Recent Progress of Fused Deposition Modeling (FDM) 3D Printing: Constructions, Parameters and Processings

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Abstract. Fused Deposition Modeling (FDM) is the most widely used 3D printing technique. The use and development of FDM cover various fields such as automotive, airplane, to biomedical. Many studies have been conducted to study the effect of various printing parameters and post-processing treatment on the performance of printing results with FDM. This literature study aims to compile and summarize the latest studies related to the effect of FDM process parameters and post-processing treatment as well as prospects and challenges. The review found that the combination of several synchronized parameter processes can produce parts that are printed better because several parameters are interconnected and can complement each other. In addition, the quality of FDM printing results is generally found to be better with post-processing treatment although it requires more effort that might not always be feasible for some applications.

Keywords: Fused deposition modeling (FDM), 3D printing, printing parameters, post-processing

1. Introduction

3D printing is a process with an Additive Manufacture (AM) technique to create or fabricate an object with complex shapes from three-dimensional (3D) data [1]. This 3D printing technology has a high potential to reduce the time and cost of making a product [2]. There are several techniques in 3D printing, including stereolithography (SLA), selective laser sintering (SLS), 3D plotting, fused deposition modelling (FDM), also known as fused filament fabrication (FFF), polyjet modelling, etc. [3]. Among these techniques, the most widely used is FDM [2,4,5]. The technology is widely used because it is easy to use, can create complex geometries and low operating costs [4].

The working principle of this FDM is mainly based on the filament extrusion concept that fed the melted plastic filament through the extrusion nozzle by a knurled feeder. This melted filament heated at the nozzle and will melt at a specified temperature and then come out in the form of small beads. The filament melted simultaneously and moved at horizontal and vertical directions to produce layer-by-layer deposition [6]. FDM has been used and developed rapidly in various fields or segments ranging from automotive, aircraft to biomedical. Applications in the automotive and aircraft segment such as fiber-reinforced composite structural components [7-9], degradable biocomposite structure [10], unmanned aerial vehicle [11-13], rapid tooling [14-16], and prototype for mechatronic control unit [17], [18]. In the electronic segment, such as electrically conductive structure [19-23], and smart interphase [24]. In pharmaceutical segment such as patient-tailored/personalized tablets [25-27], and thermolabile drug [28]. The last one is medical and density segment such as nasal prosthesis [29], biomedical
implantable devices [30-32], lumbar cage [33], scaffold for tissue engineering [34-36], and biosensor [37,38].

The material used in FDM is a thermoplastic polymer material. The thermoplasticity of the polymer material used as a filament is very important because it allows the filament to fuse during printing and then solidify at room temperature after printing. Among the thermoplastic materials, the most commonly used in FDM is poly(lactic acid) (PLA) and acrylonitrile butadiene styrene (ABS). PLA has the advantage of being more environmentally friendly because it is biodegradable, and has mechanical properties that are suitable for aerospace, automotive and biomedical applications [39], but are still not good enough in other applications [40]. ABS has better mechanical properties than PLA but is less environmentally friendly because it emits an unpleasant odor when processing [40]. There are other types of materials as well such as thermoplastic polyurethane (TPU), polyethylene terephthalate (PET), nylon, etc. where each has its unique characteristics that will suit different application requirement. Although material types play a significant role in determining the main characteristics of printing results, in most cases, the quality of the printing results, especially the mechanical properties, is mainly influenced by the process parameter settings in FDM. The primary process parameters in the FDM are orientation angle, layer thickness, infill percentage, fill angle, printing speed or feed rate, shell thickness, raster gap, road width, and printing nozzle temperature [39,41]. Different printing processes allow different printing results, especially in terms of mechanical properties. The mechanical properties of the material are closely related to the bonding of each layer of printing results. The bonding of each layer is influenced by several factors such as the temperature and surface area of each layer's bonding. This is the basis that process parameters can affect printing results. The characteristics and / or geometry of the material used will determine how the process parameters affect the printing results. Therefore the same printing parameters will produce different results when implemented in different materials and or geometry. In addition, the provision of post-processing is also used to obtain more optimal printing results. Although the FDM method is widely used because of its several advantages, there are some significant weaknesses also from the FDM method which is still a concern today. These weaknesses include weak mechanical properties, layer-by-layer appearance, poor surface quality and a limited number of thermoplastic materials. This is undoubtedly a challenge to conduct research and development in order to overcome these problems.

This paper aims to summarize the progress of development in FDM which includes setting printing parameters and post-processing. The review is done by mapping each effect of printing parameters on the printing results. In addition, an explanation of the provision of post-processing that is commonly used in printing results is also included. The paper will also present the summarize of future challenges and potential improvements. An understanding of this will be useful for the selection of appropriate printing parameters and the future development of FDM.

2. FDM 3D Printer Construction

FDM 3D printer has the main parts, namely build platform, liquefier head, extrusion nozzle, heating element, drive wheel, and build spool material. The build platform functions as a surface for the object to be printed which is also heated to a certain temperature so that the material can stick. Liquefier head is used as a place for extrusion nozzle and a heating element that moves in X, Y, and Z direction. Extrusion nozzle is used to extrude filament into a layer by layer deposition. The nozzle diameter size is usually in between 0.1 to 0.4 mm and the maximum operating temperature ranges from 250 to 500 °C [3]. The filament extruded by the extrusion nozzle is usually has a diameter of 1.75 to 3 mm and previously heated by a heating element. To push the rolled filament into the heating element and the extrusion nozzle, the extruding drive wheel is used. In general, the selection of the filament diameter does not directly affect the printing quality, however selecting a larger diameter with using of the same nozzle size will cause pressure at the end of the filament to be greater, which will then affecting the speed of extrusion [3].


3. Printing Parameters

3.1. Description

Printing parameters are things that are set to determine the process of printing. The setting of each printing parameter has various effects on the printing results. Setting each printing parameter can give advantages in one aspect, but on the other hand, it can also cause disadvantages in other aspects. Therefore many studies have been conducted to find out how to set the best printing parameters so that it gets the most optimal results. Besides, combining the settings of several printing parameters can also be done to cover up the losses incurred. The various process parameters and their descriptions are shown in Table 1.

Table 1. Various Process Parameters and Their Descriptions [5].

| Process Parameters          | Description                                                                                                                                 |
|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Build Orientation           | Position the printout on the build platform in the direction of X, Y, or Z on the FDM machine and the angle at which the object will be printed.  |
| Layer Thickness             | The thickness of the layer after extrusion from the nozzle measured vertically. This Thickness Layer depends on the diameter of the nozzle and the type of material used. |
| Raster Angle/Raster Orientation | Is the angle of the extruded material measured in the X-direction. Usually, the variation of the raster angle is between 0° to 90°. |
| Air Gap                     | The distance between two rasters on one layer of the printed part.                                                                                                                                    |
| Extrusion temperature       | The heating temperature of the filament material in the nozzle before it is extruded. Extrusion temperature depends on the print speed and the type of thermoplastic material used. |
| Print speed                 | Represents the speed of the nozzle tip in the X and Y directions during the printing process.                                                                                                         |
Infill density/interior Infill percentage

The solidity or density of the internal structure of the printed part.

Infill pattern

The form or pattern of internal structures in the printed part. Commonly used patterns are diamond, cross, honeycomb, and linear. The honeycomb pattern infill has the greatest mechanical strength than other infill patterns.

Nozzle diameter

Nozzle tip diameter of the extruder

Raster width

The width of the raster

| (a) | (b) | (c) |
|-----|-----|-----|
| triangular infill pattern | rectangular infill pattern | honeycomb infill pattern |

Figure 2. (a) triangular infill pattern, (b) rectangular infill pattern, (c) honeycomb infill pattern [5].

| (a) | (b) |
|-----|-----|
| layer thickness | build orientation |

Figure 3. (a) layer thickness, (b) build orientation, (c) FDM toolpath parameter [5,42].

3.2. Effect of the parameters in recent studies

3.2.1. Layer thickness. Layer thickness has a considerable influence on the printing results. Ayrilmis et al. 2019 have studied the effect of thickness layer on composite wood / PLA material on water absorption and mechanical properties [43,44]. The results have shown that as layer thickness increases...
the water absorption also increases significantly. This can explain that the porosity of the printed material increases with increasing layer thickness shown by more water absorbed. The gaps that form on printed objects increase when the layer thickness also increases. The gap can be filled with water when immersed in a certain period of time. The decreasing quality of mechanical properties in the form of bending strength and tensile strength is also shown with increasing layer thickness [45]. Similar results have also been shown in studies Wang et al. [46] using PLA. The greater the layer thickness, the higher the distance between the nozzle and the printed part so that the pressure between the two becomes smaller. This is what causes the reduction in mass and increased air gap so that the quality of the mechanical properties of the printed part will decrease. Small layer thickness allows the strength of bonding between layers to be stronger.

![Image of printed objects with gaps]

**Figure 4.** Printing layer thickness (a) 0.3 mm, (b) 0.2 mm, (c) 0.1 mm [43].

Layer thickness and greater printing speed also make product surface quality worse [47]. However, when using a small layer thickness to get optimal results requires longer processing time. Therefore we need supporting parameters so that optimal results can be obtained with a relatively short time.

### 3.2.2. Print speed.

This print speed is closely related to the extrusion speed / mass flow rate. Therefore the two parameters must be adjusted in order to get optimal results. The results of the analysis Hou et al. 2018 using PLA in his study showed that the effect of print speed was not significant, while the effect of extrusion speed was significant on the results of the tensile strength test [48,49]. So, a high print speed can be used to minimize processing time. Maximum UTS values are obtained at 140% extrusion speed or maximum extrusion speed from the variations tested. However, the addition of extrusion speed from 120% to 140% did not show a significant increase in UTS. Therefore, by considering the economic aspect, the selection of 120% extrusion speed is the ideal solution. Based on the Signal-to-Noise Ratio (SNR) analysis in the study, the print speed of 80 mm/s has the largest SNR value, which means that the print speed of 80 mm/s is the most stable. On the other hand, Geng et al. [4] have researched different materials namely polyether-ether-ketone (PEEK) about the effect of extrusion speed and printing speed on the dimensional stability of the extruded material. The same results are shown in this study that print speed that is not synchronized with the extrusion speed will result in an unstable dimension. The optimization of this parameter is linear with the layer thickness parameter because the solution of this parameter can minimize the problem of processing time at the layer thickness parameter.

### 3.2.3. Extrusion temperature.

Extrusion temperature significantly influences the flowing behavior and compaction process [9,50]. This will also affect rasters bonding, surface quality [51], and layers bonding [52] thus affecting the tensile strength [53]. Magri et al. 2019 in his research, revealed that with the optimal material Poly-(phenylene sulfide) (PPS) the maximum tensile strength could be obtained at the temperatures of 340°C [51]. The increase in tensile strength to its maximum point is due to the stronger bond between the rasters. However, the tensile strength and crystallinity then decrease when the temperature is raised to 350°C. That is due to collapse bonds between molecules due to temperatures
that are too high. Besides, at these temperatures, components tend to have more porosity and poor surface quality. These results can illustrate that tensile strength tends to follow the level of crystallinity. Temperature extrusion settings are very dependent on the type of material used. Therefore further research on variations in the materials used is required.

3.2.4. Raster Angle. Lorenzo et al. have studied the effect of the raster angle seen from the properties of the fracture with polypropylene material. To get the best geometry, raster angle adjustment can be done in two ways for each layer. If the direction of the load on the application of the printed component is known, then it is recommended to use the orientation of 0°, because that orientation is one of the best fracture properties. However, if the direction of loading in the component application is unknown, it is recommended to use the orientation of 0° / 45° / 90° / -45°, because it is showing the best properties in any orientation. In other studies using ABS material, the raster angle has no effect on increasing tensile strength but has an effect on increasing the charpy impact strength [6].

3.2.5. Nozzle Diameter. The use of the nozzle diameter depends on two main factors, namely, temperature and volume feed rate [54]. Nabipour and Akhoundi [55], have researched the effect of parameters on FDM, one of which is the diameter nozzle. The results show that the smallest diameter variation of the nozzle produces the most optimal tensile strength. This diameter nozzle parameter will have more effect if synchronized with other parameters such as layer thickness, raster angle and nozzle temperature. To reduce the length of production time, it can be done by choosing a larger diameter nozzle.

4. Post-processing
Post-processing is an additional treatment after the model has been printed. Post-processing is done to repair or optimize printed objects or parts. The following are some post-processing studies that have been studied recently to optimize printing results.

4.1. Annealing
Annealing is the most commonly used post-processing on Polyaryletheretherketone (PEEK) material to increase the crystallinity which then causes increasing the mechanical properties of the semi-crystalline polymer [56]. The results of Basgul et al. 2020 show that annealing improves the mechanical properties of printed objects at slower speeds [57]. In addition, annealing also increases the adhesion of each layer under certain conditions. However, it was only increases by 14% of the compression strength. On the other hand, this annealing process cannot reduce the porosity of the printed object.

4.2. Machining
Post-processing machining is usually focused on getting good surface quality. Del-Sol et al. 2019 have conducted research on the surface quality of ABS material after machining operations [57]. The results show that the roughness is reduced to a range of 0.5 to 1.2 μm. This method does not affect the internal structure or mechanical properties such as post-processing with chemical treatment. Therefore the use of this method is suitable for surface quality optimization needs only. However, post-processing with machining will reduce the dimensions which are quite a lot, so that when printing, the dimensions need to be increased.

4.3. Laser polishing
Laser polishing is a new polishing technology where technology has more advantages than traditional technology [58]. The use of laser polishing in post-processing can reduce roughness a lot [59,60] and even reach the value of 0.32 μm [61]. This laser polishing can also reduce porosity, increase tensile strength [58-60], increase dynamic mechanical properties [62], improve interfacial adhesion, and can even improve existing fractures on printed parts [60]. Several optimizations can be done at once by using this method, which creates a particular advantage of this method.
4.4. Chemical vapor smoothing
Chemical Vapor Smoothing (CVS) or also known as the cold vapor treatment process, is a treatment process using chemical vapors after an object has been printed. The chemical commonly used for CVS is acetone. In the research of Beniak et al. 2018 about the effect of acetone on compressive strength and roughness on ABS material shows a significant influence [61]. When exposed to acetone vapor for 5 minutes, the compressive strength increases by more than 21%. However, if more than 5 minutes, the strength decreases. The roughness value also decreased from 16.92 μm to 0.4 μm when exposed to steam for 10 minutes. However, the provision of steam for 7.5 minutes and 10 minutes did not show a significant change, it means that significant changes only occur on exposure with a certain period of time. In other studies, the same thing was also shown, namely CVS or cold vapor treatment greatly reduced the level of roughness from printing results [54,62,63]. CVS also reduces the dimensions slightly of the part due to reflow material [54] and increase value to its hardness [58].

5. Future Challenges and Potential Improvements
Many studies have been carried out to improve the mechanical properties, surface quality and build time of the FDM 3D Printing. Most research have concluded that the printing process variables strongly influence the quality of 3D printing results. However, there are not enough data to explain the relationship between print quality and mechanical properties for the various types of materials used in FDM. The same printing process can produce different printing results if the material is different and, so far, there are no absolute rules and guidelines that can be used to assist users in optimizing the printing process to get the best printing results.

Many studies have studied the effect of printing FDM parameters on ABS material. Unfortunately, only few studies were conducted for other materials although other materials are also widely used and applied for different purposes. Therefore, research related to the influence of process parameters also needs to be done on other materials. In terms of large scale applications, when compared with the traditional process such as injection molding, FDM still cannot be used as an alternative when looking at the mechanical work performance produced. Porosity, gaps between layers and rasters generated in the FDM process are still becoming the major problem of the printout with FDM. Most studies also only show the results of the analysis of tensile and flexural properties while other analysis such as hardness, production time, creep, vibration were rarely studied. In addition, process parameter optimization is mostly done for the mechanical properties of printing results. Meanwhile, the optimization of process parameters for thermal, chemical and dynamic mechanical properties is still rarely found.

In terms of combined parameters, most optimization studies are conducted for one output variable or several output variables individually. Studies that conduct optimization for several variables simultaneously are rarely found. Therefore further studies on the analysis of overall mechanical performance and optimizing multiple output variables simultaneously are required to get more evident analysis results.

Lastly, economic analysis is also required to determine profitable or not profitable when using post-processing on a product. Post-processing generally gives an increase in surface quality from printing results. The surface quality in the results of printing with FDM is relatively poor. The surface quality of the printing results has the potential to be improved so that it no longer requires additional post-processing.

6. Conclusion
The parameter processing and post-processing in FDM 3D printing have a significant influence on the final results of the printed part. The effect of parameter processing and post-processing on this recent study has been explained in this article. The results of a review conducted in this article show that in general, process parameters have an effect on mechanical properties, surface quality, and build time. Process parameters can influence and be a solution for each other. The combination of several synchronized parameter processes such as layer thickness and print speed can produce more optimal
printed parts and shorter printing times. In addition, if FDM is integrated with post-processing it will also get better results, especially on its surface quality. Future research with an overall analysis of mechanical properties and economic analysis is needed for more evident results.

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