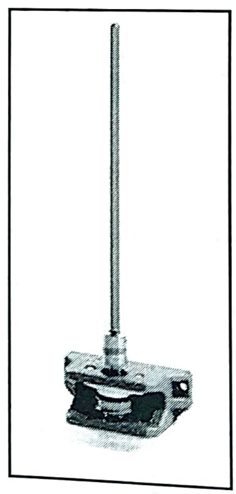
- Choose to mount linear rails on inside of the extrusion as it reduces the amount of XY space required to build or construct the system, ensures an even loading on the rails, and helps to protect them from dust which will extend the failure of rail.
- This assembly will provide a lightweight but rigid support and a wide range of options for mounting. This is the only structural plastic part in the entire motion platform.

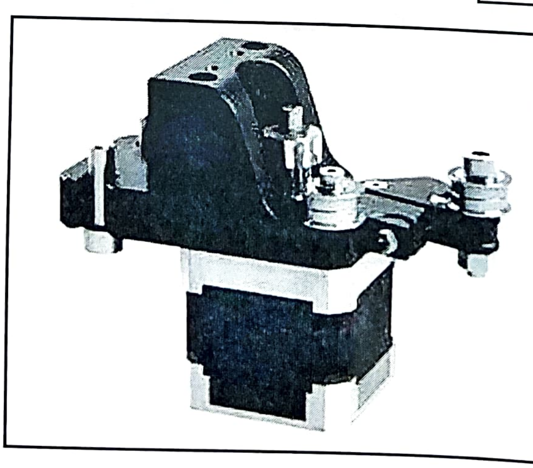
Tool Head

- The tool head holds the assembly of hotend, Z probe and part cooling fans together. The printer to be adaptable and open to other hotend and cooling options and so wanted to use a quick-change head. Instead of reinventing the wheel here and introducing another competing standard decided to use the quick change tool head since it offers quick tool changes.

Step 4: Z Axis



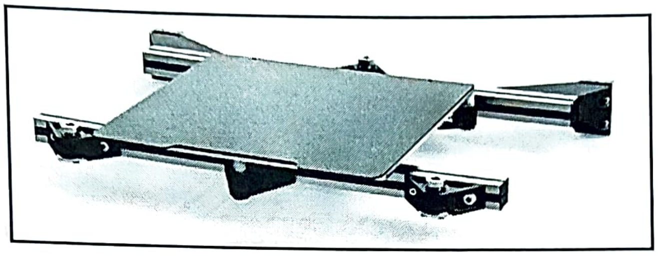




- The Z axis is sole responsible for the fine positioning of the bed to create the layers of the 3D print. One of the important concern here is the infamous "Z Wobble" effect where the axis central run out from side to side as it travels creating significant and repeated patterns.

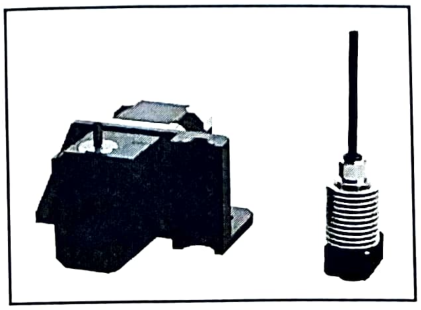
- A lot of popular printers have a cantilevered bed where the bed is only driven and supported on one side. While this makes the mounting much simpler it also doesn't fully support the bed and so you get inaccurate movement the further away from the support column thanks to the drooping of bed.
- Aligning the lead screws to the bed is additionally essential as otherwise they will apply a force to the bed inflicting Z wobble. Every screw is mounted to a versatile coupling which is able to leave a tiny low quantity of angular placement creating assembly considerably additional forgiving. Every screw is mounted through the versatile coupling to a shaft that holds a GT2 machine and is command in situ by 2 KFL08 bearing blocks mounted to housing.

Step 5: Bed



- The main construction of the bed is an eight millimeter thick metallic element tooling plate that has been machined flat. The thickness of the bed makes it somewhat significant however offers it vital thermal mass that means it will maintain a awfully stable temperature. Its thickness conjointly means it's resistive to warp because it undergoes heating.
- A twenty millimeter margin is additional round the build space on the bed in order that the extra cooling impact that the sting of the plate can see is not at intervals the build volume. The tooling plate sits on a frame manufactured from 2020 metallic element extrusion that mounts it to the linear rails and screws of the Z axis. The bed is mounted to the frame with three screws to forestall the screws from over-defining the bed, however this can not scale well to larger machine sizes.
- A two hundred WDC silicone polymer heater is warranted to the side of the bed to heat the assembly and improve bed adhesion. The two hundred Wheater was designated to limit the heating power of the bed to a suitable Georgia home boy temperature. Associate AC battery powered bed would provide the next heating power however comes with the supplementary risk of getting to run mains cabling and a grounding loop through the printer whereas the inflated heating power might cause permanent injury to the printer within the event of thermal runaway.
- Aluminum tooling plates and silicone heaters come with a significant cost so save a bit of money they can be replaced with a much cheaper PCB heated bed. These beds often have issues with flatness, but this can be overcome with software mesh compensation and will act as a suitable stopgap.
- Take away giant prints from the bed and therefore the ability to quickly switch build plates to change back to back print jobs. A removable bed is that the obvious answer and then opted for a spring steel sheet control down with magnets. This enables it to be simply removed and reinstalled while not the requirements for a posh clamping arrangement. A magnetic sheet is secure to the bed for a fast answer.

Step 6: Extrusion System



- The extrusion system of the printer is particularly responsible for the flow of plastic out of the nozzle and is comprised of the extruder and the connecting parts.

1. **Hot End**

- The hot finish is wherever the plastic is heated and extruded out of the nozzle and is formed of the cold aspect (typically an outsized sink to dissipate heat), the warmth break (responsible for separating the new and cold sides), and also the hot aspect (formed of a heater block and nozzle).
- The key consider hot finish style could be a sharp hot-to-cold transition to urge the most effective management of the flowing filament.

2. **Drive System**

- With each the extruder and hot finish chosen all that's left is to attach them along. The apparent answer could be a direct association exploitation the groove mount connection, however this implies that the load of the extruder and its motor should be carried by the top.
- To beat this a bowden system will be used that places the extruder (and its motor) on the printer frame and feeds the recent finish via a bowden tube. While reduces the amount of control over the filament, it permits the top acceleration to be augmented and reduces print artefacts.

Step 7: Electronics

1. **PSU (Power Supply Unit)**

- Overall there is no reason to select a 12 V supply at the time of scripting this. Because the school develops it's probably we will see the extinction of 12 V printer electronics in favour of 24 V and maybe even higher voltages. For this reason, made a decision to choose up a four hundred W twenty four V PSU from Steppers Online.
- For example select a four hundred W PSU because it lined all of the facility needs for machine with a small amount of head space which can scale back electrical strain thereon extending its life a bit.
- The Duet Wiki features a nice article on scheming the desired power for a 3D printer PSU.

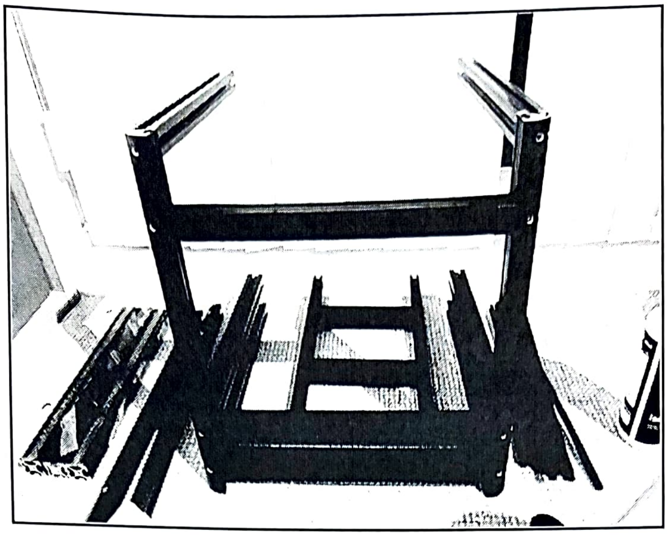
2. **Motors**

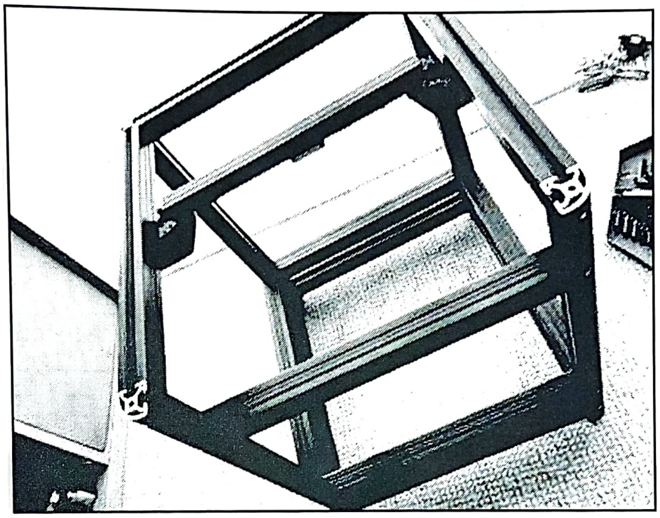
- Stepper motors are very common in 3D printing because of their easy open-loop management (control while not a feedback system), glorious low speed performance, and correct positioning capability. Select to use NEMA 17 motors with a step-angle of 0. 9° step angle throughout the whole machine.
- The augmented step resolution over typical stepper motors provides finer control and smoother motion however additionally has reduced force and high speed.
- A rating that permits a lot of current to be accustomed recover some of the lost force and therefore the high step rate of the Duet wireless fidelity ought to enable a reasonable high speed to be maintained.

3. **Wiring**

- High flexibility silicone wiring was used throughout the machine as there are a large number of moving parts and the silicone wiring offers a superior life when being constantly flexed.
- Making the right selection of wire thickness is also essential to ensuring that the load on the wires is safe. Used 20 AWG for all of low current connections and 14 AWG for bed connections. This will provide a small safety margin over the expected current.
- All wires are fixed at both ends with cable anchors to reduce the chance of them becoming loose and mains wiring is contained within plastic conducting. This provides essential protection from wires creating shorts or bringing components like the frame live.
- Drag chains are used to manage the cables on the Z axis to keep the wiring tidy and prevent it getting trapped in the motion system.

Step 8: Building the Machine

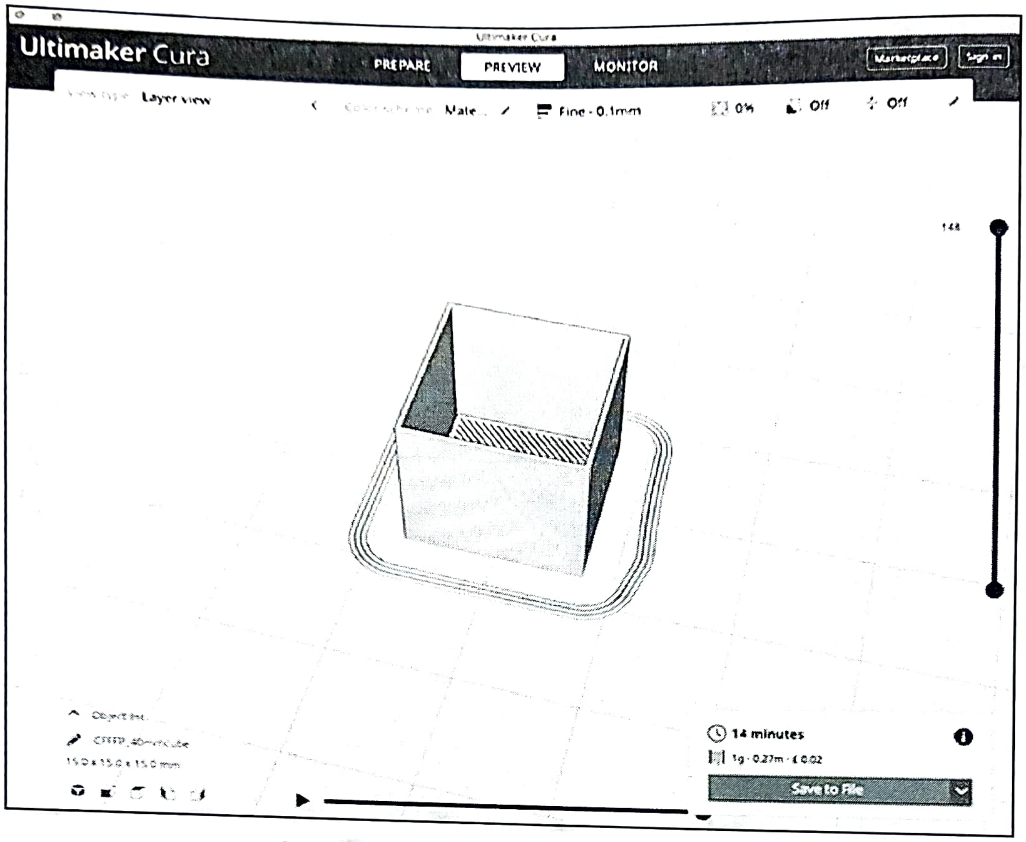


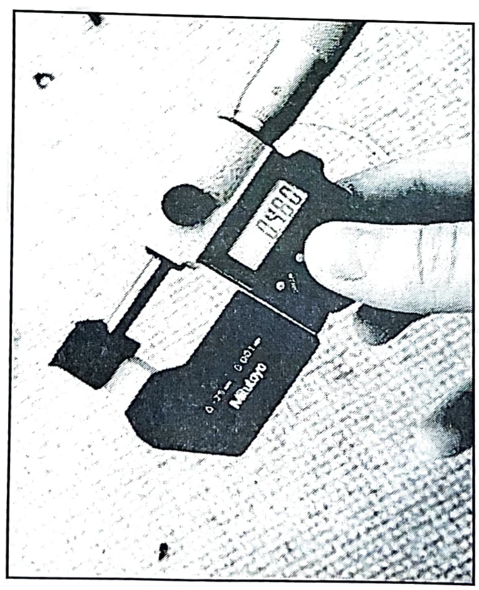


5. More Images

- With the design finalized its time to order the parts and start building! Before assembly it is always good practice to run through the assembly process in your CAD package to help iron out any final issues and familiarize yourself with at least a rough plan of what you are going to do, how you will do it and in what order.
- Special attention is required in the assembly of the chassis to ensure rails donot bind, and prints come out square. A critical area is ensuring flatness of the top 3 members so that the linear rails can be installed with minimal issue. I worked from the top down using a table to hold the extrusions flat to a common plane.
- Ensuring the squareness of the top frame is also essential for good motion (although a small amount of error can be corrected in software). An engineer's square is an essential tool for this. If blind joints have been cut non square you can correct them by adding small shims into the joint or rotating the extrusion 90 degrees to shift the error to a less critical dimension.
- Installing the linear rails that are operating in pairs (Y axis and Z axis) requires careful alignment to ensure smooth running. There are several methods to align the rails but the easiest method I have found is to denote one rail as the master and another as the floating rail.
- With the master rail securely fixed to the frame the other rail can be aligned using a Dial Test Indicator. If you donot own a Dial Test Indicator the rails can be aligned "close-enough" by sweeping the axis back and forth ensuring smooth motion as you tighten down the floating rail.

Step 9: Test and Calibration





$$\text{ESteps X} = \frac{\text{Measured V}}{\text{Requested V}} \qquad \ldots(5.1)$$

- With the machine built, wired, and powered up all that is left is to calibrate it! There are quite a few calibrations steps required when setting up a printer but here I will outline a couple of the key ones.
- These calibration steps consist of brief descriptions of the calibration process and so will require an understanding of GCode and your machine to enable you to carry them out.

XYZ Steps per mm

- The steps per mm define the axis scaling and so accurate setting is required to get parts that are dimensionally accurate. Several methods exist based on the measurement of printed artefacts such as calibration cubes, but these can often introduce inaccuracy due to the inclusion of errors from the printing process such as thermal contraction of the plastic, flow of the plastic, and surface defects like layer misalignment or Z-wobble which are not accounted for.
- Better tests use a stepped artifact that allows multiple measurements to be taken and consistent errors to be detected and removed. While these tests still include an error, they are typically sufficient for printing.
- A good stepped axis calibration test along with ready-made excel sheet to calculate steps per mm can be found here: on online platforms like thing verse.

Stall Detect Homing

- Stall detect homing is a great feature as it can simplify the amount of wire runs have to make around machine and saves you from buying extra homing switches.
- It does however have the drawback of reduced homing accuracy (especially on CoreXY machines) ability to locate items on the bed may be limited. Fortunately, don't have to accurately locate anything on bed, so chose to use it.
- The calibration procedure is relatively straight forward but relies on repeated testing to narrow down both the optimal current and stall detection sensitivity.
- Step one is to slowly reduce stepper current whilst moving, at the homing speed, around the bed. The aim here is to find the lowest motor current that will reliably allow the motors not to stall during free movement. Make sure test all of the areas of the XY movement in case one area is stiffer. This lowest motor current that still allows reliable movement will become the motor current used for homing moves.
- With the motor current set we next want to set the stall sensitivity to the highest sensitivity that does not cause false positives. We can do this by setting the sensitivity to the highest setting and repeat the previous movements around the bed.
- The motor will detect a stall as soon as it starts moving so reduce the sensitivity slowly until find a stable sensitivity that does not cause false positives. Now have the optimal sensitivity and motor current and can use these to write homing macros.

Z Probe

- The machine uses a PINDA probe which is an inductive probe with a built-in thermistor to allow for measurement temperature compensation. The Z probe requires calibration to get the perfect first layer. Start by fixing the probe to the machine so that it triggers before the nozzle hits the bed but is higher than nozzle itself.
- Now use the Z-probe to home the machine. Find the Z probe offset by moving the Z axis up to the nozzle using a piece of paper to set the correct distance and finally set the Z offset for the probe to the current position of the head in the Z axis.

E-Steps per mm and Flow Rate

- Correct control of flow through your hot end is essential to consistent layers. First, we can set the E-steps of the extruder which describes the movement of filament through the extruder before the hotend. Setting flow controls the extrusion out of the nozzle allows you to finely adjust the extrusion based on varying filaments to compensate for this effect.
- Start by marking a point on filament and measure the points distance from the start of Bowden tube. Extrude or retract the filament by a set amount and then remeasure the distance from the Bowden tube. Use these two measurements to calculate the correct E-steps using the equation (5.1).

Tolerance Test

- A final check that is helpful to complete to characterize your printer's performance may be a tolerance check. This tells you the minimum clearance you will be able to leave between elements before they become secure along.
- Several fast and straightforward to print tests exist on-line.

5.2 RAW MATERIAL MANIPULATION

- There are different technologies that are used in 3D printing and so there are various materials that are used in this process.
- Some printers support around 170 different types of materials for printing. This can broadly be categorized into four important heads.
  1. Plastic
  2. Powder
  3. Resins
  4. Other materials

1. Plastic

At present the most commonly used printing technology is Fused Deposition Modeling (FDM).

The FDM printers use thermoplastic filament which is heated to the melting point and then the molten plastic is manufactured by positioning layer by layer to form the model. These printers tend to use the following materials.

(a) Polylactic Acid (PLA)

It is most likely the best to figure furthermore as atmosphere friendly. It's primarily bio degradable plastic that has been derived from sources like corn starch and sugar canes. This is often offered in soft and laborious grades. With the rise within the quality of PLA, this material is predicted to overtake ABS within the close to future.

(b) Acrylonitrile Butadiene Styrene (ABS)

It is popularly called Lego set plastic and is taken into account to be the simplest material to figure with because it is robust and really safe. It's made of pasta like filaments. It's obtainable in a very wide selection of colours and is used for creating of toys, bumper stickers etc.

(c) Polyvinyl Alcohol Plastic (PVA)

It is a type of plastic that is used as dissolvable support materials or is used for special applications. Makerbot and Shapeways are manufacturing lower-cost desktop printers like the Makerbot replicator 2; the material that these printers are using is PVA.

2. Powders

The higher end printers use powder based materials for the construction of 3D models. The various powders available by which printing can be done are:

- ***Polyamide (Nylon)***

  It is a strong and flexible material that allows a high level of detailing on the model. It is commonly called as white, strong and flexible / durable plastic / white plastic. It is a very strong and highly flexible plastic that is very fine and is basically a white granular powder. Due to these characteristics it is used in the interlocking and moving parts of the model.

- ***Alumide***

  It also belongs to the polymide family and has a distinct sandy and granular look. This material is very rigid and strong. The objects that are made from this material are made from a blend of gray aluminum powder and polymide; which are very fine granular powder.

- **Multicolor**

  It has a sandy and granular appearance. The objects are made from a fine granular powder.

3. **Resins**

Resins are used in 3D printing though the freedom of designing by this material is very limited. It is a bit rigid and delicate. Liquid polymer is cured with UV light to give the end product. The typical colors of this material are white, black and transparent. There are principally three different types of resins.

- **High Detail Resins**

  Models that use this material are constructed from a photo polymeric liquid. This material is used for models that require fine detailing and are small.

- **Paintable Resin**

  Models that have been constructed using this material have a very smooth surface and are beautifully painted.

- **Transparent Resin**

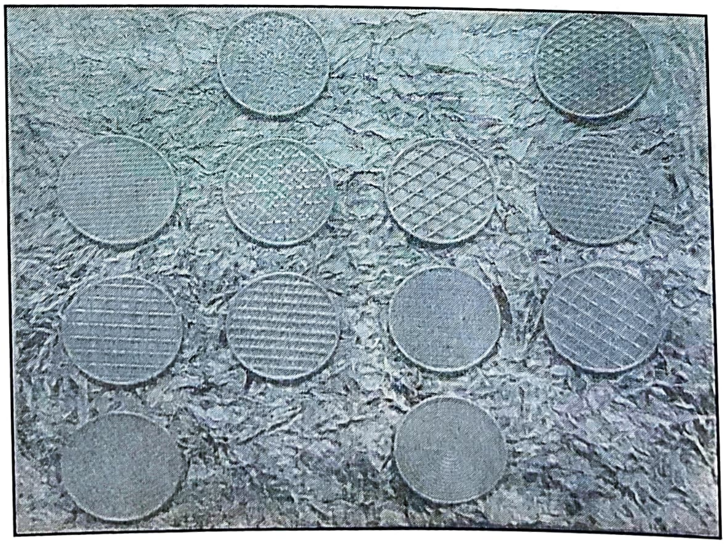
  Models are made of hardened liquid so the material is very strong, hard, stiff and water resistant by nature. This makes it an ideal material for 3D models. This material is suitable for models that require a smooth surface along with a transparent look.

4. **Other materials**

- Apart from all these materials others materials are also used for 3D printing. Such as titanium, stainless steel, bronze, brass, silver, gold, ceramics, chocolate, bio ink, bone material, Objet Digital Material, Objet Tango Family, hot glue, glass, full color sandstone and gypsum.
- There are a few other materials that are still in the experimental phase and which will be a ground breaking moment if turned into reality. These materials are medication and skin.
- The nature of material changes with the requirement of the model. So, there is a wide array of materials from which the most appropriate material is to be chosen.

5.3 SOFTWARE AND CONTROLLER

5.3.1 Types of In-fill

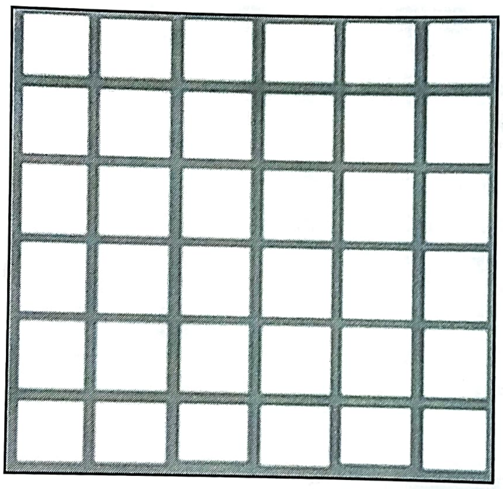


- Infill is the material which fills the part of volume in percentage. Infill pattern is placed between walls, top layers and bottom layers. Infill patterns affect part strength because not all geometries are equally strong.

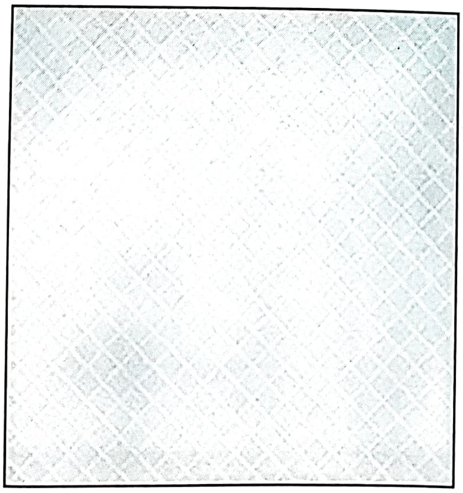
- A triangle for instance, is more stable than a square, because it is the only rigid polygon: two sides always support the other. The infill density defines the amount of plastic used on the inside of the print.
- A higher infill density means that there is more plastic on the inside of print, leading to a stronger object. An infill density around 20% is used for models with a visual purpose, higher densities can be used for end-use parts.

Different Infill Patterns

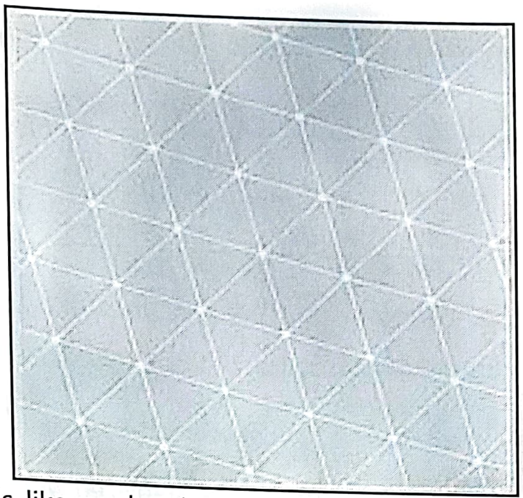
- **Grid:** Strong 2D infill
- **Lines:** Quick 2D infill
- **Triangles:** Strong 2D infill.
- **Cubic:** Strong 3D infill.
- **Concentric:** Flexible 3D infill
- **Gyroid infill**: Infill with increased strength for the lowest weight.
- **Lightning**: Infill that is extremely fast to print and only supports top surfaces.
- **Honeycomb**



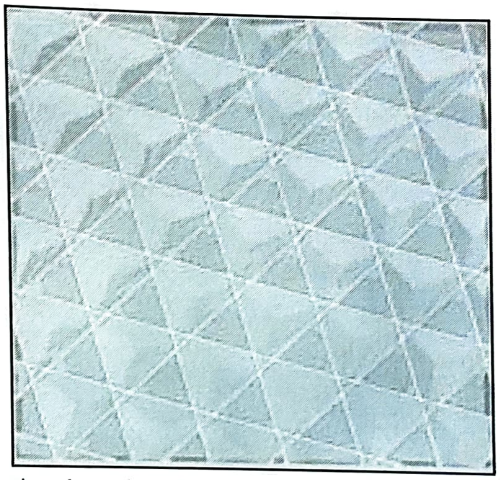
- **Grid :** It is an infill pattern where material is deposited in such a way that square bracket is formed. One layer is horizontally moved and another one is vertically. The Grid pattern is used on everyday prints that require a high amount of strength.



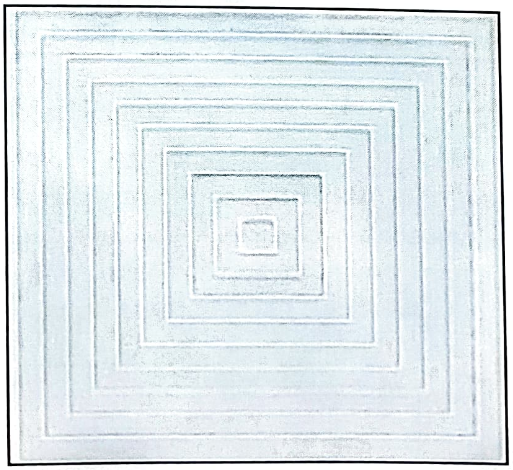
- **Lines Infill :** Lines infill is the infill where material is deposited in single direction of lines. Compared with other patterns line pattern has less strength. The lines pattern does not use an excessive amount of material and keeps weight pretty light.



- **Triangle :** Triangles pattern sounds like overlapping triangular lines, with lines occurring into three directions within the XY plane. This infill pattern provides strength only in two dimensions but still works for prints that require being strong.

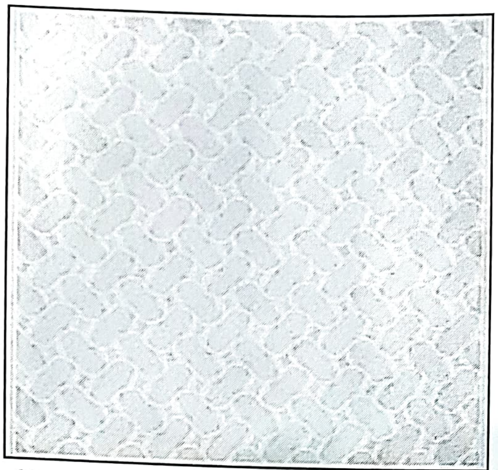


- **Cubic:** This pattern produces stacked cubes, but because they are tilted by 45 degrees around both the X- and Y-axes, they seem more like triangles at any one moment. The pattern provides excellent strength in three dimensions but takes a bit more material and time than others.

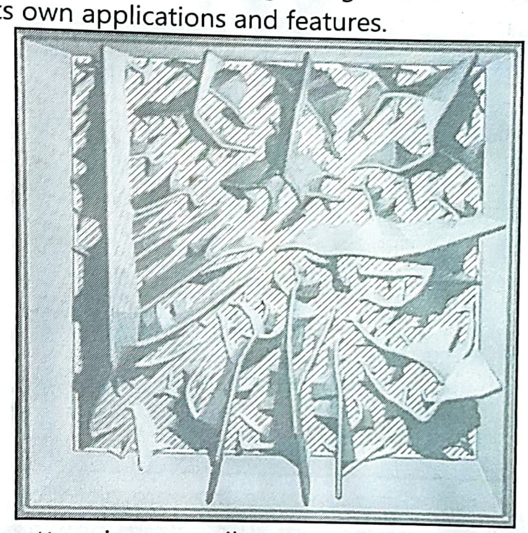


- **Concentric :** This infill pattern is an interior structure composed of concentric lines that match a part's outline (i.e. its perimeters). This pattern is quick to print, good for flexible parts, and consumes significantly less material than most patterns.

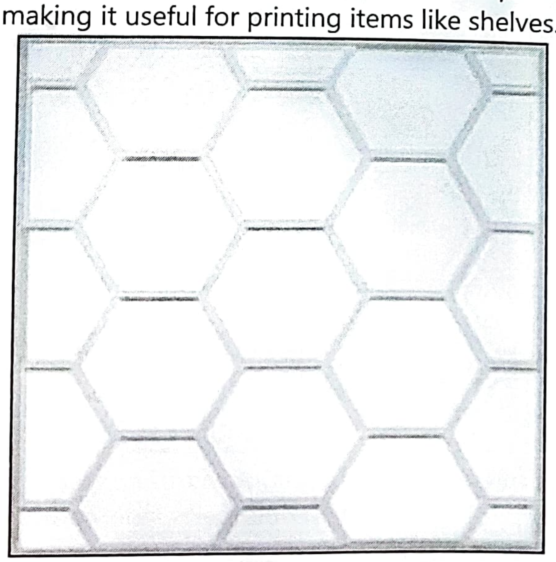
- **Gyroid Infill:** Gyroid infill pattern is maybe the good looking but strangest infill pattern. It includes concaving irregular curvatures that eventually cross paths. It's meant to strike an optimal balance between strength, material, and print time.



- **Lightning:** With the Cura Lightning Infill, hollow objects can be stabilized with a lightning-like infill pattern. This special infill ensures that the upper layers of the roof can be printed with high quality. This infill pattern is especially suitable for decorative objects and saves a lot of material. Cura Lightning Infill was introduced with version 4.12.0 and gives you a whole new infill alternative with its own applications and features.



- **Honeycomb:** The honeycomb infill pattern is a versatile pattern that yields a structure with many connected hexagons stacked on top of each other, which looks pretty cool when exposed. The pattern is also pretty strong and distributes physical stress across a wide area, making it useful for printing items like shelves.



5.3.2 Types of Slicing

1. **STL-based Slicing**

- Uniform slicing generates constant layer thickness slices. Adaptive slicing is a variant of the uniform slicing, where the spacing between the slices is not constant but determined by the geometry and machine capability.
- Adaptive slicing mainly addresses the geometry issues and need a specific 3D printing system to achieve the desired results. However, there are still not 3D printers that fully support or able to take full advantages of adaptive slicing.
- Therefore, uniform slicing seems more versatile. Slicing (obtain contours for each layer/slice) Infill (choose infill pattern to add on each layer) Toolpath (Apply toolpath methods like TSP etc. on each layer, ready for producing the machine instruction) G-code file STL file 887 Various slicing approaches in the current literature are discussed to aim in overcoming the constraints of computer memory and the problems of computation instability.
- S. H. Choi et al. presented a memory efficient tolerant-slicing algorithm. Instead of storing the whole model into the computer memory, it reads only the facets of the current layer, hence greatly reduces the amount of computer memory required and involves less computationally intensive searching operations.
- H. Ye et al. proposed a slicing process by reusing the topology information obtained from the template model for other customized products of the same category. D.Ding et.al proposed the multi-direction slicing.

2. **Direct Slicing:**

- Although STL file format is widely used as a de facto industry standard in the 3D printing industry due to its simplicity and ability to tessellation of almost all surfaces, but there are always some defects and shortcoming in their usage, which many of them are difficult to correct manually. Direct slicing can generate precise slice contours from original 3D models and obviates the error-detection and repairing process of STL files.
- However, a severe disadvantage of direct slicing is the capability among various 3D CAD systems. In other words, it can only be used for a specific set of software and machine and is not applicable to any other 3D CAD combinations.
- As a matter of fact, STL-based slicing is still the commonly used method in processing the problem of layered 3D printing.

5.4 SOFTWARE INTEGRATION

- Software integration means combining software sub divisions to gather. After building the 3D printer, the next step is to configure the software. There are several different types of softwares that are necessary for the 3D printer and the 3D component to be printed. The first type of software required is modeling software. 3D Modeling software will be used to create a part in 3D space. There are several different programs that can be used to create a part.
- These range from free open-source software such as Google Sketchup to commercial softwares such as SolidWorks and Catia. Software that creates 3D models is often referred to as computer-aided design (CAD) software. 3D models can also be downloaded online. A good place to download parts from is Thingiverse, a free online database of 3D designed models. After the part is created, another type of software is needed to slice up the object into layers.
- This is necessary because when the machine is printing, it prints one layer at a time. The slicing software takes each slice and converts it to a path for the hot extruder end to follow. All the slices combined form the solid 3D part. A variety of slicing software exists, but Cura and Slicer are considered the most robust and easiest to use slicing software. The software transforms the part into a "g-code," which is a software language that can translate a sliced model into a format that can then be printed using the printer.
- The third and final software needed is an editor to modify the firmware that controls the electronics and the motors of the 3D printer. Often this firmware comes with the 3D printer being used such as the MakerBot Desktop firmware, which comes with MakerBot products, and the PreForm firmware, which comes with FormLabs products. However, there are some open source firmware, such as Marlin, which can also be used. There are several motors that control the X-, Y-, and Z-axes, and another motor that controls the speed at which the filament is fed into the hot extruder head, all of which are controlled by the firmware.

- The firmware also tells the extruder head to heat up to a specific temperature. Firmware is able to read the g-code commands and transfer them to actual movements. It is necessary to be able to edit firmware to tailor it to a specific machine and tailor the settings.

5.5 CONTROL SYSTEM

- The invention relates to the design of a simple 3D printer control system. The design of the simple 3D printer control system is characterized in that ATmega2560 is used as a main controller; computer slicing software is used for slicing a 3D model and generating a G code; the G code is transmitted to the main controller via a serial port; a three-axis motor driving module controls an extruder of the printer to carry out 3D printing; a fuzzy PID algorithm is used for accurately controlling the temperature; the three-axis motor is controlled by PWM technology; the test result shows that the temperature of an extrusion head is controlled to be 245 DEG C and the control accuracy is 1 DEG C after the fuzzy PID algorithm is used; the time for entering constant-temperature state is changed from about 250 seconds in the prior art into about 70 seconds; the three-dimensional printing constant-temperature control performance is improved; the phenomena that the printing material is broken and the thickness is not uniform in the printing process are reduced; the requirement on the printing quality is met; the simple 3D printer control system with low cost and low power consumption is achieved.
- The selection of the control board was most critical, since so much of the 3D printer's functionality relies upon this single component. In order to control the additional stepper motors needed for the double print head feature, the team required a board which could support an above average number of drivers, in addition to meeting the reliability and availability factors.
- Budgeting played a relatively minor role in our selection process, both because of the eclectic specifications and its show-case nature. The chosen control board is the Rumba Control Board from RepRap.
- All research indicates that the Rumba will easily live the team's expectations and needs.

5.6 CAD SOFTWARE AND CONTROLLER INTERFACING

- Computer aided design tools are always used for creating a design model representing all the decided features.
- It is clear that additive manufacturing would not exist without computers and would not have developed so far if it were not for the development of 3D solid modeling CAD.
- Virtually every commercial solid modeling CAD system has the ability to output to an AM machine. This is because, for most cases, the only information that an AM machine requires from the CAD system is the external geometric form.
- There is no requirement for the machine to know how the part was modeled, any of the features or any functional elements. So long as the external geometry can be defined, the parts can be built. Number of cad softwares can be used for creating models like Catia Solidworks etc.

Controller Interfacing

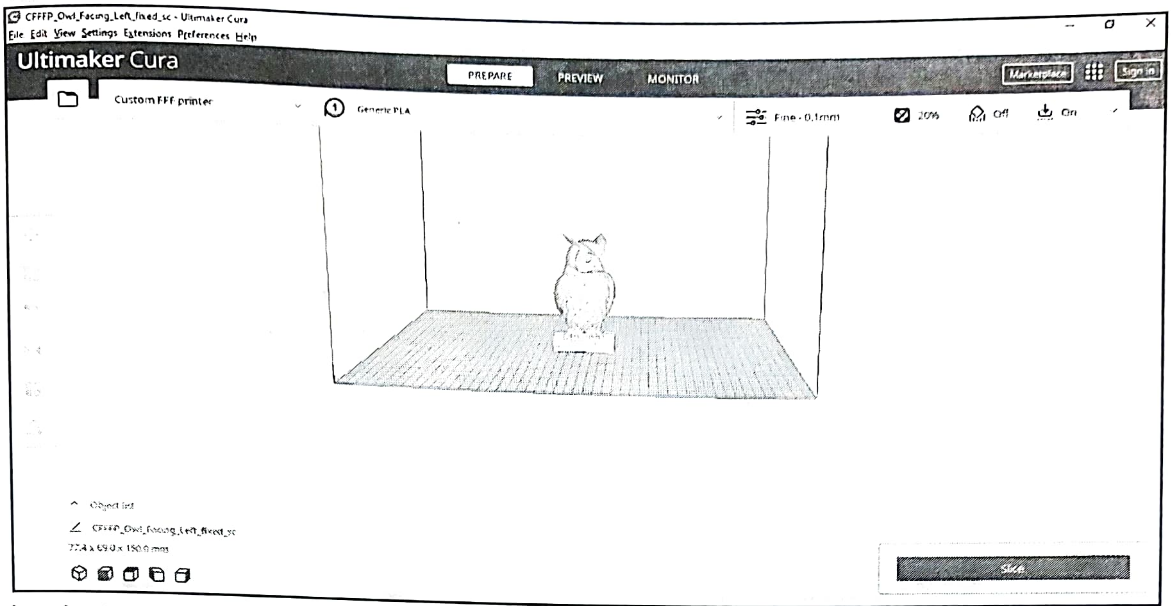
Different controls are used for interfacing software and hardware in Additive manufacturing. Different PLC are used to control axial motion according to the extrusion process.

5.7 CURA SOFTWARE

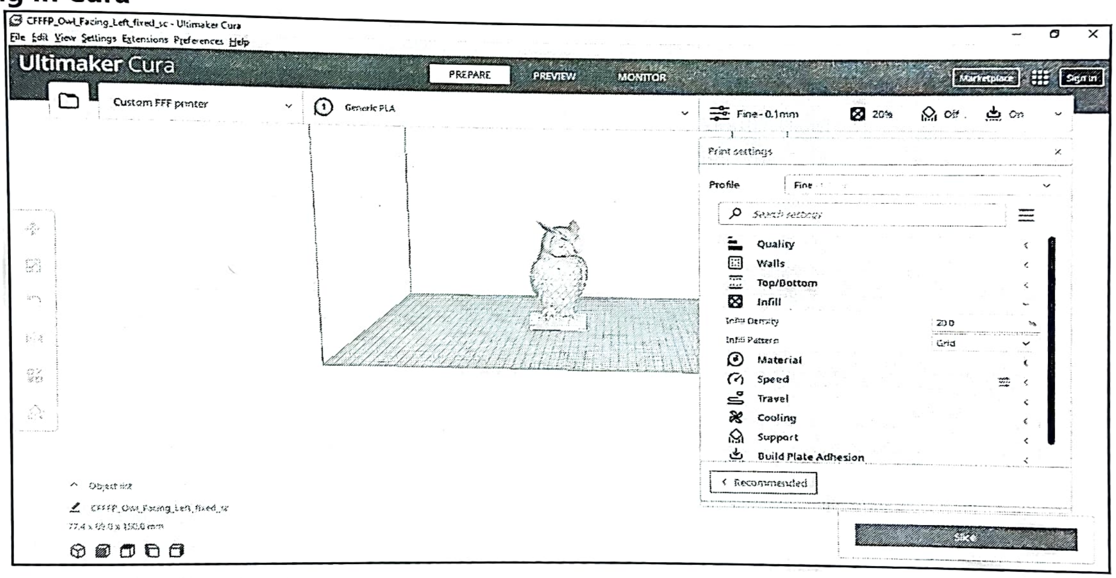
- Cura is a 3D printing host open source software manufactured by Ultimaker. Widely used software has many functions of slicing. Cura is the end solution for the software requirements in FDM technology.
- All slicing settings can be done by using Cura software. Layer height, infill parameters, wall thickness top and bottom layer thickness etc are the parameters usually used in setting up with cura. Machine setting is a huge part in cura software, preset machines are also available.
- Custom machines may be created in cura for slicing the product. Grid, lines, triangle, tri-hexagon, Cubic, Cubic-sub division, Octet, Quarter Cubic, Concentric, Zig-Zag,Cross, Cross 3D, Gyroid, lightning are the available infill patterns in cura software.

5.7.1 Important Steps in Cura

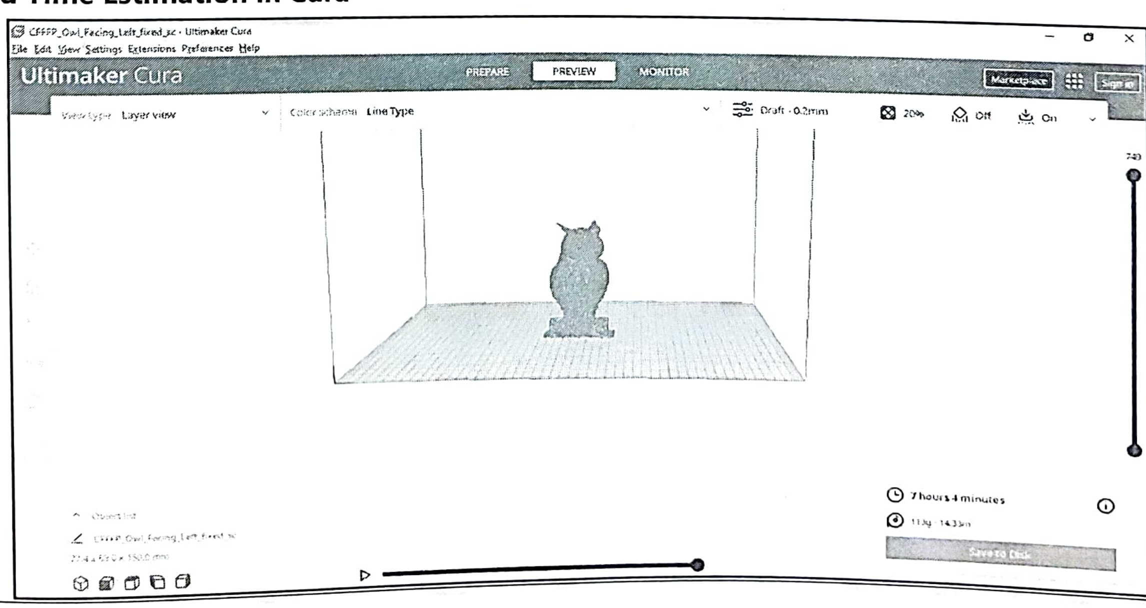
1. Load a Model



2. Slicing Setting in Cura



3. Preview and Time Estimation in Cura



5.7.2 Relevant

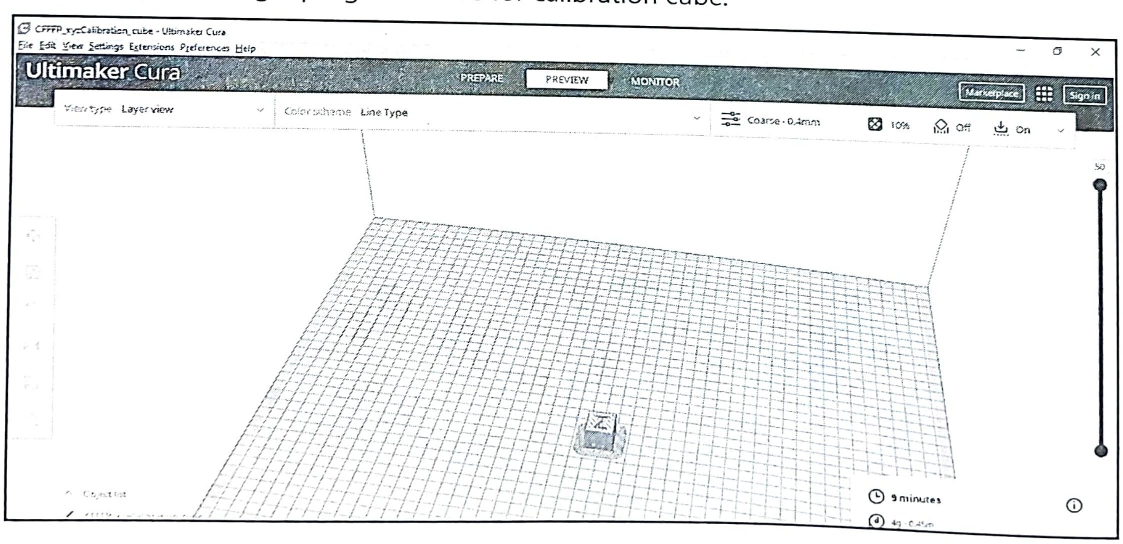
G/M Code

Table 5.1

Block	A single line of G Code
Canned Cycle	Complex cycle defined by a single block of code.
Dwell	Program pause with a duration defined by "P" in seconds.
EOB	End of block. Required at the end of every block of G Code. In Mach4 this is a carriage return.
Group	Collection of G codes that control the same function or mode, i.e. G90 and G91 positioning modes.
Origin	Point in a coordinate system where X, Y and Z are zero.
Word	A single word of G Code is a letter followed by a number. G01, X1.0, etc. are words.
G	Preparatory function, G followed by a numerical code, specifies machining modes and functions.
M	Miscellaneous function, M followed by a numerical code, defines program flow and can control auxiliary functions such as coolant.
X, Y, Z, A, B, C	Movement commands followed by a numerical value, define the endpoint of a motion command

G and M codes are the codes used to program the machine. Readable program instructions are always coded in the programming language so that it can be understood by machine too.

The following codes are representing a program made for calibration cube.



G Code

;FLAVOR:Marlin

;TIME:566

;Filament used: 0.449765m

```
;Layer height: 0.4
;MINX:232.2
;MINY:232.2
;MINZ:0.3
;MAXX:267.8
;MAXY:267.8
;MAXZ:19.9
;Generated with Cura_SteamEngine 4.13.1
M104 S200
M105
M109 S200
M82    ;absolute extrusion mode
G28    ;Home
G1 Z15.0 F6000    ;Move the platform down 15mm
;Prime the extruder
G92 E0
G1 F200 E3
G92 E0
G92 E0
G92 E0
G1 F1500 E-6.5
;LAYER_COUNT:50
;LAYER:0
M107
G0 F3600 X234.623 Y234.349 Z0.3
;TYPE:SKIRT
G1 F1500 E0
G1 F1800 X235.222 Y233.834 E0.01486
G1 X235.87 Y233.383 E0.02971
G1 X236.561 Y232.999 E0.04458
G1 X237.286 Y232.687 E0.05943
....................
....................
....................
....................
G1 F1800 X241.17 Y248.147 E449.62352
```

```
G0 F7200 X241.17 Y247.582
G1 F1800 X245.151 Y243.601 E449.76473
G1 X245.221 Y243.531
;TIME_ELAPSED:566.094928
G1 F1500 E443.26473
M107
M104 S0
M140 S0
;Retract the filament
G92 E1
G1 E-1 F300
G28 X0 Y0
M84
M82 ;absolute extrusion mode
M104 S0
;End of Gcode
```

Above G code program is representing a manufacturing cycle of a calibration cube.

5.8 STANDARD FIRMWARE

- Marlin is an open source firmware for the RepRap family of replicating rapid prototyper popularly known as "3D printers." It was derived from Sprinter and grbl and became a standalone open source project on August 12, 2011 with its Github release. Marlin is licensed under the GPLv3 and is free for all applications.
- From the start Marlin was built by and for RepRap enthusiasts to be a straightforward, reliable and adaptable printer driver that "just works." As a testament to its quality, Marlin is used by several respected commercial 3D printers. LulzBot, Průša Research, Creality3D, BIQU, Geeetech and Ultimaker are just a few of the vendors who ship a variant of Marlin. Marlin is also capable of driving CNC machines and laser engravers.
- One key to Marlin's popularity is that it runs on inexpensive 8-bit Atmel AVR micro-controllers - Marlin 2.x has added support for 32-bit boards. These chips are at the center of the popular open source Arduino/Genuino platform. The reference platforms for Marlin is an Arduino Mega2560 with RAMPS 1.4 and Re-Arm with Ramps 1.4.
- As a community product, Marlin aims to be adaptable to as many boards and configurations as possible. We want it to be configurable, customizable, extensible, and economical for hobbyists and vendors alike. A Marlin build can be very small, for use on a headless printer with only modest hardware. Features are enabled as-needed to adapt Marlin to added components.

5.9 IN-PROCESS MONITORING

- In-process Monitoring is a technique to handle many printers at a time. Nowadays 3D printers are coming with cameras to monitor. In process monitoring can be done visually or by using NDT methods.
- Some of the sensing elements are used for in process monitoring for example if the material is not extruding properly then a sensor will recognise that there is no filament in position and the machine will automatically stop.
- When the machine will automatically stop we will be notified by using Wi-Fi and the materials and time wastage will be saved.

5.10 CALIBRATION

Calibration is a technique which is generally performed for checking the level of accuracy. In 3D printing technology axis calibration is generally done.

Calibrate your extruder:

- Disconnect your hotend from the extruder.
- Cut the filament flush with whatever fitting you have.
- Using whatever interface you use to control your printer extrude 100mm/10cm of filament.
- Your firmware may have a safety temperature preventing cold extrusion. If this is the case you will have to bring your hotend up to temp in order to extrude filament.
- Cut the filament and repeat this procedure two more times.
- Measure the three pieces of filament.
- Get an average (add the three measurements and divide by 300).
- If your average is not close to 100 you need to change your extruder steps per mm. Take the current steps per mm and divide it by (your average/100).
- Repeat until you are happy.

Calibrate Filament Diameter, do this Every Print -

Using a caliper, measure your filament diameter at several locations. Average out the measurements, at least 3, and enter that into your slicer under filament diameter.

Calibrate z Height and First Layer:

- Print a single layer (of say a 20*20mm cube) with your first layer at 100% height and width.
- Using a caliper measure the print in several places (at least 8) and adjust your bed or gcode z offset.
- Repeat until you are happy

Calibrate Temperatures:

Do this for every different filament (color, brand, material, etc)

- Grab a temperature calibration tower off thingiverse: https://www.thingiverse.com/thing:915435 6.1k
- Set the temperature range to the range listed on your filament or by the manufacturer.
- Print the calibration tower and choose the best temp.

Calibrate Fan Speed:

We have a Delta with three really powerful layer fans. If they all three run at 100% the hotend loses temperature.

- Print calibration tower again but change the fan speed vs the extruder temp.
- Choose the best fan speed for the finish desire.

EXERCISE

1. Explain design of build platform and extruder design.
2. Explain raw material manipulation.
3. Enlist and explain types of infill.
4. Explain calibration process and in process monitoring.
5. Explain control systems used in additive manufacturing.
6. Explain use of CURA software with basic commands.

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Unit VI : Case Studies, Application and Special Topics **[08 Hr.]**

Case Studies and Application of AM: 3D printing in prominent industries (Aerospace, Electronics, Defense, Automotive, Construction, Architectural, Machine-Tools), Other industrial applications (Health-Care, Personalized Surgery, Bio-medical Applications, Assistive Devices, Food-Processing, Food & Consumer Applications, Art, Fashion, Jewelry, Toys & Other Applications, etc)

Special Topics: 4D/5D Printing, Bio-printing, Bio-materials, scaffolds and tissue and Organ Engineering, Mass Customization and Future trends.

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UNIT VI

CASE STUDIES, APPLICATION AND SPECIAL TOPICS

6.1 CASE STUDIES AND APPLICATION OF AM

A collection of case studies aimed to inform you of how additive manufacturing can impact your business, the latest developments in the technology and the applications where we see the technology applied.

6.2 3D PRINTING IN PROMINENT INDUSTRIES

- Today, Additive Manufacturing (AM) technologies are thought to be revolutionary manufacturing technology. In this present techno-commercial world, due to frequent changes in the customer demand as well as product design the service life of components is relatively reduced, these innovative technologies have made significant treads for the past few years with massive relevance to design creativity, time-compression, and digital fabrication with varieties of product. These processes involve the fabrication of three-dimensional parts through material addition in the form of layer by layer.
- AM technologies are being used for the manufacturing of functional/non-functional parts with ample amount of variety of materials such as polymers, ceramics, metals, and thereby combinations. The parts thus manufactured could be used for various applications such as architecture, construction, industrial design, aerospace, engineering, automotive, military, dental and medical industries, biotech (human tissue replacement), fashion, jewellery, footwear, eyewear, geographic information systems, education, food and many other fields.
- In spite of the best efforts, there are to be some mistakes found. Same may be found to rectification. We sincerely hope that Additive Manufacturing: Innovations and Applications, which is of the Manufacturing Design and Technology Series meets the expectations of readers on this subject of production technology.

6.2.1 Aerospace Industry

Additive manufacturing is a clear fit for many prototyping and applications within the aviation and aerospace industry. Parts produced via additive manufacturing can be lighter and stronger than those made using conventional manufacturing. Aerospace was a very early adopter of 3D printing and still continues to contribute at huge scale to its development. Companies in this industry began using 3D printing in 1989, and in 2015 aerospace accounted for 16% of additive is $4.9B global revenue.

Howdoes3Dprintingimproveaerospace manufacturing?

Geometric Design Freedom

- Aerospace applications make use of advanced complex geometries and engineering materials in an attempt to reduce weight at the same time improving performance. Aerospace parts frequently include internal channels for conformal cooling, internal features, complex curved surfaces and thin walls .3D printing is capable of manufacturing such features and allows for the fabrication of highly complex structures with high stability.
- This high degree of design freedom enables the integration of functional features topological optimization in a single component as well as a product. Also, certain 3D printing technologies, such as SLS, DMLS and Binder Jetting, are capable of batch production at reasonable costs.
- Consolidating assemblies into a single part the design freedom you get with the Additive manufacturing process also helps to combine multiple parts into a single component. This leads to weight savings, cost reduction and also reduces the amount of inventory to be kept.

Surface Finish

- Surface finish level expected by aerospace industry is difficult to achieve. Additive manufactured parts can be post-processed to a very high surface finish. Technologies like material jetting can produce parts with surface fiish like injection moulding with small amount of post processing needed. High-performance metal parts manufactured with DMLS parts produced with Binder Jetting can also be smoothed and polished by using CNC machines after printing to improve their surface finish and accuracy.

Part Orientation

- Orientation for functional parts plays important role. Loading condition and layers produced relative act as a big reason for failure. Due to the layer-by-layer nature of Additive manufacturing, most parts will have superlattice mechanical properties and will reduce the strength in the Z direction. This should be taken into consideration during the process of design for AM.

Support Structures

For depositing material above overhangs or at walls with steep angles support structures are used in 3D printing to provide a solid base. Support also plays crucial part in metal 3D printing, it protects against wrapping.

What are the best materials for 3D printing aerospace? Check out this table 6.1 for a more in-depth comparison of materials used to 3D print custom aviation and aerospace components.

Table 6.1

Application	Recommended Process	Requirements	Recommended Material	Example part
Engine compartment	SLS	Heat resistant functional parts	Glass-filled Nylon	Tarmac nozzle bezel
Cabin accessories	SLA	Customized functional knobs	Standard Resin	Console control part
Air ducts	SLS	Flexible ducts and bellow directors	Nylon 12	Air flow ducting
Full size panels	SLA	Large parts with smooth surface finish	Standard Resin	Seat backs & entry doors

3D printing in Practice: Printing Parts for Satellites

- Satellite designs include more often geometrically specific brackets to link the body of the satellite with reflectors mounted on each end. Manufacturing these critical brackets comes with two well defined challenges.
- These brackets must attach feeder and reflector facility components securely to the body of the satellite. These brackets must be able to withstand the stress of manoeuvre against temperatures ranging from –170 to 100 degrees celsius. Very few materials can meet the requirements for the amount of stress these brackets undergo.

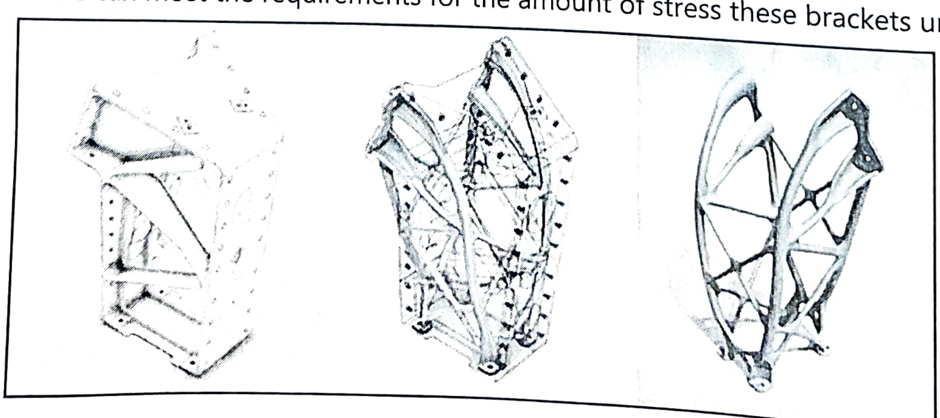

Fig. 6.1

- This satellite frame was printed using titanium. Image courtesy of Airbus.
- Engineers at Airbus found the solution for these challenges by 3D printing these brackets using titanium. By choosing to manufacture the brackets by the additive way, the engineers at Airbus cut down on material waste, consolidated parts (making assembly easier and less labor-intensive), optimized part geometries and ended up with components lighter in weight.
- 3D printing helped reduce costs to produce parts and will save fuel over the life cycle of the satellites thanks to the lightweight components.

6.2.2 Electronics Industry

- Additive manufacturing is the fabrication of a 3D object under computer control, with one or more materials being added layer by layer. Additive manufacturing is used across various electronics applications energy storage devices, including circuit boards, actuators, and sensors.
- It can be actuated using a variety of technologies, including Stereo Lithography (SLA), Selective Laser Sintering (SLS), Fused Filament Fabrication (FFF). 4D printing (also called 4D bioprinting, shape-morphing systems, or active origami) uses the same techniques like 3D printing, but 4D printing unables the dimension of time and fabricates an object that can change its shape or other parameters over time.
- 4D printing produces a programmable material that responds to environmental inputs such as temperature, light, or humidity and transforms into another structure. This FAQ will consider the application of 3D and 4D printing in circuit boards, energy storage, sensors, actuators, solar panels, and sensors. The next point will review specific applications of 3D printing in 5G telecommunications systems.

3D Printed Circuit Boards

- Additive manufacturing is being opted to make Printed Circuit Boards (PCBs) for a increasing variety of applications. These PCBs can be used for prototyping, short production cycles, for their unique properties and combination of reasons.
- For example, encumbrance in 3D circuit boards can be precisely controlled and 3D circuit boards can be designed with multiple layers of high density embedded and interconnected components that warrant the board's surface to shelter a high component density. Multiple power and ground planes can be used in the interior of the layers, enhancing isolation, and signal integrity.
- Additive manufacturing is very beneficial technology for Mixed-signal PCBs. 3D PCBs can now withstand the soldering process needed to place components on both sides of a PCB using a recently developed conductive ink and dielectric polymer ink. Those newly developed inks have been used to manufacture a 10 layer PCB with high-performance electronic devices soldered to both sides. This capability of the 3D printed PCB's can be instrumental in high-performance military sensor systems.

3D Printed Supercapacitors

- Energy storage devices such as supercapacitors and batteries can limit the working performance of exploration systems operating in extremely cold environments such as Earth's Polar Regions. On Mars, for example, temperatures can dive to –62° C (–81° F) at night, and heaters are required to keep batteries away from freezing. Those heaters consume energy that may be used for exploration activities.
- Scientists recently additively manufactured a porous carbon aerogel using cellulose nanocrystal based ink further used in resulting of structure to fabricate a supercapacitor capable of operating at –70° C (–94° F). The electrodes are printed into a matrix structure which is then freeze-dried, and a high quality surface treatment is performed. The result after testing is a porous structure having holes measuring 500 microns (μm) across. There are smaller pores in the beams of the additively manufactured matrix structure. These smaller nanometer scale pores allow charge transfer and ion through the electrode.
- The additively manufactured structure is called a 3D multiscale porous aerogel. It has a very large surface area that allows it to achieve high amount of capacitance at low temperatures. In addition, it retains that high capacitance at

high charge rates. Compared with 3D-MCAs produced with other manufacturing methods, the 3D-printed aerogel retains its capacitance 6.5 times better.

3D Printed Sensors

- Additive manufacturing allows the production of low-cost sensors based on resistive and capacitive technologies. The sensors may have a unique size and shape that can be printed directly into the robot's fingers. In the case of resistive sensors, as the fingers flex while gripping an object, each conductor deforms slightly, and its resistance changes with respect to motion, providing a simple way to inspect and control a robotic hand for gripping small objects.
- Additively manufactured capacitive touch sensors have been manufactured directly on the fingertips of a robot hand. Interface electronics was developed to produce a digital output based on changes in the capacitance, activating touch feedback control. 3D printed electrodes were manufactured using a copper-based conductive filament. The capacitive touch pressure sensor has two soft capacitive sensors that bear a resemblance to the fingertip of a human thumb. The device is 20mm wide, 30mm long, and 8.3mm thick, and the overlapping areas of the parallel capacitive sensors are 163.24mm square with a dielectric thickness of 1 mm

3D Printed Actuators

- Miniaturized actuators made using electroactive polymer (EAP) technology are difficult to manufacture with conventional photolithographic processes. Additive manufacturing processes such as Vat polymerization are being developed specifically to produce EAP macrobiotic actuators to use in miniaturized robots. Additive manufacturing is expected to simplify the fabrication of EAP actuators, making them cost-effective across a wide range of applications.
- One development effort additively manufactured three microrobots, measuring $6 \times 4.5\ mm^2$, $7 \times 9.5\ mm^2$, and $14 \times 12\ mm^2$, each with high accuracy and four micro actuator limbs. The limbs can be driven with an initial voltage of −1.0 V, simplifying their integration into systems. These microrobots can potentially be used to grip and release objects or as micro walkers. The micro actuators have to be combined with ionogels or other solid state ion sources to enable air operation.

6.2.3 Defense Industry

- According to research, an enormous 78% of industry leaders believe that additive manufacturing will become customary within the globe's defense industry within the next ten to twelve years. 3D printing can transform the defense industry, providing new ways to 3D print replacement parts on demand while enabling new design engineering possibilities and reducing production costs.
- 3D printing is unlocking a ocean of opportunities for the defense industry, reducing production costs for components and tooling cost though, localized manufacturing and additional design flexibility. Additionally, additive manufacturing can also improve the maintenance of military systems by producing spare parts.

Advantages of 3D Printing in Defense Sector

- **Rapid Product Development :** 3D printing speeds up the design process as it requires no specially designed and manufacture tooling. Generally traditional manufacturing can take long time to produce the necessary tools to create end usable parts. Therefore, the defense industry can take advantage of the Additive manufacturing technology to reduce the time required and product cost for product development.
- **Freedom of Design :** The defense industry can also focus on the ability of additive manufacturing to produce freeform, optimized objects. It means that a part's weight can be significantly reduced using additive manufacturing, saving production time and material costs.
- **Customised Equipment :** Additive manufacturing also offers the opportunity to create customized parts for specific functions. Instead of carrying parts and pieces for all possible configurations, soldiers can directly use 3D printing systems to design and fabricate parts based on demand. For example, the US Army is now 3D printing customized drone airframes to some extent tailored to a given mission's specific needs.
- **On-site Production :** Defense staff can now harness additive manufacturing technology to manufacture tailored parts and spare parts of equipment directly by use of design and scanning on the site at any time. They are no more waiting

around on the battle field for emergency reinforcements! The ability of additive manufacturing to produce the right part at the right time. This can be advantageous in fabricating customized parts on site production, on-demand production on the battle field and challenging territory emergencies.

- **Metal 3D Printing :** Metal 3D printing makes it conceivable for complex military components to be made in less time and be utilized on the war zone. Take the adversary by astonish!
- **Titanium Printing :** Additive manufacturing used for fabricating within the defense industry can offer assistance in squander decrease will result into decrease of taken a cost. Numerous parts of defense hardware are made by utilizing costly materials such as titanium. In conventional fabricating raw material wastage is exceptionally high. On the off chance that material like titanium is squandered at that point it will obstruct costing of the component.

Application of 3D Printing in Indian Defense Sector

- Recently, the Indian Army signs a pact to procure high altitude drones from Idea Forge for $20 million. The start-up was founded and incubated by the Indian Institute of Technology-Bombay (IIT-B). Idea Forge: The premium product of the company is the SWITCH UAV. SWITCH UAV is a first of its kind VTOL and fixed-wing hybrid Unmanned Aerial Vehicle. SWITCH features advanced flight time, higher safety, and simple operation with additional fail-safe redundancies. It is used for long-duration operations, long-endurance surveillance and security, inspection, and photogrammetric.

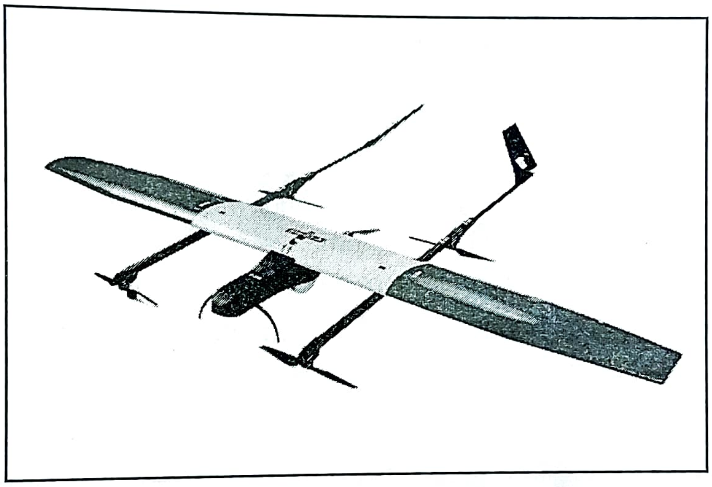

Fig. 6.2 : Additive manufacture for aero dynamic shapes

- The Indian defense establishment has been using 3-D printers to build components or prototype models for scientific investigations. Hindustan Aeronautics Limited (HAL) and the Gas Turbine Research Establishment (GTRE) are the two major aeronautic establishments in the country with decades of aerospace technology experience, are using AM technology for design and development. A brief study of these two organizations' expertise with AM technology clearly shows that the technology will play an essential role in the Indian A&D sector.
- HAL, the only aircraft manufacturer in India, has set its sights on AM technology to build several components for its indigenous engine program. HAL claims that they are using the Direct Metal Laser Sintering (DMLS) technique to print parts for the indigenously developed Hindustan Turbofan Engine. HAL is also taking the lead by using the technology for its indigenous aircraft program because it is sure that it will get DMLS built features certified soon.

6.2.4 Automotive Industry

- Electric cars have as of now unavoidable portion of our lives, as well as driver behavior observing systems and cloud to car mapping systems which are esteemed by drivers and protections companies a like. The dynamic financial environment and increasingly demanding buyers are making automakers explore for unused openings and materials to catch up with other businesses.
- This can be an environment where need breeds innovation. Deloitte College specialists as of late shared how additive manufacturing innovations, commonly known as 3D printing, and their progresses "have changed the potential ways in which items are outlined, created, made, and distributed".

Impact of 3D Printing in the Automotive Industry

- For the past few decades, additive manufacturing within the automotive industry was primarily used by carmakers to make automotive models to check their shape and fit. The primary innovation for building parts was specific laser sintering. This permitted automakers to form aesthetically wonderful parts, but they were weak in strength and might not be utilized long.
- Nowadays there are more vigorous innovations for automotive 3D printing, such as combined fiber creation (FFF), which can be utilized not as it were for the generation of models but moreover for end use parts. 3D printing for car parts can be a game changer within the industry. The World Wide Car Viewpoint 2017 ventures that "the worldwide automotive industry is set to reach 110 million in around the world deals yearly by 2024". This market has exceptionally large obstructions of passage because it is ruled by fair a couple of OEMs. The parts and extras showcase looks diverse. There are a part of huge scale and smaller players.

Advantages of 3D Printing in the Automotive Industry

- Printing solutions for the automotive industry provide benefits that can be easily evaluated in terms of performance characteristics. 3D printing can replace expensive and long lead-time CNC production. 3D printed plastic parts are cheaper and their production time in-house is shorter and this means reductions in production costs, especially when dealing with the manufacturing of complex bodies.
- In-house 3D prototyping can moreover offer assistance to control Intellectual Property (IP) infringements information spills as everything is manufactured on-site. 3D prototyping can moreover essentially decrease turnaround times over all stages of manufacturing permitting more nimbleness.
- Not at all like conventional approaches to vehicle plan where a variety of materials are utilized, has 3D printing in automotive plan permits lowered utilization of materials and wastage which is advantageous for all stages of manufacturing. 3D printer helped plan within the automotive industry permits creators to undertake numerous alternatives of the same detail amid the stages of modern demonstrate improvement.
- It brings more adaptability, which comes about in effective plans and flexibility in making changes in plan all through the method of demonstrate assessment. This, in turn, makes a difference auto producers remain up to date with showcase needs and be ahead of the field.

6.2.5 Construction Industry

- Using a 3D printer to print and develop structures layer-by-layer may be a common assignment. To illustrate the innovation, analysts and business people have off-site printed bridges in metal, polymer or concrete y on-site. Development 3D printing may be a strategy for manufacturing development components or whole buildings by means of a additive manufacturing printing concrete, polymer, metal, or other materials, layer-by-layer.
- The foremost common sort of printer is based on a automated arm that moves back and forward whereas extruding concrete. Other strategies for 3D printing incorporate powder binding and additive welding. Powder authoritative is 3D printing inside a bowl of powder, cementing powder layer-by-layer to make the required question. Additive welding substance welding has been illustrated by printing a full-scale, working metal bridge in Amsterdam

Benefits and Challenges

- Faster construction
- Lower labour cost
- Fewer people means more safe construction
- Less material used
- New designs are possible as the 3D printer can create complex surfaces
- The method and resulting physical properties of the printed construction elements are not yet recognized by building standards

Application Examples

- Inside the final 5 years, a few improvement projects have illustrated the possibility of utilizing concrete and development 3D printing innovations to create buildings. In 2014, Chinese WinSun pioneered as they built a few homes utilizing 3D printing innovation to make components off-site. In 2017, ApisCor where the primary to 3D print a complete home on-site in Russia.
- In 2019, 3D Printhuset created the primary European on-site 3D printed house in Copenhagen (The BOD), utilizing concrete and a 3D printer with a mechanical arm. Furthermore, companies have tested with 3D printing bridges. In 2017, Illustrious BAM gather and researchers from TU Eindhoven introduced the world's to begin with concrete 3D printed bridge within the Netherlands.
- In 2018, MX3D wrapped up the production of the primary 3D printed metal bridge, which is presently being tried in Amsterdam. FreeFAB could be a licensed innovation created by Laing O'Rourke, where wax is utilized as a form for the concrete. A short time later the wax

6.2.6 Architectural Industry

- Planners, Engineers and Development (AEC) experts get it the foremost significance of exact and substantial scale models. It makes a difference to them and their clients visualize thoughts reasonably and distinctively. Conventional ways of planning and assembling scale-models are monotonous, exorbitant, and depend intensely on modest bunch gifted craftsmen.
- Additive manufacturing is set to revolutionise the way planners investigate plans and improve. 3D printing for designers engages them effortlessly make complex, exact and strong scale models rapidly and cost-effectively. Wonderful 3D printed engineering scale models can offer assistance planners impress their clients make and seize more opportunities. All of this may be done in-house, in a matter of clicks

Benefits of 3D Printing for Architects

- Numerous driving scale demonstrate creators as well architectural firms have as of now harvested the benefits of 3D printing in engineering. 3D printed engineering scale models successfully pass on the ultimate appearance of plan making plan unmistakable clearing out a enduring visual impression. additive manufacturing for architects offers the taking after advantages.
- **Saves Time and Cost:** One of the major benefits of 3D printing for designers is time-saving and cost effectiveness not at all like the conventional ways, 3D printed building scale models can be created in a matter of hours. Conventional strategies require numerous days, numerous man-hours and gifted skilled workers, hence including to the cost.
- **Seamless Integration:** Most engineering firms as of now have in-house plan groups utilizing CAD applications. 3D printer can effectively communicate with these applications to render scale models precisely, without presenting human-errors, subsequently joining Added Plan Conceivable outcomes: 3D printers permit architects to plan unreservedly without stress

3D Printing Buildings on Other Worlds

- NASA and other educate are formulating ways to utilize 3D printing to construct livable structures on the Moon o Mars. The common thought is that NASA would send a group of robots to the goal a long time long some tim recently people arrive. The group would comprise of a rover/collector that mines and conveys crude materials; a fib plant that changes over crude materials to "filament" to be utilized by the printer; and the portable printer whi changes over the fiber into different buildings.
- This would dispose of the need send tons of building materials and a have of devices on the long and costly voyage the goal. All that would be required is to send the robots, the CAD plans and maybe a few chemicals for the char handle. In case AI and robots got to be progressed enough. The robots can be observed and modern programs for robots and the structures transferred from Earth.

6.3 HEALTHCARE INDUSTRY

- The medical industry is known to be most progressed within the way in which unused medicines and strategies have been created. Not to specify the innovations that drives all of this forward. There has been no shortage of supernatural occurrences which proceeds to happen.
- Presently 3D printing in healthcare is coming as well. One of the ways in which the medical industry has been progressed and improved is through the utilize of 3D printers. Additive manufacturing in healthcare makes it conceivable for medical experts to supply patients with a unused frame of treatment in a number of ways.
- 3D printing is utilized for the improvement of modern surgical cutting and penetrates guides, prosthetics as well as the creation of patient-specific copies of bones, organs, and blood vessels. Recent propels of 3D printing in healthcare have driven to lighter, stronger and more secure items, decreased lead times and reduced cost.
- Custom parts can be custom-made to each person. These moves forward the understanding of patients by medical experts and progresses.

Requirements of 3D Printing in Healthcare

Customization

- Due to the individualized nature of healthcare, 3D printing may be a perfect solution for this industry. As contradicted to manufacture a huge number of identical parts, 3D printing enables the creation of prosthetic and orthotic devices custom fitted to a patient's specific life systems.

Lead Time

- To process to create modern apparatuses can be time consuming and expensive. Indeed when it's made in-house. Inside basic circumstances, the long lead time can actually be live threatening. Additive manufacturing in healthcare gives creators and engineers the apparatuses to quickly make and repeat designs.
- Next to quicker prototyping, the communication can be more successful when utilizing reasonable models. An basic portion of the victory of any restorative gadget is the input from specialists and patients. Combined with the speed these plan enhancements can be actualized. The 3D printer is so exact that the custom parts can be outlined and sent to print in exceptionally small time. Inside a matter of hours it is produced.

Costs

- Creating custom parts and gadgets requires a significant sum of detail. When the method is completed physically, there's a hazard of human mistake and this seem set projects back in terms of cost and time. However, 3D printing has empowered specialists to create a few cycles some time recently it is printed, making a difference them to distinguish any potential errors, ensuring that the ultimate item is perfect.
- In expansion to the capacity to create custom, complex parts, 3D printing in healthcare is most fitting for low volume generation meaning costs will drop whereas viability increments. Expensive tooling or machining forms are not required. Too waste is diminished which advance decreases the costs.

Sterilizable

- Due to the application of a few parts utilized within the medical industry, sterilizable is an vital fabric property. 3D printing knows a parcel of materials that are solid, lightweight and sterilizable with PEEK and Ultem being the foremost appropriate.

Complexity

- Where before, conventional manufacturing may have battled to make complex, the plans that 3D printers are presently able to produce are possibly boundless. Modern composites and crossover plastics make it possible to make bodyparts that have progressed quality and are lightweight. Through selecting the proper materials and combining them with plans that are totally precise and exact, the patients advantage from an upgraded quality, consolation and freedom.

Common Applications of 3D Printing in Healthcare

Learning and Anatomical Replicas

- While the center has been on 3D printing implants and medical gadgets utilized by patients, one of the biggest ranges of application is the creation of anatomical replicas. Specialists are right now utilizing models created by 3D printing from understanding check information to upgrade the conclusion of sicknesses, clarify treatment choices, arrange, and, in a few cases, indeed hone chosen surgical mediations in development of the real treatments.
- The models empower specialists to get it quiet life structures that are troublesome to imagine, particularly when utilizing negligibly obtrusive procedures. Models too help in accurately measuring restorative gadgets. Specialists can too utilize the models to clarify an up and coming restorative strategy to patients and their families and to communicate the surgical steps to their colleagues.
- To offer assistance decrease taken a toll, a few offices have created methods where specialists acuminate and arrange operations on cheap mannequins that are transplanted with patient-specific.

Surgical Tools

- Doctors utilize apparatuses to help in surgery. These were customarily made of titanium or aluminum. With 3D printing in healthcare, specialists can make devices that precisely take after a patient's special life structures. 3D printed tools are utilized to form the situation of remedial medications (screws, plates and inserts) more exact, coming about in way better postoperative comes about. The FDM 3D printing innovation is perfect for iterative, low-cost prototyping to optimize the plan of a tool.

Prosthetics

- In the Joined together States near to 200.000 removals are performed each year. Substitution or modifications can be time devouring and expensive. Because prosthetics are such individual things, each one should be custom-made or fit to the wants of the wearer. 3D printing changed all this and is presently routinely being utilized to deliver quiet particular components of prosthetics that coordinate impeccably with the user's anatomy.

6.4 PERSONALIZED SURGERY

- Three dimensional printing technology has been received by specialists at an noteworthy rate and in a huge assortment of applications. About each part of human life systems that can be worked on has a 3D model printed on it. Besides, specialists have gone past printing these amazing patient-specific anatomic models to printing patient-specific medical equipment, such as inserts, prosthetics, outside fixators, props, surgical instrumented, and surgical cutting guides.
- The later blast in ubiquity of 3D printing may be a confirmation to the guarantee of this innovation and its significant utility in surgery. Most of the surgical divisions these days have attempted utilizing 3D printing in one way or another, beginning from visual-tactile helps for pre-planning surgery and up to total virtual planning of the surgery and customized surgical guides as well as Patient-Specific Inserts (PSI) which remain within the living body.
- Most of the applications of 3D printing in surgery centered on these categories: surgical 3D models, surgical guides, and implants. While models and guides can be printed using FDM and SLA, implants are usually printed using SLM, SLS, or EBM. There are many reports in the literature describing the use of all three technologies in surgery.
- Printing life-size anatomic models can advantage in a few angles, including education of youthful specialists on models permitting for material and 3D assessment of the tissues.
- The models can also be further used to allow mock surgeries thus improving the prediction of the results. These models may also be used for presurgical adaptation of instrumentation, thus reducing the time of operation and achieving superior compatibility
- Three-dimensional printed models were appeared to be prevalent in preoperative planning compared to 3D pictures These applications were used in many fields such as vascular surgery for printing aortic models, in endovascular aneurysm repair to select the proper device, in cardiac surgery for presurgical planning of tumor resections and repair of congenital defects, in neurosurgery for navigation training, and in orthopedic surgery for planning of tumor resection and treatment of injury wounds.

6.5 BIOMEDICAL APPLICATIONS

- Medical applications for 3D printing are extending quickly and are anticipated to revolutionize health care Medical employments for 3D printing, both real and potential, can be organized into a few wide categories, including: tissue and organ manufacture; creation of customized prosthetics, anatomical models and inserts; and pharmaceutical research with respect to medicate measurement shapes, conveyance, and disclosure.
- The application of 3D printing in pharmaceutical can give numerous benefits, counting: the customization and personalization of medical items, hardwares and drugs; cost-effectiveness; increased efficiency; the democratization of plan and making; and upgraded collaboration.
- Be that as it may, ought to be cautioned that in spite of later noteworthy and energizing medical progresses including 3D printing, outstanding logical and administrative challenges stay and the foremost transformative applications for this innovation will require time to advance.
- Tissue or organ failure due to maturing, infections, mishaps, and birth abandons could be a basic medical issue. Current treatment for organ failure depends generally on organ transplants from living or expired donors. However, there's a persistent deficiency of human organs accessible for transplant. In 2009, 154,324 patients within the U.S. were holding up for an organ. As it were 27,996 of them (18%) received an organ transplant, and 8,863 (25 per day) died whereas on the holding up list.
- As of early 2014, roughly 120,000 people within the U.S. were anticipating an organ transplant. Organ transplant surgery and follow-up is very costly, costing more than $300 billion in 2012. An extra issue is that organ transplantation includes the frequently troublesome errand of finding a donor who could be a tissue coordinate.
- This issue may likely be eliminated by utilizing cells taken from the organ transplant patient's possess body to construct a substitution organ. This would minimize the risk of tissue rejection, as well as the need to take lifelong immune suppressants.

6.6 ASSISTIVE DEVICES

- Assistive Technologies (AT) are tools that help people function independently in their daily life. These devices can be low-tech, or high-tech depending on how they're built. 3D printed devices are usually more affordable and more customizable than manufactured versions
- The time it takes to 3D print something is determined by a lot of factors such as size, how hollow or solid it is, complexity of the design, and type of material used so sometimes we can make more than one item a day depending on the design.
- In addition to prosthetics, additive manufacturers are also taking innovative new approaches to assistive devices like wheelchairs and walkers. One designer worked along side Materialise to create a customized and lightweight 3D printed wheel chair that combines comfort and ease of use with a design that is more sleek and modern than traditionally manufactured models.
- In the same space, Icon wheel chairs has created customized parts of wheelchairs, including products designed with SOLIDWORKS to handle rugged terrain. Other notable designs include the prototype for a stylish and functional walking stick and a multifunctional prototype walker.

6.7 FOOD - PROCESSING

- A 3D food printer comprises a food-grade syringe or cartridge that holds material, a real food item and deposits exact fractional layers through a food-grade nozzle directly onto a plate or other surface in a layer-by-layer additive manner.
- Another method is a mold-based method wherein 3D printing food machines are used to give shapes to a dough with the help of a hollow container or molding box). 3D printing requires hardware and software to work in collaboration. Advanced 3D food printers are equipped with user-friendly interfaces and preloaded recipes with designs that can be easily accessed by the computer or even with a mobile or IoT device.

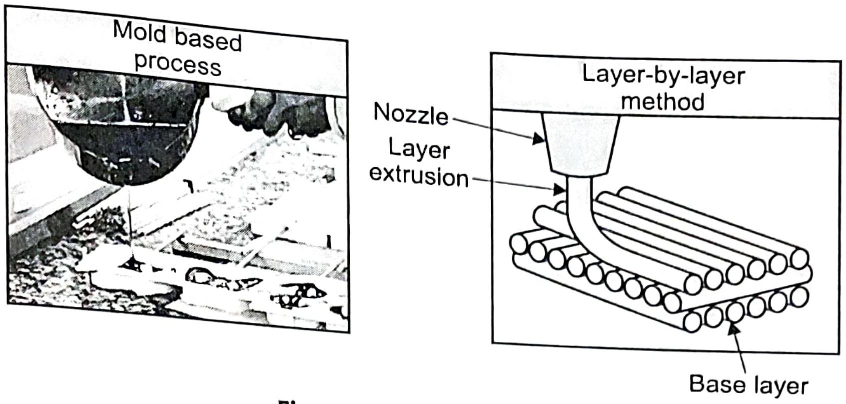

Fig. 6.3 : Layer deposition

Table 6.2 : 3D printer types and food materials manufactured

3D Printer Type	Food Material Type	Raw Material USED
Extrusion Base	Soft foods such as chocolate, cheese, dough, and meat puree	Polymers, hydrogels and biogels
Inkjet-based	Low viscosity materials like fruit puree and pizza sause	Liquid / solid phase (ink, fruit concentred, and fruit juice)
Binder Jetting	Powered materials like sugar, starch and flour	Sugar and starch mixtures
Selective laser sintering	Powered materials like fact chocolate and sugar	Non-sticky powered materials without any tendency to agglomerate

- Currently, 3D food printers make use of nozzles, fine materials, lasers, and robotic arms. The raw material flows smoothly from the print cartridge to the printing platform and protects the solid build on the platform. In a similar fashion, substances such as starch and proteins, which can form hydrogel structures, can easily be obtained from cheese, chocolate, and humus that can easily flow from the printer cartridge to the platform.
- The 3D printed food consuming community favors a variety of culinary options, such as crystallized sugar cake, detailed chocolate designs, ready-to-bake pizzas and ravioli, and cracker-like yeast structures having seeds and spores, which can sprout over time.

3D Printing Usage Comes with its own set of Advantages

- Allows food customization according to the choice, as the 3D printer can help determine the exact quantity of vitamins, carbohydrates, and fatty acids as per the input and assess the correct percentage of nutrients for a particular age.
- 3D printing saves both time and energy when it comes to experimenting with different types of food dishes. It also helps in achieving perfection with less effort and less time.
- The use of the food printing technique enforces innovation and creativity. Users can create dishes in entirely new ways by customizing ingredients. In addition, users of 3D printing can modify composition or amalgamate two products to produce an innovative dish.

- Food reproducibility is possible using 3D printing. Using the same set of ingredients to produce a similar dish again eventually drives the minimization of food waste. Additionally, it allows the sustainable usage of materials, such as duckweed, grass, insects, or algae, which can be used to form the basis of familiar dishes.

Challenging Aspects

- A few challenges associated with the use of 3D printing are mentioned below. Firstly, food safety is a significant concern. 3D printing process develops food in minimal time, which eventually restricts cooking food at certain temperatures or may result in fluctuating temperatures due to which microbes can grow and contaminate the food.
- Hence, to avoid contamination-related issues, manufacturers are required to follow certain standard practices and guidelines while processing the food.Food manufacturers cannot use all ingredients that are used at the time of conventional cooking. Every ingredient has its storage and cooking requirements, such as an optimum temperature, which needs to be met.
- All ingredients cannot be placed together in one container, along with the main component or dough, when manufacturing food via 3D printingThe use of a 3D printing machine requires skillful personnel. Appropriate training is offered to individuals on how to use a 3D printer for food manufacturing, which results in high-cost investment.
- The knowledge base and skills needed to operate the machine adds to the cost for training purposes. Additionally, 3D printers are expensive, with prices ranging between USD 1,000 to USD 5,000. The use of skilled labor and machine cost exerts a huge burden on the manufacturer.

Conclusion

- 3D printing technology in food industries offers new possibilities, such as personalized nutrition, automated cooking, reduction in food wastage, etc. This 3D printing technology in the food industry can fulfill the unmet needs in terms of personalized nutrition, food wastage, demand, and availability of food. It is an evolving technology that has a large number of benefits, such as saving time, highly efficient, sustainability, and many more. Nowadays, food manufacturing companies are moving towards the techniques or methods that can help them use food ingredients in the right manner for making healthy and tasty food to reduce food wastages.
- The population of the world is increasing rapidly, so there will be an increase in the food demand as well as wastage of it will lead to food source scarcity. This situation needs to be handled with novel technologies, such as 3D printing, which can efficiently use food resources with no or very less amount of wastage. Globally, there are a variety of prototype printers available for food production. 3D printing will continue to evolve as an exceptional technology in the food industry; however, high adoption will likely come from companies focused on product innovations and/or direct-to-consumer strategies.

6.8 FOOD AND CONSUMER APPLICATIONS

- Generally speaking, 3D printed food is a meal prepared through an automated additive process. While this definition can be quite abstract (and it is), think of those pizza vending machines that surfaced back in 2015. The dough is prepared, extruded, topped with tomato sauce and cheese, and finally sent to the oven – all within the same machine. This process, in a way, can be considered a primitive 3D printing food process.
- Fast forward to 2021 and we have exclusive 3D printing restaurants and dozens of food printers available on the market. This rapid growth in both technology and public interest has led many to claim that, soon enough, every household kitchen will be equipped with its own food 3D printer.
- In reality, 3D printed food is still in its infancy and has a long way to go before seeing a broader adoption from professionals and consumers. However, this doesn't stop us from marveling at these fascinating machines and their intriguing edible designs.
- The foods that can be 3D printed are limited to the processes available (as we'll see in the next section). Material extrusion is by far the most common process for 3D printing food, and, similar to FDM printing, requires paste-like inputs like purées, mousses, and other viscous foods such as chocolate ganache.
- At first, it might feel a bit restricted in terms of options, but think of all the possible combinations between doughs, mashes, cheeses, frostings, and even raw meats.

Do Food 3D Printers Cook the Food

- Food 3D printers are mostly suited for architecting intricate shapes and designs, not actually cooking the ingredients. Usually, the edibles are either ready for consumption or will be cooked in an external oven (or grill) once the 3D printing process is finished. There are some exceptions of course.
- The PancakeBot is a machine that only makes pancakes, by extruding the batter directly onto a hotplate. It still requires someone to flip it, but everything else is done with the same equipment.

Benefits

- It is completely safe to consume 3D printed foodstuffs as long as they've been prepared in an appropriate machine in a clean environment (as with any other kitchen). In addition to creating amazing-looking meals, there are other positives to 3D printing food:
- Personalizing meals: In terms of controlling the diversity and amount of nutrients, vitamins, and calories per meal, 3D printing food allows for precision. This could be extremely important in hospitals where restricted diets are more common, and offers the potential for easy patient customization.
- Unconventional food consumption: When you process nutritious plants and protein-rich insects in a semi-liquid state, these foods could be presented in a more attractive way and thus incentivize their consumption. In the future, even synthetic food might be 3D printed.
- Easy reproducibility: Sharing recipes could be as simple as transferring a digital file over the internet. All that would be required is the same raw materials, printing settings, and compatible printing equipment.

Drawbacks

- With all these interesting advantages that 3D printing food brings, we had be remiss not to mention that it does have some downsides. Although times can vary based on the printer and the food being printed, according to Choc Edge, a food 3D printer manufacturer, a very simple six-layer design can take 7 minutes to print, while more detailed 3D models take more than 45 minutes each. It might not sound like much a first, but at these speeds, the whole enterprise lacks scalability.

Consumer Printers

- The cost of equipment and consumables also presents barriers as we'll see next, not to mention the time spent on training. Furthermore, the edibles used in these machines either require pre-cooking or pre-processing to achieve the consistency required for extrusion. Therefore, the expected reproducibility and reliability for these machines depend heavily on the proper preparation of those materials.
- 3D printing food is not exclusive to special events and fine restaurants. Although less popular, there are a couple of dedicated machines for an enthusiast home user.

Mycusini

- The Mycusini is a chocolate 3D printer released by German startup Print2Taste, originally funded through a Kickstarter project. It has a great design and is compact enough for a kitchen countertop, while its internal battery allows off-grid printing for up to two hours. The stainless steel cartridges are easy to fill and clean, but the refills must be purchased directly from Print2Taste. The Mycusini costs around \$690 (~€600).

Procusini

- The Procusini 5.0 is yet another food 3D printer from Print2Taste, but aimed at the prosumer market. This machine costs around \$4,100 (~€3,550) and could potentially handle small events catering. The cartridges can be heated up to 60°C during printing to aid the extrusion of thicker materials like marzipan or fondant for cake decoration. The Procusini is advertised as a plug-and-play system, and, just like with the Mycusini, this printer's refills must be purchased directly from the manufacturer.

6.9 3D PRINTING IN ART

- The last few years have witnessed the emergence of 3D Printing Art as a form of creative expression. Artists utilize their imagination to take their thinking further ahead and help us look at things from a different perspective. In a similar hue, 3D printing has already disrupted limitations across various aspects of design and manufacturing. The amalgamation and creation of 3D printing art was only the natural next step.

Benefits of 3D Printers in Art and Modeling

- Although 3D printing art and modeling is rather nascent, artists are finding new applications for 3D printing technologies in their work. Visionary and futuristic artists and creative professionals have already used 3D printing for designing art installations, modern sculptures, character and prop design – the possibilities and benefits are endless.
- **Sparks Creativity:** 3D printing in art has the prowess to spark creativity and give birth to a new breed of art form. It acts as a magic portal between imagination and life-like tangible reality. Just like artists, 3D printing can push the envelope of conventional, to deliver artifacts that simply amaze and inspire.
- **On-the-fly Customization:** Art is dynamic. This dynamism leads to custom design in most forms of creative arts. 3D printing offers a quick, reliable, and agile solution in this custom-design-driven application. Creative professionals such as filmmakers, game designers, and set-designers have already started reaping the benefits of 3D printing in their artwork.
- **Easy Replication:** Numerous artworks and styles rely on replication of components as a part of their creative expression. Replication can be tedious and prone to errors and kinks. 3D printers can help artists overcome this challenge and let them focus on the big picture.
- **Infinite Possibilities:** 3D printed art is a renaissance of infinite design possibilities; empowering artists and designers capture imagination with technology. To add to this, new-age 3D printers have fewer design limitations. 3D printing is at the frontier of transcending the potential of human imagination.
- Perhaps the most obvious of the art forms to utilize 3D printing technology are visual arts. 3D printed art installations, sculptures, and more can be found virtually anywhere. 3D printing gives these artists more freedom to create complex structures that would otherwise be almost impossible to make, or extremely time-consuming and difficult. It also puts the power of creation into the hands of the artists, since they don't need specialized skills to physically make the 3D printed pieces, just some CAD design know-how and a 3D printer.

These are a few of the most unique projects we found:

- **Joshua Harker:** Harker is responsible for the 3D printed, sugar-like skulls you've probably seen online. Not only that, but he's also considered the father of 3D printing art due to his innovative approach to sculpture design; he is famous for combining CT and 3D scans to create stunningly accurate plastic facial/skeletal structures. On his website, he writes his "art is about pushing the limits of form & dimensions to share visions... an exploration into what can be made and how to accomplish it in an effort to tell a story or create an experience."
- **Kate Blacklock:** Sculpture doesn't stop at just plastic filaments. Blacklock uses clay to make 3D printed pottery. Her mesmerizing work includes many cutouts and delicate patterns done with the accuracy of a 3D printer and the vision of a creative genius.
- **Danny van Ryswyk:** Van Ryswyk designs whimsical, nightmarish figures, prints them, paints them by hand, and places them carefully in ornate glass display cases. He uses a polyamide filament to bring his fantastical creations to life as opposed to sculpting by hand because he claims printing improves the clarity and accuracy of the image he wants to form

6.10 3D PRINTING IN FASHION INDUSTRY

- Currently, when it comes to 3D printed clothes, the practices are mostly limited to art pieces or haute couture for major fashion designers.
- 3D printing in fashion is an interesting avenue for designers and artists interested in creating complex geometric designs and wearable art. However, many of these designs are not really wearable in day to day life.
- Although designers are innovating and developing new techniques, it is only on a mainstream level, 3D printed fashion is still growing. We expect to see this side of the fashion expand over the coming years.

Practical Uses of 3D Printers in Fashion

- In a more day-to-day application, we use 3D printing in fashion to create accessories, build prototypes and manufacturing tools, boost sustainability efforts, and expand customization options.

3D Printed Fashion Accessories

- Instead of 3D printing full items of clothing, 3D printers in fashion are used to supplement parts of a whole design, like embellishments, accessories, and buttons.
- Small end-use accessories can be easily assembled in just minutes using 3D printing. Such materials with a flexible nature, as TPU, can be used to add accent pieces or unique embellishments onto the garment themselves. 3D printing is also helpful when creating costume jewelry with complex geometric shapes.

Prototyping and Tooling

- Creating prototypes and tools for manufacturing are two of the most common uses of professional 3D printers, and the fashion industry is no exception to this.
- Camper, a popular Spanish shoe company, uses BCN3D printers to build prototypes and concept models for each new shoe collection they create. Previously, they used to outsource the production of these models, adding more costs and time to the overall design process. Now, with several 3D printers in-house, their designers can get a much better understanding of the volumes and shapes of their designs.
- 3D printers also encourage designers to take more design risks, since they can quickly assess the viability of their designs. Prototyping different design iterations in this way allows designers more time and freedom to come up with new innovative designs.
- 3D printers are practical to create tools that will help in the manufacturing of the final garment or accessory. For example, Louis Vuitton, a prominent high fashion company, uses 3D printing to produce tools that help ensure that their final products are produced efficiently yet elegantly.

Sustainability

- 3D printing technology in the fashion space is also gaining traction for sustainable fashion, as more designers and brands are beginning to seek sustainable methods to create their collections.
- A great example of this is the innovative Spanish fashion brand ZER. They use additive manufacturing throughout their designing and creation process as a means to be a sustainable force in the fashion industry.

Customization

- Finally, 3d printing in fashion opens the doors to new possibilities when it comes to customization options. Brands can begin to fabricate pieces based on the consumer's specific needs or body parts.
- The German sportswear company Adidas has been experimenting with this concept since 2015. Using running data from athletes, they have created a shoe that provides the optimal fit for any runner. They continue to experiment with different iterations of this 3D printed shoe today.

Conclusion

In conclusion, from end-use designs to behind the scenes processes, 3D printing is establishing its presence and benefits in the fashion industry. It will be exciting to watch the innovations, tactics, and designs that are created as this technology grows.

6.11 3D PRINTING IN JEWELRY DIGITAL WORKFLOWS AUGMENT TRADITIONAL TECHNIQUES

- 3D printed jewelry production augments the principles of investment casting, or lost wax casting with the advantages of a digital design and manufacturing process.

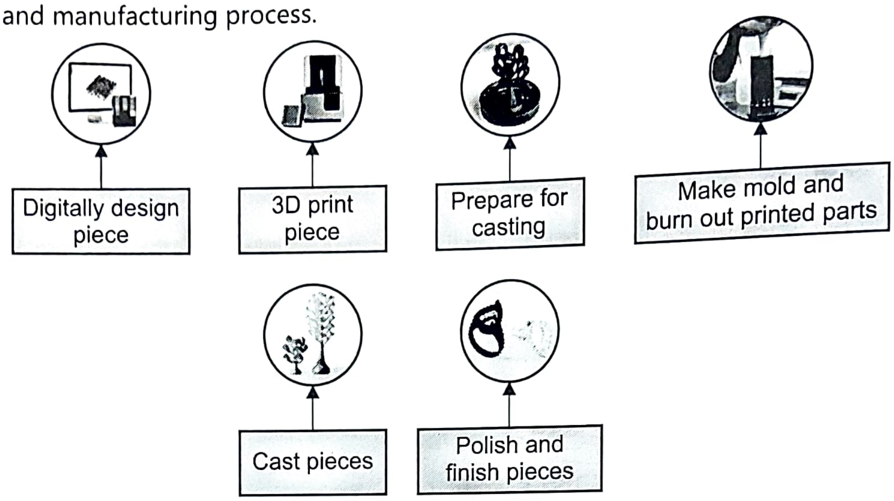

Fig. 6.4

- With traditional lost-wax casting, jewelry designers hand-carve the original pattern in wax, place the wax pattern in a mold to be burned out, and then pour precious metals like gold or silver into the mold cavity to create the cast piece. To achieve its final appearance, designers polish and finish the cast piece to shine.

How Jewelers and Customers Benefit?

New Frontiers in Customized Jewelry

- Until now, the complexity of the design and production process made customized jewelry an expensive privilege. With digital tools, however, jewelers have already started offering personalized creations as part of their basic service or as a value add. If you go to a jeweler today and ask for an engagement ring, often you will have the option to customize a unique design.
- Jeweller and customer can discuss the design together, and an hour later, the customer can hold and try on a real, physical model of the ring. In jewelry retail, on-site digital design combined with the speed of 3D printing has drastically shortened the feedback loop between designer and customer.
- Moving from design to production is easier and faster, as hand carving a precious one-off is no longer a requirement. The try-on pieces can be tailored based on the customer's requests, 3D printed again, and then manufactured with lost-wax casting, which translates to a considerable reduction in the cost of making customized 3D printed jewelry.

Design Freedom

- With 3D printing, jewelry designers are able to produce designs that would be incredibly difficult to hand carve in the traditional manner. Breakthroughs in castable resins are setting new standards for the quality available through an affordable desktop 3D printer.
- 3D printing jewelry patterns in Formlabs' Castable Wax 40 Resin combines the smooth surface finish characteristic of Stereo Lithography (SLA) 3D printing technology with precise print settings. Thanks to a precisely controlled laser, extraordinary design details delicate filigrees, raised text, and detailed pave stone settings can be captured with amazing sharpness.

- With these long established design restrictions now removed, we're seeing entirely new genres of design emerging from jewelers who have digital capabilities in the US as well as in South Asia and Asia Pacific, and the Middle East.

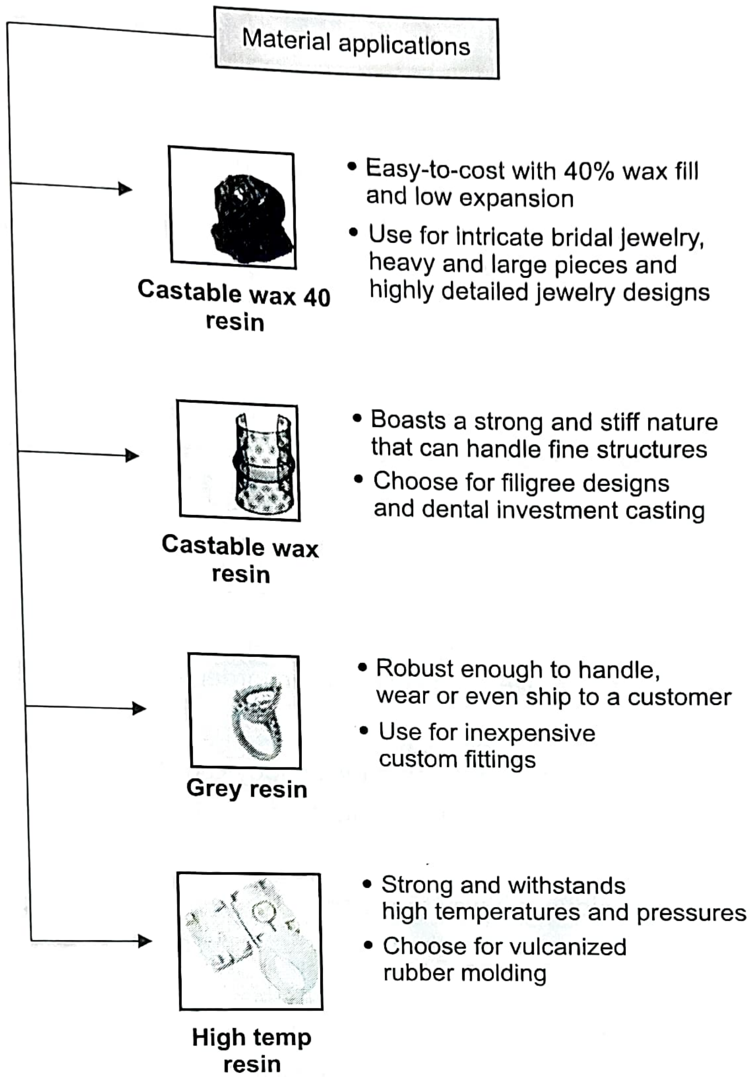

Fig. 6.5 : Easier Mass Production

- Digital tools are not only making jewelry easier to customize, but also simpler to mass-produce designs.
- Vulcanized rubber molds are used to produce wax patterns in quantity for lost-wax casting, but the "master" pattern is traditionally made from an investment cast, hand-carved wax pattern.
- 3D printers can produce master models that are used to form Room Temperature Vulcanization (RTV) molds and even durable high temperature vulcanized rubber molds.

The Future of the Jewelry Industry

- Owing to the formerly high cost of large-scale 3D printing and the perceived barrier-to-entry of digital jewelry design, 3D printed jewelry, despite its potential, currently represents a relatively small fraction of the market.
- Nevertheless, with increasingly easy to use and accessible 3D printing technologies, the 3D printed jewelry market is poised for growth.
- New, easy-to-use materials like Castable Wax 40 Resin are easing the learning curve, leading to greater adoption of the workflow and the subsequent expansion of the market.

6.12 3D PRINTING IN TOYS

- Using 3D printing offers opportunities for hobbyists to create their own customized figurines quite easily. Desktop 3D printers using Fused Deposition Modeling (FDM) technology are used most of the time but thanks to the advanced technologies offered by online 3D printing services, it becomes even easier to create figurines thanks to this manufacturing technique.
- These printing services are also a way to create high-quality sculptures and customized figurines. With technologies such as ColorJet and its Multicolor 3D printing material, manufacturing colored figurines has never been so easy! But 3D printing action figures and toys is not only interesting for hobbyists.

3D Printing Toys: Offering New Business Opportunities

Creating Spare Parts and Re-thinking the Supply Chain

- As you may know, additive manufacturing is the best technique to manufacture spare parts. While using 3D printing, manufacturing spare parts becomes useful for many different aspects and is starting to be used in some interesting sectors. 3D printed spare parts can be used to repair broken parts that are no longer produced.
- The automotive sector is making the most of this technology, some big manufacturers are already using it such as Porsche or Jaguar for their classic cars: this is an opportunity for them to recreate these old parts identically. This technique is also a great advantage for spare parts as it is adapted to the production of small volumes.
- But the automotive industry is not the only sector to use 3D printing to create spare parts. Indeed, the home appliance manufacturer Whirlpool is also using additive manufacturing in order to digitize its part catalog, to fight against obsolescence!
- For toys, the process can be exactly the same: 3D printing technology can be used to repair toys, create spare parts, or create customized toys. It is a way to recreate and repair old toys. Most of the time, these spare parts don't exist, or they are not produced individually.
- Implementing this manufacturing technique is a way to change a whole supply chain, by avoiding storage but gaining the opportunity to print as many parts as you need when you actually need them.
- We see people launching their businesses to repair toys, but this is evolving and might go even further in the upcoming years. 3D printing is drawing a new business model for toy manufacturers that will necessarily have to implement 3D printers in their workflows, which would significantly improve customer experiences.

The Toy Rescue Project

- The French 3D printers, Dagoma, started an initiative called Toy Rescue, in order to reduce the number of toys that are thrown away, using additive manufacturing. Among all these toys, a lot of them are not entirely defective, some just have broken parts or parts missing. The goal here is to use 3D in order to create a new wheel, a new leg, etc.

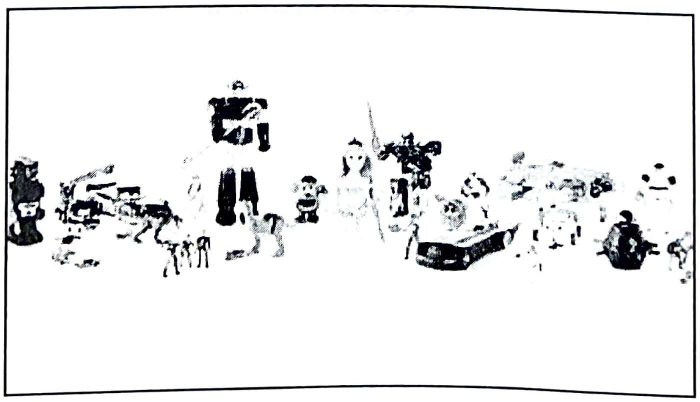

Fig. 6.6

Credit:

- Dagoma, Toy Rescue. This project started by identifying what were the most broken or missing parts on toys during the last 40 years. Thanks to this research, digital STL files of these parts have been created, making it easy to 3D print.
- It is now that easy to get a new Spiderman's arm or Mr. Potato's ear! As all these toys are already made of plastic, it is easy to recreate them with 3D printing, using FDM with materials such as ABS or PLA, but also using the Selective Laser Sintering (SLS) 3D technology with Nylon-based materials.
- For extremely detailed parts, you can also consider resin technologies such as Polyjet or DLS. Just like Whirlpool and its digital catalog of spare parts, toy manufacturers could soon start to offer the possibility to get spare parts of their most famous toys and fragile parts. Some big names of the toy industries are already showing some interest in 3D printing. For example, the toys store Toys'R'Us partnered with PieceMaker Technologies, to install 3D printers in some stores and give their customers access to these 3D machines in order to create customized toys for kids.

3D Printing Toys: What about intellectual property?

- 3D printing and intellectual property is a big subject. To ensure that an existing object isn't protected before you reproduce it, you must consider the source used to print the object: the 3D file. Using 3D printing to repair a toy also means printing the part of an existing toy, and you have to keep in mind that you don't own the design of these parts.
- If you want to print an existing object with 3D files you got from a scan the object is certainly protected, the company manufacturing the object holds the rights. 3D scanning an object constitutes a reproduction, it may constitute counterfeit reproduction if you 3D print it.
- However, making a new 3D file of an object using 3D modeling software cannot be considered as a reproduction since it is done directly by the 3D software user.
- Fortunately, the reproduction of a protected object is not enough to be considered a counterfeit. There are exceptions such as:
- Prior authorization from the right holder is needed in order to print their object and exploit it.
- Denaturing the object during printing (altering its form without respecting the form chosen by its author, for example) and not mentioning the name of the right holder(s) is forbidden if there's no authorization.
- If you are not the toy manufacturer and want to replicate parts, you can't produce these parts without authorization. Be sure to read our ebook about 3D printing and intellectual property to get all the information you need about this. Sculpteo is not a law firm, this is not legal advice, keep in mind that each situation differs and you may consider taking some advice on your specific situation with your lawyer. If 3D manufacturing offers a lot of freedom there are still rules you have to keep in mind, because you don't own the rights of these toys, or these spare parts.

6.13 SPECIAL TOPICS

6.13.1 4D/5D Printing

- 4D printing refers to single-material or multi-material printing of a device or object that can be transformed from a 1D strand into pre-programed 3D shape, from a 2D surface into pre programmed 3D shape and is capable of morphing between different dimensions. Such transformations are facilitated by, e.g., heating, light, or swelling in a liquid, electrochemically and by programming different sensitivity to, e.g., swelling into various parts of the designed geometry.
- These techniques offer adaptability and dynamic response for structures and systems of all sizes, and promises new possibilities for embedding programmability and simple decision making into non-electronic based materials. Potential applications include; robotics-like behavior without the reliance on complex electro-mechanical-chemical devices as well as adaptive products, garments or mechanisms that respond to user demands and fluctuating environments.
- In this paper, we have discussed fundamentals and laws governing 4D printing, materials that are employed in 4D printing along with applications such as soft robotics and challenges that need to be overcome for 4D printing to evolve as a mainstream manufacturing technology.

- During the TED conference at MIT in 2012, Skylar Tibbits showed how transformations occur in a static printed object (by 3D printing) over time. It has been seen that a simple 3D structure can be transformed with time into a more complex structure. This resulted into a new era of printing involving a new dimension in 3D printing i.e. time, and this was given a separate name of 4D printing technology.
- The fourth dimension is time, and we can say in a simple way that 4D printing is 3D printing with an extra dimension of time added to it. Or we can say the changes in the 3D printed materials with time result in the 4D printed materials. And after that speech by Tibbits, 4D printing started to gain its popularity among the researchers and engineers of various disciplines.
- The first research paper on 4D printing was published in 2013 (a year from the TED speech). In this research work, the concept of Printed Active Composites (PACs) was used to transform a printed sheet into a complex structure with the help of shape memory effect . Since then, the research in 4D printing has increased exponentially all over the world. One of the basic characteristics of the 4D printing is that it is not static and can reshape with time with the pre-programmed command from the computer.
- About two years ago, the first talks around 5D printing started to circulate in American Universities but one company had actually implemented this new technology partially, namely Mitsubishi Electric Research Labs (MERL). William Yerazunis, Ph.D. Senior Principal Research Scientist of this lab explained: A 5D printer allows for objects to not be printed from one point upwards but from five axes. Hence, where the number five in 5D comes from.
- The printhead moves around from 5 different angles while printing because the plateau on which the object gets printed moves as well. These movements allow for the printer head to come in from many different angles, otherwise not achieved with 3D printing.
- These new angles result in the printing head being able to follow the path of the object's shape and outline. By not having to follow a straight path on a static plateau and using the shape of the object instead, the printed parts can be created with curved layers instead of flat layers. These curved layers allow for stronger parts that have a complex design to be printed.

6.13.2 Bio-printing

- 3D bioprinting is an additive manufacturing process where organic and biological materials such as living cells and nutrients are combined to create artificial structures that imitate natural human tissues. In other words, bioprinting is a type of 3D printing that can potentially produce anything from bone tissue and blood vessels to living tissues for various medical applications, including tissue engineering and drug testing and development.
- Perhaps the most significant driver of 3D bioprinting is regenerative medicine. According to Chris Mason and Peter Dunnill, this involves replacing or regenerating "human cells, tissue, or organs, to restore or establish normal function." Here, bioprinting can have a central role, especially considering the high demand for organ and tissue transplants worldwide.

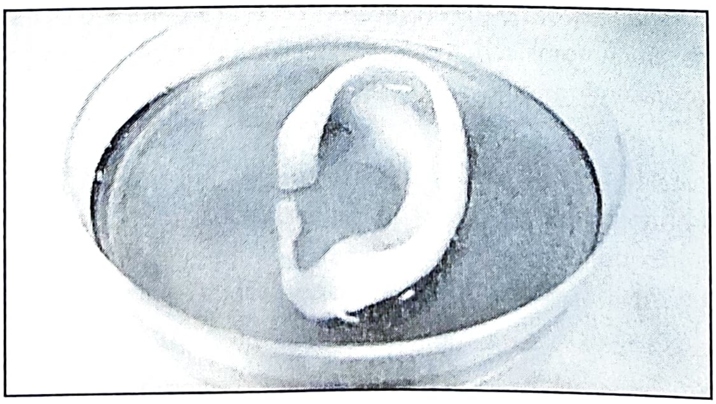

Fig. 6.7 : Bio printing with tissue material

The products obtained from bioprinting technologies can mimic both the biological and functional properties of our bodies' natural-occurring structures and tissues. This can potentially lead to different kinds of applications, but today there's only one feasible use for bioprinting: pharmaceutical drug testing and research. While the ultimate goal of 3D bioprinting is the production of artificial organs for transplantation the complexity involved in making them function as real organs is huge.

- However, scientists today can successfully create biological structures and tissues that imitate natural ones. So, instead of bioprinting fully functional kidneys, researchers can already create structures that chemically behave like kidney tissue. While far from the original goal, these structures can be used to test new drugs without having to rely on real-life patients that could suffer from unexpected side effects.
- Besides the ethical part of it, drug development with bioprinted materials can make pre-clinical trials of new drugs much more cost-effective, helping them to be validated and reach the market sooner, while also potentially reducing the need for animal testing.

6.13.3 Scaffolds and Tissue and Organ Engineering

- Since its emergence in the mid-1980s, tissue engineering has continued to evolve as an exciting and multidisciplinary field aiming to develop biological substitutes to restore, replace or regenerate defective tissues. Cells, scaffolds and growth-stimulating signals are generally referred to as the tissue engineering triad, the key components of engineered tissues.
- Scaffolds, typically made of polymeric biomaterials, provide the structural support for cell attachment and subsequent tissue development. However, researchers often encounter an enormous variety of choices when selecting scaffolds for tissue engineering. Hence, this paper reviews the functions of scaffolds, the scaffolding approaches and the tissue-specific considerations for scaffolding, using intervertebral disc as an example.
- Apart from blood cells, most, if not all other, normal cells in human tissues are anchorage-dependent, residing in a solid matrix called Extra Cellular Matrix (ECM). There are numerous types of ECM in human tissues, which usually have multiple components and tissue-specific composition. Readers are directed to detailed reviews for types of ECM [9, 90, 95] and their tissue-specific composition [13, 91, 112]. As for the functions of ECM in tissues, they can be generally classified into five categories (Table 1).
- Firstly, ECM provides structural support and physical environment for cells residing in that tissue to attach, grow, migrate and respond to signals.
- Secondly, ECM gives the tissue its structural and therefore mechanical properties, such as rigidity and elasticity that is associated with the tissue functions.
- For example, well-organized thick bundles of collagen type I in tendon are highly resistant to stretching and are responsible for the high tensile strength of tendons. On the other hand, randomly distributed collagen fibrils and elastin fibers of skin are responsible for its toughness and elasticity. Thirdly, ECM may actively provide bioactive cues to the residing cells for regulation of their activities.
- For example, the RGD sequence on fibronectin triggers binding events [47] while the regular topological pattern stimulates preferred alignment of cells [26, 127]. Fourthly, ECM may act as a reservoir of growth factors and potentiate their bioactivities.
- For example, heparan sulfate proteoglycans facilitate bFGF dimerization and thus activities [102]. Fifthly, ECM provides a degradable physical environment so as to allow neovascularization and remodeling in response to developmental, physiological and pathological challenges during tissue dynamic processes namely morphogenesis, homeostasis and wound healing, respectively.

6.13.4 Mass Customization and Future Trends

- Mass Customization is a rising trend that is gaining popularity and becoming more accessible through the years. This practice is already allowing companies from all shapes and sizes to cut down on costs while increasing customer satisfaction and creating brand diversification. As eCommerce becomes the new norm of the retail world, tailoring experiences to the individual will no undoubtedly become the next step.

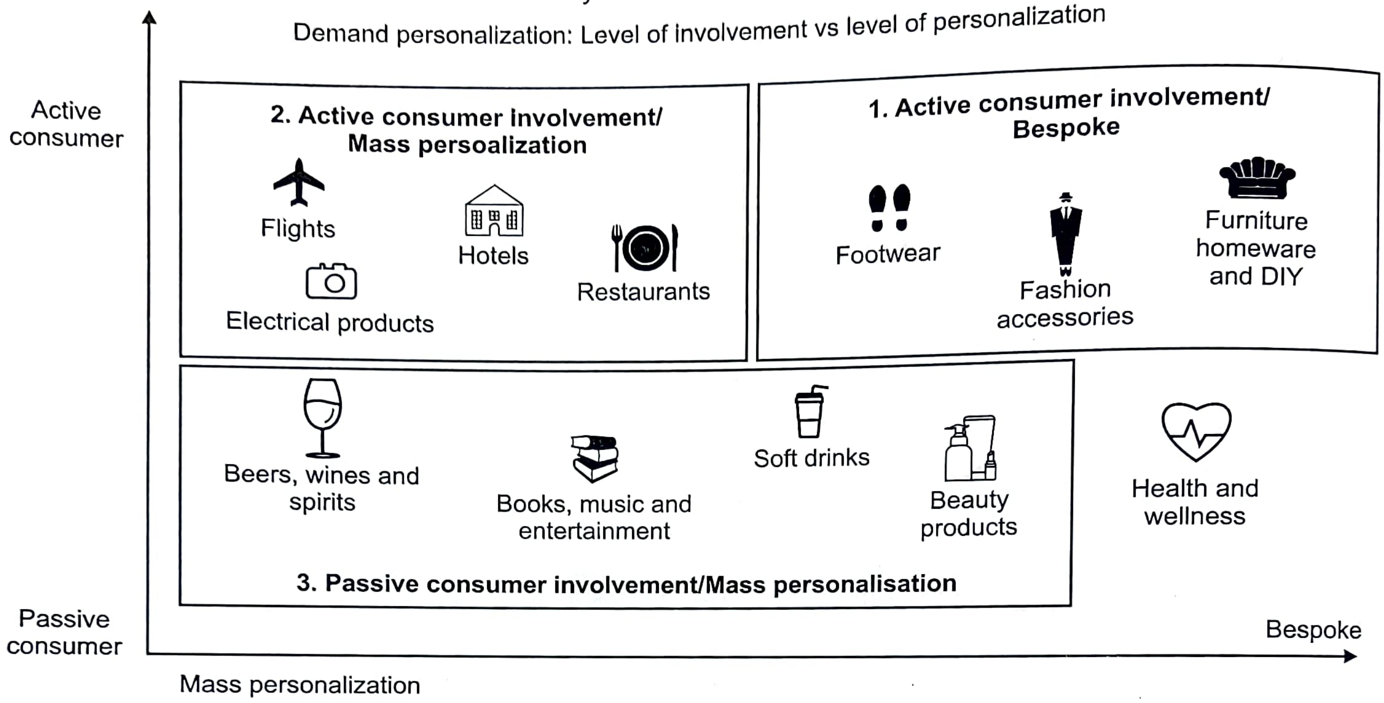

Fig. 6.8

- All in all, mass customization is the next step in the evolution of eCommerce. Its implementation can help create an even more successful online marketplace by providing better customer service and creating a personalized buying experience.
- Although the global pandemic has accelerated the adoption of eCommerce worldwide, mass customization is simply beginning to take up. Ecommerce and Mass Customization, according to eMarketer research, is all but set to increase in both volume and capital in the coming years. With the right tools and strategies at your helm, for incremental growth, the right time to push is now.

EXERCISE

1. Explain case studies of Additive manufacturing in aerospace.
2. Explain 4D/5D printing.
3. Define Bio-printing and bio-materials with organ engineering.
4. Explain the use of 3D printing in jewel of industry.

MODEL QUESTION PAPERS

In-Semester Examination

Time : 1 Hour **Marks : 30**

Instructions to the candidates :

(1) Answer Q. 1 or Q. 2, Q. 3 or Q. 4, Q. 5 or Q. 6.

(2) Neat diagrams must be drawn wherever necessary.

(3) Figures to the right side indicate full marks.

(4) Assume suitable data, if necessary and mention it clearly.

(5) Non programmable calculator is allowed.

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1. **(a)** Explain relevance of additive manufacturing in Industry 4.0. **[5]**

(b) Explain classification of additive manufacturing process according to process. **[5]**

OR

2. **(a)** Differentiate between SLS and SLM. **[5]**

(b) List and explain different types of materials in 3D printing FDM technology. **[5]**

3. **(a)** Explain AM process chain with the help of block diagram. **[5]**

(b) Write short note on 3D laser cladding with diagram. **[5]**

OR

4. **(a)** Differentiate between additive manufacturing and conventional manufacturing. **[5]**

(b) Explain type of liquid base technologies by using sources to curve the resin. **[5]**

5. **(a)** Explain Micro and Nano additive processes in AM. **[6]**

(b) Explain current trends in the industry regarding AM. **[4]**

OR

6. **(a)** Explain DMLS technology with suitable diagram and application. **[6]**

(b) Write short note on the importance of AM in prototyping. **[4]**

End-Semester Examination

Time : 2.30 Hours **Marks : 70**

Instructions to the candidates :

(1) Answer Q. 1 or Q. 2, Q. 3 or Q. 4, Q. 5 or Q. 6, Q. 7 or Q. 8.

(2) Neat diagrams must be drawn wherever necessary.

(3) Figures to the right indicate full marks.

(4) Assume suitable data, if necessary and mention it clearly.

(5) Use of non-programmable calculator is allowed.

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1. **(a)** Explain the difference between conventional manufacturing and additive manufacturing. **[6]**

(b) Write short note on stereolithography with neat diagram. **[6]**

(c) Explain the role of additive manufacturing in reverse engineering. **[6]**

OR

2. **(a)** Write short note on Direct Metal LASER sintering with principle diagram. **[6]**

(b) Explain the difference between FDM, DLP and SLA. **[6]**

(c) Explain classification of additive manufacturing with flowchart according to raw materials used. **[6]**

3. **(a)** Enlist limitations and applications of extrusion based techniques and explain one of them. **[6]**

(b) Explain Fused Deposition Modelling (FDM) with neat diagram and its applications. **[6]**

(c) Enlist several post processing techniques. Justify its significance according to surface finish and explain acetone treatment. **[6]**

OR

4. **(a)** Explain Robocasting and Bio-printing with suitable example. **[6]**

(b) Explain different categories of materials used in additive manufacturing with suitable example and technology used for the material. **[6]**

(c) Explain Hot isostatic processing and polishing technique of post processing with examples. **[5]**

5. **(a)** Write a short note on 4D printing. **[9]**

(b) Explain the process and mechanism used in multi jet modeling. **[9]**

OR

6. **(a)** What are the bio-active materials in additive manufacturing state its applications. **[9]**

(b) Define extrusion base process and differentiate between MJM and multi jet fusion. **[9]**

7. **(a)** Explain two types of slicing and enlist different parameters included in slicing technique. **[6]**

(b) Explain the construction of axial systems in FDM 3D printer. **[5]**

(c) Explain with the example of case studies additive manufacturing in aerospace and machine tools. **[6]**

OR

8. **(a)** Write use, method and applications of bio printing. **[5]**

(b) Enlist different fields of application for additive manufacturing explain any one of them with the use of case study. **[6]**

(c) Explain controls in additive manufacturing also write a short note on GURA software. **[6]**

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