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A Comprehensive Review on Optimizing FDM Process Parameters for Improved Tensile Properties

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Abstract

In today's rapidly evolving manufacturing landscape, Additive Manufacturing (AM), commonly referred to as "3D printing," has gained significant prominence and is transitioning from a prototyping tool to a full-scale production method. Among various AM techniques, Fused Deposition Modelling (FDM) stands out due to its straightforward process and capability to fabricate intricate geometries, making it the focus of this study. Enhancing the mechanical properties of printed components through process parameter optimization is crucial to meeting the increasing demand for customized manufacturing. This paper reviews existing literature to determine the optimal FDM printing parameters for maximizing the tensile strength of ASTM D638-compliant specimens. Key process parameters, including nozzle temperature, printing speed, layer thickness, orientation, and raster angle, are examined as critical decision variables.

Keywords

FDM; tensile strength; ABS; PLA; raster angle; print orientation.

Introduction

AM technology is the process of manufacturing parts by joining material in a layer-by-layer fashion. AM builds parts in 3D by adding the material in a layer wise manner, allowing conformability of printing parts of any geometrical shape and of any complexity with reduced manufacturing cost and time compared to its traditional manufacturing counterparts. With characteristics like reduction in product development time and being able to make a part with any complex geometry, AM has its scope in the various engineering fields like aircraft industries, automobile sectors, defense and medical [1]. The main advantages for the AM process are its ability to achieve on-demand, complex design parts in a short period of time with no complex procedure to undergo.

There are various types of AM processes in modern world. Some are listed here [2]

1 Material extrusion process a subset of fused deposition modeling (FDM)
2 Directed energy deposition (DEP)
3 Powder Bed Fusion process
4 Material Jetting Process
5 Vat Photopolymerization

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6 Binder Jetting Process
7 Laminated Object Manufacturing (LOM).

FDM Process

The term FDM was trademarked by Stratasys Inc and is also called fused filament fabrication (FFF).2 FDM process is widely used AM technique offering simplicity, inexpensiveness and ease in operation since the 1990s. The FDM process is a method to produce complex shapes at the low cost without making use of any complex tooling. In FDM, filament wire is fed from a spool through a small-diameter nozzle, heated at printer extruder head and is deposited on the build platform of FDM printer to produce parts in a layer wise manner. The movement in x- and y-direction is achieved by nozzle and movement in z-direction is achieved by movement of the build platform (see Fig.1). Due to the very good efficiency of the FDM process it has become a promising technology for various manufacturing industries. FDM offers several advantages over traditional manufacturing processes but when it comes to fabricate strong mechanical structure having superior properties, the FDM process lags behind the conventional manufacturing methods as it is controlled by large number of process parameters [3].

It has been observed that the mechanical properties and performance of any material manufactured by FDM processes changes with increase in temperatures during printing. Tensile and compressive strengths decrease with the increase in temperature whereas creep properties of materials increase with increase in temperature. Table 1 shows the significant process parameters.

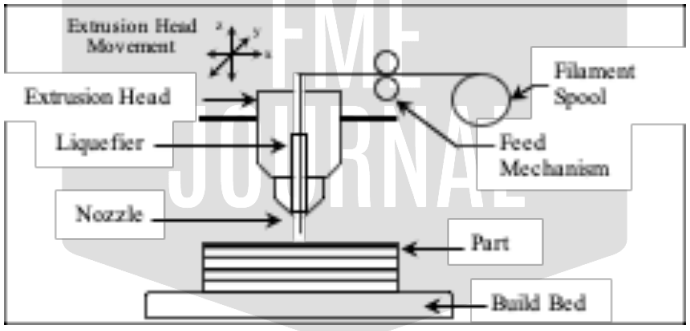


Fig. 1. Components of FDM technique

Steps followed in FDM

1 Make a computer-aided design (CAD) model of the part to be printed in CAD software.
2 Export CAD model to STL file format.
3 Use any 3D printing software to read STL (stereolithography) file and set various print parameters on to the sliced CAD model.
4 Fed sliced CAD model file with print details to the FDM machine.
5 Check for the orientation and offset of the CAD model from build platform before actual printing.
6 The feedstock of material is extruded from the nozzle in layer-by-layer fashion.

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7 To prevent the overhanging part of the structure from breaking support-structure is provided.
8 Build component is taken for post processing parts.

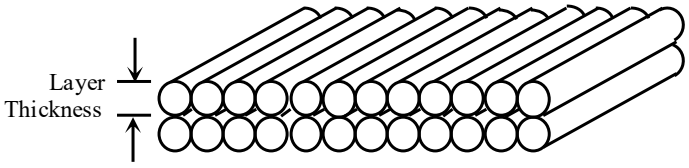


Fig. 2. Layer thickness

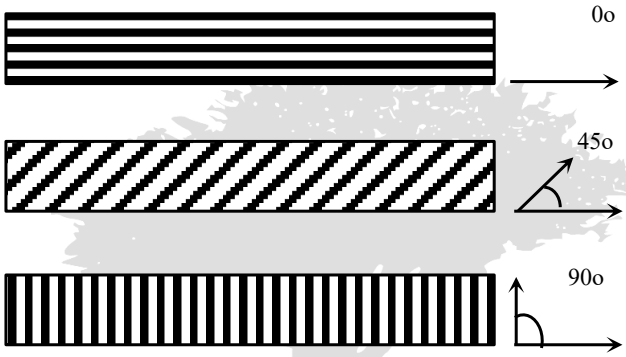


Fig. 3. Different raster angles

Table 1. Significant process parameters on FDM

FDM Process Parameters	Definition
Layer Thickness	The height of layers which is deposited from the extruder nozzle (see Fig.2).
Build Orientation	It is the orientation of parts with respect to X, Y and Z-direction of the machine.
Raster Angle	It is the angle of extruded material deposited in accordance to X- direction of the build platform (see Fig.3).
Extrusion temperature	The temperature at which the heated material filament is drawn through the extruder nozzle.
Print Speed	The speed at which nozzle tip moves on the platform is known as print speed.
Infill density	It implies the density of filled material inside the printed model.
Nozzle diameter	Diameter of the nozzle is called the nozzle diameter.
Infill pattern	Infill pattern is the pattern in which the material is deposited to form the final component.
Number of contours	It is the solid outline, that forms along the internal infill pattern.

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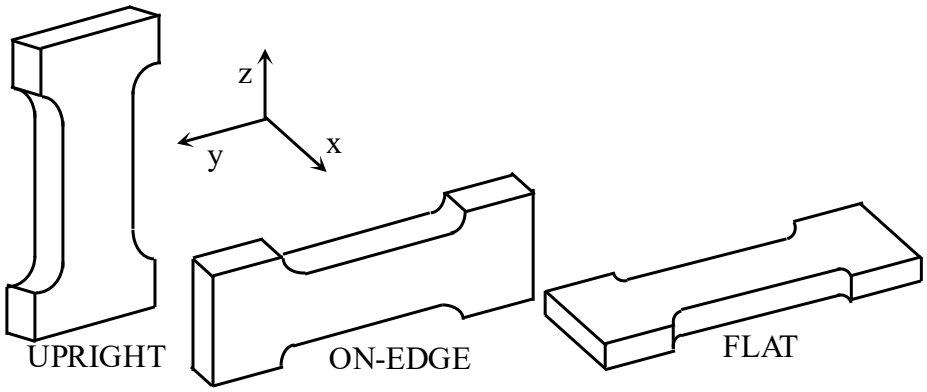


Fig. 4. Different build orientation

Materials Under Study

The materials considered in this paper are acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polyether-ether-ketone (PEEK), polycarbonate (PC), Polyethylene terephthalate glycol (PETG) and blends of ABS and PLA.

Recent Research

A rich literature is available on the work carried out by the researchers aiming to optimize both tensile strength and wear strength of FDM produced parts with variations of printing material and process parameters in recent years [4, 5].

Effect of Materials on Tensile Strength

Higher tensile strength of FDM printed parts may be achieved by selecting a suitable AM material from the available range. There are data available from the tests carried out by researchers across the globe aiming to enhance tensile strength in the parts made out of variety of materials under similar input parameters. Table 2 show the performance of various popular AM materials when specimen bult with these materials and tested to measure various mechanical properties. Data in the table show that specimen made of PLA, PC or PEEK performed better in tests conducted in comparison to ABS [6 -9].

Table 2. Comparison of tensile strength in FDM produced parts

Author(s)	Findings	Reference
Ebel et al.	PLA is on an average around 1.5 times stronger than ABS	6
Tymrak et al.	Generally tensile strength of PLA is twice of ABS	7
Cantrell et al.	The strength of PC is nearly 1.9 times of ABS	8
Wu et al.	It is found that PEEK is 108% stronger than ABS	9

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Effect of Raster Angle on Tensile Strength

Many researches have witnessed that angle of extruded material during printing on build platform significantly affects the tensile strength of the product (see Table 3). The specimens can be printed with raster angles of 00, 150, 300, 450, 600, 750, 900 layer-wise with respect to x-axis of build platform [8, 10-12]. Tests have also been conducted on specimens having cross pattern with raster angles of 00, 900 and crisscross pattern with raster angles of -450, 450 in alternate layering during build [13-15].

Table 3. Effect of raster angle on tensile strength of FDM produced parts

Raster angle investigated	Material	Findings	Reference
0^0, 45^0, 90^0	ABS	Specimens printed with 0^0 raster angle came out approximately two times stronger than those printed with 90^0 raster angle.	[10]
0^0, 30^0, 45^0, 60^0, 90^0	ABS	Specimens printed with 0^0 raster angle attain the highest tensile strength when building flat on edge only.	[11]
0^0, 15^0, 30^0, 45^0, 60^0,75^0,90^0	PC	Specimens printed with 0^0 raster angle came out approximately three times stronger than those printed with 90^0 raster angle.	[12]
45^0, 90^0, 30^0, 60^0	PC	Optimal results were obtained with specimens printed with 45^0 raster angle for flat orientation only.	[8]
0^0, 90^0, 45^0	PLA	Specimens printed with 45^0 raster angle were found on an average 10% stronger.	[13]
0^0, 90^0, 45^0	PLA	Specimens printed with 0^0 raster angle were found approximately 25% stronger than those printed with 90^0 raster angle.	[14]
-45^0, 0^0, 45^0, 90^0	ABS	With (-45^0, 45^0) Modulus of Toughness was increased by 200% as compared to specimen build at (0^0, 90^0).	[15]

Effect of Print Orientation on Tensile Strength

Experiments conducted by the researchers in testing the mechanical properties of FDM produced specimen printed with varying print orientation (or build orientation) show that the print orientation significantly affect the mechanical properties of printed specimen. Three print orientations are set as flat, on-edge and upright (see Fig. 4). Table 4 shows the results of the tests conducted by the researchers to observe the variation in mechanical properties of specimen with build orientation. Specimen with flat and on-edge build orientation achieve better mechanical properties than the specimen with upright build orientation [8,11,16-17].

Table 4. Effect of print orientation on tensile strength of FDM produced parts

Material and print orientation investigated	Print orientation for maximum tensile strength	Findings	Reference
ABS: flat, on-edge, upright	Flat and on-edge	There is very little difference between flat and on-edge orientation. Both are generally 50 to 100% stronger than upright orientation	[11]
ABS: flat, on-edge, upright	None	No significant difference observed	[8]
PC: flat, on-edge, upright	On-edge	Flat orientation performed better in comparison to upright orientation	[8]
PLA: flat, on-edge, upright	Flat and on-edge	No significant difference between flat and on-edge. Flat and on edge are twice the strength of upright.	[16]
ABS and PETG	Flat	For better compressive strength the flat orientation is preferable	[17]

Effect of Layer Height on Tensile Strength

Data available have witnessed that layer thickness affect the properties of printed specimen to a great extent.7 Experiments showed that thinner the material layer during printing, better will be the strength of the printed specimen [16,18,19]. Table 5 presents the data of the experiments

to measure strength of FDM produced parts conducted by the researchers when parts are printed with variability in material and layer thickness.

Table 5. Effect of layer thickness on tensile strength of FDM produced parts

Material: Layer thicknesses investigated	Layer thickness for maximum tensile strength	Findings	Reference
ABS: 0.127, 0.178, 0.254 mm	-	Thinner layers add strength but it also increases distortion in sample	[18]
ABS: 0.2, 0.4 mm	0.2 mm	layer thickness of 0.2mm is strongest among all raster angles	[19]
PLA: 0.2, 0.3, 0.4 mm	0.2 mm	0.2 mm layer is better than other two	[7]
ABS: 0.2, 0.3, 0.4 mm	0.2 mm	0.2 mm layer does not show any significant value	[7]
PLA: 0.06, 0.12, 0.18, 0.24 mm	0.06 mm	Among various variables, a sample of 0.06 mm layer thickness is the strongest.	[16]

Other Variables Affecting Tensile Strength

Apart from controlling the FDM process parameters, investigations are made to enhance tensile strength by a variety of ways:

1. Some studies suggested that tensile strength depends upon inner part structure, build direction and tool path generation [20].

2. Rectilinear pattern with 100% infill material shows the highest tensile strength, with a value of 36.4 MPa which is nearly strength close to raw ABS material within 1% range [21].

3. With increasing nozzle temperature, strength increases from 34 to 56 MPa. A negative effect on PLA-based samples was observed during annealing process, because of the possible stress build-up in material. Therefore, annealing of PLA-based material is not recommended [22].

Conclusions

The key findings of the literature studied are:

1. On an average PLA, PC and PEEK showed almost around two times the tensile strength of ABS manufactured parts.

2. For ABS material, specimen produced with 00 raster angle showed highest tensile strength. For PLA based samples 00 or 450 raster angle resulted in higher tensile strength. For parts produced with PC on 450 raster angle showed better results.

3. Printing should not be recommended in upright position if tensile strength enhancement is the priority. ABS, PLA and PC showed better tensile strength in flat position or edge position.

4. Different research work on ABS samples showed that negative air gap gives better results in achieving high tensile strength in FDM produced parts.

5. Layer height in the case of flat or on-edge orientation for both ABS and PLA samples should be low so as to obtain maximum tensile strength.

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