3D Printing Technology for Thermal Application: A Brief Review

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ARTICLE INFO	ABSTRACT
  	3D printing is an emerging technology to construct complex geometry by adapting layer-by-layer addition technique from a 3-dimensional CAD model. Mass customization, freedom of design, and wastage minimization are the main advantages of Additive Manufacturing (AM) based 3D printing. 3D printing is currently used in many sectors worldwide, such as automotive, aerospace, agriculture, medical, electronics, and other household products. However, the usage of the AM technique is limited in large production sectors due to the limitation of the materials and properties of the produced parts. In this review, the different methods of 3D printing, the materials used in different processes, various fields of applications, and the properties of the different approaches are discussed. Also, the effect of process parameters such as layer thickness, nozzle temperature, platform temperature, printing speed, extruding rate, and layer height in 3d printing was reviewed. This will be helpful for further development of 3D printed product quality and applications in various sectors.

1. Introduction

3D printing, one of the methods in Additive Manufacturing (AM), is a process of constructing materials with complex geometry using a layer-by-layer technique from 3-dimensional CAD data [1]. In 1986, Charles Hull developed the initial AM process named stereolithography (SLA) and further enhanced it to various other technologies such as powder bed fusion (PBF), fused deposition modeling (FDM), and contour crafting (CC). The increasing demands for the cost-efficient project, lightweight products, and polymer-based composites materials upsurge the use, research, and technology development of 3D printing. These days, 3D printing is used in many sectors like aerospace, medical, electronics, construction, and other housed hold products [1]. 3D printing is a truly revolutionary technology that has evolved as a multifaceted process step. It opens new possibilities for businesses trying to maximize production productivity and offers hope for many

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opportunities. Materials such as polymers, polymer composites, ceramics, metals, and nanomaterials are used in the AM process. The 3D printing technology is extensively used for the development of customized complex geometries for the automotive, aerospace, agriculture, and healthcare sectors [2].

Conversely, the use of 3D printing technology in the industry has several drawbacks. The application over many sectors has been restricted because of the availability of limited materials. Another primary reason is product quality, cost-effectiveness, and mass production capability [3]. The 3D printing technique is not suitable for mass production compared to the conventional process as they are more time-consuming and high cost. Apart from that, the product's mechanical properties are also affected by the processing technique, processing parameters, and limited material availability.

Thus, the present review is focused on reviewing and providing insights related to the various process of 3D printing, materials used in the 3D printing process and the properties and the various applications of the 3D printing, and the effect of the process parameters in the AM process.

2. Types of 3D Printing Process

American Society of Standards classified the AM into seven categories, Material Extrusion (ME), Powder Bed Fusion (PBF), Binder Jetting (BJ), Material Jetting (MJ), Sheet Lamination (SL), Vat Photopolymerization (VP), and Direct Energy Deposition (DED) [3]. No debate exists about which machine or technology works best because each one has its specific applications and advantages. At present, 3D printing methods are no longer limited to prototyping but are rapidly being used to produce a wide range of products [4]. The various categories of the AM process are discussed below.

(i)   Materials Extrusion (ME)

Materials Extrusion (ME) is an AM technique in which the material is heated and selectively dispensed to form a 3D component through a nozzle. Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF) is one of the imperative machining processes of this category. The material extrusion process can be used to print plastics, foods, and living cells in multi-color or multi-materials. This method is widely used to build up fully functional parts cheaper and quicker [5]. The first example of the material extrusion process is FDM, which was developed in 1989. Polymers are used as the primary material in this process [6]. Figure 1 indicates the schematic diagram of the material extrusion FDM process.
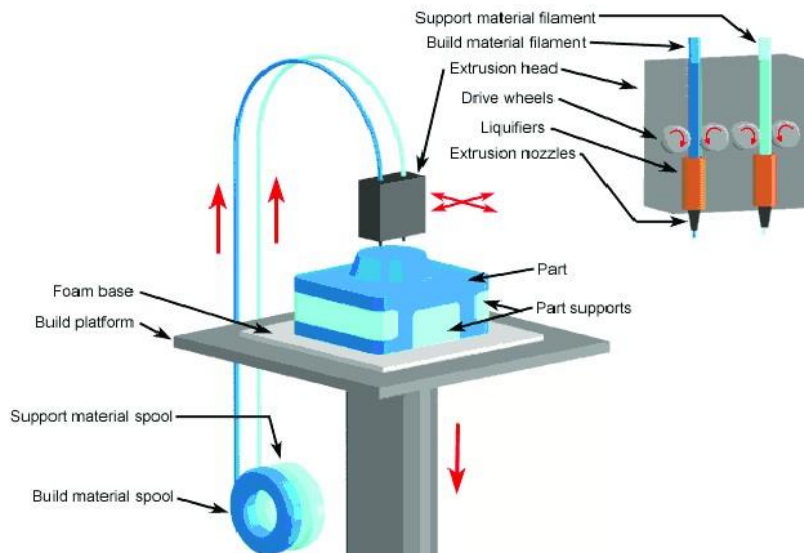
Fig. 1. Schematic representation of the FDM printer [2]

(ii) Powder Bed Fusion (PBF)

Powder Bed Fusion (PBF) is operated by deliberately melting the powder using either an electron beam, laser, or other heating elements. Selective Laser Sintering (SLS), Electron Beam Melting (EBM), and Selective Heat Sintering (SHS) are examples of printing techniques in this process [8]. Polymers, metals, ceramics, composites, and hybrid materials can be prepared using this process. SLS is the prominent printing techniques of this process. The SLS printing technology is developed in 1987 by Carl Deckard. The product in this technique is produced by sintering the powders using a high-power laser. The key advantage of this process is the machine speed, accuracy, and good surface finish [9]. Figure 2 represents the working of the SLS technique.
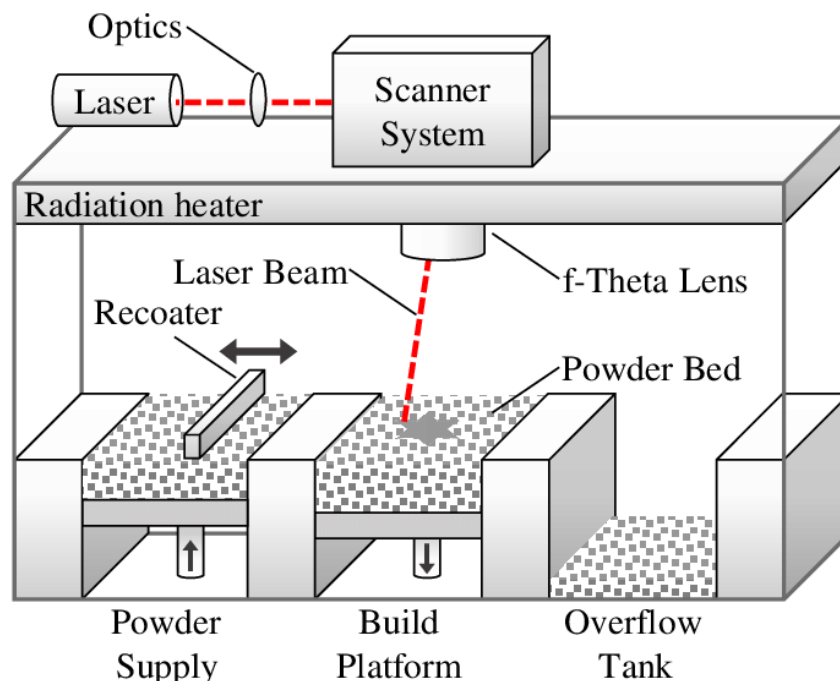

Fig. 2. Schematic diagram of Selective Laser Sintering [3]

(iii) Binder Jetting (BJ)

Binder Jetting (BJ) is an AM technique that distributes powdered material into a layer and selectively joins them using a binder into the desired layer form, usually, they are in the form of polymer liquid. In this process, the layer is formed using a jet chemical binder [2]. A roller is used to spread the powder from the powder supply platform to the fabrication platform, and a recoater is used to spread powder from a top hopper by vibration. Binder jetting can print materials such as polymers, metals, ceramics, sands, and hybrids. 3D printing and inkjet printing are important techniques of this process. The process is simple, fast, cheaper, and able to print using large particles. Figure 3 shows the working of the BJ process.
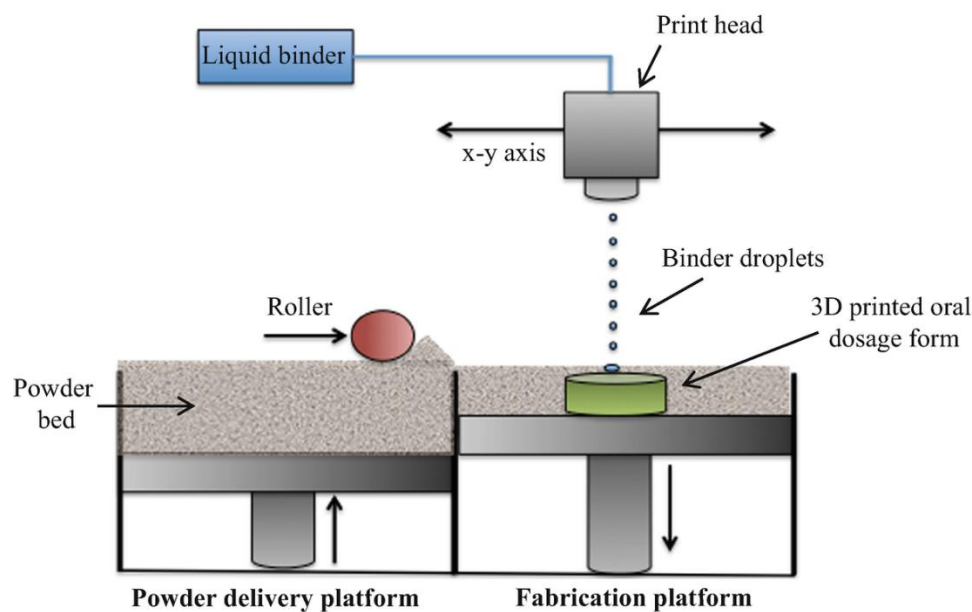

Fig. 3. Working principle of Binder Jetting process [4]

(iv) Material Jetting (MJ)

Material Jetting (MJ) is an AM technique that uses thermoplastics droplets and photopolymers that are selectively deposited with the help of ultraviolet (UV) light [5]. These systems adapt the inkjet-headed and popular polyjet machines [6]. The dispenser drops droplets of the material, which solidifies under UV light [7]. The MJ process produces parts with a high surface finish and high dimensional accuracy. Multi-material printing is also possible using the MJ process [8]. Figure 4 indicates the schematic diagram of the MJ process.
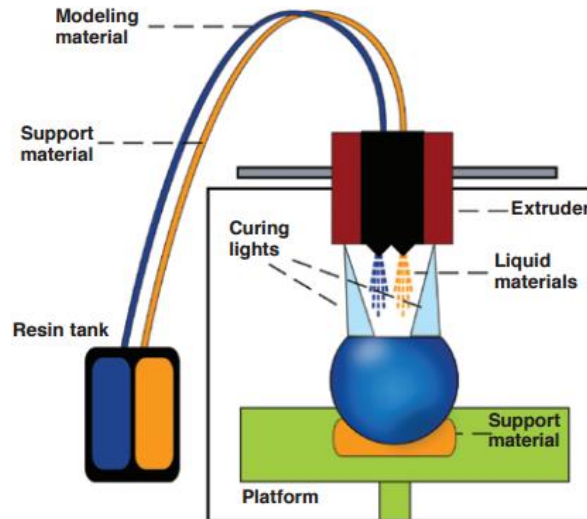
Fig. 4. Schematic diagram of Material Jetting [5]

(v) Sheet Lamination (SL)

Sheet Lamination (SL) is an AM technique that bonds together sheets to form the final product [7]. Ultrasound Additive Manufacturing (UAM) and Laminated Object Manufacturing (LOM) are the prominent methods of this technique. The LOM process can make full-color prints, recycling the excess material, and the process is relatively inexpensive. LOM process can print complex geometry at less operation time, quicker and inexpensive [9]. Figure 5 shows the schematic diagram of the LOM technique.
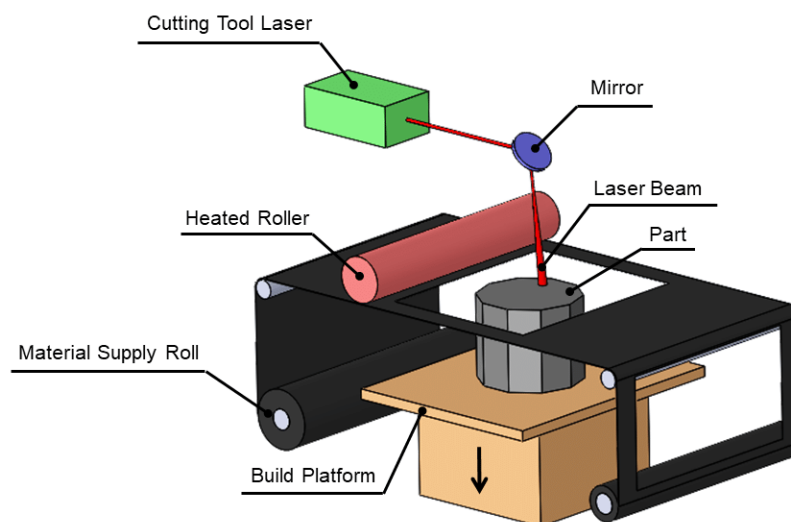

Fig. 5. Laminated Object Manufacturing (LOM) [10]

(vi) VAT Photopolymerization (VP)

VAT Photopolymerization (VP) is an AM process in which photoreactive polymer in a VAT is cured by laser, light, or ultraviolet (UV) polymerization [11]. The prominent examples of this method are Stereolithography (SLA) and Digital Light Processing (DLP) [12]. The photo-initiator and the radiation exposure affect the SLA and DLP process. DLP uses a more convenient source of light, like an arc lamp

with a fluid crystal panel, and it can be used to cure the entire surface of the photopolymer resin vat in a single pass. Also, this process is faster than the SLA technique [13]. VAT Photopolymerization's essential parameters include the exposure period, wavelength, and power source. Photopolymerization effectively produces parts with a high degree of surface quality and build quality [14]. Figure 6 shows the construction and working of the VAT Photopolymerization process.
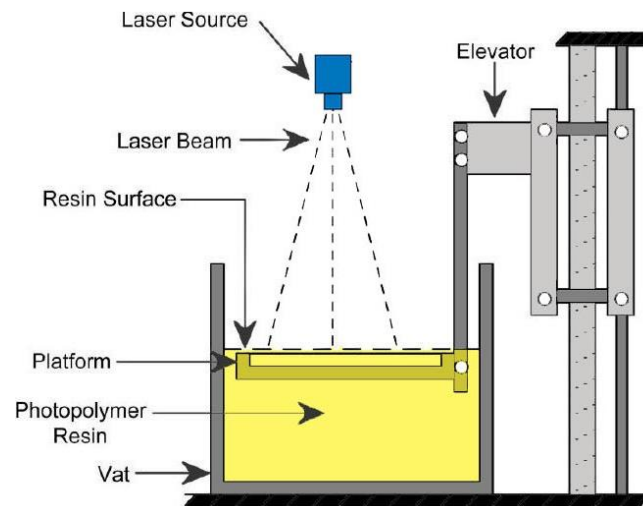

Fig. 6. Vat photopolymerization process [15]

(vii)   Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is a relatively complicated printing method [16]. It has a high degree of grain structure control and can produce good object quality. In theory, the DED method is identical to material extrusion; the key difference is the nozzle which can move in multiple directions and not be fixed to a specific axis. Laser Deposition (LD) and Laser Engineered Net Shaping (LENS) are prominent examples of the DED process. Laser Deposition is the latest technique to produce or repair particles from millimeter to meter. This process can be used with ceramics and polymers but highly preferred for metals and hybrids based on metals of wire or powder [12]. Figure 7 shows the schematic diagram of the LENS process.
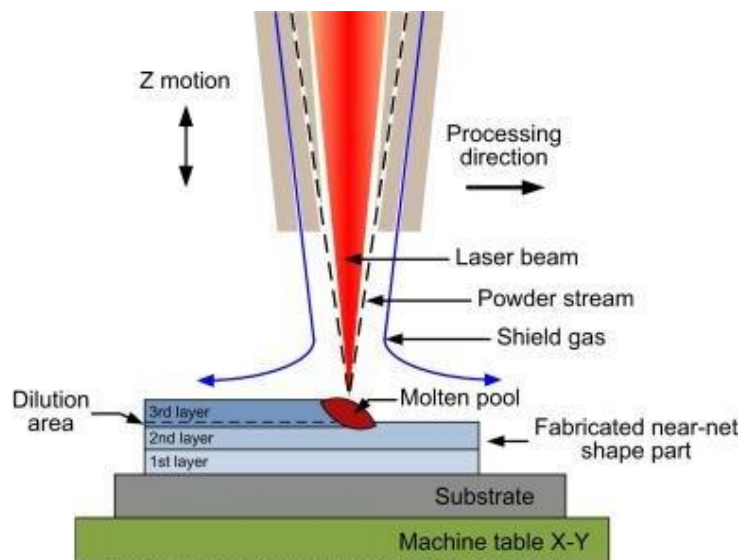

Fig. 7. Laser Engineered Net Shaping (LENS) process [17]

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From the conducted literature studies, every different process reported having its own specification of materials, size, design, and properties. Each approach has merits and demerits by the use of materials, productivity, and cost-effectiveness. The advantages and disadvantages of different AM techniques are shown in Table 1.

Table 1
Advantages and disadvantages of different AM techniques, [18,19]

AM Technique	Advantages	Disadvantages
Material Extrusion (ME)	• Low startup cost • Wide range of raw materials • Adaptable • Can build fully functional parts	• Longer built time with lower precision • Hard to print sharp angles • Vertical anisotropy
Powder Bed Fusion (PBF)	• No support structure is required for polymer powder • Recyclable for both polymer powder and metal • Ability to print a variety of materials with complex geometry • Better resolution and accuracy for metal powder printed part	• Low printing rate • Higher startup cost required (expensive machines) • Limited built part size • Rough surface finish for polymer
Binder Jetting (BJ)	• Wide range of raw materials • Automatically fabricate support structure; thus, no support structured required	• Printed parts are rough surfaces and poor strength • Required post-processing to improve strength & remove moisture
Material Jetting (MJ)	• Produce high resolution and accuracy parts • Variety of colors and materials are possible • No wastage of model material	• Wastage of support materials (not to be recycled) • Post-processing is not suggested for small features to minimizes damage
Sheet Lamination (SL)	• Variety of colors and materials are possible • Higher printing speed • Low internal stress and warping and stress. • No support structured required	• Removal of support structure could be difficult. • Wastage of materials • The heat of the laser might cause warpage of lamination
Vat Photopolymerization (VP)	• Produce good surface finish, high resolution, and accuracy parts. • Wide range of materials • Higher printing speed • Low-imaging specific energy	• Support structure required. • Post-processing and post-curing are required
Direct Energy Deposition (DED)	• Effective for add-on and repair features • Suitable for large metal components • High material utilization • High degree control of grain structures	• Printed parts are poor accuracy and surface finish • Complex geometry is not possible • Many materials are not suitable for this printing process

3. Materials For 3D Printing

In the 3D printing process, a wide range of materials has been developed and shown successful use with this process. These materials have different mechanical and other properties. Researchers are also continuously developing a new class of materials to be used with the 3D printing process.

The common materials used in the 3D printing process are polymers, polymer composites, ceramics, metals, and hybrid composites. Table 2 demonstrates the various materials used for the 3D printing process, method of processing, resolution of various processes, and applications.

Table 2
Materials used for various 3D printing processes [20-22]

Method	Materials	Process	Resolution	Build volume (mm^3)	Applications
ME	• Polymers • Ceramics • Composites	Material is continuously pushed through the nozzle in the filament form	50-200 µm	900 x 600 x 900	Aerospace parts, Prototypes, Jigs & fixtures, Supporting parts, food applications,
PBF	• Polymers • Ceramics • Composites • Metals • Hybrid	The build materials are fused by the thermal energy	80-250 µm	300 x 300 x 350	Prototypes, Small series types, Supporting parts
BJ	• Polymers • Ceramics • Composites • Metals • Hybrid	The component is formed layer after layer as the particles are bonded together	5-200 µm	4000 x 2000 x 1000	Prototypes, Green parts, Casting patterns, Moulds, and cores
MJ	• Polymers • Ceramics • Composites • Hybrid • biologicals	Deposited droplets of building materials	5-200 µm	300 x 200 x 200	Prototypes, casting patterns
SL	• Polymers • Ceramics • Papers • Metals • Hybrid	Sheets of raw materials are bonded	The resolutions vary depending on the thickness of the sheets	250 x 200 x 150	Less detailed parts, rapid tooling patterns
VP	• Polymers • Ceramics, • resins with photo-active monomers	The liquid polymers in a VAT were cured by light	10 µm	2100 x 700 x 800	Rapid tooling patterns, Snap fits, Presentation models, High heat applications
DED	• Metals • Hybrid	Thermal energy concentrates on melting materials during deposition	250 µm	3000 x 3500 x 5000	Rapid tooling, High heat applications, Medical implants, Aerospace parts

3.1 Material Properties and Applications

The material selection for the 3D printing process varies depending on the application and the expected quality of the product. The leading process of this 3D printing is Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS). The various materials used in these processes, their properties, and the applications are shown in Table 3.

Table 3
Materials, benefits, and applications of major processes of 3D printing technique [23]

Process	Material	Properties	Applications
FDM	• ABS • PLA • PC • NYLON • PC-ABS • ULTEM	• strong and tough • Good surface quality and tensile strength • High tensile and flexural strength • High impact and fatigue resistance and good chemical resistance • High impact and heat resistance • High thermal and chemical strength, biocompatible, high strength to weight ratio	• Aerospace, automobile, medical, end-user parts • Printed parts for home and office that environmentally friendly and required aesthetic details • Aerospace and automobile industries, functional prototypes • Prototypes for electrical housings, automotive parts, brackets, and parts for outdoor use • Low volume production parts, industrial equipment, functional prototypes • Aerospace, medical, food contact applications, ECS ducting, metal forming tools, aircraft interior replacement tools
SLA	• Somos® NeXt • SC 1000P • Somos® ProtoGen 18420 • Somos® WaterClear Ultra 10122	• High impact strength and durability, Enormously versatile • Low cost, high accuracy • High accuracy and functional properties • Colorless, easy to finish	• Tough, functional end-use prototypes, jigs & fixtures, food packaging, and sporting goods • Investment casting, lightweight models • Automotive parts, consumer, and electrical products • Automotive lenses, bottles, light pipes
SLS	• Flex TPE • Nylon 12 PA • Nylon 12 GF	• Rapid operating prototypes with elastomeric properties • Good chemical resistance and surface resolution, low moisture absorption, • Good mechanical stiffness, elevated temperature resistance, dimensionally stability	• Compression seals, protective boots, and shields • Impellers, connectors, complex plastic parts, end-use parts • Housing and enclosures, consumer sporting goods, functional prototypes
DMLS	• Stainless steel • Aluminum • Nickel alloy • Titanium	• Good strength and creep resistance, excellent weldability, and corrosion resistance, cost-effective • Low weight, good thermal properties, hardness, and strength. Superb machinability • High corrosion resistance, nigh creep, tensile and rupture strengths • Good mechanical properties, good wear, and carrion resistance	• Aerospace, automotive, and oil & gas industries. Parts requiring high strength and corrosion resistance • Aerospace, automobile. Complex geometries and low-cost prototypes • Turbine engine components, petroleum industries • Aerospace structures and engine components, biomedical implants

4. Parameters of 3D Printing

Process parameter is an important element in the 3D printing process. As to date, several parameters of 3D printing have already been studied for optimum mechanical properties, surface finish, and printing time. Layer thickness, build orientation, raster angle, printing temperature, air gap, and infill pattern has been reported to be the primary parameters that affect the properties of the 3D printed parts. Optimizing these parameters would lead to better properties. Table 4 shows the process parameter optimization of various methods.

- Layer thickness: Is the thickness of the building part for every layer. The less the thickness of the layer, the better accuracy of the part.
- Raster angle: Is the direction of the raster with respect to the loading direction.
- Build orientation: It is known as the orientation of the part over the build plate on the X, Y, and Z-axis.
- Printing temperature: The temperature is classified into two types. (i) Nozzle temperature: It is the temperature of the extrusion nozzle (ii) Bed temperature: It is the temperature of the bed (build plate).
- Air gap: The gap between two rasters is called an air gap.
- Infill pattern: Is the structure or shape of the material inside the part.
- Infill density: Is the amount of material used inside the printed part.
- Raster width: The raster width or road width implies the width of the deposition path related to tip size.

The 3D printing parameters have been investigated by numerous researchers using various types of experimental investigations. The experimental is necessary to understand the effect of printing parameters and optimization required for better materials behavior. From Table 4, it can be seen that quite a number of parameters have been analyzed, and the output of the properties varies depending on the parameters. The present review findings show that the minimum layer thickness has superior mechanical properties and surface finish than the thicker layers. Also, minimizing the layer thickness reduces the air gap, which improves the bonding of the layers and increases the product's strength. The printing speed is also seen to be a critical factor to increase the quality of the product. Slower printing speed ensures the filament extruded from the nozzle is continuous and without breaking. The slower printing speed also produces better surface finish and mechanical properties than the higher printing speed. The nozzle temperatures are suggested to be high during printing for a better mechanical property. The high temperature provides a good bonding between the layers resulting in better properties. Raster angle, infill pattern, and the build orientation are also the critical parameters for optimum properties of the product. The present review has also identified that the flat orientation and 0° raster angle produces a good quality product.

Table 4
Process parameter optimization of various methods

Parameters	Properties	Results	Ref
Printing orientation - vertical and horizontal Layer thickness - 0.1, 0.2, 0.3, 0.4 (mm)	• Resistivity of conductive material • Electron transfer kinetics	Electrodes printed with a layer thickness of 0.1 mm in a vertical orientation achieved the highest conductivity. Increased layer thickness and horizontally oriented printing resulted in more resistive electrodes.	Abdalla *et al.,* [24]
Nozzle temperature - 400, 410, 420, 430, 440 (°C) Platform temperature - 240, 250, 260, 270, 280 (°C) Printing speed - 5, 10, 15, 20, 25 (mm/s) Layer thickness - 0.1, 0.15, 0.2, 0.25 (mm)	• Impact strength • Flexural strength • Tensile strength	Nozzle temperature: tensile and flexural strength showed that increasing temperature is increasing the strength. The impact strength result shows that the strength increases slowly and drops at 410 and continues to increase. Platform temperature: All the strength increases as temperature increases. Printing speed: Increasing the speed of printing has decreased strength. Layer thickness: Increasing the layer thickness has decreased the strength.	Wang *et al.,* [25]
Extruding rate - 27.3, 29.2, 32.3, 35.4, 39.7, 44.1, 50.2, 52.4, 54.7, 60.5 (mm3/s) Printing speed - 18.3, 20.6, 22.4, 25.7, 37.9 (mm/s)	• Food paste properties	The most suitable printing speed and the extruding rate is 22.4mm/s and 39.7mm^3/s. The most not suitable is 21.1mm/s and 20mm^3/s.	Liu and Ciftci [26]
Printing speed - 50, 52, 54, 56, 58, 60 (mm/s)	• Deformation of printed 3D cementitious material	The deformation of the printed filament increases with the decrease of printing speed	Liu *et al.,* [27]
Volume flowrate - 37.9, 45.2, 48.0, 51.3 (ml/s) Printing speed - 200, 180,160, 140, 120, 100, 80, 60 (mm/s)	• Effect of printing parameters in 3D concrete printing	Large filament surface area was found in high flow rate and slow printing speed. It is given better mechanical strength, but poor geometrical resolution and surface finish. Low flow rates and fast printing speed gives large breaks. This break was caused by the disproportionate slow flow rate of the material exiting the nozzle.	Tay *et al.,* [28]
Deposition rate - 1, 88, 175 (mm^3/s) Deposition temperature - 153, 173, 190 (°C) Layer thickness - 0.1, 0.2, 0.3 (mm)	• Young's modulus • Tensile strength • Elongation	Increases in layer thickness led to lower mechanical properties. Temperature increases tended to increase in both mechanical properties. Increases in deposition rate were increasing the mechanical properties.	Carlier *et al.,* [29]
Printing speed - 25, 50 (mm/min) Layer thickness - 0.1, 0.2 (mm)	• Stereolithography parameters optimization • Mechanical properties of flexural strength and hardness	For flexural strength, layer height0.1 mm is higher than the 0.2 mm, and for up speed, the slower 25mm/min also has higher flexural strength than 50 mm/min. For hardness, 0.2mm layer height has a better result than the 0.1mm, while the up-speed result is 25 mm/min is higher than 50mm/min.	Munprom and Limtasiri [30]

5. Future Perspective

3D printing has benefits such as the ability to print complicated structures and relatively quicker than the conventional methodologies. The productivity of this technology has also been proven effective in various sectors such as aerospace, automobile, electronics, medical, food packaging, construction, and home appliances. However, to further cater to the demand for specific and customized parts, 3D printing technology is enthused to another level known as 4D printing. 4D printing uses shape memory polymers for more specific applications.

Also, several disadvantages need serious attention for better technological development. The drawbacks are anisotropic mechanical properties, limited applications due to limited materials, and high-cost limited applications in large structures. Material and methodology study and development have helped to avoid some of these difficulties. But few problems remain to be tackled to extend additive manufacturing (AM) to a broader variety of applications and industries. The 3D printing process takes more time to produce the part compared with conventional machining and injection molding processes. Compared with FDM and Inkjet printing process, the PBF and SLA processes are more time-consuming. The time consumption and the cost will restrict the mass usage of the 3D printing process.

The void formation between the consequent layers is also a significant challenge in this 3D printing process. The porosity created between the layers will reduce the mechanical strength of the product. Anisotropic mechanical properties even the major problem in the AM process. The microstructure of the inner layers is different compared with the outer layers. The insufficient parameters of the process are the main reason for these problems. As such, the future perspective should be mainly focused on optimizing the parameters of the AM process.

6. Conclusions

Over the last few years, 3D printing technology has emerged as a versatile and efficient technique for advanced manufacturing. This technology has been widely used in many sectors, particularly in the manufacturing sector. Liberty in design, the ability to print complex structures, and minimize wastage are the important benefits of the 3D printing process. This review contains various techniques in the 3D printing process. The various materials used and the properties and the applications in various sectors and parameters to optimize the better mechanical properties were discussed. From the studies compared with the Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) process, the mechanical properties of the Fused Deposition Modeling (FDM) are comparatively low. Still, this process is cost-efficient, easy to use, and high-speed processing. Layer thickness, raster angle, and build orientation are the crucial parameters in the 3D printing process. Optimizing the processing parameters will be helpful for optimum utilization in various sectors such as aerospace, medical, electronics, and others.

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