Research Article

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A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters

Abstract: This study aims to review research the progress on factors that affect the 3D printing results of the fused deposition modeling (FDM) process. The review is carried out by mapping critical parameters and characteristics determining FDM parameters, the effects of each parameter, and their interaction with other parameters. The study started from the filament manufacturing process, filament material types, and printing parameters of FDM techniques. The difference in each section has determined different parameters, and the respective relationships between parameters and other determinants during printing have a significant effect on printing results. This study also identifies several vital areas of previous and future research to optimize and characterize the critical parameters of the FDM printing process and FDM filament manufacturing.

Keywords: fused deposition modeling, 3D printing, filament, critical parameters

1 Introduction

Fused deposition modeling (FDM) is one of the methods used in 3D printing. This technique is one of the manufacturing methods under the additive manufacturing engineering class, gaining popularity among researchers and industry to study and develop. Additive manufacturing techniques can create various complex shapes and structures while properly managing materials, resulting in less waste and various other advantages over conventional manufacturing, making it increasingly popular [1–3]. Technically, the FDM technique has the same role as injection molding in the manufacturing aspect. For example, mass customization. It means producing a series of personalized items, so that each product can be different while maintaining low prices due to mass production. It does not need the additional costs of making molds and tools for customized products [1,3].

The basic concept of the FDM manufacturing process is simply melting the raw material and forming it to build new shapes. The material is a filament placed in a roll, pulled by a drive wheel, and then put into a temperature-controlled nozzle head and heated to semiliquid. The nozzle precisely extrudes and guides materials in an ultrathin layer after layer to produce layer-by-layer structural elements. This follows the contours of the layer specified by the program, usually CAD, which has been inserted into the FDM work system [4,5].

Since the shapes in FDM are built from layers of the thin filament, the filament thermoplasticity plays a vital role in this process, which determines the filament's ability to create bonding between layers during the printing process and then solidify at room temperature after printing. The thickness of the layers, the width, and the filament orientation are the few processing parameters that affect the mechanical properties of the printed part. The complex requirements of FDM have made the material development for the filament a quite challenging task [6].

Research on this material stigmatizes the limitations of the material for this technique. Currently, 51% of the products produced by the additive manufacturing system are polymer–plastic filament types. It is because these materials not only have sufficient criteria to be used and developed but also help to make FDM processes for manufacturing products more manageable and more optimal [4]. The most well-known polymers used in this technique are polylactic acid (PLA) and acrylonitrile

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butadiene styrene (ABS). Moreover, other materials such as polypropylene (PP) also began to be noticed for development because it is one of the plastics that is commonly found in everyday life [1,7]. In Japan, filaments made of PP are being used and offer superior resistance to heat, fatigue, chemicals, and better mechanical properties such as stiffness, hinges, and high tensile strength with a smooth surface finish. Also, several other types of filaments are currently being developed and introduced as commercial filaments [8].

Some previous studies showed that although the filament composition is the same, the test may obtain different results [9–11]. In other studies, some researchers optimized the performance of FDM machine by changing some of the parameters [3,12–14] and concluded that each combination of parameters would be showing different results. These studies have shown that many factors critically determine the results of the FDM process [10,15–18].

This study aims to provide a comprehensive picture of the various factors that influence the mechanical characteristics of FDM products. The review is carried out by critical mapping parameters and critical parameters determining FDM factors and analyzing each parameter's main effects and their interactions in the FDM process. The review starts with producing the filaments, the impact of different filament materials, and the critical printing parameters of the FDM techniques. Understanding these factors will be useful to get a combination of each influential factor, which can later be optimized to obtain printing results with mechanical properties that can be adjusted to the target application.

2 Filament manufacturing process

The filament is the primary material used in the FDM process. In general, the filament is made of pure polymer with a low melting point. In some cases, the strength of pure polymer needs to be enhanced. Therefore, many researchers and industries have developed polymer composites as 3D printing filament material by combining the matrix and enhancing the components to achieve systems with structural properties and functional benefits which cannot be achieved by just any constituent [19]. The filaments made from pure polymers that are usually commercial can be directly processed as FDM material. However, the process of making composite filaments must first receive special treatment because every reinforcement in a composite polymer will result in different characteristics [12,20–22].

The pure polymer filament for FDM materials can be made through the process of extruding pellets or raw materials from polymers. This process is carried out using extruders that push or force the material through holes in the die to get the product as an extrudate [23].

Meanwhile, making filament from polymer composites or by strengthening is accomplished by mixing the material before the extrusion process is carried out
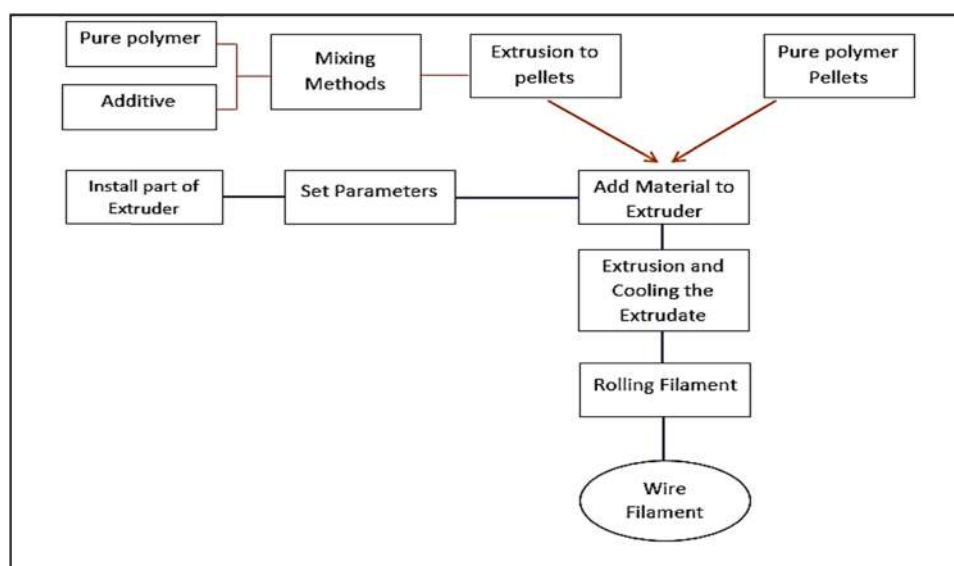

Figure 1: Filament work flow.

by preparing each composition in advance so it can be associated [24]. The materials can be mixed by several methods depending on the characteristics of the ingredients of the mixture. It can be completed by mixing the solution and then drying before being extracted [20] or by the dry mixing method. This method is most often used for mixing polymer filament material using a pure polymer stirred in a stirring machine with spinning roller blades at a melting point temperature of the polymer. Then after the compatibilizer process, additives are added in stages according to the required percentage. It usually takes about 30 min. After that the melted material is then allowed to stand at room temperature to achieve homogeneity. The resultant mixture can be processed into pellets or pieces of fabric of small sizes ranging $4 \times 4\ mm^2$ [25], and then it is processed in an extruder.

In this extrusion process, several things affect the filament. Die temperature, roller puller speed, spindle speed, and inlet temperature affect the filament cable diameter. Because in this process, the parameters will affect the viscosity of the material, which causes the output of the material to be extruded at the nozzle die, not according to the desired diameter. In contrast, the winding screw shape affects the regularity of the filament. Especially in composite filaments, the shape of the thread will affect the direction of the filler used in the filament [10,26].

Several stages are involved in the making of filament by an extrusion machine. The earliest stage starts from determining the diameter of the filament to be made, preparing the extrusion parameters, inserting the material in the form of a pellet, and extruding from the nozzle die hole until it is wrapped around the roller machine. The steps of the filament-making process are shown in Figure 1 [27].

Figure 2 illustrates the working principle of the extruder machines in general. It shows how the pellets are processed into a filament – starting from being inserted into the hooper, melted until it is extruded out as a filament [29,30].

Several recommendations are involved in the extrusion of pure polymers' filament extrusion process, as in Table 1 [3,29]. Miron et al. (2017) researched to find filament extrusion results with as little deformation as possible, but in a orderly and smooth manner. They run tests to find the relationship between extrusion temperature, extrusion speed, and problem solving from what is produced by the interaction between the extrusion parameters. The results are summarized in Table 2. For example, the first row shows that if the temperature is lower, the pellets there are put into the extruder does not reach the melting temperature of the polymer. So in that condition, the pellet does not properly melt and results in the block of screw rotation and hence not working as expected because it is stuck and the rotation becomes slower. These problems are the result of slow thrust and high viscosity, causing the extrudate diameter to become oversized. Their findings can be applied to consider the interaction between parameters to obtain the expected filament yield [29].

3 Filament types

According to its composition, polymer filament is divided into two categories, namely, pure polymer filament and

Table 1: Extrusion value recommended

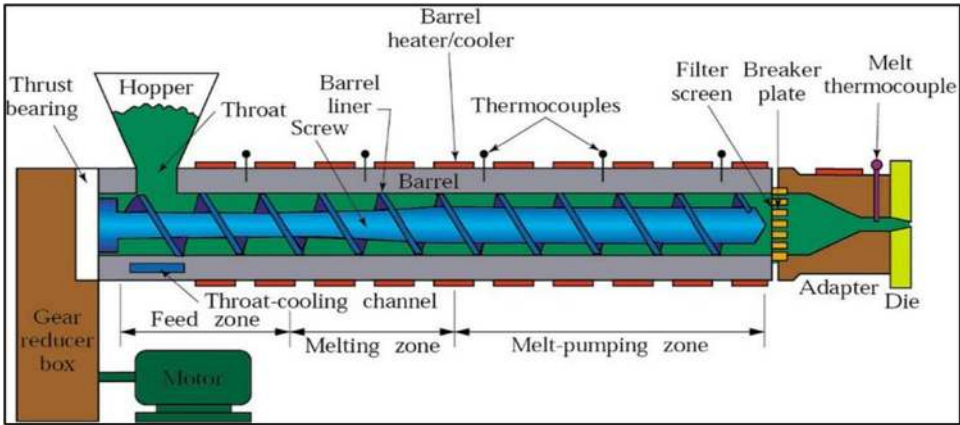| Plastic type	Processing temperature
PLA	175–195°C
ABS	165–185°C
PP	204–240°C

Figure 2: Extruder machine parts [28].

Table 2: Extrusion parameters relation

Extrusion temperature	Extrusion speed	Result	Solutions
165°C	Very slow	High diameter	Increasing temperature
170°C	Slow	High diameter	Increasing temperature
175°C	Good	—	—
180°C	Good	—	—
185°C	Fast	Filament blister and small diameter	Decreasing temperature
190°C	Too fast	Filament blister and small diameter	Decreasing temperature

composite filament. The pure polymer filament is entirely made from a polymer compound without adding additive solutions [2,8,31–33]. Each type of pure polymer filament has its inherent characteristics and mechanical properties [34]. Still, sometimes the intrinsic properties of pure polymers cannot accommodate the need for mechanical properties for certain products. This problem requires researchers and industries to continuously develop polymer filaments suitable for commercial needs. One of the steps that can be taken to improve the mechanical properties of a filament is adding additives to the filament composition. This process finally led to the composite filament [20,35]. The following is using some pure polymer filaments that are often used in 3D printing and development processes.

3.1 PLA

PLA is one of the most innovative materials developed in various fields of application. This type of polymer is thermoplastic and biodegradable. PLA can be developed in medical applications because of its biocompatibility which is not metabolically harmful [24,36]. This process can be achieved by turning it into a filament and then processing it through the FDM method. The filament can then be converted into various forms commonly used as implants [14,26]. The 3D printing scaffolding technique of FDM made a recent development of a PLA/graphene oxide (GO) nanocomposite material with a customized structure. This study was carried out to analyze many scaffolding parameters such as morphology, chemistry, structural and mechanical properties, and biocompatibility to show their potential uses in biological applications. The study concluded that the use of PLA/GO nanocomposite in 3D printing is a platform with promising mechanical properties and cytocompatibility, which has the potential in bone formation application [37]. The development of PLA-based filaments to improve their mechanical properties has been carried out comprehensively, starting from testing pure PLA, thermoplastic

elastomeric thermoplastic (TPU) blends, and E-glass fiber-reinforced composites (GF). From these studies, it is concluded that GF as fiber reinforced is generally very beneficial because it can increase the tensile modulus and flexural modulus. On the other hand, the addition of TPU provides increased toughness to PLA blends [38].

3.2 ABS

ABS is a general term used to describe various acrylonitrile blends and copolymers, butadiene-containing polymers, and styrene. ABS was introduced in the 1950s as a stricter alternative to styrene–acrylonitrile (SAN) copolymers [39]. ABS was a mixture of SAN or better known as nitrile rubber at that time. Nitrile is rubbery, and SAN is glassy and the room temperature makes this structure an amorphous, glassy, tough, and impact-resistant material. ABS has complex morphology with various compositions and effects of additives, therefore making it quite bad in some aspects. However, ABS is a prevalent material used in the 3D printing process of the FDM method. Still, the choice of other ingredients also has their respective weaknesses [40]. Researchers carried out various developments to correct the deficiencies in the mechanical properties of ABS, one of which was to develop an ABS composite filament reinforced with GO with the addition of 2 wt% GO, made from a solvent mixing method. This method succeeded in printing the filament ABS into a 3D model. The tensile strength and Young's modulus of ABS can be increased by adding GO [6].

3.3 PP

PP is a homopolymer member of polyolefins and one of the most widely used low-density and low-cost thermoplastic semicrystals. PP applications are generally used in

different industries such as the military, household appliances, cars, and construction because of their physical and chemical properties. However, PP has low thermal, electrical, and mechanical properties compared to other engineering plastics (PC, PA, etc.) and has a high coefficient of friction in dry shear conditions [3,20,41]. The mechanical properties of PP are improved by combining with inorganic fillers in the form of nanoparticles. Yetgin (2019) examined the effect of GO addition to PP, with and without maleic-anhydride-grafted-polypropylene (PP-*g*-MA) as a compatibilizer agent using extrusion and injection processes. The results show that the friction and wear rate of PP nanocomposites increase with the applied load and sheer speed. The coefficient of friction is reduced to 74.7% below the shear speed [20]. Another research tried to compare the printing ability of PP filled with 30% glass fiber to unfilled PP in terms of mechanical properties. The addition of glass fibers increases Young's modulus and ultimate tensile strength of about 40% for the same printing conditions [3]. Similar enhancements in modules were also observed for 3D-printed PPs filled with cellulose nanofibrils [42] as well as studies of optimizing PP compounds that contain spherical microspheres for FDM application by maximizing matrix–filler compatibility that affects printability, properties' pull, and toughness. In a concluding impact test on printed composites, the optimized system exhibited impact energies 80% higher than pure PP [1].

4 Printing process on the FDM machine

The FDM machine's working principle is to heat the filament on the nozzle to reach a semiliquid state and then extruding it on a plate or layer that was previously printed. Thermoplasticity of polymer filaments allows the filaments to fuse during printing and then solidify at room temperature after printing [2,43]. Although a simple 3D printing using the FDM method has complex processes with various parameters that affect product quality and material properties, each of these parameters is linked to one another, making this combination of parameters often challenging to understand [9,44]. In contrast, every product that results from the 3D printing process has different quality requirements and material properties [19]. The print parameter combination on the FDM machine is determined by the type of filament and the size of the filament used in the FDM process [45].

Therefore, it is crucial to examine the effect of a combination of mechanical performance parameters [46–49].

The parameters that affect the printing process are divided into two categories, namely, the parameters of the FDM machine and the working parameters. Machine parameters include bed temperature, nozzle temperature, and nozzle diameter. In contrast, the working parameters include raster angle, raster width, build orientations, etc., and these parameters are usually inputted in the slicing process using the software before the design and work parameters are entered into the FDM machine [1,9,48,50].

The following explains some of the main parameters of the FDM printing process. Figure 3a explains the build orientation guided by the step where the part is oriented toward the X, Y, and Z axes on the build platform. Layer thickness shown in Figure 3b is the thickness of the layer deposited on the nozzle tip. The user's thickness value in a specific range is defined by the nozzle diameter and limited by the printer accuracy. Some studies suggest using a thinner layer to increase both the surface quality and dimensional accuracy [51]. Figure 3c describes the FDM tool path containing several parameters, namely, raster angle, raster width, contour width, number of contours, and so forth.

Raster angle refers to the rise of the raster pattern concerning the X axis in the lowest layer. The proper raster angle is from 0° to 90°. In part with a small curve, the raster's angle must be precisely determined, so that the results are optimal. Raster width is the width of the material droplets used for the raster. Raster width values vary based on the size of the nozzle tip. A more considerable raster width value will build the part with a more muscular interior. A smaller value will require less time and material production.

Several studies have shown that the use of this parameter has significant results. For example, Lee (2005) conducted a study of a combination of layer thickness, raster angle, raster width, and its strengths and weaknesses to find the optimal result. Also, the raster angle parameter on the tensile test specimen has a significant effect on the load distribution. If the opposite angle is used, it will decrease the strength of the test specimen and *vice versa*. Furthermore, the raster angle build orientation will have a similar effect [21,48,50,51]. Contour width refers to the width of the contour tool path that surrounds the part curves. The number of contours to build around all the outer and inner curves is shown in Figure 3c. Additional shapes are used to increase the walls of the perimeter.

Figure 3c also shows the effects of the air gap on the printing results. The air gap in Figure 3c is based on the
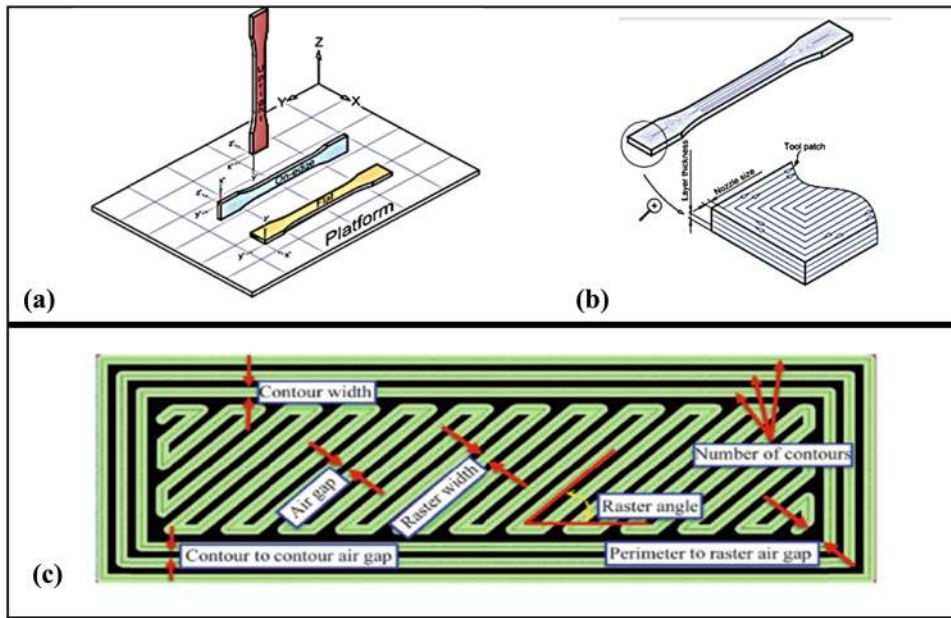
Figure 3: (a) Build orientations [9], (b) layer thickness [9], and (c) FDM tool path parameters [52].

gap between adjacent raster chisel paths in the same layer. The air gap is an effect that occurs during the extrusion of the filament to the bed or the previous layer. It can be affected by raster width, raster orientation, and some other things like machine calibration. The contour air gap is based on the gap between the profile shapes when the part filling force is set to several shapes. Perimeter-to-raster water gap refers to the gap between the innermost contour and the raster's edge filling inside the shape.

Build style refers to how the part is filled, and this controls the density of elements. Building styles are of three types. The first is a solid normal which is achieved by filling the interior. The second one is sparse by minimizing the material volume and making time by leaving gaps. It is usually done in a unidirectional raster. The third is a sparse double dense by reducing the material volume and manufacturing time, and this uses a raster crosshatch pattern. The visible surface is used to maintain appearance parts while allowing for a coarser, faster fill by normal rasters or fine rasters. The fill style part determines the fill tool path of the bead to build the solid model. These parameters greatly determine the shrinkage factor of the printing result, because the air gap in the printing result can be affected by the build style, which affects the surface quality and size accuracy when the filament begins to harden [21].

5 Summary of the previous work on optimizing the final output of FDM filament processing

After reviewing the literature study, it is clear that the filament manufacturing process, the composition of filament making, and the optimization of printing process parameters from FDM additive manufacturing technology are the essential indicators in the quality evaluation. It is imperative for obtaining high-quality components, improved material responses, and improved properties. Many types of filament material, extruder machines, and FDM machines are available in the market. Each unit has different specifications. The process of filament making, the composition of the filament, and the optimization of the printing process parameters of the FDM additive manufacturing technology must be further investigated to understand and obtain the product's mechanical properties and behavior [31,32,52–58]. Table 3 summarizes the relationship between the process of making filament, the composition of the filament, and the optimization of the final output of FDM filament processing with the output of the combination.

As mentioned earlier in Table 3, the process of making a filament, the composition of the filament, and the

Table 3: Summary of published work on optimizing the final output of FDM filament processing

Material	Additive	Parameters for making filament	Print parameters	Significant input	Output	Ref.
PLA	HPMC	Extrusion speed, extrusion temperature	Layer thickness, build orientation	Additive	Tensile strength	[59]
PLA	ABS-HIPS	Commercial	Layer type, layer thickness, build style	Layer, additive	Tensile strength, elongation, Young's modulus	[60]
PLA	Cetylated tannin (AT)	Mixing methods, extrusion temperature, screw model	Layer thickness, road width, raster angle, model temperature	Additive	Tensile strength, elongation, Young's modulus, aquatic degradation system	[61]
PLA	Wood flour (WF)	Extrusion temperature	Part fill style, layer thickness, raster angle	Additive	Microstructure, Young's modulus, melting temperatures	[62]
ABS	—	Commercial	Layer thickness, road width, raster angle	All input parameters	Surface quality and dimensional accuracy	[21]
ABS	Pigment	Commercial	Raster orientation, bead width, raster width, model temperature, color	Raster orientation	Tensile strength, compressive strength	[63]
ABS	OMMT	Extrusion speed, extrusion temperature	Model temperature, extrusion speed, nozzle diameter	Additive extrusion speed–temperature	Tensile strength, elastic modulus	[16]
ABS	Graphene oxide (GO)	Mixing methods (melt and solvent), extrusion temperature	Model temperature, build orientation	Additive mixing methods (melt and solvent)	Tensile strength and Young's modulus	[6]
PP	Short glass fiber (GF) and (POE-*g*-MA)	Mixing methods	Model temperature, layer thickness nozzle diameter, raster angle	Additive	Strength and modulus	[64]
PP	Spherical glass microspheres	Mixing methods (melt and solvent), extrusion temperature	—	Additive	Tensile, thermal, and impact properties	[1]
PP	Glass fiber	Commercial	Raster angle, layer thickness	All input parameters	Tensile strength and Young's modulus	[3]
PP	Polycarbonate (PC)	Extrusion speed, extrusion temperature	Model temperature, layer thickness, extrusion speed	All input parameters	Tensile strength	[65]

optimization of the printing process parameters affect the result quality. Starting from the main material, additives, and the process of making filaments can already be a variable to improve the quality and mechanical properties. In the parameters for making filament column, if it is written commercially, it means that the filament is obtained from purchasing on the market, and it is assumed that the manufacturing process is uniform with other materials. Although the filament is made from the same factory, if the process of determining print parameters is different, it will produce different print quality, as shown in the literature. Significant input is a parameter that is used as a variable variation in related research, and output is the result observed in the study [9,21,48,63,66]. Moreover, trials using only a few parameters without explaining the other parameters can produce incorrect data because each parameter in the course of raw material to become a product has a relationship to determine the nature and quality of the work [43].

The conducted review has revealed the relationship of each part of the FDM process, from the extrusion process of the raw materials to the printing process on the FDM machines. From the study, it is clear that each process influences the product's nature and characteristics. However, at least four critical aspects must be considered to get good characteristics of the final product with the FDM process. The first aspect involves the parameters related to the filament making, namely, the material types (such as PLA polymers, ABS, PP, and others), the material additives (such as glass fibers, carbon nanotubes, MCC, and others) as well as the mixing method of the composition of the material to be used as a filament base material. The second aspect is the extrusion parameter on the extruder machine. This parameter is determined by looking at the factors in the first part, including the extrusion temperature, the nozzle temperature, the extrusion speed, the nozzle diameter, and the screw model. After going through the extrusion process on the extruder machine, certain types of filament will be obtained, such as pure polymer filament or composite filaments such as PLA/MCC, PP/glass fiber, ABS/carbon nanotubes, and various other types of composite filaments produced from polymer compositions and additives [64,67,68]. The nozzle diameter used in the extrusion process will also determine the third aspect, which is the diameter of the filament. The last aspect that influences the determination of printing parameters in the FDM machine is the printing parameters of the FDM machine. These parameters are the raster angle, the raster width, the layer thickness, the part fill style, the build styler, the countour width, and others. The combination of these printing parameters is critical in determining the printing product characteristics.

In the recent years, many studies were carried out to identify various optimal factors and parameters to improve the surface finish, aesthetics, mechanical properties, model material consumption, and development time. The quality characteristics of FDM builder parts such as flexural strength, hardness, tensile strength, compressive strength, dimensional accuracy, surface roughness, production time, yield strength, and ductility are the main concerns for producers and users. However, there is still no best condition for all types of parts and materials [43].

It is difficult to determine all combinations of factors and input parameter variables to produce the best quality and properties. In some cases, there is always a need to adjust parameters that must be deeply explored and can be ruled out. For example, in the printing process, sometimes, the parameter/method must be replaced with the conventional injection molding process based on several considerations such as production time, costs, and others [38].

After reviewing previous related work, many improvements and development of FDM techniques that can be carried out in the future. From the filament manufacturing process, one of the steps is to reproduce the material that has already reinforcement and to be added with other reinforcement to obtain better quality results. According to Sodefian et al. (2019) and Stoof and Pickering (2017), developing a glass fiber-reinforced PP with other enhancers or recycling of the existing materials can improve its quality [41,69].

Other variables can also develop various aspects that exist in this FDM process. The development can be applied either in the extrusion filament process or in machine parameters, such as the nozzle hole diameter that affects the contour width and many more.

Until now, to the best of the authors' knowledge, there is no study on the optimization of complex FDM techniques that compare various combinations of parameters in the FDM process. The solution to this problem is by making a complete and structured design of experiments [10,26,29,41,43,70], starting from the composition filament material, the differences in the mixing composition method, the differences in the parameters of the extrusion process, to the differences in the working parameters of the FDM machine. In this way, researchers are expected to be able to find relevant and reliable results.

6 Conclusion

This literature review found that every aspect of factor and input parameters in the FDM engineering process affected the quality and mechanical properties. Aspects that have been stated to influence the results are as follows: filament material composition, extrusion working parameters such as those related to extrusion speed and temperature, FDM machine specifications, extrusion machine specifications, type of filament polymer, and FDM work parameters when printing the filament. This study has identified the additive manufacturing field's scope by using a 3D printing process made from polymer filament for the future research in optimizing and characterizing FDM processes and materials. It has been emphasized that FDM is characterized by a large number of process parameters that determine mechanical properties and the quality of results. Nevertheless, there are still some relationships between factors and parameters that are not yet clear, making future work very important to be determined to give the best results.

Conflict of interest: Authors state no conflict of interest.

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