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Review Article

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Effect of FDM Process Parameters on Performance of Printed Products: A Short Review on Current Trends

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Abstract

Fused deposition modeling (FDM) is simplest and cost-effective additive manufacturing (AM) technique, which prints the components by squeeze out the molten material through a nozzle and deposits on a substrate in a controlled manner. The advantage of FDM is to fabricate complex geometry without using the pattern, die and tools. The mechanical properties and build quality of 3D printed parts greatly depend upon process parameters that could be enhanced by selecting optimal parameters. Recently, FDM has been a preferred choice of researchers to develop polymers-based nanocomposites. A good number of research works are carried out to study the influence of FDM process parameters on the performance of printed products. Therefore, there is a great need to review the research works performed on the effect of FDM process parameters. The present review discusses the impact of FDM process parameters on the performance of the products and identifies the vital parameters.

Keywords

Additive manufacturing, Fused deposition modeling, Printing parameters, Part characteristics

Introduction

AM is also recognized as rapid prototyping or layered manufacturing process, in which a 3D component manufactures directly from a CAD model without using jigs, fixtures, and expensive tools. In this technology, the material is deposited by one layer over the other in a controlled manner instead of removing materials [1]. It offers to build 3D parts with complexity in geometry and materials in easy steps with minimum wastage of materials and minimum post-processing, which ultimately reduces the cost of the product. There are many ways to classify the AM process. Here, AM is classified based on the state of starting raw materials (depicted in figure 1) as solid-based, liquid-based, and powder-based, in which material is initially in a solid state, liquid state and powder state, respectively. The solid-based process can be further classified as: Fused Deposition Modeling, Wire Arc Additive Manufacturing, and Laminated Object Manufacturing. The liquid-based process can be further classified as: Stereolithography apparatus, first 3D printing technique developed around the 1980s [2], and Polyjet. The powder-based process can be further classified as: Selective Laser Sintering, Selective Laser Melting, Laser Metal Deposition, and Electron Beam Melting.

FDM is one of the solid-based AM processes, materials used in the form of filament. The FDM technology is not commercially used due to its weak mechanical properties of printed parts and limited range of materials. Several printing parameters need to be controlled to produce a desirable customized product. This paper's main aim is to present a brief intensive review on the impact of various parameters on the performance of FDM printed part and identify the crucial parameters.

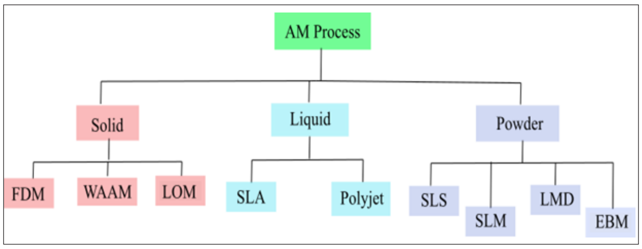

Figure 1: Classification of the Additive Manufacturing processes.

FDM

It is an extensively used AM process because of its compact design, economical, easy to operate and low maintenance cost. The FDM technique was first developed in the 1990s and is growing rapidly [3]. A schematic presentation of FDM is depicted in figure 2a. In this technique, filament is fed to the liquefier through the roller, melted when it reaches the heating block, extruded through the nozzle, and deposited in layers on the substrate. FDM is generally fashionable for thermoplastic materials such as PLA (Polylactic acid), ABS (Acrylonitrile butadiene styrene), PP (Polypropylene), PA (Polyamide) and recently, some thermoplastic based composite materials such as; ABS-Fe [4], ABS-Cu-Fe [5], PP-carbon black [6], and PLA based nanocomposites are also have been investigated and in trends [7]. The liquefier geometry and process parameters are key factors which are responsible for the build quality of the product.

FDM printing parameters

Ahn et el. [8] presented that the mechanical properties of the FDM printed part are anisotropic and extensively depends on the parameters. Here, printing parameters are categorized into three groups: Nozzle geometry based – nozzle angle (β) and exit diameter (d), Process based – extrusion temperature and rate, substrate temperature, and Structural based – raster angle, air gap, raster width, layer height, build orientation, infill pattern and density. The effect of these parameters is discussed in the following several paragraphs.

Nozzle angle and exit diameter

Roxas et al. [9] presented that print quality is the function of the extrusion temperature (T), pressure drop (ΔP) across the liquefier and nozzle exit diameter (d). For better resolution, these parameters should be less.` Yardimici et al. [10] noticed that pressure drop decreases with an increase of 'β' for constant 'd' and decreases with an increase of 'd' for constant 'β' But the increase in nozzle diameter decreases the print resolution. They suggested optimum values of 'β' and 'd' are 120° and 0.5 mm, respectively. The optimum value of nozzle angle 120° and nozzle exit diameter 0.4 mm have been suggested for printing PLA and ABS, through FDM [11].

Extrusion temperature and rate

Extrusion temperature is the temperature of the heating block or nozzle at which material extrudes from the nozzle. Extrusion rate is the material flow rate coming out from the nozzle exit. It varies as the extrusion temperature and filament feed velocity changes. It was observed that the printed part's density increases with increased extrusion rate because more material is deposited [12]. It also causes wavy microstructure as excessive extruded material is challenging to deposit layer by layer. At high extrusion temperature, the quality of the printed part was not good because of low viscosity; the layer spreads and causes weak interlayer bonding between adjacent layers [13]. At the beginning or end of the layer deposition, the material flow was intrinsically different due to visco-elastic material behavior and requires special control to hold it. Ertay et al. [14] stated that if the extrusion rate is constant throughout the part fabrication, the excess material is accumulated at the sharp corner, thereby reducing the sharpness of the curvature. Therefore the material extrusion rate should be synchronized with tangential path velocity and temperature of extruded material [14].

Substrate temperature

It is necessary to have strong interlayer bonding between adjacent layers to obtain a printed part with good strength. The bottom layer's temperature must be sufficiently high until the subsequent newly deposited layer forms good interlayer bonding. The temperature of already deposited layers is maintained by adjusting the appropriate substrate temperature. Less temperature gradient between the layers leads to good interlayer bonding and improves the product quality [15]. Bellehumeur et al. [16] investigated the interlayer bond formation of ABS material in the FDM process. It is presented that the bond quality depends on the neck's growth (i.e., contact area) formed between two adjacent layers and molecular diffusion at the interface. Neck growth takes place above the glass transition temperature of the deposited layer, which significantly depends on the cooling temperature profile of the deposited layer [17]. Costa et al. [18] discussed that when the surrounding temperature is decreased, the void content increases, which leads to a decrease in the compactness of the part because of the weak interlayer bonding.

Air gap

It is the raster-to-raster gap between two contiguous deposited layers (as shown in figure 2b). Mohamed et al. [19] in his study they observed that with the minimizing of air gap, the mechanical properties considerably increased because at no air gaps the adjacent layers are joined by strong interlayer bonding with less porosity. The positive air gap increases heat dissipation but at the same time voids are also formed. A negative air gap reduces the heat transfer and develops residual stresses in the fabricated parts [8, 20]. Ang et al. [21] observed that air gap had more impact on the compressive strength and comprehensive modulus than raster width for ABS. If an air gap increases from 0 to 1.27 mm, the comprehensive strength and comprehensive modulus decreased by 35.13 MPa and 586 MPa, respectively.

Raster width

It is the width of the layer deposited on the substrate, as depicted in figure 2c. It depends on extrusion temperature and substrate temperature. Rajpurohit et al. [22] studied the consequence of various FDM parameters on tensile strength for PLA. They observed that tensile strength initially increases with the increase of raster width and then decreases. The larger raster width means more material is deposited, so it solidifies slowly, and the temperature of the deposited layer is prolonged above glass transition temperature for a long time, resulting in strong interlayer bonding strength between adjacent layers. But further increase of raster width affects the cooling rate significantly and forms voids that might be the possible reason for the decrease in strength with further increase of raster width. Mohamed et al. [19] observed that storage and loss modulus were slightly higher at low raster width for PC-ABS. This has happened because less raster width fills the cavity and reduces the chance of porosity. Ang et al. [21] analyzed the impact of raster width on mechanical properties of ABS scaffold, and found that by varying the raster width from 0.305 to 0.98 mm, the compressive strength and compressive modulus increased by 7.8 MPa and 154 MPa, respectively.

Layer height

It is the thickness of the layer deposited on the substrate (shown in figure 2c), which depends on the type of nozzle used. Wu et al. [23] optimize the parameters for printing PLA cylindrical model. In this investigation, they observed that layer height significantly affects the print quality; dimensional accuracy was decreased with the increase of layer height. They concluded that printing with 0.14 mm layer height produces a product of good quality in a minimum time. Wu et al. [24] observed that mechanical properties were increased with an increase in layer height, then significantly reduced with a further increase of layer height. The maximum tensile, compressive, and bending strengths for FDM printed polyether-ether-ketone (PEEK) materials were observed at 0.3 mm layer thickness and 0° raster angle. Aliheidari et al. [25] studied the effect of layer height on the interlayer adhesion and fracture resistance of the fabricated ABS polymer part. It was observed that fracture resistance was initially increased with an increase in layer height from 0.1 to 0.2 mm, and then sharply reduced with further increase. Therefore, the optimum value for fracture resistance was observed at 0.2 mm. In another study, Dave et al. [26] reported the 0.2 mm layer height as the optimum value for the compressive strength for printing PLA scaffolds.

Build orientation

It is the inclination of the printing part in a substrate with respect to axes X, Y, and Z during the printing. X and Y-axis are considered parallel to the build platform and Z-axis is perpendicular to the substrate in the direction of printing. The parts are usually printed in three orientations 0°, 90°, and 45° w.r.t. X-axis of the build platform (shown in figure 2d). From the literature review, it has been perceived that the build orientation causes a considerable effect on the tensile and fatigue behavior of PLA material printed through the FDM [27]. They reported that the parts printed along 0° build orientation have high tensile strength than 90° and 45° build orientation, which is about 60 - 64% of injection molded PLA [28]. In 0° builds orientation, layers are deposited along the maximum dimension which is parallel to the substrate therefore, it offers more resistance to deformation. However, in 90° build orientation, layers are deposited perpendicular to the longer dimensions, which offer minimum resistance for the deformation and in 45° build orientation, printed parts offer the intermediate resistance [28]. In repetitive loading, the parts printed in 45° build orientation offer higher fatigue life than the other two build orientations. Ashtankar et al. [29] demonstrated that FDM printed ABS's tensile and compressive strengths are considerably less than injection molded parts. The tensile strength reduces in the range of 48 - 60% and compressive strength reduces in the range of 57 - 64 %. Both the strengths decrease as build orientation increases from 0° to 90°.

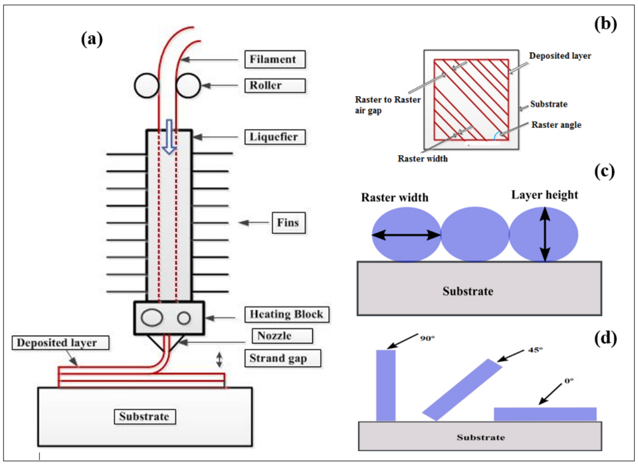

Figure 2: FDM: **(a)** Schematic view, **(b)** various printing parameters, **(c)** raster width and layer height, and **(d)** build orientation.

Raster angle

It can be described as the direction of the deposited layer with respect to X-axis of the substrate of the FDM machine. The layers can be deposited with raster angles of 0°, 90°, 0°/90°45°, and 45°/45° (shown in figure 3). The surface finish of printed products depends on the raster angle due to stair-step effect. Lokesh et al. [27] analyzed the consequences of several FDM printing parameters on mechanical properties for PLA material. The remarkable tensile strength and elastic modulus were noticed for the parts printed at 0°/90° raster angle. Wu et al. [24] also observed similar trends for PEEK material, maximum value of tensile, and bending strength were noticed at 0°/90° raster angle.

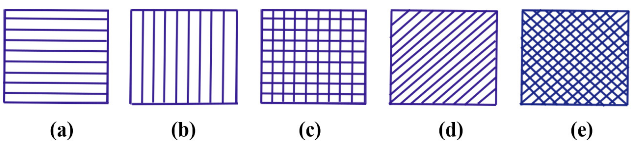

Figure 3: Raster angle: **(a)** 0°, **(b)** 90°, **(c)** 0°/90°, **(d)** 45°, and **(e)** 45°/45°.

Infill pattern and density

Infill pattern indicates the internal design and shape of the printing material inside the part and infill density indicates the percentage of the internal space of the part filled by the materials. Different slicer software is incorporated with several infill patterns, such as: Cura (4.13) provides 14 and Prusa slicer (2.4) provides 16 infill patterns. The most commonly used infill patterns are: line, grid, rectilinear, and honeycomb or hexagonal [13]. Pandzic et al. [30] presented that tensile strength increases with the increase of infill density for each patterns, the maximum strength was achieved for concentric infill pattern for PLA. The part fabricated with concentric infill patterns and 100% infill density has the maximum ultimate tensile strength and yield strength of 42.15 MPa and 36.40 MPa, respectively. The tensile strength is reduced by 40% if the infill density changes from 100% to 90%. Dezaki et al. [31] compared the different infill patterns and observed that honeycomb and grid pattern printed parts have high tensile strength and are lighter than solid. The surface texture and integrity of the parts are also greatly influenced by these parameters [32]. The parts printed by concentric and grid infill patterns have surface finishing as compared to other patterns. The surface finishing of the part produced by the zigzag pattern was the worst.

Conclusion

In current review communication, the effect of each process parameter of FDM on the performance of printed parts has been reviewed. The characteristics of the 3D printed parts are substantially affected by varying different parameters such as layer thickness, layer height, air gap, build orientation, raster angle, extrusion temperature, and infill pattern and density. It is also observed that print quality is the function of extrusion temperature, pressure drop across the liquefier and nozzle exit diameter, for better results, these parameters should be less. The optimum value for nozzle angle and nozzle exit diameter for printing PLA and ABS were observed 120° and 0.4 mm, respectively. The strength was observed maximum at 0° build orientation. The raster angle affects the surface face finish due to stair-step effects. At zero raster to raster air gap, porosity and residual stress was observed minimum. The optimum layer height value for PLA, ABS, and PEEK was observed at 0.14 mm, 0.2 mm, and 0.3 mm, respectively. The components printed with concentric, honeycomb, and grid infill patterns have optimum mechanical properties and surface finish.

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Conflict of Interest

The authors declare no conflict of interest that are relevant to the content of this article.

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Credit Author Statement

Alok Kumar Trivedi and Manoj K. Gupta: Conceptualization, Design, Experiment, Analysis, Writing - original draft preparation, Writing - review and editing. All the authors read and approved the manuscript.

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