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# Effect of printing parameters on the mechanical behaviour of the thermoplastic polymer processed by FDM technique: A research review

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**A B S T R A C T**

Fused deposition modelling (FDM) is an additive-based manufacturing technique used by various industries due to its effectiveness & ability to make complicated geometries possible. This technique requires sufficient knowledge about the process and its parameters including their effect on the component's mechanical characteristics. Thus, it is crucial to review the available articles on this topic not only to identify the practical and useful aspects, limitations, and process variables but also to understand how the results of the literature are relevant to be used for real applications and further studies. A systematic literature review is carried out based on the type of 3D printing materials. The printing parameters which influence the mechanical characteristics of the FDM specimens are discussed based on the results presented in the literature. From the present study, it has been found that the process variables such as orientation, raster angle, raster width, layer height, and contours directly affect the quality of the 3D-printed parts. It has also been found that the effect of these process variables also varies with the type of thermoplastic materials. The present article will help researchers to select FDM processed material and appropriate process variables for further research.

**A R T I C L E I N F O**

*Keywords:*
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## 1. Introduction

Plastic manufacturing is one of the cutting-edge market that produces plastic components at a low price and least time [1]. There are many processes available to manufacture plastic components like injection moulding, Blow moulding, etc. These processes are beneficial for large volume production as mould development for a specific component is quite costly. In contrast, other techniques are also available which are cheaper for low volume production, such as fused deposition modelling (FDM) or fused filament fabrication (FFF) [2]. FDM uses 3D CAD data for creating a physical model with the help of CAD softwares and 3D printing machines. This technique rapidly transfers design ideas into functional prototypes from the regular CAD model. It builds the product with complex geometry and is hard to be fabricated using conventional manufacturing techniques at low costs. It uses a 3D scanner for an existing product and CAD software for a new product to generate virtual CAD model and build physical products using different AM technologies.

These technologies are used in various manufacturing sectors like defence, aerospace, medical, art and design for customization and rapid production [3-5].

Additive manufacturing is a modern manufacturing technique to create components by depositing materials layer by layer using a virtual model developed in CAD. In this process, the CAD model is exported into stereolithographic (*.stl) format, which defines the entire model into a series of 2D cross-sections. The converted file is then transferred to any of the AM machines for creating the physical part [6, 7] with more accuracy, stability, and durability. Additive manufacturing is generally designated as (ISO/ASTM standard 52900:2021 [1]).

- Stereolithography (SLA): The final product is generated with the help of an ultraviolet laser inside a vat of resin. This method uses light-sensitive polymers, whose limited availability limits the application of this technique. Though, it provides a better surface finish and lesser raw material wastage.
- Selective laser sintering (SLS): This process uses powder as raw material which is melted and fused with the help of a laser beam. The fused powder is then stacked layer upon layer to form the part based on CAD data. The performance of the components sintered through SLS process is significantly affected by the quality of powder used.
- Polyjet 3D printing (PJP): This technology uses a variety of printing materials. In the dentistry and medical field, patient anatomy can be better understood by printing the model using this technique.
- Inkjet 3D printing (IJP): This technique uses the liquid formed of polymer solution to build parts layer by layer. It is economically good for printing the part using a variety of materials.
- Laminated object manufacturing (LOM): it uses material sheets to fabricate components layer by layer with the help of a laser, which cut the sheets as per the requirement. The layer of the sheet is combined using adhesives, and the part is fabricated by repeating the steps.
- Multi-Jet-Printing (MJP): In this technique, a thin solid layer of ceramic or metallic powder is created by spraying a liquid binder through a nozzle. In order to have higher strength the fabricated part is sintered in the furnace.
- Colour-Jet Printing (CJP): This technique is frequently used in medical applications due to its ability to print coloured products. In this technique, powder and binder are used as core material and resin respectively. The powder is spread over a platform with the help of a roller to form a layer and then the binder is sprayed through a printing head jet over each layer at a point specified by CAD software to form the final product.
- Fused Deposition Modelling (FDM): This technique is based on the extrusion method, in which, the thermoplastic material is melted through heating and deposited layer by layer over a printer bed to fabricate a model.

These techniques vary according to the building layers and based on the materials type that can be used for part fabrication. Among the available additive manufacturing technology, the FDM process is best to manufacture thermoplastic components due to its low initial investment, less material wastage, simplicity of the process, and easy availability of 3D printing software [8].

## 2. The FDM technique

The brief layout of FDM technique is graphically represented in Fig. 1. In this process, the part is modelled using CAD software and converted to STL format. Almost all CAD software can generate this format and sent it to RPT software to check the defects in the model [9]. In the FDM process, wire of polymer is liquified and extruded along a precise toolpath creating the shape of each layer. The system extrudes both build material and temporal support material with the help of nozzles mounted on the extruder [10]. The movement of the extruder head is controlled through the motor, and the low temperature of the printing bed allows the deposited material to solidify very fast [11]. The system repeats the step until the part is finalized. After completion of the process, parts are moved out of the machine bed and support material is removed using a different technique.

In the fused deposition modelling process, as described above, two forms of materials are used. One is to build the physical model, and another is for generating a support structure.

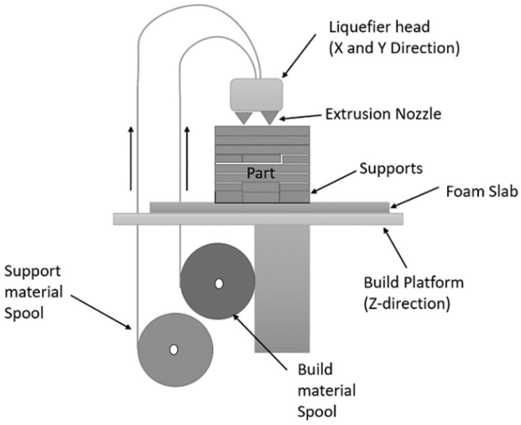


**Fig. 1** Simplified layout for FDM process

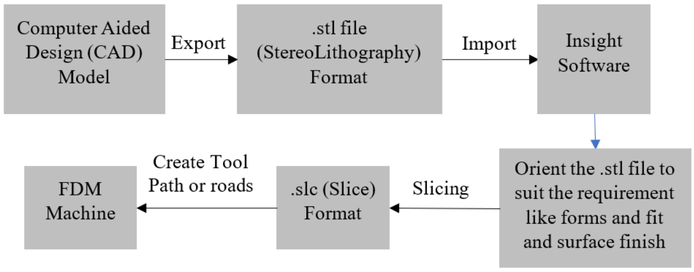


**Fig. 2** Fused deposition modelling process flow diagram

This process produces low stiffness products of thermoplastic polymer material. ABS and PLA polymers are compatible and cheap; therefore, it is widely used with 3D printers. Recently, NASA designed a space exploration vehicle for transporting humans to Mars with almost 70 FDM parts onboard such as vents, ducts, etc. [15]. An ability of functional efficiency under a cryogenic environment made PLA and ABS to be used for the fabrication of the rover.

The performance of PLA is quite well under low temperatures and has also been used in the medical field [16]. However, the low toughness characteristic of PLA made it to use with the composition of ABS [17]. ABS found its wide application in automobile sectors [18].

For complete understanding of the FDM process, one has to perform many trials, although many researchers have investigated the mechanical behaviour of FDM built components and found that those are affected by various process variables/parameters.

All these parameters are represented through the fishbone diagram shown in Fig. 3. The present work is focused on identifying how these variables affect the 3D printed part quality.

The selection of appropriate process parameters has made FDM a complicated manufacturing process. Understanding the selection of these parameters is quite difficult [19, 20].

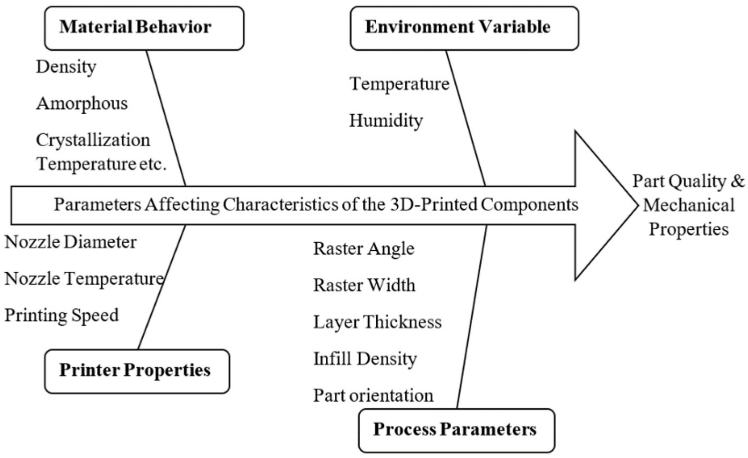


**Fig. 3** Parameters/variables affecting FDM part quality

## 3. A research review and discussion

### 3.1 FDM process parameters

The mechanical behaviour of FDM based parts is affected by various process parameters like infill-density, pattern (via honeycomb, rectilinear, concentric), raster-width, layer thickness (h), temperature, extruder speed, the air-gap in the same layer or between the layers, raster-angle (via 0°, 45°and 90°), nozzle diameter, build-orientation (via on-edge, upright, and Flat), etc [21, 22]. The different process variables affecting the mechanical characteristics of the part are described as follows.

- Layer thickness: when a material is extruded from the tip of the nozzle to form a layer, the height of that layer along a vertical direction is termed layer height or thickness (Fig. 5). The layer height value is always lower than the diameter of the nozzle tip [22]. The selection of layer thickness is based on:
  - The diameter of nozzle tip [19]
  - The material [19]
- Build-orientation: It is the alignment of the built component within the printing bed along X-axis (Flat), Y-axis (Up-right), or Z-axis (On-edge) of the 3D printing machine [19, 23] Build-orientation of the part is shown in Fig. 4.

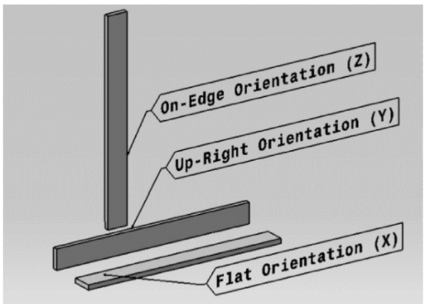


**Fig. 4** Build-orientation of the Component

- Raster-angle: It is the inclination of extruded material with the X-axis of a printing bed (Fig. 5). This angle ranges from 0° to 90° [19, 23].
- Air-gap: The free space between two successive beads on the same layer of the 3D printed part is termed as air-gap [19, 23] (Fig. 5).
- Build-style: Build-style is the way rasters are filled to build the part. The build-style of any component defines its density. The parts can be fabricated with three different Build-styles [19].
  - Solid normal: This build-style completely fills the interior of the part and provides a strong interior.
  - Sparse: This Build-style leaves the gap while material deposition uses a unidirectional raster thereby minimizing the material consumption and part-build time.
  - Sparse double dense: This build-style uses a crosshatch raster pattern, which reduces material consumption and part-build time.
- Support-style: It helps to prevent the collapsing of components during fabrication by extending the surface of the model [19]. It can be provided in four different ways.
  - Basic: it is the default support-style, which provides support to all the part features using small support raster curves.
  - Sparse: Compared to basic support, it utilizes less amount of material, which reduces the support material consumption.
  - Surround: It is used for all the parts to fill the small features or small components.
  - Break-away: It's equivalent to "Sparse," except it has separate blocks that are easier to remove compared to the other three types of support styles.

- Extrusion temperature: It is the temperature with which the polymeric filaments are treated within the nozzles prior it extruded. Its value varies with the type of material and printing speed [23].
- Print Speed: It is the movement of nozzle tip along the printing bed plane for fabrication of the part [23].
- Nozzle diameter: It is defined as the diameter of the nozzle tip of the extruder [24]
- Infill pattern: It is defined as the pattern in which extrusion of material takes place to fill the internal zone of a 3D printed part. Some of the widely used infill patterns are cross, linear infill, diamond, and honeycomb [23]. Honeycomb infill pattern has the capacity to resist a higher load compared to others [24].
- Raster/bead width: It is the beads size that are extruded on the printing bed to create rasters. The raster width for depositing any material is selected based on the diameter of the nozzle tip mounted on the extruder head [23, 19] (Fig. 5).
- Infill-density: The infill-density reflects the internal structure solidity of the fabricated component. Unlike the external structure of the part, Inside, the structure isn't always solid; it can be sparse, with a variety of shapes, sizes, and infill patterns [23, 24].
- Contour Number: Number of outer solid layers surrounding internal structure of the 3D printed component [19]. This process variable can also be referred to as perimeter (Fig. 5).
- Contour width/Perimeter width: It is defined as the thickness of each contour/perimeter measured horizontally [19] as shown in Fig. 5.
- Contour to contour air-gap: The free space between two successive perimeters [19] as shown in Fig. 5.

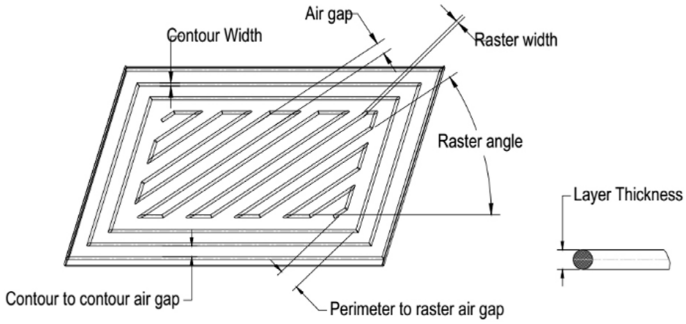


**Fig. 5** FDM Tool path parameters

### 3.2 Influence of process parameters on mechanical behaviour of parts

It is mandatory to investigate the influence of FDM printing variables on part characteristics, since, the influence of layer height on the part characteristics with flat orientation-built components is vague [25]. Some researchers reported that an increase of layer height causes decrease in mechanical behaviour [26-28]. Whereas Abbott *et al.* [29] reported the opposite behaviour. Wu *et al.* [30] found that, for P-E-E-K, an increase of layer height from 200 μm to 300 μm increased the bending, compressive, and tensile strength but a further increase of layer thickness causes a decrease in these properties. Samples fabricated with the lower speed along with lower layer height have higher tensile strength [31].

Rouf *et al.* [32] investigated the impact of various process variables on the mechanical behaviour of the component, and it was found that along with the strength of the component the process parameter also affects tribological properties [33-35]. Bhosle *et al.* [36] analysed the Impact of layer height, Printing speed, and infill percentage on tensile strength, printing time, and surface finish. From the analysis, it was found that layer height and infill percentage are highly contributing to the surface roughness and strength [37-38] of the build parts. The author suggested keeping layer height lower to improve the performance of FDM for surface roughness and tensile strength. Kaur *et al.* [13] analysed the impact of printing variables on the tribological behaviour of ABS polymer. The authors found that FDM process parameters not only improve strength but also improve surface finish and tribological behaviour. These improvements are obtained through optimization of the process variables as well as the addition of material to the raw polymer.

Kumar and Ranjan [39] analysed the effect of bed temperature, infill percentage, and outer perimeter on the elongation behaviour of Nylon 6. The authors found that at 100 infill per-centage, 60° C bed temperature, and four contour numbers provide maximum elongation in the component and thereby increase the tensile strength. They also found that infill percentage was more significant followed by bed temperature and outer perimeter.

Patil *et al*. [14] optimized some of the input variables viz. infill percentage, infill pattern, print speed, and layer thickness using multi-objective optimization for achieving better surface roughness, printing time, and filament length consumed for PLA. They reported the best response after the optimum setting of the parameters to the triangular pattern with 70 % infill, 100 mm/h printing speed, and 0.2 mm layer height.

Casavola *et al*. [20] explored the influence of raster orientation on the residual stresses that occur in FDM-fabricated ABS material parts due to the sudden change in temperature during processing. The authors concluded that components fabricated at a ±30° raster orientation is the worst configuration because the component exhibited higher residual stress, whereas the part fabricated with ±45° was the best configuration with the lowest residual stress.

Chacon *et al*. [40] analysed the impact of layer height, build direction, and feed-rate on the flexural and tensile behaviour of PLA specimens. The authors found that with an increase of layer height the mechanical properties decreased for flat oriented built specimens. However, for on-edge built orientation, the flexural strength was found lower at low layer height. On the contrary, for upright built orientation, specimens with high layer thickness possessed higher mechanical properties.

Shubham *et al*. [41] analysed the impact of layer height on impact, hardness, and tensile characteristics of ABS samples. The authors reported that Izod impact and tensile strength increased with the reduction of layer height. Whereas, the hardness value was first decreased and then increased with the increase of layer height. Later on, Shubham *et al*. [42] optimised the various printing parameters (viz. infill percentage, nozzle temperature, and layer height) by reporting the dynamic mechanical characteristics of ABS built components. The authors found the highest storage modulus at higher values of printing parameters. They also found that the impact of layer height and percentage of infill on dynamic mechanical behaviour was most significant, whereas the impact of nozzle temperature was low.

Daminabo *et al*. [43] gave an overview of AM techniques. The authors focused on FDM technique due to its cost efficiency, scalability, and ability to process a variety of materials. They suggested the use of biodegradable, bio-based, and eco-friendly materials having the capability of multi-functionality for future research and development. Ramesh and Paneerselvam [44] analysed the effect of various input variables like print speed, layer height, and infill percentage on the mechanical behaviour of fabricated nylon samples. Through the analysis, the authors found that parts printed with 100 infill percent exhibit optimum (max) flexural strength, Shore-D hardness, and UTS. This is due to the fact that 100 % infill don't have pores and therefore, the sample strength increased. The infill percent was found to have the highest impact on the mechanical behaviour of the fabricated components. Complete filling of the material eliminates the space caused for the crack growth of the sample. The layer height of 0.1 mm has affected the mechanical characteristics like impact, tensile and flexural strength. However, maximum Shore-D hardness was found at 0.3 mm layer height. The selected parameter of print speed didn't have a effective influence on the mechanical behaviour however, low speed causes heat-affected zones and higher speed causes the wrapping defect. The authors have suggested extending this work through the use of fillers in the nylon matrix and evaluating and comparing the related properties with pure material.

Pazhamannil *et al*. [45] assessed the effect of various process variables on the UTS of PLA component using the Taguchi technique. The values of UTS were predicted using an artificial neural network. The authors found that the tensile strength of the specimens increases at reduced layer height due to improved inter-layer bonding at reduced layer thickness. They also found the higher tensile strength with increased nozzle temperature due to quick growth of the neck caused by long-duration intermolecular diffusion across the interface. The authors concluded that infill speed did not influence the tensile property of the component significantly. Therefore, one can alter the infill speed without affecting the strength of the component. In order to get better tensile properties, one should keep a high nozzle temperature with a low layer height.

Yadav *et al*. [46] analysed the impact of printing variables like material density, layer height, and extrusion temperature on the tensile behaviour of different materials like ABS, PETG, and their different compositions. The analysis showed that extrusion temperature was found more dominant factor for the tensile strength compared to other considered parameters. The maximum tensile strength for PETG material was found at an extrusion temperature of 225 °C and 0.1 mm layer height. The authors suggested analysing the influence of other printing variables using the ANFIS model, or other models can also be developed to analyse these parameters.

Gebisa and Lemu [47] carried out a study to analyse the tensile behaviour of ULTEM-9085 material using the design of an experiment by varying some of the printing variables. The authors considered five printing variables viz. raster-angle, raster-width, air-gap, contour width, and contour number and found only the raster-angle to have a substantial influence on the tensile behaviour of the material. They suggested doing the flexural and impact test to analyse the parameters. Wankhede *et al*. [48] analysed the influence of the printing variables viz. support-style, layer height, and infill percentage on the build-time and surface roughness of part made of ABS material. The authors performed the experiment using Taguchi's L8 Orthogonal Array. The significant behaviour of the parameters was presented using the Analysis of Variance (ANOVA) technique. From ANOVA results, they found that the layer height has a more dominant effect on surface roughness and build-time among all the process parameters considered.

Solomon *et al*. [49] reviewed the development of the various samples and input parameter optimisation for the FDM technique. Through this review, the authors found that layer thickness or layer height was considered to be more significant factor in evaluating the part quality. It was also observed that the raster orientation dominates in evaluating the mechanical behaviour of the fabricated component. They also found that much work has been done on the printing variables and their optimisation; still, many unknown factors affect the part quality and process efficiency that need to be explored and suggested exploring more material as filament.

Vicente *et al*. [50] analysed the influence of two input variables, i.e., density and pattern of the infill, on the mechanical characteristics of ABS components. Through the experiment, 5 % variation in maximum tensile strength was observed with variation of infill pattern. This variation was significantly improved by varying the infill-density. Maximum tensile strength was observed for the component fabricated with rectilinear pattern and 100 infill percentage. The authors have reported that if the density is kept constant, then the honeycomb pattern exhibits a better tensile strength.

Rajpurohit and Dave [51] highlighted the impact of input variables like. layer thickness, raster-width, and raster-angle on the material characteristics of 3D printed PLA material. The authors chose tensile strength to analyse the mechanical behaviour of the fabricated component. They used the Taguchi method to optimise the process variables and also used the ANOVA tool to predict the significant process variables. Based on the experimental results, they observed the maximum tensile at a raster-angle of 45°, and it was also observed that tensile strength increases with increase of layer height. Among the selected parameters, raster-width was found to be the most significant process variable affecting strength.

Dawoud *et al*. [52] compared FDM and injection moulding techniques by analysing the mechanical behaviour of ABS material. The authors explored the potential of the FDM technique by varying the parameters like raster angle and gap. They varied the raster angle of odd as well as even layers. Through the investigation, they found the raster gap as a significant input for FDM, where denser components equivalent to moulded parts can be fabricated using a negative gap of −0.05 mm. It was also observed that the flexural and tensile strength of the FDM component fabricated with +45° raster-angle of even layer, −45° raster-angle of odd layer, and gap of −0.05 was able to attain 86 % and 91 % respectively of the moulded parts strength respectively. The FDM technique showed the dimensional accuracy acceptable and found within the specified range of size. Further, raster angle and gap did not find to be affecting the dimensional preciseness of the component.

Wang *et al*. [53] analysed the impact of input variables on the mechanical behaviour of 3D printed PEEK material. The authors reported the impact of process parameters like the layer height, printing speed, and printing temperature on the microstructure, mechanical characteristics, and surface quality of the fabricated component. Through the analysis, they found that components possessed maximum density, along with improved surface quality and reduced internal defects when printed with a small printing layer height of 0.1 mm, a higher printing temperature of 440 °C, and a printing speed of 20 mm/s. Though the author considered some of the input parameters, the effect of other parameters still needs to be investigated like density, pattern, line direction, overlap percentage of infill, the diameter of nozzle and filament, the flow of filament, orientation of rasters, print direction, enable print cooling, UV Light, etc. The authors only focused on analysing the tensile characteristics and density of the part whereas, the other parameters like flexural strength, impact strength, etc. need to be analysed.

Kaplun *et al*. [54] explored the impact of raster patterns and print orientation on the mechanical behaviour of 3D-printed 9085 and Antero 840CN03 (PEKK) for their potential use in aerospace and defence-grade polymers. Through the analysis, the authors found that the mechanical strength of PEKK was higher than ULTEM 9085. They concluded that raster angle and pattern both play a major role to enhance the mechanical characteristics of FDM parts.

Sheoran and Kumar [12] reviewed the literature on the optimisation of FDM parameters and found that limitations in physical parameters, like availability of nozzle diameter and some specific values of layer height, restrict the integration of DOE and optimisation techniques. Thus, this limitation has to be addressed by coupling statistical DOE tools and modern optimisation techniques. Consequently, a newer mathematical modelling approach needs to be developed.

Kumar *et al*. [55] presented the influence of print orientation and fill density on flexural and tensile strength for a standard ASA material. The authors have followed ASTM standards to fabricate and test the specimen. Through the testing, the tensile strength was reported with 52.2 MPa when printed with Z-90 print orientation and 100 % fill density. The results were compared with injection moulded components and were found with higher tensile strength. Whereas, components fabricated with Y-90 print orientation and 25 % fill density exhibit high flexural strength of 65.7 MPa.

Szykiedans *et al*. [56] explored the mechanical behaviour of 3D printed PET-G. The authors only focused on tensile strength and elastic modulus. The author found variation in tensile modulus due to the presence of air-gap in the print structure

Durgashyam *et al*. [57] perceived the impact of printing variables on tensile and flexural properties of PET-G material fabricated using the FDM technique. They considered the process parameters like infill-density, feed-rate, and layer height to analyse their effectiveness. They found that the components with lower layer height and feed-rate and with higher infill-density have shown good tensile properties. In contrast, the material showed good flexural strength at minimum layer height, a lesser percentile of infill-density, and a moderate feed-rate. Through, this work authors concluded that among layer height, infill-density, and feed-rate, the significance of layer height is much higher compared to other process parameters.

Gebisa and Lemu [58] investigated the impact of FDM processing variables on the flexural strength of ULTEM 9085 considering five processing variables viz. air-gap, raster-angle, raster-width, contour width, and contour number. They found that raster-angle and raster-width have influenced the flexural property of the material to a larger extent.

Mohamed *et al*. [59] analysed the impact of printing variables on the dynamic mechanical characteristics of PC-ABS components fabricated using the FDM method. Through this analysis, they showed that air-gap, contour number, and layer height have the highest influence on the mechanical characteristics of the part. The authors also varied layer thickness, raster angle, air gap, build orientation, and road width to analyse the dynamic and cyclic conditions of 3D printed parts [60]. The authors used same material as before to optimise the parameters with a combination of artificial neural network and fractional factorial design. They found that dynamic modulus of elasticity increases with increase of layer thickness; whereas reverse trend was found with increase of other parameters.

Ahn *et al*. [61] analysed the impact of bead width, raster orientation, model temperature, air-gap, and material colour on the compressive and tensile behaviour of ABS parts fabricated using the FDM method. Their analysis showed that the mechanical behaviour of the fabricated components was found to be anisotropic and parameter-dependent. They also revealed that raster orientation and air-gap have an impact on the mechanical characteristics of the part.

Deng *et al*. [62] studied the optimisation of the mechanical behaviour of P-E-E-K in terms of printing variables. The authors considered layer height, printing speed, filling ratio, and extrusion temperature to analyse the tensile characteristics of the component. They revealed the optimum mechanical characteristics that can be obtained for the process parameters with a set of filling ratio at 40 %, printing speed at 60 mm/s, layer height at 0.2 mm, and extrusion temperature at 370 °C.

Onwubolu and Rayegani [63] looked at the impact of raster-angle, width, orientation, air-gap, and layer height on the tensile behaviour of ABS components fabricated using the FDM technique. Their study revealed that the optimal process variables that could enhance the tensile behaviour of the component are increased raster-angle, minimum raster-width, minimum layer height, and negative air-gap. It has also been observed that for zero-part orientation, maximum tensile strength is obtained.

Bagsik *et al*. [64] reported the impact of build direction on the compressive and tensile behaviour of ULTEM-9085-part build with FDM technology. The authors showed that the build-direction of the edge exhibits the highest tensile strength among all build directions, i.e., edge, upright and flat. Their investigation also revealed that compressive strength was maximum for the part built along upright-direction.

Bagsik and Schöppner [65] also explored the influence of other process variables like raster-to-perimeter and raster-to-raster air-gap, build-orientation, raster-angle, and raster-width. The tensile behaviour of the same material fabricated using FDM technology. Their study revealed that for all build directions with a negative raster air-gap, the tensile strength was highest. They also revealed that thicker filament can enhance the tensile behaviour for both build directions, i.e., edge and upright. However, the tensile behaviour for the components fabricated with build-orientation flat can be enhanced by using a thinner filament.

Motaparti *et al*. [66] analysed the impact of printing variables on the compressive nature of 3D-printed ULTEM-9085 component. The authors considered three process variables, like, build-orientation, raster-angle, and air-gap. They concluded that the compressive strength of the component gets affected by raster-angle and build-orientation.

Motaparti *et al*. [67] also highlighted the influence of the process variables like air-gap, raster-angle, and printing direction on the flexural behaviour of ULTEM 9085 fabricated using the FDM process with Build-styles of sparse and solid. Their analysis uncovered that the build-orientation of vertical or on-edge could provide higher flexural yield strength compared to other build directions.

Masood *et al*. [68] presented the impact of the airgap, raster-angle, and raster-width on the tensile strength of Polycarbonate (PC) polymer. The authors found the highest tensile strength of the selected material on a process parameter setting as in air-gap type of solid normal, raster-width of 0.6064 mm and raster-angle of 45°.

Gorski *et al*. [69] presented the impact of part orientation on tensile, bending, and impact strength of the part fabricated by ABS. The result showed that with a change in the orientation, the values of strength increased due to a change in macroscopic material behaviour.

Durgun and Ertan [70] explored the influence of part orientation and raster-angle on surface roughness, tensile and flexural characteristics. Through the result, the authors suggested that the part orientation has the highest influence on the product quality and mechanical properties of the part compared to the raster-angle. The result also showed that surface roughness has a close relationship with mechanical behaviour.

Ognzan *et al*. [71] explored the influence of deposition angle, layer height, and infill on the flexural strength of FDM samples fabricated using PLA material. The results showed that layer height has a dominant effect on flexural strength compared to the other two parameters. Table 1 shows an overview of the various process parameters for different polymers.

**Table 1** Some published work on FDM process parameters

| Ref. | Mat. | Input parameters | Remarks |
|---|---|---|---|
| Al-Ghamdi [72] | ABS | Fill density, Layer thickness, Shell thickness, Feed-rate, | Specific mass was not affected by feed-rate. The specific time and energy both decrease with the decrease of layer height and infill-density and by increasing feed-rate. |
| Garzon-Hernandez *et al*. [73] | ABS | Layer height, Number of layers, Raster orientation, | Maximum stress and higher elastic modulus were found for lower layer thickness and longitudinal raster direction. low mechanical property with an increased number of layers. |
| Pramanik *et al.* [74] | ABS | Printing, Speed, Extruder temperature, Fill density, Bed temperature, Layer height | Extruder temperature and print speed were found to be the most dominant parameters of surface roughness followed by the layer thickness and infill-density. |
| Galeja *et al.* [75] | ABS | Raster-angle (Fill angle) | With an increase in raster-angle, the strength of the component reduces. However, maximum strength is obtained at a raster-angle of 55°. |
| Divyathej *et al.* [76] | ABS | Layer height | Injection-moulded part exhibits higher tensile properties, and low layer thickness showed better mechanical properties among FDM printed samples. FDM specimens showed excellent flexural strength compared to moulded ones, and 0.15 mm layer thickness gave optimum flexural strength. 0.2 mm layer thickness showed the most preferable compressive strength. The surface finish of moulded samples was found to be better than FDM. |
| Kuznetsov *et al.* [77] | PLA | Nozzle diameter, Printing speed, Layer thickness | The Layer height has affected the intra-layer cohesion to a greater extent. An increase in layer height reduces the part strength for all nozzle diameters. |
| Rodríguez-Panes *et al.* [78] | ABS, PLA | Layer height, Infill density, Part orientation | The results for ABS showed a lower variation compared to PLA. The infill percentage has a higher influence on the mechanical characteristics of the part, although this effect is higher in PLA compared to ABS. The specimens fabricated using PLA having higher tensile strength than ABS due to their more rigid nature. |
| Arif *et al*. [79] | PEEK | Part orientation | The part orientation H-0° was found to be best for tensile, flexural, and fracture toughness, followed by H-90° and V-90°. |
| Rinaldi *et al*. [80] | PEEK | Infill density, Part orientation | The mechanical properties of FDM and injection moulded samples were found same for 100 % infill printed in the X-Y plane, whereas, samples printed in the Z direction were found to be extremely brittle with premature failures. Low mechanical properties were found in the samples fabricated with a low infill percentage. |
| Mishra *et al.* [81] | ABS | Contour number, Layer thickness, Raster-width, Part orientation, Raster angle and air-gap | Flexural strength was increased with increase of external perimeter (Contour). The failure also shifted from the edge to the centre. Anisotropy of the specimen was also reduced at 30° raster angle. |
| Samykano [82] | PLA | Fill percentage, Raster angle and layer height | Infill percentage significantly influenced the tensile strength out of selected input parameters. |
| Mendricky and Fris [83] | PLA | Layer height, Extruded line width, Top layer thickness, Number of walls, Infill percent, Infill pattern, Print speed, Part orientation etc. | Top layer height, Shape of the top layer, and print speed were found most influencing the roughness at the top of the fabricated part. Overall layer height, part orientation, and wall printing speed were found to be dominating for wall roughness. |

The effect of main process variables on the mechanical behaviour are presented in Table 2. The table also consists of most frequently used optimisation techniques. It is also observed that Taguchi and ANOVA based method is most often used for almost all the parameters. However, machine learning methods based on ANN and fuzzy is implemented with few parameters. The ANN and fuzzy based optimisation methods have proved to be more accurate in providing optimal set of parameters value.

**Table 2** The effect of the main process variables on the mechanical behaviour

| Process parameters | Influence on the mechanical behaviour | Optimisation technique used |
|---|---|---|
| Raster angle | Tensile strength, Flexural strength, Impact strength, Surface roughness, Dimensional accuracy | Taguchi method [19, 84], Gray relation analysis [84], ANOVA [84], Fuzzy Logic [85, 86], Artificial Neural Network (ANN), GA |
| Layer thickness | Tensile strength, Flexural strength, Impact strength, Hardness, Compressive strength, Dimensional accuracy, Surface roughness | Taguchi method [84], Hybrid particle swarm, Bacterial forage optimization, Artificial Neural Network (ANN), Gray relation analysis [84], ANOVA [84], Fuzzy logic [85, 86] |
| Raster width | Elasticity, Tensile strength, Flexural strength, Impact strength, Dimensional accuracy | Taguchi method [84], ANOVA [84], Artificial Neural Network (ANN), Fuzzy logic [85, 86] |
| Contour number | Elasticity, Tensile strength, Impact strength, Flexural strength, Impact strength, Dimensional accuracy | Taguchi method, ANOVA, Regression analysis [88] |
| Infill density | Flexural strength, Tensile strength, % Elongation | RSM, ANOVA, Taguchi method [89], GA, GA-ANN, GA-ANFIS [90] |
| Infill pattern | Surface roughness, Hardness, Flexural Modulus, Tensile strength | Taguchi method, ANOVA, Regression analysis [87] |
| Build orientation | Tensile strength, Flexural strength, Fracture toughness | Fuzzy Logic [85, 86], ANOVA [84], Regression analysis, Taguchi method [84] |
| Air gap | Tensile strength, Flexural strength, Impact strength, | ANOVA [84], Regression analysis, Taguchi method [84], Fuzzy logic [85, 86] |
| Support style | Tensile strength, Dimension accuracy, Surface roughness | ANOVA along with gray relational analysis, Taguchi method [91] |

## 4. Challenges and future scope

From the above discussion, it has been found that the process variables influence the quality of the FDM product to a great extent. Manufacturers and users are mainly concerned with the mechanical characteristics of the component like tensile strength, compressive strength, yield strength, flexural strength, impact strength, hardness, dimensional accuracy, production time, surface roughness, and durability. Therefore, researchers are investigating the most significant process parameter to enhance the mechanical characteristic of the component. However, there are still no unique significant parameters found for all materials, parts, and mechanical properties. There is always a need to adjust most of the parameters to meet the required part quality. After all these parameter adjustments, porosity remains within the FDM fabricated component because of its layering approach. The presence of porosity within the components fabricated through the FDM technique leads to having lower mechanical properties compared to the injection-moulded components. To enhance the mechanical behaviour and quality of these components, it is necessary to develop the relationship between printing variables and material characteristics through mathematical modelling approaches.

From the literature review, it has been found that various printing variables (parameters) influence the quality of the component fabricated using the FDM technique. Hence, it is required to identify the critical parameters and determine their optimum values to improve the quality of the component. However, there are very few authors who have developed the relationships of the process variables with the mechanical behaviour and part quality, which is not enough for all types of FDM processed materials.

Many authors have analysed the influence of FDM process variables on PLA, ABS, ULTEM 9085, PETG, Nylon-6 built parts. However, very few authors have reported on other FDM processed materials, both in terms of FDM process optimisation and material characterization. Therefore, it is necessary to fabricate and identify the significant process parameters for other FDM processed materials like ASA, PEEK, PEKK, PET-G, and nylon-12.

As far as material behaviour is concerned, most authors have reported on the optimisation of the printing input variables for enhancing the material characteristics of the parts fabricated using the FDM technique. However, very few authors have worked on the optimisation technique of FDM printing input variables for chemical, dynamic mechanical characteristics, chemical resistance, UV resistance and thermal of the parts printed using the FDM technique. Therefore, the impact of process variables on these factors needs to be investigated.

The impact of printing variables on surface roughness, dimensional accuracy, impact, flexural, compressive, and tensile strength have been studied thoroughly by the authors. However, the other types of material properties like stress-strain behaviour at high-strain-rate loading conditions, porosity, product and process cost, vibration, production time, creep, and hardness need to be studied. The researchers should also work on the application of new optimisation techniques integrated with DOE, modelling techniques, and new statistical designs in the future, and identify the optimum setting of printing variables, and should also test the functionality of parts fabricated using the FDM technique.

Environmental factors like relative humidity and temperature also affect the part quality. These factors may affect the surface quality and the dimensional accuracy of the FDM processed parts of materials like ABS, PLA, nylon-12, etc. Therefore, it is necessary to determine the optimal sets of humidity and temperature for FDM processed materials.

The process of FDM machines is restricted by some physical constraints and has an impact on the setting of the optimum values of process variables, which must be addressed in future research. Among these constraints, the most crucial is the layer thickness whose value depends on the nozzle diameter; therefore, the user cannot select the layer thickness values other than specified values for that particular machine. The second constraint is imposed on nozzle diameter, which has a specified range of raster-width. In these conditions, the user cannot use any arbitrary values other than those defined by their range. These constraints complicate the optimisation of the FDM process variables and their selection on the machine for fabricating the component. Therefore, it is difficult to solve FDM process-related problems using traditional DOE techniques. Thus, the development of new mathematical modelling and optimisation approach is required for solving the constraints-related problems for the selection of optimum values of process variables beyond the specified range and also make it possible and feasible for practical applications.

## 5. Conclusion

This work presents the various process parameters of fused deposition modelling-based additive manufacturing technique and their effect on mechanical characteristics of 3D-Printed components made of different thermoplastic materials. Through this study, it has been found that many researchers have worked on ABS, ABS+, PLA, ULTEM 9085; however, there exists future scope to analyse the influence of FDM process variables on the mechanical behaviour of other thermoplastic materials like ASA, PET-G, PEEK, and PEKK, etc.

The present study also identified that printing process parameters have their roles and influence. Among all the process parameters, layer height has the highest influence on surface finish, build time, and strength of the component. Maximum strength is obtained with a rectilinear pattern,100 % infill-density, and increased layer thickness. Raster width, raster angle, and contour numbers also affect the mechanical property of the component. It has also been found that most of the researchers analysed the influence on tensile and flexural properties; however, very few researchers have analysed the effect on impact strength. Overall, the parameters like part orientation, layer height, raster-angle, raster width, and contours directly affect the quality of the 3D-printed part.

From the investigation, the input variables which affect the mechanical behaviour of the part can be set with most significant (layer height, raster-angle, and raster-width), significant (contour width and contour number) and least significant (air-gap). Although many authors have suggested a minus air-gap for enhancing the mechanical characteristics of the component, it was observed that minus air-gap has some drawbacks. Its effect can differ based on the thermoplastic used for processing. Although FDM process saves time and cost for low volume production, whereas, mechanical behaviour of its product doesn't exceed injection moulded product. Hence, one should investigate other methods to improvise the properties of FDM products. Here, an effort is made to help researchers toward the selection of FDM processed material and variables for further research.

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