A REVIEW ON EFFECT OF PROCESS PARAMETERS ON FDM-BASED 3D PRINTED PLA MATERIALS

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ABSTRACT

3D printing is an advanced technique of creating three-dimensional solid objects from a digital 3D model. Additive manufacturing processes are adaptive techniques that can be applied to polymers, metals, ceramics, and other materials. The objective of this paper is to review the research which is available on various process parameter which affects the mechanical and surface properties of 3D printed PLA models. The proper selection of printing parameters is critical to identify for producing high-quality 3D printed objects. Many input parameters like Infill percentage, layer thickness, building orientation, raster direction angle, infill pattern, air gaps, extrusion temperature, and many more in the structure of FDM printed objects can be modified during the processes. However, to generate high-quality products, the manufacturing must carefully evaluate the printing parameters for each piece. The study showed that Young's modulus and surface roughness of the printed parts increases with the increase in infill density for the rectilinear and Hilbert curve but decrease for line pattern.

Keywords: Additive Manufacturing; Fused Deposition Modeling (FDM); Polylactic Acid (PLA); Tensile Modulus; Surface Roughness.

I. INTRODUCTION

Over the last few years, 3D printing technology has advanced dramatically. It allows users to manufacture real objects from a virtual computer model, opening up almost limitless range of possibilities. 3D printing is an additive manufacturing technology that allows users to produce a real product directly from a 3D computer model by layering materials. Hideo Kodama of the Nayoga Municipal Industrial Research Institute is often credited with being the first person to print solid items from a digital design. However, Charles Hull is commonly credited with inventing the first 3D printer. Charles H. was a pioneer of the stereolithography solid imaging method and the STL file format, which is now the most extensively used format in 3D printing [1, 2]. Users can make complicated shapes that would otherwise be impossible to achieve by shaping and molding [3]. Prototypes, small series, and one-of-a-kind products for the market are best created with 3D printing. Traditional subtractive procedures, such as CNC milling, in which material is removed from the product; formative method (casting or forging), in which a mould is required; and joining processes, such as welding and bonding, are the polar opposite of such technology resulting in more cost-effective models [4]. Additive manufacturing, which is linked to the fourth industrial revolution (Industry 4.0) is emerging as a very promising global manufacturing technology because it allows for “mass customization” rather than “mass production”. 3D printing is projected to play a significant role in the production of high performance structures [5, 6].

Fig 1: 3D printer
II. MAIN METHOD

Additive manufacturing (AM) technologies that are available commercially i.e., selective laser melting (SLM), binder jetting (BJ), selective laser sintering (SLS), laminated object technology (LOM), fused-deposition modelling (FDM), and stereolithography (SLA), FDM is the most widely used and cost-effective method for producing 3D models and prototypes [7]. Fused deposition modelling is an AM that uses extrusion to drive material through a nozzle selectively [8]. The procedure begins with a 3D digital design, which may be created using any CAD software. This 3D geometry is converted into G-code movement commands. The machine control electronic are compatible with the commands. A thermoplastic filament is put onto the printing surface using an extruder. A tangible 3D item is created by stacking two-dimensional layers on the top of the each other [9].

**Fused deposition modelling (FDM)**

A continuous filament of a thermoplastic polymer is utilized in the FDM method to 3D print layers of materials. The filament is heated to a semi-liquid condition at the nozzle before extruded onto the platform or on the top of previously printed layers. This process relies on the thermoplasticity of the polymer filament, which allows the filaments to fuse together during printing and then harden at room temperature thereafter. The primary processing parameters that affect the mechanical qualities of printed objects are layer thickness, width and orientation of filaments, and air gap (in the same layer or across layer) [11]. The main cause of mechanical weakness was discovered to be inter-layer distortion [12]. The key advantage of FDM are its low cost, high speed, and ease of use.

![Fused deposition modelling](image)

**Fig 2**: Fused deposition modelling (courtesy of [10])

**Stereolithography (SLA)**

SLA is one of the first additive manufacturing processes, have been created in 1986 [13]. It starts a chain reaction on a layer of resin or monomer solution using UV light (or an electron beam). UV-active monomers transform to polymer chains almost instantaneously after activation. After polymerization, a design is cemented inside the resin layer to hold the subsequent layers in the place. After the printing is finished, the unreacted resin is removed. Some printed items may require a post-process treatment such as heating or photo-curing to get the desired mechanical performance. SLA produces high-quality products with a precise resolution of 10 micrometers or less [14].
Laminated object manufacturing (LOM)

Laminated objects manufacturing (LOM) is a layer-by-layer cutting and lamination of sheets or shell or rolls of materials that is one of the first commercially available additive manufacturing technologies. Using a mechanical cutter or a laser, successive layers are cut accurately and then joined together or vice-versa. The form-then-bond process is very beneficial for the thermal bonding of ceramics and metallic material, and it also helps with internal feature development by reducing surplus materials before bonding.

After cutting, the extra materials are left for support and can be removed and recycled once the operation is completed [15]. LOM is suitable for a wide range of materials including polymer composites, ceramics, paper and metal filled tapes. Depending on the type of material and desired qualities, post-processing such as high temperature treatment may be required.

Inkjet printing and contour crafting

One of the most common ways for additively manufacturing ceramics is inkjet printing. It’s utilized to print intricate and advanced ceramic structures for things like tissue engineering scaffolds. In this approach, a stable ceramic suspension, such as zirconium oxide powder in water is pumped and deposited as droplets onto the substrate via the injection nozzle [16]. The droplets then solidify into a continuous pattern that is strong enough to hold future layers of printed materials. This process is quick and efficient, giving you more option
when it comes to designing and printing complicated structures. Wax-based inks and liquid suspensions are the two primary types of ceramic inks. To solidify wax-based inks, they are melted and applied on a cold substrate. Liquid suspension, on the other hand, are cemented by liquid evaporation. The quality of inkjet printed parts is determined by characteristics such as ceramic particle size distribution, ink viscosity, and solid content, as well as rate, nozzle size, and printing speed [17].

**Fig 5:** Inkjet printing and contour crafting (courtesy of [14])

### III. 3D PRINTER MATERIALS

Filament produced from petroleum-based thermoplastics are used in less priced 3D printed. However, because the majority of these thermoplastics are synthetic, they pose a risk of introducing dangerous compounds into the environment and individual. 3D printing could extend into the domain of manufacturing unique end products or small quantities of customized product with the development of new materials and cheaper pricing for 3D technology. 3D printer filaments are often constructed of petroleum thermoplastics like Acrylonitrile Butadiene Styrene (ABS), Polyethylene terephthalate-glycol (PETG), Polyether ether ketone (PEEK), Polyamide (PA), Polycarbonate (PC), and polyacetal (POM), as well as bioplastic like PLA (Polylactic Acid) [1]. For fused deposition modelling (FDM) printer, PLA is one of the most used printing substrates. It’s a compostable bioplastic created from renewable material like corn, beets, and potatoes that can be composited in commercial compositing facilities. PLA is a more environmentally friendly polymer than petroleum-based plastics like ABS, polyethylene, and polypropylene [18, 19]. The structure of PLA is much harder than the one of ABS. It melts at lower temperature than ABS, at 180-220°C [20]. PLA, a leading candidate, is a high-strength, high-modulus polymer that may be manufactured from annually renewable resources to yield a variety of components for application in industrial packaging or biocompatible/bioabsorbable medical devices. It may be easily processed into moulded pieces, film, or fibers using ordinary plastics equipment [21, 22]. Metal and its alloy, ceramic and concrete also used in different industries.

<table>
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<tr>
<th>Material</th>
<th>Main application</th>
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<td>Polymers and composites</td>
<td>Aerospace, Automotive, Sports, Medical, Architecture, Toys, Biomedical</td>
<td>Fast prototyping, Cost-effective, Complex structure, Mass-customisation</td>
<td>Weak mechanical properties, Limited selection of polymers and reinforcements, Anisotropic mechanical properties</td>
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<tr>
<td>Metals and</td>
<td>Aerospace and</td>
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**Table 1.** The Comparison Of Different Materials For 3d Printing.
3D printing is a common method of creating three-dimensional solid objects from a digital 3D model. The proper selection of printing parameters is critical for producing high-quality 3D printed objects. Using the majority of commercially available, low-cost 3D printer, 3D printed goods can usually deliver smooth surface with accurate proportions. Many parameters in the structure of FDM printed objects can be modified during the process. Since then, the impact of process settings on mechanical (such as tensile, compressive, bending, flexural impact, and fatigue) and surface properties has been extensively studied for various production scenarios. Infill percentage, layer thickness, building orientation, raster direction angle, raster pattern, air gaps, number of perimeters (contour width), extrusion temperature, deposition speed as well as color of PLA were are among the most reviewed 3D printing process parameters in the literature. However, in order to generate high quality products, the manufacturing must carefully evaluate the printing parameters for each piece. In this context, the purpose of this paper is to review the research that are now available on various process parameter that effect the mechanical and surface properties of 3D printed PLA material.

### Mechanical Properties

The impact of process parameters on the mechanical characteristics of printed objects was explored experimentally by Alafaghani et al. [23] under various processing settings, including infill pattern, printing speed, infill %, build direction, layer thickness, and set nozzle temperature. The infill pattern, infill density, and printing speed had only a little impact on the tensile characteristics, according to the researchers. Goyanes et al. [24] argued that the quality of manufactured parts is affected by the nozzle travelling speed and printing speed of a 3D printing process. Harpool [25] investigated the strength of PLA pieces using rectilinear, diamond, diamond, honeycomb or hexagonal design had the strongest strength, while the solid pattern had the weakest strength at 100% infill density, resulting in products that behaved like brittle material. The findings revealed that the infill pattern has a significant impact on the mechanical qualities of printed items. The effect of the set nozzle temperature on the mechanical properties of 3D printed objects were investigated by Benzadnasab and Yousefi [26]. They discovered that increasing the set nozzle temperature to certain temperature enhance the robustness of a PLA 3D printed item. Higher set nozzle temperatures, which is the standard upper bound of set temperature limits in 3D printing of polymeric material, induced polymer deterioration.
Furthermore, the printing speed has a clear impact on the mechanical qualities of printed objects. Dave et al. [27] investigate the impact of infill pattern and infill density on the tensile strength of PLA pieces. For the experimental settings studied, they discovered that the concentric pattern had the highest tensile strength.

![Infill pattern at varying densities](image1)

**Fig 6:** Infill pattern at varying densities [28]

Sood et al. [12] Layer thickness, orientation, raster angle, raster width, and air gap are all crucial process characteristics to consider. The compressive strength of FDM-processed Polylactic acid (PLA) parts for various infill design patterns is examined by Pushpendra et al. [29]. For six infill designs: Hilbert curve, honey-comb, line, rectilinear, Archimedean curve, and octagram spiral, compressive strength was investigated for densities ranging from 20 to 80 percent in steps of 20. The Hilbert curve design has a maximum compressive strength of 121.35 MPa, which is much greater than other designs like rectilinear (78.88 MPa), line (73.84 MPa), honey-comb (62.56 MPa), Archimedean (70.07 MPa), and octagram spiral (70.07 MPa) (60.01 MPa). Compressive strength increases as infill density increases for all of the infill design patterns assessed.

![Compressive strength](image2)

**Fig 7:** Peak stress for different combination of infill design patterns and density [29].
The Young's modulus of printed components increased as the infill density increased, according to Abeykoon et al. [32]. In pure PLA, parts with 100 percent infill density exhibited the highest Young's modulus of 1538.05 MPa. Infill speeds of 70 to 110 mm/s were tested, with the 90 mm/s speed producing the greatest Young's modulus for pure PLA. Meanwhile, as compared to the typically used infill speed of 90 mm/s, there was a minor change in Young's modulus between low speeds (70 mm/s and 80 mm/s) and high rates (100 mm/s and 110 mm/s). The DSC results revealed that the level of crystallinity of the 3D printed PLA specimen had no direct effect on the mechanical characteristics. The strength of the printed sample was found to be dependent on the layer arrangement in SEM pictures. Furthermore, it was discovered that for pure PLA filaments, the best processing temperature and infill speed are 215°C and 90 mm/s, respectively. Carbon fiber reinforced PLA (CFR-PLA) has the highest Young's modulus of the five printing materials evaluated, measuring 2637.29 MPa at 90 mm/s. Overall, the ideal process setting for the most materials employed in this investigation were 100% infill density, linear fill pattern, 90 mm/s infill speed, and 215°C set nozzle temperature.

**Effect of infill density on tensile properties**

The density of the infill material has a direct impact on the strength of 3D printed items. According to the data in the research report, increasing the infill density can enhance the tensile modulus, as demonstrated in Fig. 9. The tensile modulus of the specimen with a 100% infill density is around two times that of the specimen with a 25% infill density. In addition, the amount of material consumed has increased. Although, for mass scale manufacturing lines to optimize resources, determining the needed infill density based on the type and application of the product is critical.

**Fig 8:** Peak load values for different combination of infill design patterns and density [29].

**Fig 9:** Relational between the tensile modulus and infill density for pure PLA [30].
Effect of infill speed on tensile properties

Another crucial component that might affect mechanical characteristics is infill speed (also known as print speed). Figure 10 shows how Young's modulus fluctuates with different infill speeds (70-100 mm/s). Because polymers are poor thermal conductors, fast infill speeds are likely to influence filament melting, resulting in poor adhesion between neighboring layers and particles, and hence a reduced strength.

![Graph showing the relationship between tensile modulus and infill speed for pure PLA.](image)

**Fig 10:** Relationship between the tensile modulus and infill speed for pure PLA [30].

Effect of printing temperature on tensile properties

PLA specimens were printed at various set nozzle temperatures to assess the effects of the set nozzle temperature on the mechanical qualities of 3D printed items. Figure 11 shows the tensile modulus of these specimens. The findings show that printing temperature has a considerable impact on the tensile modulus but only a minor impact on the printed part's mass. Furthermore, if the set temperature is too high (i.e., less viscous melt), an overflow of materials is conceivable, making it difficult to maintain the part's dimensional stability. As a result, printing speed and set nozzle temperature are linked and should be carefully chosen based on the material and component geometry to be printed.

![Graph showing the variation of the tensile modulus of pure PLA parts printed at different set nozzle temperatures.](image)

**Fig 11:** Variation of the tensile modulus of pure PLA parts printed at different set nozzle temperatures [30].

Effect of infill pattern on tensile properties

PLA specimens were printed with various infill patterns (linear, hexagonal, Moroccanstar, catfill, sharkfill, diamond, and Hilbert) at various printing speeds, infill densities, and nozzle temperatures. The linear pattern has the highest tensile modulus of all the infill designs as shown in fig. 12. This is understandable because the linear design should have the best layer arrangement (in terms of layer bonding) and the least porous structure.
Surface Roughness Profile

Researchers have recently begun to explore the surface roughness of 3D printed parts using post-processing techniques. With the widespread usage of 3D printing in a multitude areas, issues related to additive manufacturing have been found and addressed. Jess et al. [31] sought to identify the discrimination thresholds equivalent to change in printed parameter. It established that even small changes in printing will produce detectable difference in surface roughness. It was investigated that human examination can reliably sense difference between various sample even if their Ra and Rq value are equivalent. Anitha et al. [34] investigated the impact of various set factors on surface roughness. For attaining acceptable surface roughness qualities, the best practicable values for layer thickness, road width (i.e., the width of each layer of deposited material), and deposition speed were 0.3556mm, 0.537mm, and 200mm/s, respectively. Hanon et al. [33] The effect of print orientation and color is evaluated by manufacturing samples in various orientations (horizontal, 45 angle, and vertical) and filament color (white, black, and grey). Surface roughness and product hardness are also taken into consideration because they are essential factors in understanding tribological behavior. The results show that tribological behavior varies depending to the various print orientations and filament colors. The surface roughness of rectilinear and Hilbert curve increases with increase in infill densities, whereas for line patterns, it decreases [30]. With increasing printing layer thickness, the specimen’s surface roughness rose dramatically. The surface roughness parameters that were parallel and perpendicular to the printing direction (longitudinal direction of the specimen). The specimens generated with a printing layer thickness of 0.05mm had the lowest average roughness (Ra) of 2.92, while the specimen created with the a printing layer thickness of 3.0mm had the greatest average roughness (Ra) of 7.86. Similarly, the maximum peak-to-valley height (Ry) and mean peak-to-valley height (Rz) value had similar findings. The finding revealed that the direction of printing had a considerable impact on the roughness of the specimens [34].

Morphological observation of 3D printed parted parts

Effect of Infill density

A secondary electron signal SEM was used to examine the fracture surfaces of a broken PLA specimen, and some of images produced are shown in fig. 13. As can be seen, the air gaps in the 25% infill density sample are bigger than those in the 100% infill density sample. In addition, the spaces between layers are not all same size. The porosity of a sample with 100% infill density to see with the naked eye. The white colored margins in the fracture surfaces are caused by the samples deforming during testing. PLA is a polymer that is semi-crystalline in nature. When semicrystalline polymers are stretched, the amorphous section of the polymer can align in the direction of the strain axis by increasing the opaqueness [30].
Fig 13: The normal and SEM images of the fracture surfaces of PLA sample: (a) 25% infill density, and (b) 100% infill density [30].

Effect of Infill speed

SEM images at 57x and 250x magnification are shown in fig. 14. In terms of layer arrangement orderliness, it can be shown that the 90mm/s infill speed has the best orderliness. Also, at 70mm/s, the layer arrangement is better than at 110mm/s. At 110mm/s, the layer arrangement may have been improved if the set nozzle temperature was matched to the printing speed, allowing proper filament melting and hence improved adhesion between nearby particles and layers [30].

Fig 14: SEM image of the specimens printed at different infill speeds: Top-Left: 70 mm/s (57X), Top-Right: 70 mm/s (250X), Middle-Left: 90 mm/s (57X), Middle Right: 90 mm/s (250X) Bottom-Left: 110 mm/s (57X), BottomRight: 110 mm/s (250X) [30].

V. CONCLUSION

To gain a better understanding of the impacts of infill density, infill pattern, infill speed, print orientation, set nozzle temperature, layer thickness, and air gap (i.e., essential process parameters) on the mechanical and physical attributes of 3D printed structures, a comprehensive study was conducted. The following are some of the most important findings/observations:
1. The parts printed with 100% infill density had the highest Young's modulus, as expected. As the infill density falls, so does the strength of the printed parts.

2. Surface smoothness of the samples significantly improved for Hilbert curve and rectilinear pattern.

3. The linear pattern has the highest tensile modulus of the seven infill designs evaluated (diamond, moroccanstar, sharkfill, catfill, hexagonal, and Hilbert), presumably because of the narrower intervals between individual layers than other pattern.

4. The layer thickness and printing direction had a direct impact on the surface roughness. The surface roughness of the specimen increased with increasing printing layer thickness.

5. Overall, it’s clear that the printing parameters you choose can have a big impact on the mechanical qualities of your 3D printed objects. To ensure correct melting of filaments and regulate the material solidification process, the printing speed and specified nozzle temperature should be matched, it can be asserted.

VI. REFERENCES


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